Puerto Rico's STATE OF THE CLIMATE 2014 – 2021

ASSESSING PUERTO RICO'S SOCIAL-ECOLOGICAL VULNERABILITIES IN A CHANGING CLIMATE

TEMPERATURES

PRECIPITATION

SEA LEVEL

STORMS

OCEAN ACIDIFICATION

CLIMATE CHANGE COUNCIL PUERTO RICO

DRNA

PROGRAMA DE MANEJO ZONA COSTANERA

NOAA

CLIMATE CHANGE COUNCIL
PUERTO RICO

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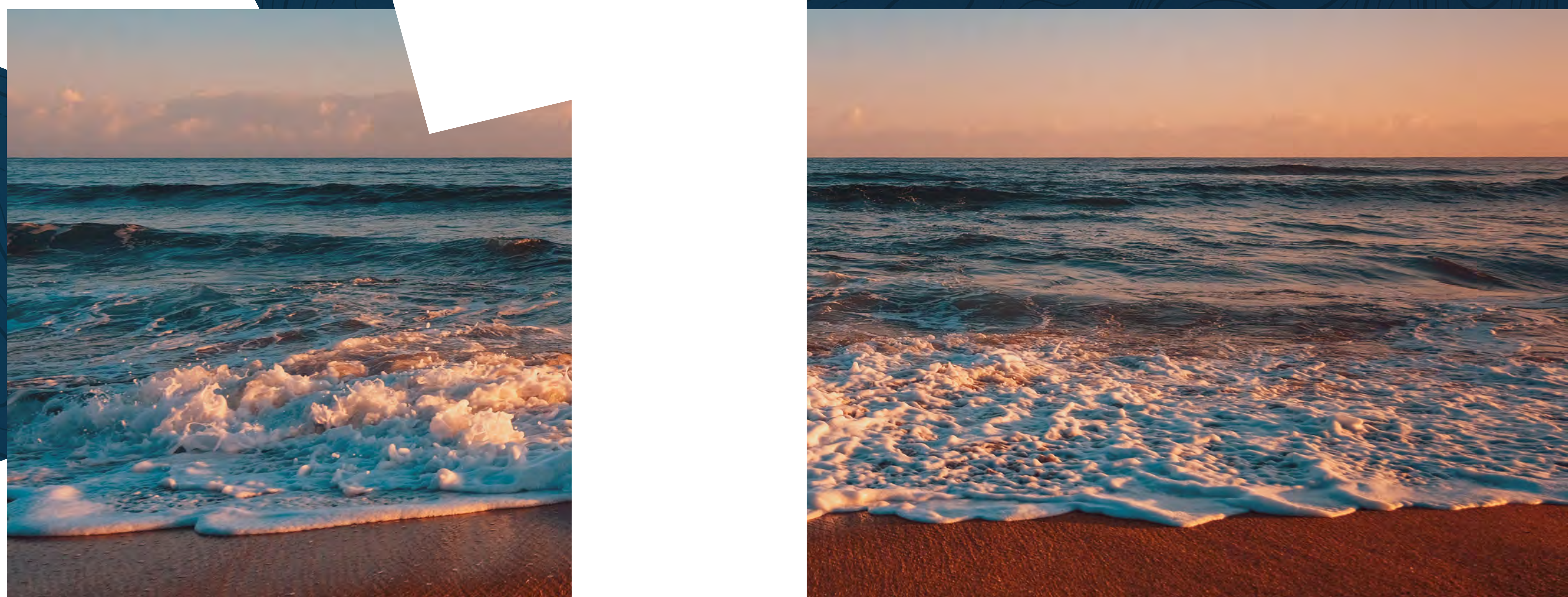
Puerto Rico Climate Change Council

Consejo de Cambio Climático de Puerto Rico

01

WORKING GROUP 1

Geophysical and Chemical Scientific Knowledge



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EXECUTIVE SUMMARY

The climate of Puerto Rico is influenced by the changing global climate. The following chapters present the current knowledge of the geophysical and chemical drivers and signals of global climate change as they affect the climate of Puerto Rico and influence the climate-dependent services, risks, and vulnerabilities that govern human well-being. These include sustainable economic development, delivery of ecosystem services, the conservation of natural and cultural resources, resiliency in built and natural systems, and food security. The chapters draw on global expertise of land, atmosphere, and ocean geophysical interactions associated with increasing greenhouse gases (GHG) that drive global warming and on local scientific expertise, data, observations, and modeled projections. They present the global warming scenario (section 1), the contribution of Puerto Rico to global climate change as GHG emissions and aerosols (section 2), the context of natural climate variability (section 3), observed and projected trends in temperature (section 4), rainfall (section 5), sea level rise (section 6), ocean acidification and sea surface warming (section 7), and the expected implications of warming climate on tropical cyclones affecting Puerto Rico (section 8).

Global scenario. Heat trapping GHG concentrations have been rising due to human activity for over 170 years, from preindustrial levels of annual average carbon dioxide (CO_2) of about 280 ppm to current (2021) levels of over 411 ppm. Additionally, GHG levels of methane (CH_4) and nitrous oxide (N_2O) have increased to 1891.6 ppb and 334 ppb, respectively in 2021. Global warming continues because of increased concentrations of GHG, with 7 of the 10 warmest years on record occurring since 2014. The 2020 average global surface temperature was 1.76 °F (0.98 °C)warmer than the twentieth-century average of 57.0 °F (13.9 °C) and 2.14 ˚F (1.19 ˚C) warmer than the pre-industrial period (1880-1900). Warming will likely be greater over land surfaces and will likely increase the intensity and frequency of high rainfall events and very dry weather, with implications for both flooding and drought. Projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks will influence regional rainfall trends and the location and frequency of extreme events. Thermal expansion of oceans and decreasing ice caps have led to a mean sea level rise of 0.20 m between 1901 and 2018, with rates increasing from 1.3 mm/yr between 1901 and 1971 to 3.7 mm/yr between 2006 and 2018. Anthropogenic increase of atmospheric CO_2 has altered the upper ocean's pH and heat content. Surface pH has declined globally causing reductions in the saturation state of calcium carbonate and affecting a variety of marine organisms and ecosystems.

Mitigation. Puerto Rico has a small carbon footprint relative to continental regions and developed nations. Reducing GHG emissions and sequestering carbon in Puerto Rico will have slight impact globally. However, mitigating climate change is a shared responsibility and quantifying GHG emissions and carbon sequestration is important to reach targets and align best practices for mitigation with local conditions and incentives, funding, regulations, and priorities identified at a national and multinational levels. Puerto Rico ranks 19th among 38 Latin American and Caribbean countries with the highest CO_2 emissions. Primary contributors to Puerto Rico net GHG emissions include industry, energy supply, and transportation.

Emissions. Estimates of GHG emissions in Puerto Rico range from approximately 25 to 46 million metric tons of gross CO_2 equivalent ($MtCO_2e$) emitted in 2018 and 2013 respectively. Either estimate represents less than 1 percent (~0.4-0.7%) of the total emissions emitted in 2019 in the U.S. Per capita emissions rates are between 50% to 78% of national averages. Emissions have declined by ~42% since 2005 and per capita emissions have declined as well, although at a lower rate since some of the decline in absolute emissions is associated with population loss.

Aerosols. Airborne particulate matter directly and indirectly affects the earth's energy balance and climate. Particulate matter (PM) can be seasonally significant in Puerto Rico, primarily in the form of Saharan dust plumes, but also as wildfire smoke and ash, volcanic emissions, and industrial and automotive exhaust. Black carbon (BC) is a fraction of the PM that absorbs radiation and has positive radiative forcing values. In Puerto Rico, BC concentrations have been found to be low to non-detectable.

Natural variability. The El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) have been associated with climate variability in Puerto Rico. One of the most important climate drivers for the year-to-year (interannual) climate variability is ENSO, a coupled ocean-atmospheric circulation feature within the equatorial Pacific with periodic changes in near surface ocean temperatures (El Niño) and the overlying atmosphere surface pressure (Southern Oscillation). Two anomalous ENSO phases that generate extreme weather include a warm phase (El Niño) with anomalous warm water in the central and eastern equatorial Pacific Ocean and a cold phase (La Niña) with anomalous cooler water for the same regions. ENSO phases impact tropical cyclone activity. El Niño events can increase vertical wind shear in the region and produce an unfavorable atmospheric environment for tropical cyclones formation, hence the number of storms is typically reduced during El Niño years. The opposite is true for La Niña years. ENSO is also influenced by global warming. While there have been observed changes of increasing amplitude of ENSO and frequency of El Nino events, the role of anthropogenic forcing is still uncertain. Other drivers of natural variability include the North Atlantic Oscillation (NAO) and Saharan dust concentrations. A positive NAO can increase trade wind strength, increase evapotranspiration potential, reduce sea surface temperatures, and reduce precipitation. Increases in Saharan dust concentrations within the tropical Atlantic have been associated with rainfall reductions within the Caribbean and Puerto Rico.

Temperature observations. Temperatures across Puerto Rico vary strongly with topography, with cooler high elevations and warmer low elevations. Low elevation minimum nighttime temperatures in Puerto Rico have steadily increased and are at the highest levels since, at least, the beginning of the observing period in the middle of the 20th century. These temperatures have increased by 1.6 [0.9 to 2.2] ˚C between 1950-2000 and 2011-2020. It is also possible (but with lower confidence) that nighttime temperatures at high elevation locations are also at the highest levels in the observing period. High elevation nighttime temperatures have increased by 1.2 [0.1 to 2.1] ˚C ˚C between 1950-2000 and 2011-2020. Daytime maximum temperatures have not warmed significantly across the island over the past 70 years (1950 to 2020).

Temperature projections. Temperatures are projected to increase in Puerto Rico and across the Caribbean region over the 21st century across scenarios that correspond to both, lower and higher levels of human-caused greenhouse gas emissions. However the amount of warming that occurs, particularly for the end of the century, will depend on the future emissions pathway. Model simulations indicate that maximum temperatures could significantly warm by the middle of the century if greenhouse gas emissions continue to rapidly increase.

Rainfall observations. Annual rainfall varies over short distances from less than 1000 mm to over 4000 mm with gradients driven by the easterly trade winds and island topography. The year-to-year variability is also large. For instance, annual mean rainfall in San Juan from 1925 to 2020 has a minimum of 903 mm in 1991 to 2275 mm in 2010. Trends in annual mean rainfall are not significantly different from the mean for the period 1925 to 2020 while heavy rainfall events (> 3 inches in a day) are increasing in frequency as are periods of drought, indicating that while annual rainfall may not be changing, severe rainfall and drought events may be increasing.

Rainfall projections. The annual average rainfall from the most recent global Climate Model Intercomparison Project (CMIP6) ensemble depicts decreasing rainfall with increasing emissions. Decreases in the annual rainfall averaged over the Caribbean for mid-century (2041-2060) range from approximately a 1% to 6% decrease for the lowest and highest emission scenarios respectively. Late century drying (2080-2099) increases, with a 20% decrease in annual rainfall totals for the highest emission scenario, but almost no change for the lowest emission scenario. Understanding potential future rainfall scenarios in Puerto Rico requires downscaling global climate models to resolve rainfall gradients within the island. Statistical and dynamical downscaling indicate a shift to drier conditions within Puerto Rico as greenhouse gas concentrations increase. The magnitude of the decrease is sensitive to the generation of the global climate models, with larger reductions in CMIP3 (~50%) compared to CMIP5 (~25%) at 3 °C mean global warming. Dynamical downscaled projections of select CMIP5 global climate models centered on mid-century indicate within island reductions exceeding 20% for many locations. Modelled rainfall reductions are mainly the result of a reduction in rainfall intensity during afternoon and evening hours when thunderstorms are more pronounced. Additionally, there is evidence that higher elevations in northeastern Puerto Rico may mitigate drying.

Sea level rise observations. Reconstructed monthly means of water level elevations from Magueyes Island, La Parguera, Lajas (1955 to 2020) and La Puntilla, San Juan Bay (1964 to 2020) show a current relative sea level trend of 1.89 mm/yr at Magueyes Island and 2.10 mm/yr at San Juan. Since 2010, the sea level at Magueyes Island and San Juan have risen approximately 4.4 mm/yr and 1.8 mm/yr respectively. Long-term data sets from both tide gauges show an increasing acceleration in sea level rise of approximately ~0.3 m.

Sea level rise projections. Sea levels will likely continue to rise for centuries, even under ambitious mitigation scenarios. Long range projections indicate possibilities of sea levels rising 2.3–5.4 m by 2300. Adaptation will be challenging for small islands with low-lying and intensively developed and urbanized coasts. Projected low emission scenario indicate SLR of 0.19 m (0.62 feet) and 0.36 m (1.18 feet) by 2050 and 2100, respectively for San Juan, Puerto Rico. The intermediate extreme scenario SLR ranges between 0.83 m (3.09 feet) and 3.10 m (10.14 feet) by 2050 and 2100, respectively.

Ocean acidification and sea surface warming. Surface seawater pH levels from 1988 to 2020 decreased at a rate of -0.017 ±0.0002 units per decade within the Puerto Rico Exclusive Economic Zone. The current surface ocean is 12% more acidic (based on H+ concentration) than in 1988. Analysis using remotely sensed sea surface temperature data from 1992 to 2020 at an open ocean location off the southwest Puerto Rico returned a warming rate of 0.26 ± 0.006˚C per decade. This is double the global rate and has resulted in a 2.3% higher surface ocean temperature than in 1992. Ocean warming has resulted in frequent seasonal occurrence of temperatures well above the coral bleaching threshold (29.5 ˚C). An average 25% of the observations off La Parguera and 13% of those off Ponce exceeded this threshold.

Tropical cyclones. Tropical cyclones encompass tropical depressions, storms, and hurricanes. From 1855 to 2019, there were on average 2.9 tropical cyclone events per five-year period within 200 nautical miles of Puerto Rico. There has been above average tropical cyclone activity for each of the last 5 five-year periods (25 years). Warmer sea surface and atmospheric temperatures are associated with parameters that influence cyclone development, intensity, and rainfall. Climate model projections are used to understand potential changes in tropical cyclone frequency, intensity, and rainfall that occur as the climate warms. With a warming of 2 °C, projected changes in the total number of storms remains uncertain, but tropical cyclone intensity is projected to increase. This includes increases in the longevity of associated surface winds, and the proportion of tropical cyclones that reach the category 4 and 5 levels. Climate model simulations depict heavier rainfall associated with tropical cyclones as sea surface and atmospheric temperatures warm. Projections of tropical cyclone precipitation rate show global mean increases of 14% for 2 °C of global warming. Combined effects of increases in tropical cyclone intensity (wind speeds and rainfall rates) with rising sea levels will lead to increases in storm surge and coastal flooding.

Fuente: CARICOOS

RESUMEN EJECUTIVO

El clima de Puerto Rico está influenciado por el cambio climático global. Los siguientes capítulos presentan el conocimiento actual de los impulsores geofísicos y químicos y las señales del cambio climático global que afectan el clima de Puerto Rico e influyen los servicios, riesgos y vulnerabilidades dependientes del clima que gobiernan el bienestar humano. Estos incluyen el desarrollo económico sostenible, la prestación de servicios ecosistémicos, la conservación de los recursos naturales y culturales, la resiliencia en los sistemas naturales y artificiales y la seguridad alimentaria. Los capítulos se basan en la experiencia global de las interacciones terrestres, atmosféricas y geofísicas oceánicas asociadas con el aumento de los gases de efecto invernadero (GEI) que impulsan el calentamiento global y en la experiencia científica local, los datos, las observaciones y las proyecciones modeladas. Se presenta el escenario de calentamiento global (sección 1), la contribución de Puerto Rico al cambio climático global como emisiones de GEI y aerosoles (sección 2), el contexto de la variabilidad climática natural (sección 3), las tendencias observadas y proyectadas en la temperatura (sección 4), precipitación (sección 5), aumento del nivel del mar (sección 6), acidificación de los océanos y calentamiento de la superficie del mar (sección 7) y las implicaciones esperadas del calentamiento del clima en los ciclones tropicales que afectan a Puerto Rico (sección 8).

Escenario global. Las concentraciones de GEI que atrapan el calor han aumentado debido a la actividad humana durante más de 170 años, desde los niveles preindustriales de dióxido de carbono (CO_2), con un promedio anual de aproximadamente 280 ppm hasta los niveles actuales (2021) de más de 411 ppm. Además, los niveles de GEI de metano (CH_4) y óxido nitroso (N_2O) aumentaron a 1891.6 ppb y 334 ppb respectivamente en 2021. El calentamiento global continúa debido al aumento de las concentraciones de GEI, con 7 de los 10 años más cálidos registrados desde 2014. La temperatura promedio de la superficie global en 2020 fue 1.76 °F (0.98°C) más cálida que el promedio del siglo veinte de 57.0 °F (13.9 °C) y 2.14˚F (1.19˚C) más cálida que el período preindustrial (1880-1900). Es probable que el calentamiento sea mayor en las superficies terrestres y probablemente aumente la intensidad y frecuencia de los eventos de alta precipitación y clima muy seco, con implicaciones tanto para las inundaciones como para las sequías. Los cambios proyectados en la circulación atmosférica regional, incluyendo los monzones y las trayectorias de tormentas en latitudes medias, influirán en las tendencias regionales de precipitación y en la ubicación y frecuencia de los eventos extremos. La expansión térmica de los océanos y la disminución de las capas de hielo han provocado un aumento promedio del nivel del mar de 0.20 m entre 1901 y 2018, con tasas que han aumentado de 1.3 mm/año entre 1901 y 1971 a 3.7 mm/año entre 2006 y 2018. El aumento antropogénico del CO_2 atmosférico ha alterado el pH y el contenido de calor de la capa superior del océano. El pH de la superficie ha disminuido a nivel mundial, lo que ha provocado reducciones en el estado de saturación del carbonato de calcio y ha afectado a una variedad de organismos y ecosistemas marinos.

Mitigación. Puerto Rico tiene una pequeña huella de carbono en relación con las regiones continentales y las naciones desarrolladas. Reducir las emisiones de GEI y secuestrar carbono en Puerto Rico tendrá un leve impacto a nivel mundial. Sin embargo, mitigar el cambio climático es una responsabilidad compartida y cuantificar las emisiones de GEI y el secuestro de carbono es importante para alcanzar los objetivos y alinear las mejores prácticas de mitigación con las condiciones e incentivos locales, el financiamiento, las regulaciones y las prioridades identificadas a nivel nacional y multinacional. Puerto Rico ocupa el puesto 19 entre los 38 países de América Latina y el Caribe con las mayores emisiones de CO_2. Los principales contribuyentes a las emisiones netas de GEI de Puerto Rico incluyen la industria, el suministro de energía y el transporte.

Emisiones. Las estimaciones de las emisiones de GEI en Puerto Rico oscilan entre aproximadamente 25 y 46 millones de toneladas métricas de CO_2 equivalente ($MtCO_2e$) emitidas en 2018 y 2013 respectivamente. Cualquiera de las estimaciones representa menos del 1 por ciento (~ 0.4-0.7%) de las emisiones totales emitidas en 2019 en los Estados Unidos. Las tasas de emisiones per cápita se encuentran entre el 50% y el 78% de los promedios nacionales. Las emisiones han disminuido en aproximadamente un 42% desde 2005 y las emisiones per cápita también han disminuido, aunque a un ritmo menor, ya que parte de la disminución de las emisiones absolutas está asociada con la pérdida de población.

Aerosoles. Las partículas en suspensión en el aire afectan directa e indirectamente el equilibrio energético y el clima de la tierra. El material particulado (PM) puede ser estacionalmente significativo en Puerto Rico, principalmente en forma de columnas de polvo del Sahara, pero también como humo y cenizas de incendios forestales, emisiones volcánicas y gases de escape industriales y automotrices. El carbono negro (BC) es una fracción del PM que absorbe la radiación y tiene valores positivos de forzamiento radioactivo. En Puerto Rico, se ha encontrado que las concentraciones de BC son bajas o no detectables.

Variabilidad natural. El Niño-Oscilación del Sur (ENSO) y la Oscilación del Atlántico Norte (NAO) se han asociado con la variabilidad climática en Puerto Rico. Uno de los impulsores climáticos más importantes de la variabilidad climática de un año a otro (interanual) es ENSO, una característica de circulación oceánica-atmosférica acoplada dentro del Pacífico ecuatorial con cambios periódicos en las temperaturas oceánicas cercanas a la superficie (El Niño) y la presión superficial de la atmósfera suprayacente (Oscilación del Sur). Dos fases anómalas del ENSO que generan un clima extremo incluyen una fase cálida (El Niño) con agua cálida anómala en el Océano Pacífico ecuatorial central y oriental y una fase fría (La Niña) con agua más fría anómala para las mismas regiones. Las fases de ENSO impactan la actividad de los ciclones tropicales. Los eventos de El Niño pueden aumentar la cizalladura vertical del viento en la región y producir un ambiente atmosférico desfavorable para la formación de ciclones tropicales por lo tanto, el número de tormentas se reduce típicamente durante los años de El Niño. Lo contrario ocurre para los años de La Niña. ENOS también está influenciado por el calentamiento global. Si bien se han observado cambios de amplitud creciente de ENSO y frecuencia de eventos de El Niño, el papel de la influencia antropogénica aún es incierta. Otros impulsores de la variabilidad natural incluyen la NAO y las concentraciones de polvo del Sahara. Una NAO positiva puede aumentar la fuerza de los vientos alisios, aumentar el potencial de evapotranspiración, reducir las temperaturas de la superficie del mar y reducir las precipitaciones. Los aumentos en las concentraciones de polvo del Sahara en el Atlántico tropical se han asociado con la reducción de las precipitaciones en el Caribe y Puerto Rico.

Observaciones de temperatura. Las temperaturas en Puerto Rico varían fuertemente con la topografía, con elevaciones altas más frías y elevaciones bajas más cálidas. Las temperaturas nocturnas mínimas en las zonas de baja elevación en Puerto Rico han aumentado constantemente y están en los niveles más altos desde al menos el comienzo del período de observación a mediados del siglo 20. Estas temperaturas han aumentado en 1.6 [0.9 a 2.2] °C entre 1950-2000 y 2011-2020. También es posible (pero con menor confianza) que las temperaturas nocturnas en lugares de gran altitud también estén en los niveles más altos en el período de observación. Las temperaturas nocturnas a gran altitud han aumentado en 1.2 [0.1 a 2.1] °C entre 1950-2000 y 2011-2020. Las temperaturas máximas diurnas no han aumentado significativamente en toda la isla durante los últimos 70 años (1950 a 2020).

Proyecciones de temperatura. Se prevé que las temperaturas aumenten en Puerto Rico y en toda la región del Caribe durante el siglo 21 en escenarios que corresponden tanto a niveles más bajos como más altos de emisiones de gases de efecto invernadero causadas por los humanos. Sin embargo, la cantidad de calentamiento que se produzca, especialmente para finales de siglo, dependerá de la ruta de las emisiones futuras. Las simulaciones de modelos indican que las temperaturas máximas podrían aumentar significativamente a mediados de siglo si las emisiones de gases de efecto invernadero continúan aumentando rápidamente.

Observaciones de precipitaciones. La precipitación anual varía en distancias cortas desde menos de 1000 mm hasta más de 4000 mm, con gradientes impulsados por los vientos alisios del este y la topografía de la isla. La variabilidad de un año a otro también es grande. Por ejemplo, la precipitación promedio anual en San Juan entre 1925 a 2020 tiene un mínimo de 903 mm en 1991 a 2275 mm en 2010. Las tendencias en la precipitación promedio anual no son significativamente diferentes del promedio para el período de 1925 a 2020, mientras que los eventos de lluvias fuertes (> 3 pulgadas en un día) están aumentando en frecuencia al igual que los períodos de sequía, lo que indica que si bien las lluvias anuales pueden no estar cambiando, las lluvias severas y los eventos de sequía pueden estar aumentando.

Proyecciones de precipitaciones. La precipitación promedio anual del conjunto más reciente del Proyecto de Intercomparación de Modelos Climáticos (CMIP6) muestra una disminución de la precipitación con un aumento de las emisiones. Las disminuciones en la precipitación anual promediada en el Caribe para mediados de siglo (2041-2060) van desde aproximadamente una disminución del 1% al 6% para los escenarios de emisiones más bajas y más altas, respectivamente. Para finales de siglo (2080 - 2099) la sequía aumenta con una disminución del 20% en los totales de lluvia anual para el escenario de mayor emisión, pero casi ningún cambio para el escenario de menor emisión. Comprender los posibles escenarios futuros de lluvia en Puerto Rico requiere una modificación de los modelos climáticos globales para resolver los gradientes de lluvia dentro de la isla. La reducción de escala estadística y dinámica indica un cambio a condiciones más secas dentro de Puerto Rico a medida que aumentan las concentraciones de gases de efecto invernadero. La magnitud de la disminución es sensible a la generación de modelos climáticos globales, con mayores reducciones en CMIP3 (~ 50%) en comparación con CMIP5 (~ 25%) a 3 °C de calentamiento global promedio. Las proyecciones dinámicas a escala reducida de modelos climáticos globales CMIP5 seleccionados, centrados en mediados de siglo indican reducciones dentro de las islas que superan el 20% para muchas ubicaciones. Las reducciones de lluvia modeladas son principalmente el resultado de una reducción en la intensidad de lluvia durante las horas de la tarde y la noche, cuando las lluvias son más pronunciadas. Además, existe evidencia de que las elevaciones más altas en el noreste de Puerto Rico pueden mitigar el secado.

Observaciones del aumento del nivel del mar. Promedios mensuales reconstruidos de elevaciones del nivel de agua en Isla Magueyes, La Parguera, Lajas (1955 a 2020) y La Puntilla, Bahía de San Juan (1964 a 2020) muestran una tendencia actual relativa al nivel del mar de 1.89 mm/año en la Isla Magueyes y 2.10 mm/año en San Juan. Desde 2010, el nivel del mar en Isla Magueyes y San Juan ha aumentado aproximadamente 4.4 mm/año y 1.8 mm/año respectivamente. Los conjuntos de datos a largo plazo de ambos mareógrafos muestran una aceleración creciente en el aumento del nivel del mar de aproximadamente ~ 0.3 m.

Proyecciones de aumento del nivel del mar. Es probable que el nivel del mar continúe aumentando durante siglos, incluso en escenarios ambiciosos de mitigación. Las proyecciones a largo plazo indican la posibilidad de que el nivel del mar aumente entre 2.3 y 5.4 m para el 2300. La adaptación será un desafío para las islas pequeñas con costas bajas y urbanizadas intensivamente. El escenario de bajas emisiones proyectado indica aumento en el nivel del mar de 0.19 m (0.62 pies) y 0.36 m (1.18 pies) para 2050 y 2100, respectivamente para San Juan, Puerto Rico. El escenario extremo intermedio de aumento en el nivel del mar oscila entre 0.83 m (3.09 pies) y 3.10 m (10.14 pies) para 2050 y 2100, respectivamente.

Acidificación del océano y calentamiento de la superficie del mar. Los niveles de pH del agua de mar superficial de 1988 a 2020 disminuyeron a una tasa de -0.017 ± 0.0002 unidades por década dentro de la Zona Económica Exclusiva de Puerto Rico. La superficie actual del océano es un 12% más ácida (a base de la concentración de H+) que en 1988. El análisis que utilizó datos de temperatura de la superficie del mar detectados remotamente de 1992 a 2020 en una ubicación en mar abierto frente al suroeste de Puerto Rico arrojó una tasa de calentamiento de 0.26 ± 0.006 ˚ C por década. Esto es el doble de la tasa mundial y ha dado lugar a una temperatura del océano en la superficie un 2.3% más alta que en 1992. El calentamiento del océano ha provocado la aparición frecuente de temperaturas estacionales muy por encima del umbral de blanqueamiento de los corales (29.5˚C). Un promedio del 25% de las observaciones frente a La Parguera y el 13% frente a Ponce superaron este umbral.

Ciclones tropicales. Los ciclones tropicales abarcan depresiones tropicales, tormentas y huracanes. De 1855 a 2019, hubo un promedio de 2.9 eventos de ciclones tropicales por período de cinco años dentro de las 200 millas náuticas de Puerto Rico. Ha habido una actividad de ciclones tropicales superior al promedio en cada uno de los últimos cinco períodos de cinco años (25 años). Las temperaturas más cálidas de la superficie del mar y la atmósfera están asociadas con parámetros que influyen en el desarrollo, la intensidad y las precipitaciones asociadas a los ciclones. Las proyecciones de modelos climáticos se utilizan para comprender los cambios potenciales en la frecuencia, intensidad y lluvia asociada a los ciclones tropicales que ocurren a medida que el clima se calienta. Con un calentamiento de 2°C, los cambios proyectados en el número total de tormentas siguen siendo inciertos, pero se prevé que la intensidad de los ciclones tropicales aumente. Esto incluye aumentos en la longevidad de los vientos superficiales asociados y la proporción de ciclones tropicales que alcanzan los niveles de categoría 4 y 5. Las simulaciones de modelos climáticos muestran lluvias más intensas asociadas con ciclones tropicales a medida que la superficie del mar y las temperaturas atmosféricas se calientan. Las proyecciones de la tasa de precipitación de ciclones tropicales muestran un aumento promedio global del 14% para 2 °C de calentamiento global. Los efectos combinados de los aumentos en la intensidad de los ciclones tropicales (velocidades del viento y tasas de lluvia) con el aumento del nivel del mar dará lugar a aumentos en las marejadas ciclónicas e inundaciones costeras.

SECTION 01
Our Warming Planet

Over the last 150 years the world has warmed as humans have continued to add heat-trapping greenhouse gases (GHGs) to the atmosphere (IPCC, 2021; Wuebbles et al., 2017; Figure 1). This warming has triggered many changes in the earth's climate. Numerous independent lines of evidence have documented these changes, from the atmosphere to the ocean to the polar regions. This warming, primarily in response to human activities, is causing widespread effects in the physical environment, including more intense storms, melting glaciers, disappearing snow cover, shrinking sea ice, rising sea levels, changes in rainfall patterns, and shifting droughts (Wuebbles et al., 2017).

Globally, surface temperatures have increased by 0.99 [0.84 to 1.10] °C in recent decades (2001-2020) compared to the pre-industrial average from 1850-1900 (IPCC, 2021). This warming has occurred over nearly the entirety of the earth's surface. Precipitation has also increased as the earth's atmosphere warms and contains more water vapor. But the changes in precipitation are uneven, with patterns of wetting and drying interspersed around the planet. As the earth warms, melting ice from land surfaces and expanding ocean volume has resulted in global mean sea levels to rise by 0.20 [0.15 to 0.25] m between 1901 and 2018 (IPCC, 2021). The rising concentrations of GHGs in the atmosphere, now higher than any period in the last 800,000 years, have also affected the chemistry of the ocean, causing it to become more acidic. These large-scale changes in the earth's climate are in turn causing changes locally to Puerto Rico's climate and environment.

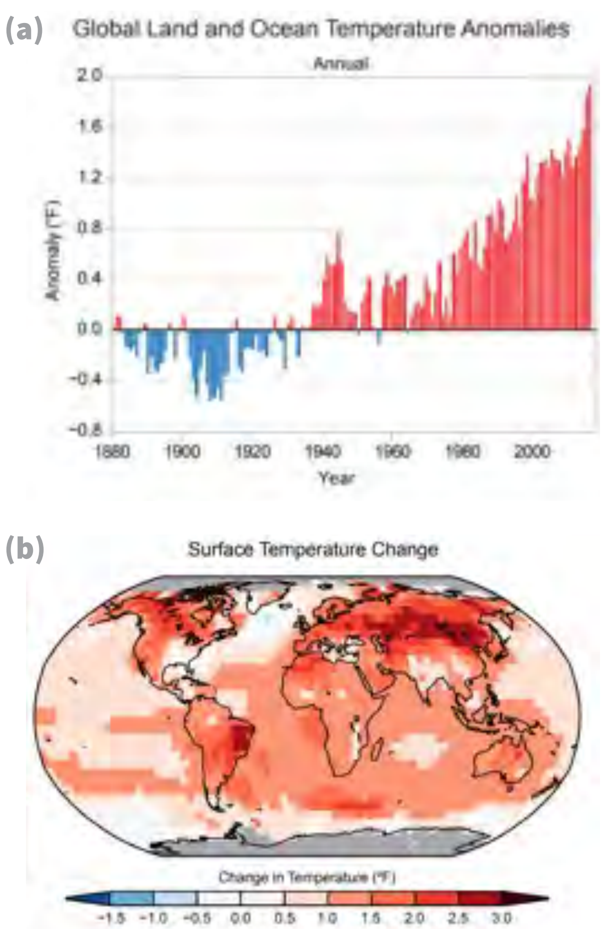


Figure 1. Global annual average temperature -

(a) Red bars show temperatures above the 1901-1960 average, and blue bars indicate temperatures below the average. From 1986 -2016 global average surface temperature increased by 0.7°C (1.26°F) compared to 1901-1960 (Wuebbles et al., 2017) and by 0.99 °C from 2001-2020 compared to 1850-1900 (IPCC, 2021).

(b): Surface Temperature Changes (in °F). (Figure from Wuebbles et al., 2017)

SECTION 02

Puerto Rico's Contribution to Global Climate Change

KEY MESSAGES

Per capita emissions of greenhouse gases from Puerto Rico are estimated to be between 37% and 63% as large as US per capita emissions, and represented between 0.4% and 0.7% of total US emissions in 2019.

Total emissions have declined by approximately 42% between 2005 and 2018 after rising by 80% from 1990 to 2005.

Particulate matter (PM) can be seasonally significant in Puerto Rico, primarily in the form of Saharan dust plumes, but also as wildfire smoke and ash, volcanic emissions, and industrial and automotive exhaust. Black carbon (BC) is a fraction of the PM that absorbs radiation and can contribute to global warming. In Puerto Rico, BC concentrations have been found to be low to non-detectable.

The most important GHGs contributing to human-caused climate change are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Globally, the atmospheric concentrations of these gases have increased by 46%, 157% (Reay et al., 2018), and 23% , respectively, from the pre-industrial era (IPCC, 2021). Based on data from the NOAA Global Monitoring Laboratory, the global annual average atmospheric CO_2 concentration was approximately 414 ppm in 2020. Puerto Rico's contribution to global climate change through emissions of greenhouse gases and local air pollution through aerosol emissions, is assessed below.

GREENHOUSE GAS EMISSIONS

Puerto Rico ranks 19th among the Latin American and Caribbean countries with the highest CO_2 emissions (EDGAR, 2016). Industry, energy supply, and transportation sectors dominate the contribution to the Puerto Rico net GHG emissions. There is some uncertainty about the current level of greenhouse gas emissions in Puerto Rico. Estimates range from approximately 25 million metric tons of gross CO_2 equivalent ($MtCO_2e$) emitted in 2018[1] to 46 $MtCO_2e$ emitted in 2013 based on the Center for Climate Strategies (2014; Figure 2). Despite the large range, these estimates represent less than 1 percent (~0.4-0.7%) of the total CO_2 emitted in 2019 in the U.S. Based on population estimates for Puerto Rico in 2018 and 2019 (US Census Bureau, 2021), total emission estimates would represent an approximate range of per capita emissions rates of between 7.4 and 12.8 $MtCO_2e$ per year. US per capita emissions in 2018 were ~20.2 tons CO_2, resulting in an estimated rate that is between 1.6 and 2.7 times higher than Puerto Rico. Historically, the energy, transportation, and the industry sectors have been the primary CO_2 emitters in Puerto Rico (Figure 3). From 1990 to 2005, Puerto Rico's gross CO_2 emissions increased by 80%. However, since that time emissions have declined by ~42%. Per capita emissions have declined as well, although at a lower rate since some of the decline in absolute emissions is associated with population loss.

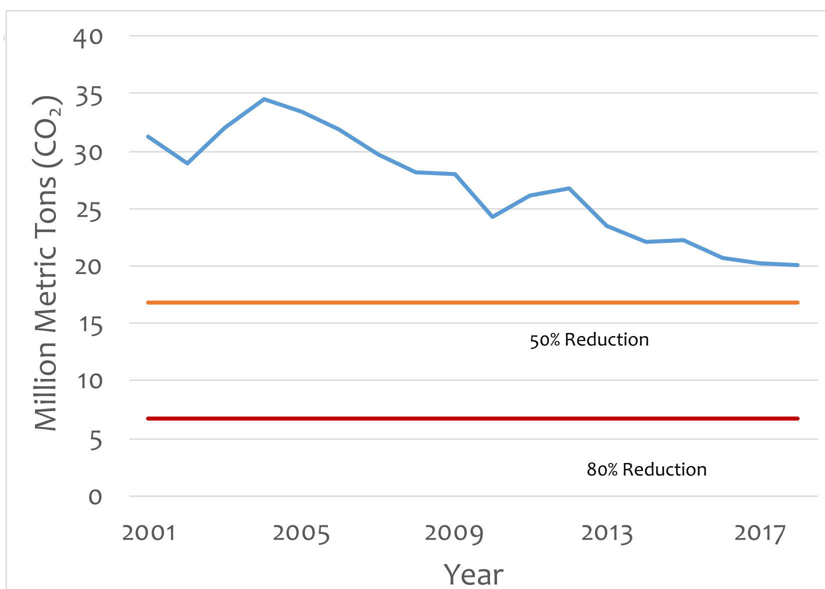


Figure 2. Estimated carbon dioxide emissions in Puerto Rico, 2001-2018. Emissions have declined by 42% since the peak in 2004. Orange and red lines represent 50% and 80% reductions, respectively from 2005 levels (the year used for US emission reduction goals). Source: Energy Information Administration (https://www.eia.gov/state/).

1 Energy Information Administration https://www.eia.gov/state/

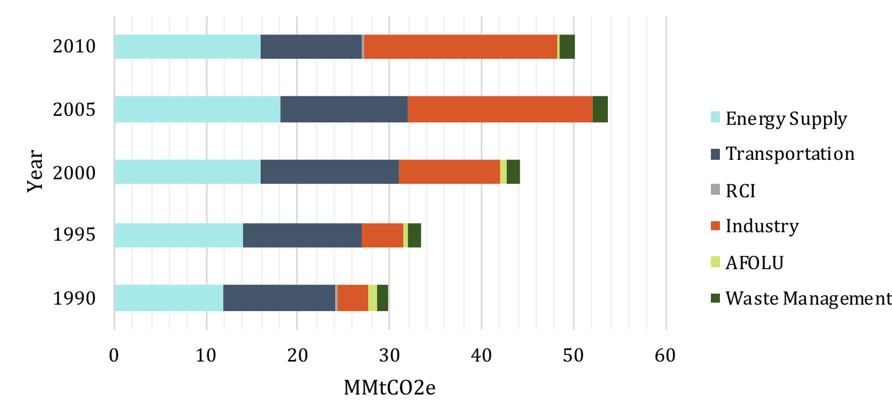


Figure 3. Net GHG emissions in Puerto Rico by sector, 1990 - 2010. The term RCI refers to residential, commercial & institutional. The term AFOLU refers to agriculture, forestry & other land uses. Adapted from the CCS Report (2014).

AEROSOLS

Aerosols are solid or liquid particles suspended in a gas, usually air. Aerosols can both directly and indirectly affect the earth's energy balance, and thus its climate. Direct effects (or forcing) occur by changing the amount of radiation energy that is scattered or absorbed in the atmosphere. Indirect effects occur through cloud formation processes, which affect the cloud's albedo (reflectance), lifetime, and precipitation. Local air quality and pollutant levels are influenced by local and global sources of these particulates which can be comprised of both natural and anthropogenic particles, such as mineral dust, sulfates, black carbon (BC) and organic carbon (OC).

Generally, the steady oceanic trade winds maintain pollutants' concentrations relatively low on the archipelago. Puerto Rico air chemistry composition is affected by Saharan dust plumes, urban-industrial sources, agricultural emissions, and sporadic volcanic emissions. Local concentrations of gases and aerosol are driven by atmospheric dispersion conditions that determine transport, mixing, and transformation (Jury, 2017).

Weather conditions impact the presence of air pollutants. Sea surface temperatures (SST) above normal in the equatorial zone and low in Northeast Pacific are related to higher aerosol concentrations. Furthermore, anomalies in easterly winds in the equatorial Atlantic contribute to an inflow of northern Amazon plumes into the Caribbean. Warm dry weather also assists in the suspension and accumulation of particulates and gases over the island (Figure 4b; Jury, 2017).

BC is a fraction of the particulate matter that absorbs radiation instead of scattering, hence it increases radiative forcing. It has been ranked as the "second most important individual climate-warming agent after carbon dioxide" (Bond et al., 2013). In Puerto Rico, BC concentrations have been found to be low to non-detectable (Jury, 2017; Allan et al., 2008). The BC concentrations have been estimated to be 0.04 ± 0.03 µg/m^3 in the Cape San Juan lighthouse and 0.04 ± 0.05 µg/m^3 in East Peak in El Yunque (Allan et al., 2008). Figure 4 shows the MERRA-2 model mean distribution of OC and BC [in 10-6µg/m^3] for 2005-2015, displaying low concentrations in the eastern Caribbean, including Puerto Rico, but higher towards the west and continental Caribbean.

Long-range aerosol plumes seem to merge with local sources of air pollutants with various radiative forcings. Mineral dust undergoes deposition and mixing before reaching Puerto Rico from Africa, increasing PM levels up to 120 µg/m^3 and causing visibility reduction, human health impacts, anticyclonic

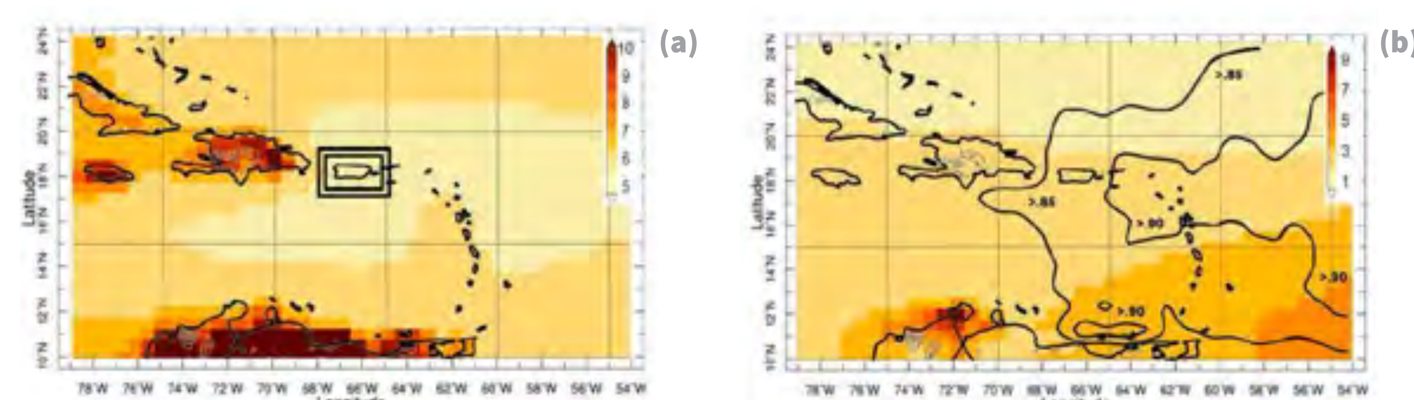


Figure 4. Mean (2005-2015) maps of near surface: (a) MERRA-2 Organic and Black Carbon (OC and BC) in µg/m^3 with index area shown in box; (b) MERRA-2 aerosol PM2.5 in µg/m^3 (colored contours) and ultraviolet aerosol index (contours depict levels > 0.85). Source: Jury, 2017.

SECTION 03

El Niño and Other Forms of Natural Climate Variability

KEY MESSAGES

El Niño Southern-Oscillation (ENSO) is an important source of natural climate variability and influences Puerto Rico's climate by way of the number of tropical cyclones that form within the North Atlantic Basin. The number of tropical cyclones since 1950 that come within 200 nautical miles is on average lower during more intense El Niño years (average of 1.56 storms per year) compared to neutral (average of 1.97 named storms per year) and La Niña (average of 2.20 named storms per year).

ENSO and other forms of natural variability, such as high concentrations of Saharan Dust that act to suppress rainfall within Puerto Rico, will continue to influence Puerto Rico's climate in the future (high confidence); however, there is low confidence in how these and other sources of natural climate variability will respond to increasing greenhouse gas concentrations.

DRIVERS OF NATURAL CLIMATE VARIABILITY

The drivers of natural climate variability are important when considering regional climate. Natural climate drivers include changes in solar irradiance, volcanic eruptions, dust, and internal variability within the climate system such as the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) both of which have been associated with the variability of Puerto Rico's climate (Giannini et al., 2001; Jury et al., 2007; Torres-Valcárcel 2018; Hosannah et al,. 2019). However, natural climate variability over the last century cannot explain the observed changes within the climate system. Over the period from 1950 to 2010, it is estimated that the natural variability contributed between -0.18 °F (-0.1 °C) and 0.18 °F (0.1 °C) to changes in surface temperature while anthropogenic greenhouse gases contributed between 0.9 °F (0.5 °C) and 2.3 °F (1.3 °C) to the observed warming trend (Bindoff et al., 2013).

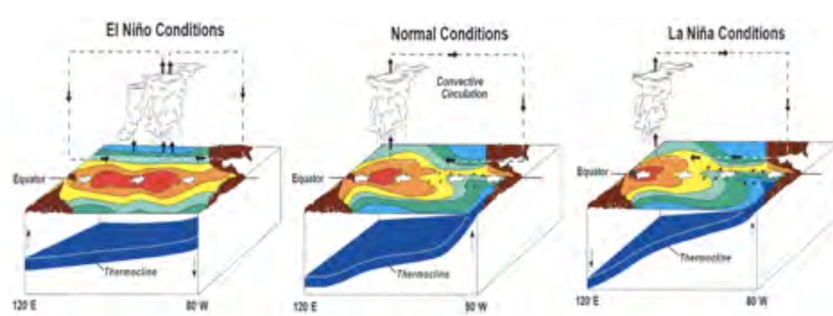


Figure 5. Changes in the atmospheric circulation, precipitation and in the transition layer where warm and cold-water mixes (thermocline) in the Pacific Ocean, due to El Niño, Normal (Neutral) and La Niña conditions. Source: NOAA

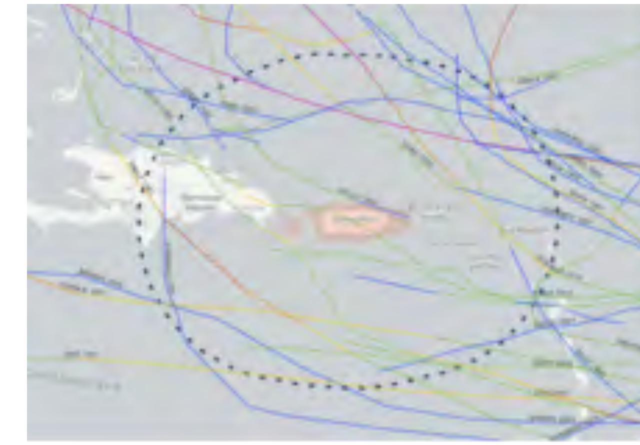
EL NIÑO/ SOUTHERN OSCILLATION (ENSO)

One of the most important climate drivers for the year-to-year (interannual) climate variability is ENSO. ENSO is a coupled ocean-atmospheric circulation feature within the equatorial Pacific with periodic changes in near surface ocean temperatures (El Niño) and the overlying atmosphere surface pressure (Southern Oscillation). There are two anomalous ENSO phases that generate extreme weather throughout the globe. The warm phase (El Niño) is associated with anomalously warm water in the central and eastern equatorial Pacific Ocean and a cold phase (La Niña) with anomalously cool water for the same regions, see Figure 5. Each phase lasts between 6 to 18 months with a frequency between the cold and warm phase of 2 to 7 years (USGCRP 2017). The interactions between the ocean and the atmosphere alter the large-scale atmospheric circulation patterns and are known to significantly impact the weather and climate, especially precipitation patterns, including locations long distances from the equatorial Pacific referred to as climate teleconnections (Trenberth et al., 1998; Giannini et al., 2001). ENSO driven climate impacts include loss of crops and food reserves, destruction of shelter and community infrastructure, disease outbreaks, among others (Fisman et al., 2016; Gabriela et al., 2019; Qian et al., 2020).

An important feature of ENSO when considering the Caribbean is the impact on tropical cyclone activity (Klotzbach, 2011). During El Niño events, the atmospheric convection shifts eastward within the Pacific Ocean. This shift favors an increase in the upper-level westerly winds as well as an increase in the low-level easterly trade winds over the Caribbean and tropical Atlantic Ocean. The result is strong vertical wind shear, especially within the Caribbean. The vertical wind shear produces an unfavorable atmospheric environment for the formation of tropical cyclones (DeMaria, 1996; Knaff et al., 2004); hence, the number of storms is typically reduced during El Niño years. The opposite is true for La Niña years when there is an increase in the probability for tropical cyclone formation in response to a more favorable atmospheric environment with weaker wind shear. Figure 6 is a comparison of the tropical cyclone tracks for El Niño and La Niña years between 1950 and 2020 that come within 200 nautical miles of Puerto Rico. The number of named storms is on average 1.56 storms per year during El Niño years and 2.20 storms per year for La Niña years, compared to neutral years with 1.97 storms. Additionally, El Niño conditions have been shown to weaken the North Atlantic Subtropical High, in return increasing the number of recurving subtropical cyclones, a track that is not favorable for landfalling storms (Colbert & Soden, 2012) including landfall within Puerto Rico.

Despite the association between ENSO and tropical cyclone activity, the influence of ENSO on mean precipitation within Puerto Rico is weak. Torres-Valcárcel (2018) reviewed many prior studies examining the link between Puerto Rico's rainfall and ENSO and performed additional research to help quantify possible links for different time periods (monthly/ seasonal/yearly) and spatial scales (internal climate regions to island wide). Overall, major ENSO events were not found to be a major driver of mean rainfall within the island over the 114-year period analyzed, such as causing major droughts within Puerto Rico. The rainfall variability is complex and multiple processes contribute to the precipitation totals within the island, such local island processes and other forms of variability including the North Atlantic Oscillation and Saharan dust concentrations (Mote et al., 2017; Hosannah et al., 2019). As for near surface air temperature, prior El Niño/La Niña events have been associated with warmer/cooler mean annual air temperatures, respectively (Malmgren et al., 1998). ENSO will continue to influence the future climate by way of natural variability. Observed changes include an increase in the amplitude of ENSO and the frequency of El Niño events in the central Pacific (Lee and McPhaden, 2010). However, the contribution of anthropogenic forcing on these changes is poorly understood in part because of the short record length (Yeh et al., 2018). Additionally, there is uncertainty in ENSO's response to future increases in greenhouse gases. For instance, climate model projections disagree regarding key changes including ENSO's intensity, spatial pattern, and ENSO-induced climate anomalies (Perlwitz et al., 2017; Yang et al., 2018).

EL NIÑO



LA NIÑA

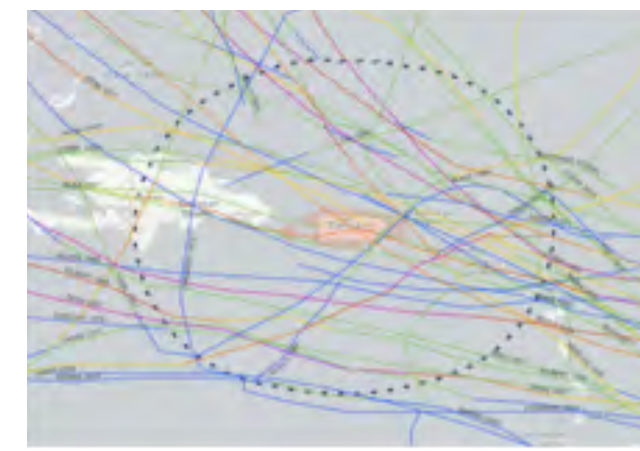


Figure 6. Tropical cyclone tracks for the period from 1950 to 2020 for El Niño years (25 named storms in 16 years) and La Niña years (44 named storms in 20 years).

OTHER FORMS OF NATURAL VARIABILITY

There are other drivers of natural variability that have implications on the regional climate within Puerto Rico: the North Atlantic Oscillation (NAO) and Saharan dust concentrations. The NAO is an oscillation in the sea level pressure between the North Atlantic Subtropical High and the Icelandic Low. The pressure varies such that when the North Atlantic Subtropical High air pressure is anomalously high the Icelandic low pressure is anomalously low (the positive NAO phase). Vice versa happens during the negative NAO phase. The NAO results in North Atlantic basin wide atmospheric changes, especially during the winter (Barnston and Levezey 1987). There is evidence that NAO influences precipitation anomalies within Puerto Rico and the eastern Caribbean (Malgren et al., 1998; Jury et al., 2007; Hosannah et al., 2019). The linkage of NAO and the impact on the Caribbean, particularly the eastern Caribbean, is related to the strength of the trade winds, which strengthen during a positive NAO (George and Saunders, 2001). During a positive NAO, the stronger trade winds increase the evaporation potential resulting in cooler sea surface temperatures and reduced precipitation.

An additional source of natural variability is Saharan dust concentrations. Approximately 2-4 billion tons of dust originate from the Saharan region each year (Goudie and Middleton, 2001). Strong low-level winds lift the Saharan dust into the upper levels of the troposphere which is transported thousands of kilometers away. Changes in dust concentrations are known to impact the atmosphere radiative budget and cloud processes (Strong et al., 2015; Logan et al., 2014). Increases in the dust concentrations within the tropical Atlantic have been associated with rainfall reductions within the Caribbean (Lau et al., 2009) and Puerto Rico (Mote et al., 2017).

A massive Saharan dust cloud affected Puerto Rico in June 2020. The first picture, taken on June 20, 2020 shows clear skies over Isla Verde and the San José Lagoon and the second on June 23, 2020, during the dust storm. Source: Wanda I. Crespo

SECTION 04 Observed and Projected Temperature Changes in Puerto Rico

KEY MESSAGES

Low elevation minimum nighttime temperatures in Puerto Rico have steadily increased and are at the highest levels since at least the beginning of the observing period in the middle of the 20th century. These temperatures have increased by 1.6 [0.9 to 2.2] °C between 1950-2000 and 2011-2020. It is also possible (but with lower confidence) that nighttime temperatures at high elevation locations are also at the highest levels in the observing period. High elevation nighttime temperatures have increased by 1.2 [0.1 to 2.1] °C between 1950-2000 and 2011-2020. Daytime maximum temperatures have not warmed significantly across the island over the past 70 years (1950 to 2020).

Temperatures are projected to increase in Puerto Rico and across the Caribbean region over the 21st century across scenarios that correspond to both lower and higher levels of human-caused greenhouse gas emissions. However, the amount of warming that occurs, particularly by the end of the century, will depend on the future emissions pathway.

OBSERVED NEAR SURFACE AIR TEMPERATURES AND TEMPERATURE TRENDS IN PUERTO RICO

Differences in average surface air temperatures in Puerto Rico are largely driven by the island's topography. The mean annual air temperature between 1990-2020 for San Juan, PR (near sea level) is approximately 27°C while the mean annual air temperature for Cerro Maravilla (one of the highest elevations of approximately 4,000 feet) is near 20 °C. Temperatures throughout the island are on average coolest during January and February and warmest during July and August. The temperature variability between years (interannual variability) is small, generally around 0.5 °C.

Changes in surface temperatures for Puerto Rico were assessed over the period 1950-2020 (Figure 7). A total of 74 observing stations were available for the analysis from the Global Historical Climatology Network (Menne et al., 2012). Some stations had temperature records from the early 20th century, but the total number of stations, or the quality of the data was insufficient to extend the analysis to these earlier decades. The most significant warming has occurred at lower elevations (below 300 m) for daily minimum (nighttime) temperatures. Average nighttime temperatures have increased by 1.6 [0.9 to 2.2] °C at these locations in the last decade (2011-2020) compared to the average over 1950-2020 [1] .Nighttime temperatures have also increased at higher elevation (> 300 m) locations over this time period 1.2 °C), but the uncertainty is larger (very likely range of 0.1 to 2.1°C), and therefore confidence is lower that the recently experienced temperatures were warmer than those occurring in the 1950s and 1960s. In contrast to nighttime temperatures, there is little evidence of warmer maximum daily (daytime) temperatures. Average daytime maximum temperatures for 2011-2020 differed by 0.0 [-0.7 to 0.6] °C and 0.0 [-0.6 to 1.3] °C compared to the average over 1950-2000 at lower and higher elevations, respectively.

The NOAA climate summaries (Runkle et al., 2022), released in 2022, provide an additional method to understand historical trends including changes in extreme temperatures. For Puerto Rico, the summary includes information on the changes in the number of very hot days (maximum temperature exceeding 95°F) and the number of extremely warm nights (minimum temperature above 80°F) since 1950 for San Juan (see https://statesummaries.ncics.org/chapter/pr/). The state climate summary for Puerto Rico does not reveal a trend for very hot days; however, annual number of extremely warm nights exhibit an increasing trend that has been above the average since 2000 with the highest number occurring since 2015.

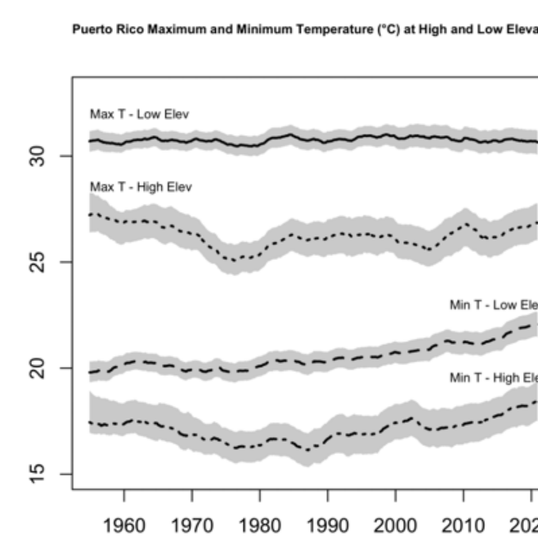


Figure 7. Puerto Rico surface temperatures over the period 1950-2020 in degrees Celsius. Average daily maximum ('Max T') and minimum ('Min T') temperatures are shown for lower elevation ('Low Elev') and higher elevation ('High Elev') regions. Gray shading indicates the very likely range of tempera-tures. Values are smoothed over five-year increments.

[1] See (Brohan et al., 2006) for methods used to estimate the *very likely* (90-100%) range of temperatures.

PROJECTED CHANGES IN TEMPERATURE

Caribbean Region Temperature Projections

Global climate model projections provide insight into average temperature changes for the Caribbean in response to increases in greenhouse gas concentrations. Annual temperature changes for the Caribbean have been projected using an ensemble of climate models from the most recent global Climate Model Intercomparison Project (CMIP6; Almarzoui et al., 2021). Annual average temperatures are expected to increase throughout the century regardless of the level of future greenhouse gas emissions from human activities. But the amount of warming, particularly by the end of the century, is highly dependent on future emissions. Increases in the annual mean change averaged over the Caribbean for the middle of the 21st century (2041-2060) range from 0.9°C for the lowest emission scenario considered to 1.6°C for the highest emission scenario. By the end of the century (2080-2099), there is a larger divergence in the annual mean change between scenarios, ranging from 1.0°C to 3.5°C for the lowest and highest emission scenarios, respectively.

Using the prior generation of global climate models (CMIP5), the annual mean temperature change within the Caribbean was compared against global mean warming targets of 1.5°C, 2.0°C and 2.5°C above preindustrial levels for a climate forcing scenario corresponding to lower levels of greenhouse gas emissions (RCP4.5; Taylor et al., 2018). The comparison illustrates the projected temperature within the Caribbean intensifies above 2.0°C including extreme changes in temperature. For instance, the projected number of warm spells goes up drastically with additional warming – extension of 70 days from 1.5°C to 2°C global warming. A follow-up study used a set of regional climate model projections to better quantify climate change projections within the Caribbean for the same global warming targets (Campbell et al., 2021). The Caribbean islands were found to warm faster than the surrounding oceans by 0.5°C to 1.5°C with the largest warming occurring during the cooler months. The regional climate model projections also indicate differential warming within the Caribbean with the largest warming occurring over the northern Caribbean. This is an indication that increased warming may favor more homogenous temperatures from south to north.

Puerto Rico Temperature Projections

Understanding and quantifying temperature projections for Puerto Rico requires downscaling global climate models to scales that begin to resolve important temperature gradients within the island. Temperature projections presented here represent both statistical and dynamical downscaled projections for the island (Hayhoe et al., 2013; Henareh Khalyani et al., 2016; Bowden et al., 2021). By the end of the century the within-island temperatures are projected to increase dramatically upwards of 4.5°C for a lower emission scenario to 7°C for an extremely high emission scenario, which is approximately double the global mean change (Hayhoe et al., 2013; Henareh Khalyani et al., 2016). An increase of this magnitude would significantly impact energy demand resulting in a two-fold increase in the energy demand for future air conditioning (Henareh Khalyani et al., 2016). However, increases below 2°C would also have significant consequences especially when considering the future of extreme temperatures within the island (Hayhoe et al., 2013; Bowden et al., 2021). Figure 8 is an illustration of projected changes around mid-century for annual maximum temperature and the number of extremely hot days that exceed the historical maximum. The island average mean change is around 1.6°C, but the number of extremely hot days increases upwards of 150-200 days for future years. Thus, it is plausible that by the middle of the century, more than half of the average daily maximum temperatures could be warmer than the most extreme temperatures experienced at the end of the 20th century. Projected changes for minimum temperatures are more spatially homogenous when compared to maximum temperatures. This is an indication of the significance of solar insolation and land surface feedbacks on maximum temperatures within the island as the climate warms. Additionally, the projections suggest an increase in the diurnal temperature range as the climate warms (Bowden et al., 2021).

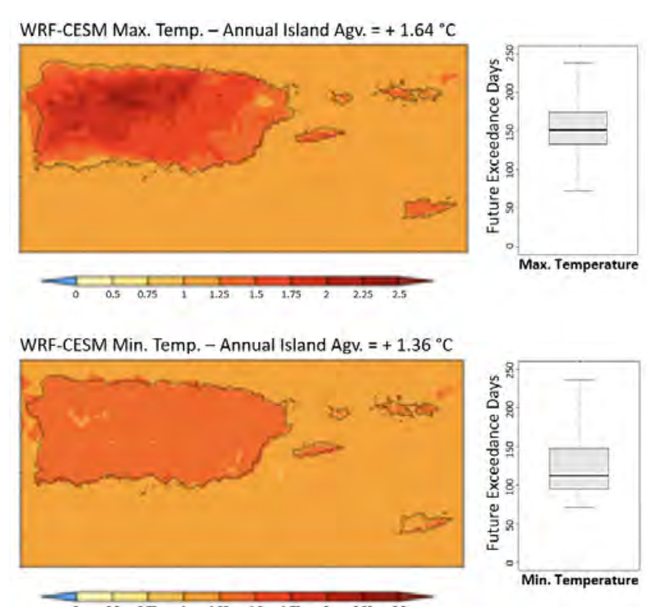


Figure 8. Annual mean change for 2-m maximum temperature (top left) and minimum temperature (bottom left) between the historical baseline period (1986-2005) and future period (RCP8.5; 2041-2060). Right panels: Boxplot of the annual count of days for each future year when the 2-m maximum temperature (top right) and minimum temperature (bottom right) exceeds the same calendar maximum and minimum day temperature within the baseline period. The number of days per year is averaged over land points within Puerto Rico.

SECTION 05 Observed and Projected Precipitation Changes in Puerto Rico

KEY MESSAGES

No trends, increasing or decreasing, are observed for annual or seasonal rainfall in Puerto Rico for the period 1925-2020. Recent droughts have more commonly been associated with abnormally low precipitation during the wet season compared to the dry season.

Simulations from both global-scale climate models, and high resolution local-scale climate models project future decreases in precipitation for Puerto Rico, particularly under scenarios corresponding to continued increases in greenhouse gas emissions. Under the higher scenario, average rainfall decreases by the middle of the century. There is medium confidence that these reductions will occur throughout the year. There is low confidence as to where within the island the largest reductions may occur.

The distribution of annual rainfall totals within Puerto Rico is complex and driven by numerous processes such as the interaction between the island's topography with the easterly trade winds and feedbacks between the land surface and the atmosphere. The wetter locations occur over the northeastern portion of the island with annual rainfall exceeding 3500 mm to drier locations on the south coast with rainfall totals of less than 1000 mm, Figure 9. The year to year (interannual) rainfall variability within the island is also large. For instance, the annual mean rainfall in San Juan is 1443 mm from 1925 to 2020 with a minimum of 903 mm in 1991 to 2275 mm in 2010 with a standard deviation of 294 mm.

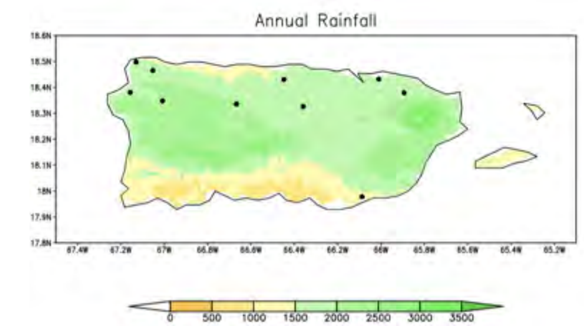


Figure 9. Annual mean rainfall (mm) from 1950 to 2000. Rainfall totals are derived from WorldClim rainfall estimates (Hijmans et al., 2005). COOP station locations with data available for long-term rainfall analysis are also shown.

Annual rainfall trends were calculated for 10 Cooperative Observer Program (COOP) weather stations with available data over the period 1925-2020, seen in Figure 10, which are mostly concentrated over the northern portions of the island. The homogenized station data values were obtained using the NWS Local Climate Analysis Tool (Timofeyeva-Livezey et al., 2015). There is no discernable rainfall trend over the observational record. Within this period, the annual rainfall on average for 1990-1994 was the most abnormally dry period since 1925. This period was 15% drier than the climatological rainfall of approximately 1700 mm for all stations over the period of record. The annual rainfall on average from 2010-2014 was the most abnormally wet period during 1952-2020 and was 12% wetter than normal. Overall, the relative differences are used to relate future rainfall projections to historical periods and is discussed more below.

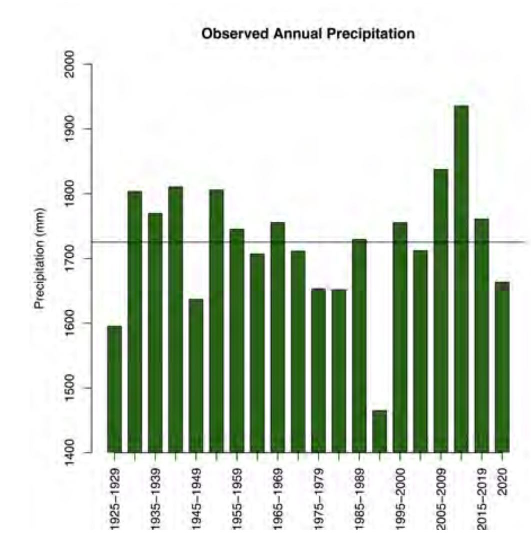


Figure 10. The observed annual precipitation for 1925-2020, averaged over 5-year periods (exception being the last year 2020); these values are averages from 10 long-term reporting stations in Puerto Rico. The black horizontal line is the long-term mean.

Heavy rainfall events, such as those greater than 3 inches in a day, currently show no trends in frequency (Runkle et al., 2022). These events are more typical during August and September (Méndez-Lázaro et al., 2014) which is also when drought is most prevalent, Figure 11. There is also a notable uptick in the frequency of droughts including the 2015 drought which lasted 80 weeks and one of the most severe in the last 50 years (Gutiérrez-Fonseca et al., 2020). Outside of the anomalously wet period in 2004 and during 2009-2012 a drought occurred within the island almost every year since 2000 with a notable increase in drought frequency for the most recent years. Seasonal rainfall changes are important within Puerto Rico. Figure 12 shows the average rainfall for the same 5-year periods for the dry (November-April) and wet (May-October) seasons. There is more variability in rainfall during the wet season compared to the dry season which has implications for seasonal drought.

PROJECTED CHANGES IN PRECIPITATION

Caribbean Precipitation Projections

Global climate model projections provide insight into mean rainfall changes for the Caribbean in response to increases in greenhouse gas concentrations. The annual rainfall change for the Caribbean has been estimated using an ensemble of climate models from the most recent global Climate Model Intercomparison Project (CMIP6; Almarzoui et al., 2021). The annual average rainfall from CMIP6 ensemble depicts rainfall will decrease with increasing emissions. Decreases in the annual rainfall averaged over the Caribbean for mid-century (2041-2060) ranges from approximately a 1% decrease for the lowest emission scenario to a 6% decrease for the highest emission scenario. By late- century (2080-2099), the amount of drying increases substantially with a 20% decrease for the highest emission scenario while the lowest emission scenario indicates very little change for annual rainfall. Using the prior generation of global climate models (CMIP5), the annual rainfall change within the Caribbean was compared against global mean warming targets of 1.5°C, 2.0°C and 2.5°C above preindustrial levels for a middle of the road emission scenario (RCP4.5; Taylor et al., 2018). The Caribbean is found to shift to a drier climate by upwards of 15% with fewer intense rainfall days at the 2.0°C global mean warming target, which is approximately mid-century. The wet season was found to be the primary season with the greatest drying (Taylor et al., 2018; Campbell et al., 2021).

Puerto Rico Precipitation Projections

Understanding and quantifying precipitation projections for Puerto Rico requires downscaling global climate models to scales that begin to resolve important rainfall gradients within the island. The precipitation projections presented here represent both statistical and dynamical downscaled projections for the island (Hayhoe et al., 2013; Henareh Khalyani et al., 2016; Bhardwaj et al., 2018; Bowden et al., 2021). Both statistical and dynamical downscaling indicate a shift to drier conditions within Puerto Rico as greenhouse gas concentrations increase. An ensemble of statistical downscaled projections for Puerto Rico show the greatest rainfall reductions during the wet season (Hayhoe et al, 2013; Henareh Khlyani et al., 2016), which is consistent with the larger drying pattern of the Caribbean. However, the magnitude of the downscaled rainfall is sensitive to the generation of the global climate models with larger reductions in CMIP3 (~50%) compared to CMIP5 (~25%) at 3°C mean global warming (Hayhoe et al, 2013). With 2°C mean warming (approximately mid-century) the amount of projected drying reduces to ~30% (~10%) for CMIP3 (CMIP5). Dynamical downscaled projections of select CMIP5 global climate models centered on mid-century (2041-2060 for RCP8.5) indicate greater within island reductions compared with the statistical counterpart exceeding 20% for many locations, Figure 13 (Bhardwaj et al., 2018; Bowden et al., 2021). Rainfall reductions are found to be consistent between the wet and dry seasons, which is an indication of persistent rainfall deficits throughout the year. The projected rainfall reductions are between 13% and 22% on average for Puerto Rico. Rainfall reductions of this magnitude are an indication of a plausible scenario that rivals the driest 5-year dry period within historical records (15% rainfall reduction on average during the early 1990s). The dynamical downscaled projections indicate the rainfall reductions are associated with a reduction in the rainfall intensity during the afternoon and evening hours when thunderstorms are more pronounced. Finally, the dynamical downscaled projections provide evidence that the amount of drying may be mitigated at higher elevations (Bowden et al., 2021), such as an increase in the mean annual rainfall within the El Yunque National Rainforest.

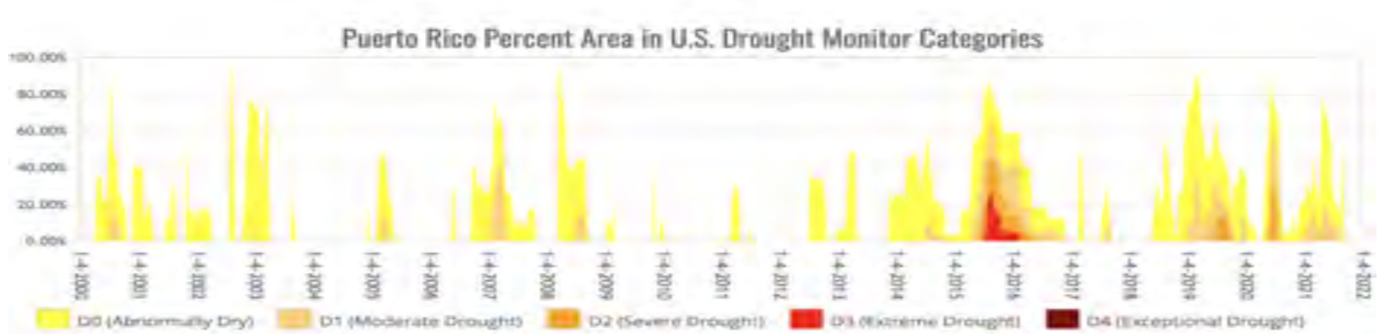


Figure 11. Percentage of area with reported drought within Puerto Rico since 2000. D0 is abnormally dry, and D4 is exceptional drought. Figure is adapted from the U.S. Drought Monitor, https://droughtmonitor.unl.edu/DmData/TimeSeries.aspx

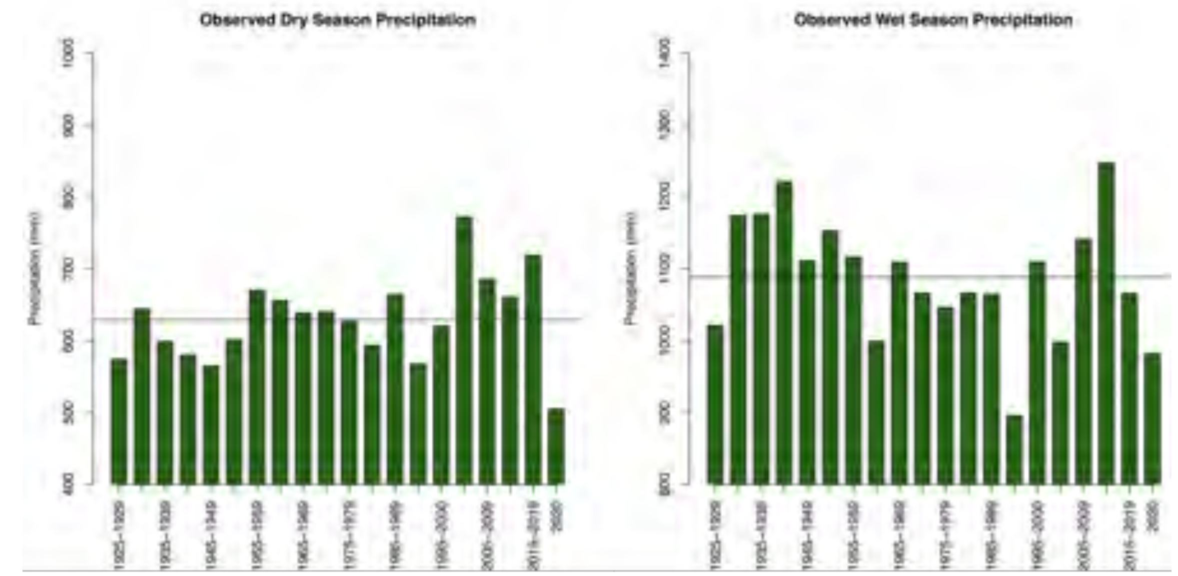


Figure 12. The observed dry season (November – April) and wet season (May – October) precipitation for 1925-2020, averaged over 5-year periods (exception being the last year 2020); these values are averages from 10 long-term reporting stations in Puerto Rico. The black horizontal line is the long-term mean.

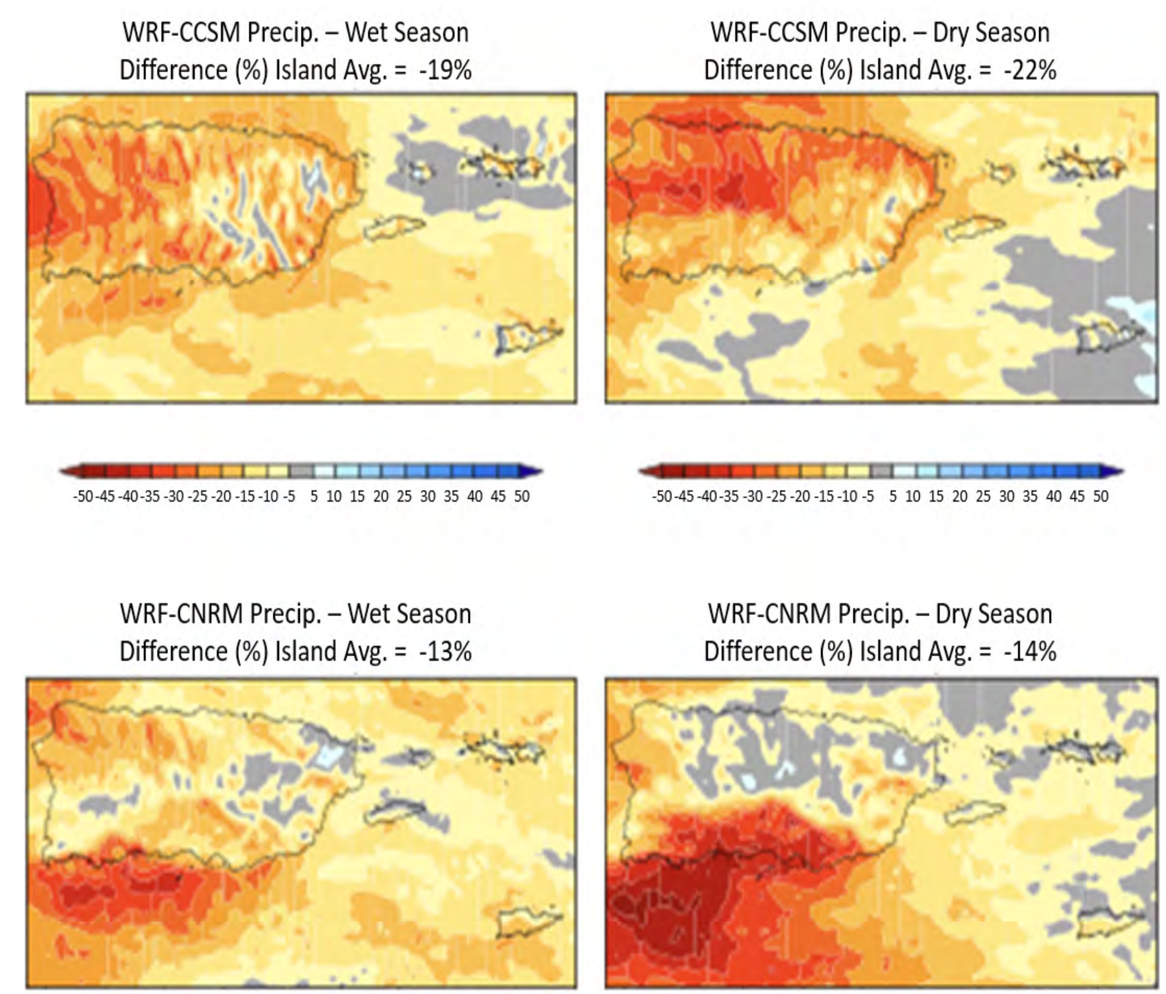


Figure 13. Dynamically downscaled rainfall projections (%) for two different CMIP5 global climate models (top vs. bottom). The left (right) panels illustrate the rainfall change for the wet (dry) seasons.

SECTION 06

Observed and Projected Sea Level Rise in Puerto Rico

KEY MESSAGES

Sea levels will continue to rise for centuries, reaching 2.3–5.4 m by 2300 and much more beyond, making adaptation extremely challenging for small islands like Puerto Rico with low-lying and intensively developed and urbanized coasts. Even under the ambitious mitigation scenario (RCP2.6), sea levels will continue to rise. Projected extreme scenario for San Juan, Puerto Rico range between 0.83 meter (3.09 feet) and 3.10 meter (10.14 feet) by 2050 and 2100, respectively.

Coastal erosion, flooding risks as well as salinization of aquifers and coastal freshwater and estuarine habitats are expected to significantly increase by the end of the century in low-lying coastal areas of Puerto Rico, unless major adaptation efforts are undertaken.

For planning and design purposes, it is recommended to adopt a scenario-based approach with special consideration given to the intermediate high and highest projections. Choosing and implementing sea level rise adaptation responses face major challenges associated to existing regulations, building codes, conflicting stakeholder's interests. Recovery funding available post-hurricanes Irma and Maria represent a great opportunity to build resilience through sea level rise adaptation.

Sea level rise represents a major threat for coastal communities, infrastructure, and biodiversity World-wide. Higher sea levels imply that tides, waves, storm surges, and winter swells penetrate further inland, resulting in increased coastal flooding, direct wave attack and alterations to dynamic and morphological responses of the coast. According to the United Nations forty-four (44%) percent of the World's population live in coastal areas. Based on the US Census 2020 projections 40% of the US population live in coastal areas [2]. Approximately 61% of the population in Puerto Rico live in the 44 coastal municipalities (Díaz and Hevia, 2017). The Puerto Rico Coastal Zone Management Program (PRCZMP) reports that 18% of the 799 miles of the Puerto Rico coastline are built up areas. All major power plants (7), airports (11), thousands of miles of electric power, communications, aqueducts, and sewers infrastructure, as well as ports facilities are located within 1 km of the shoreline. Sea level rise is most concerning for small islands like Puerto Rico and low-lying coastal cities and towns.

The two major causes of global sea level rise are thermal expansion caused by warming of the ocean (since water expands as it warms) and increased melting of land-based ice, such as glaciers and ice sheets (Sweet et al., 2017). The oceans are absorbing more than 90% of the increased atmospheric heat associated with emissions from human activity. Since the 1990s, scientists and researchers began developing scenarios to explore how the world might change over the rest of the 21st century, considering future projections of population, greenhouse gas emissions (GHG), global warming levels, economic growth, and other stressors. The Intergovernmental Panel on Climate Change (IPCC) has published six (6) assessment reports (AR) and multiple sets of scenarios have been developed to evaluate climatic and environmental consequences of future climate changes, risks and impacts, as well as assessments of alternative mitigation and adaptation strategies. The IPCC 5th Assessment Report (AR5; IPCC, 2014), published in 2015 described four (4) different pathways of climate change called Representative Concentration Pathways (RCP). The RCPs represented a range of GHG emissions which included a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and a very high scenario (RCP8.5). In the RCP2.6 scenario, there is warming of ~1°C by 2100 (relative to 1986–2005), with high probability that the global temperature stays below the 2015 Paris Agreement, which aims to limit warming to 2 or 1.5°C above pre-industrial level. In the RCP8.5 scenario, there is warming of 4.5°C by 2100. These scenarios also considered radiative forcing (2.6, 4.5, 6.0 and 8.5 watts per meter squared), but did not include socioeconomic factors. The IPCC 6th Assessment Report (AR6, IPCC, 2021), published in August 2021, derived five (5) new scenarios named Shared Socioeconomic Pathways (SSPs) which consider how socioeconomic factors and trends may change over the next century in addition to the previous climatic and environmental change drivers. The scenarios ranged between SSP1-1.9 scenario, which holds warming to ~1.5 °C in and implied net-zero CO_2 emissions around the middle of the century, to a SSP5-8.5 scenario with a warming of more than 4 °C. The five (5) scenarios (SSP1-1.19, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) span a wide range of plausible societal and climatic futures. The sea-level rise projections provided in the IPCC AR5 followed a slightly different definition of likelihood language, defining "likely" to mean a central 66% probability range, and "very likely" to be a central 90% probability range. Similarly, the recent Special Report on Ocean and Cryosphere developed by the IPCC defined "likely range" as the 17–83% probability range, and "very likely range" as the 5–95% probability range. The IPCC AR5 followed the same set of calibrated language. There are many uncertainties and open-ended questions about sea level rise projections (Horton et al., 2020). Projections up to 2050, kept consistent with the AR5 scenarios, but beyond 2050 the AR6 scenarios start to diverge, with values modestly higher than those of the AR5.

Currently, the relative sea level, measured with tide gauges, is the most relevant measurement to estimate sea level change and sea-level projections. Long-term tide gauge data records can provide information about the rates of change and frequency of tidal flooding to inferred how sea level rise is contributing to more frequent and longer-lasting tidal flooding, or in the case of Puerto Rico, coastal flooding. Higher sea levels means that local flooding thresholds can be reached more easily during average high tide. The elevation threshold used to classify such events by NOAA on their tide gauges varies along the U.S. coastline, but in general the median it is about 0.8 m (2.6 feet) above the highest average tide and locally has a 20% annual chance of occurrence. Using this flood-frequency definition, it was found that at most locations examined (90 cities along the U.S. coastline outside of Alaska) with only about 0.35 m (<14 in) of local sea level rise, annual frequencies of such disruptive/damaging flooding will increase 25-fold by or about (±5 years) 2080, 2060, 2040 and 2030 under the Low, Intermediate-Low, Intermediate, and Intermediate High subset of scenarios, respectively (Sweet et al., 2017).

Hence, knowing that the rise in sea level is accelerating both globally and regionally, there is a necessity to detect and understand the sea level trend signal and future impacts in Puerto Rico from local tide-gauge data and satellite altimetry data. For the purpose of this report, the PRCCC uses data from NOAA tide gauges with the longer data records, satellite altimetry, and NOAA and IPCC sea level projections to assess alternative mitigation and adaptation strategies.

RELATIVE SEA LEVEL CHANGE AND PROJECTIONS UP TO 2100

According to data collected since the middle of 20th century from the Lajas and San Juan, Puerto Rico tide gauges, the relative sea level is rising by about 2 mm/yr. There has been a pattern of only minor, gradual increases in sea level but the most recent data (from 2010 to present) appears to be showing an increasing rate of rise. This is believed to be driven by higher water temperatures, which, in turn, can cause more extreme weather events threatening public life and coastal property and infrastructure from the higher sea level and major storms. In addition to this global reason, the movement of the land up or down has aggravated the effect of the rise. This section inventories the best available data on historical and recent

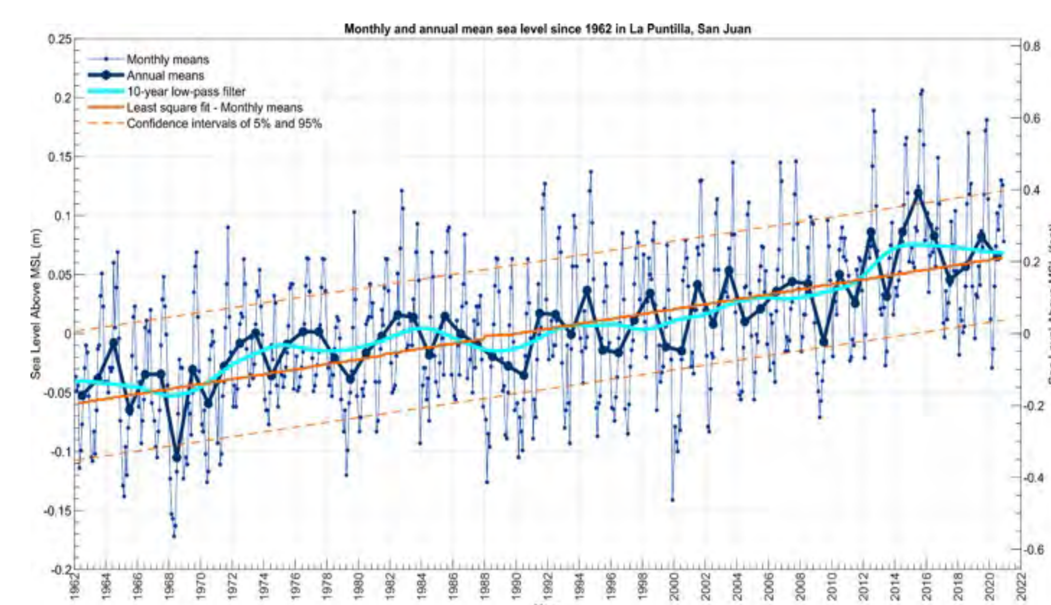


Figure 14. Monthly (blue line) and annual mean (dark blue line) sea level data since 1962 from La Puntilla, San Juan. The north coast of Puerto Rico experienced a 2.10 mm/yr rise in sea level and from 2010 to 2020 a rise of 1.8 mm/yr. The orange line indicates the least square fit of the monthly means and the dashed lines mark the 95% confidence intervals. The light blue line marks the 10-year low-pass filter showing that low-frequency oscillations of periods reappear during the last decade.

[2] http://www.oceansatlas.org/subtopic/en/c/114/

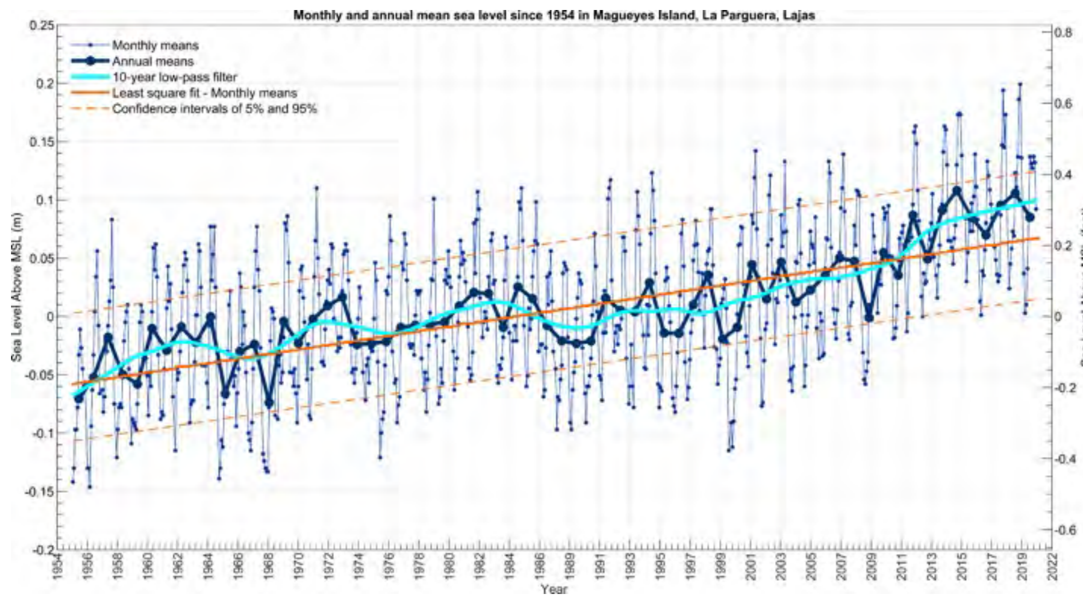


Figure 15. Monthly and annual mean sea level since 1954 from Magueyes Island, La Parguera, Lajas.

trends in sea level change and presents the best available current projections.

For this analysis, the PRCCC WG-1 selected and reconstructed monthly means of water level elevations from NOS/CO-OPS stations 9759110 at Magueyes Island, La Parguera, Lajas and 975531 at La Puntilla, San Juan Bay (Figure 14 and Figure 15). Data for the current analysis were collected between 1955 and 2020 from Magueyes Island, and between 1964 and 2020 from La Puntilla. The current relative sea level trend is 1.89 mm/yr at Magueyes Islands and 2.10 mm/yr at San Juan. Since 2010, the sea level at San Juan has risen approximately 1.8 mm/yr and 4.4 mm/yr at Magueyes Island (September 19, 2021). Long-term data sets from both tide gauges show an increasingly acceleration in sea level rise of approximately ~0.3 m compared to values reported in the Puerto Rico's State of the Climate Report (PRCCC, 2013). The noticeable upward trend in acceleration presage position and increasing sea level rise rates at the Magueyes Island tide gauge is likely associated to ocean dynamics. This acceleration could sharply increase the "best estimate" sea level projections. Furthermore, a frequency analysis shows that low-frequency oscillations reappeared during the last decade. These accelerations are in accord with satellite altimeter data (Figure 16), although not to the same magnitude of up to 3.0 mm/yr. Satellite altimeter footprint data goes from a few kilometers up to a few hundreds of meters, whereas tide gauge captures the changes close to coastal areas.

FUTURE SEA LEVEL RISE PROJECTIONS FOR PUERTO RICO

For planning purposes, it is recommended to adopt a scenario-based approach with consideration given to the range between

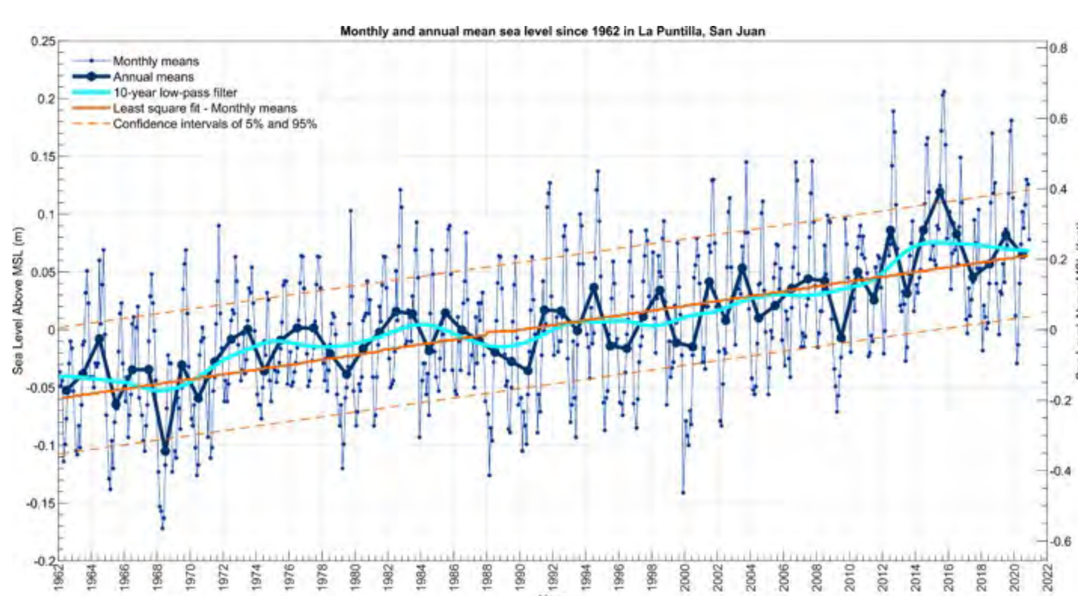


Figure 16. Estimates of sea level rise based on measurements from (black dashed line) La Puntilla tide gauge, (gray dashed line) Magueyes tide gauge, satellite radar altimeters for the: (dark blue line) Caribbean Sea, (light blue line) Atlantic Ocean, and (green line) Global. Source: NOAA tide gauges and NOAA Laboratory for Satellite Altimetry.

the lowest and the highest projections. The present analysis considers the six Sea Level Rise (SLR) scenarios reported by NOAA (Sweet et al., 2017). Each scenario assumes a non-linear rate of rise (extrapolation) in which, in La Puntilla, San Juan (Figure 17), the low scenario reaches 0.19 meter (0.62 feet) and 0.36 meter (1.18 feet) by 2050 and 2100, respectively, the intermediate-low reaches 0.25 meter (0.82 feet) and 0.50 meter (1.64 feet) by 2050 and 2100, respectively, the intermediate reaches 0.38 meter (1.25 feet) and 1.09 meter (3.58 feet) by 2050 and 2100, respectively, the intermediate-high reaches 0.55 meter (1.80 feet) and 1.81 meter (5.94 feet) by 2050 and 2100, respectively, the high reaches 0.74 meter (2.43 feet) and 2.54 meter (8.33 feet) by 2050 and 2100, respectively, and the extreme scenario reaches 0.86 meter (2.82 feet) and 3.10 meter (10.20 feet) by 2050 and 2100, respectively.

The low scenario for Magueyes Island at La Parguera, Lajas (Figure 18), reaches 0.18 meter (0.59 feet) and 0.34 meter (1.12 feet) by 2050 and 2100, respectively, the intermediate-low reaches 0.23 meter (0.75 feet) and 0.48 meter (1.57 feet) by 2050 and 2100, respectively, the intermediate reaches 0.36 meter (1.18 feet) and 1.08 meter (3.54 feet) by 2050 and 2100, respectively, the intermediate-high reaches 0.53 meter (1.74 feet) and 1.80 meter (5.90 feet) by 2050 and 2100, respectively, the high reaches 0.71 meter (2.33 feet) and 2.52 meter (8.27 feet) by 2050 and 2100, respectively, and the extreme scenario reaches 0.83 meter (3.09 feet) and 3.10 meter (10.14 feet) by 2050 and 2100, respectively. It suggested to adopt higher SLR scenarios (intermediate-high, high, and extreme) to plan and design projects that could be exposed to flood impacts, such as primary and critical infrastructure. It is important to recall that these scenarios/projections are extrapolations and can be altered from other global stressors such as changes in the Earth's gravitational field and rotation due to melting of land ice, ocean circulation, vertical land motion, wind motion, and the increase of ocean surface temperature.

Projections of likely 21st century global mean sea level rise presented by the IPCC AR6 provide information of how things would look in the absence of climate policy and allow scientists researchers to search for opportunities for climate mitigation and adaptation in each possible future world when combined with mitigation targets. The AR6 uses a combination of historical observations, climate models and an updated estimate of climate sensitivity to provide the likely sea level rise estimate depending on the future emissions scenarios. The likely sea level rise by 2100 for La Puntilla, San Juan (Figure 19) is 0.31-0.60 m under very low GHG emissions scenario (SSP1-1.9), 0.36-0.73 m under the low GHG emissions scenario (SSP1-2.6), 0.47- 0.89m under the intermediate GHG emissions scenario (SSP2-4.5), 0.56-1.0 m under the high GHG emission scenario (SSP3-7.0), and 0.63-1.14 m under the very high GHG emissions scenario (SSP5-8.5). Meanwhile, the likely sea level rise by 2100 for Magueyes Island, La Parguera, Lajas (Figure 20) is 0.30-0.76 m under very

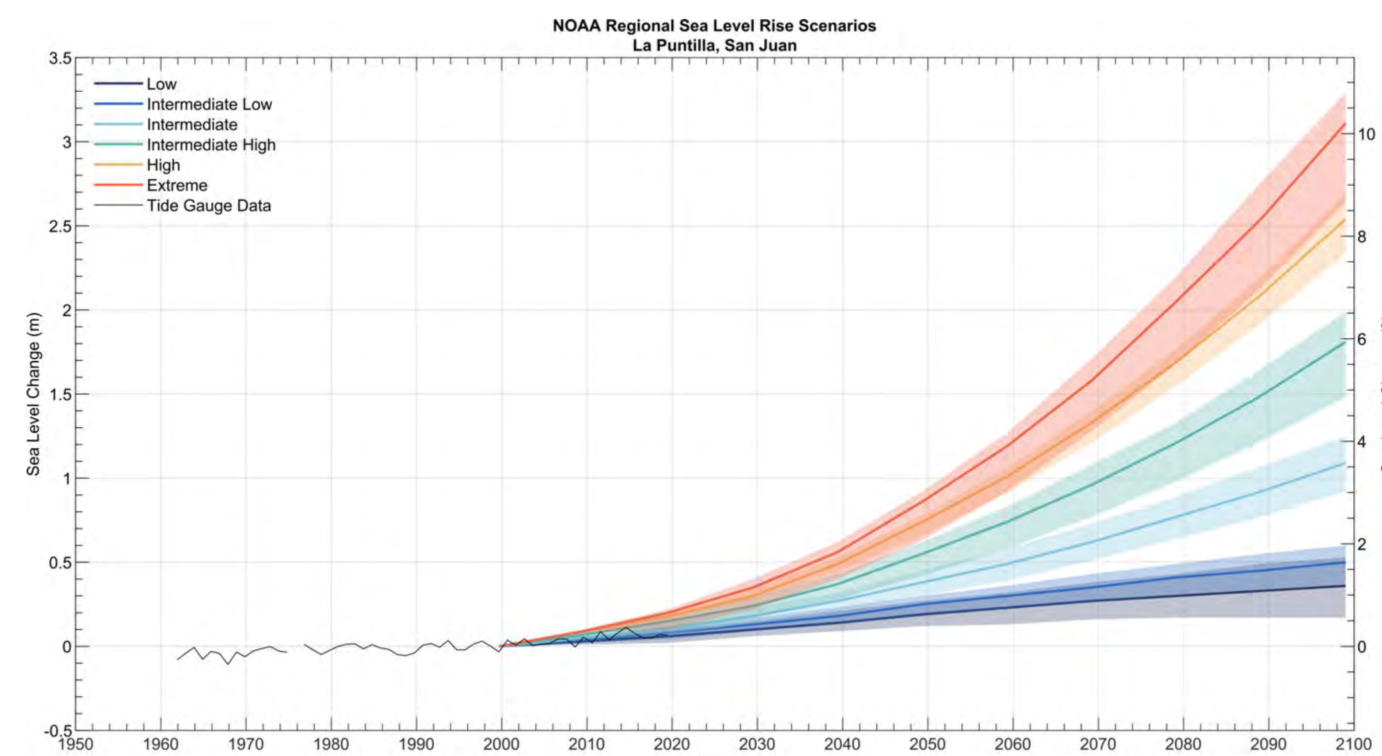


Figure 17. Relative sea level change scenarios for San Juan, Puerto Rico associated with the six different SLR scenarios reported by NOAA (Sweet et al., 2017). The low and extreme SLR scenarios represent the minimum and maximum plausible future sea level rise. Sea level change projections curves are computed using the NOAA Tide Gauge in La Puntilla, San Juan (station 9755371), the estimated local vertical movement rate and the global mean sea level change.

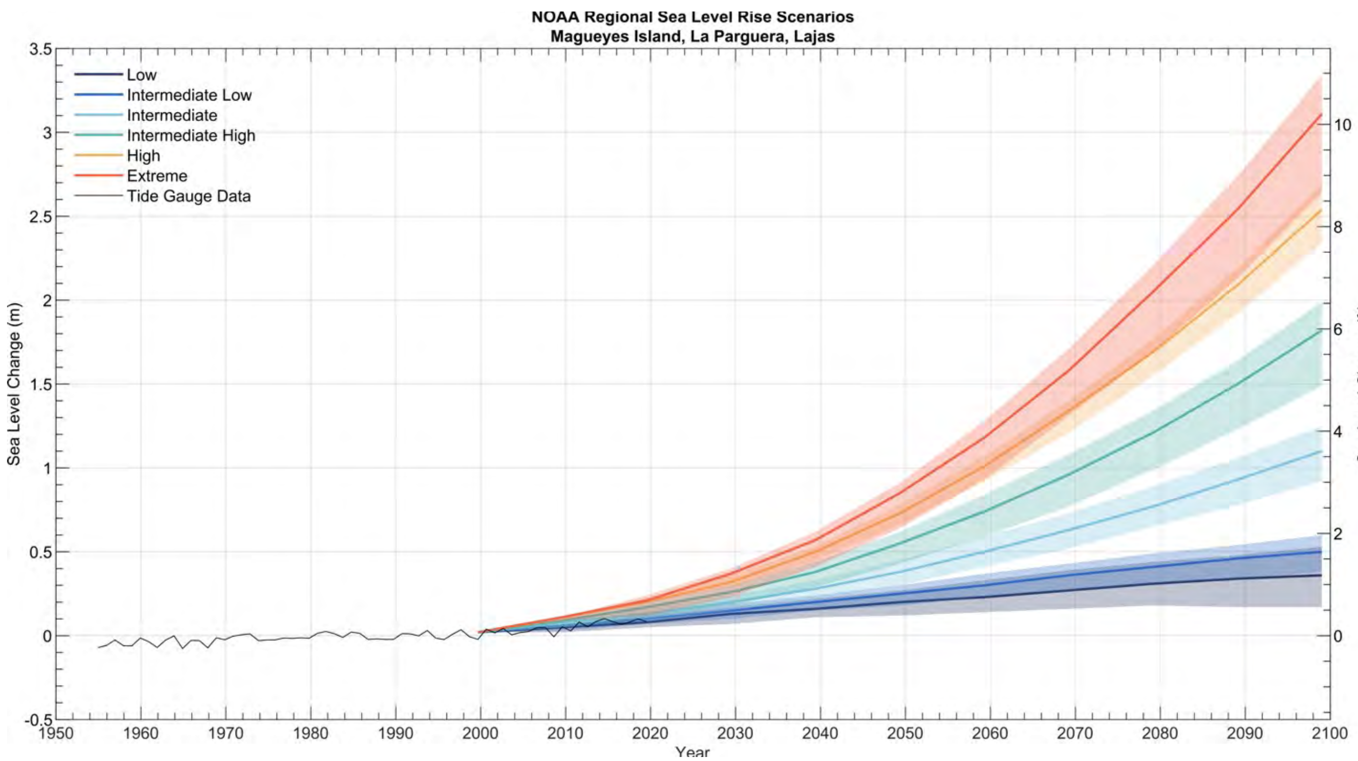


Figure 18. Relative sea level change scenarios for La Parguera, Lajas, Puerto Rico associated with the six different SLR scenarios reported by NOAA (Sweet et al., 2017). The low and extreme SLR scenarios represent the minimum and maximum plausible future sea level rise. Sea level change projections curves are computed using the NOAA Tide Gauge in Magueyes Island, La Parguera, Lajas (station 9759110). Shaded ranges show the 17th - 83rd percentile ranges for each scenario.

low GHG emissions scenario (SSP1-1.9), 0.35-0.72 m under the low GHG emissions scenario (SSP1-2.6), 0.48-1.01m under the intermediate GHG emissions scenario (SSP2-4.5), 0.57-1.13 m under the high GHG emission scenario (SSP3-7.0), and 0.62-1.32 m under the very high GHG emissions scenario (SSP5-8.5)

SUMMARY OF OBSERVED AND PROJECTED TRENDS FOR SEA LEVEL RISE

The assessment of observed and projected change in the sea level reveals a steadily rise and provides information for evaluating climatic and environmental consequences of future climate changes, risks and impacts, and for assessing alternative mitigation and adaptation strategies. With approximately 400,000 people living within Puerto Rico's coastal zone, future sea level rise poses some of the greatest risks associated to a warming climate. A major challenge for managing impacts and implementing effective mitigation and adaptation strategies for coastal areas affected by future sea level rise is our limited capacity to predict sea level change at the coast. As the depth of coastal waters increases, due to erosion, rising sea levels and subduction associated to seismic activity, many of the coastal processes will be modified. Ocean waves will break closer to the coast increasing the overtopping of natural and artificial coastal protection, in other words accelerating coastal dynamic and morphological responses; tides, surges and river discharges will be altered implying changes to extreme sea levels and amplifying flooding frequencies. The interaction and cumulative impacts of these processes will increase the vulnerability of coastal communities, infrastructure and marine habitats.

This section of the PRCCC WG1 report provides the basis to support adaptation alternatives design and selection, as well as to initiate the implementation of responses to sea level rise in Puerto Rico. Adaptation implies that proactive and difficult decisions need to be made. This poses significant governance challenges and addressing conflicting interests. The PRCCC WG3 science-supported decision-making analysis and policy development recommendations combining land use planning, conflict resolution and meaningful public participation can effectively contribute to foster sound and timely adaptation. Puerto Rico as most Small Island Development States is highly vulnerable to sea level rise, therefore adaptation decisions have to be made now.

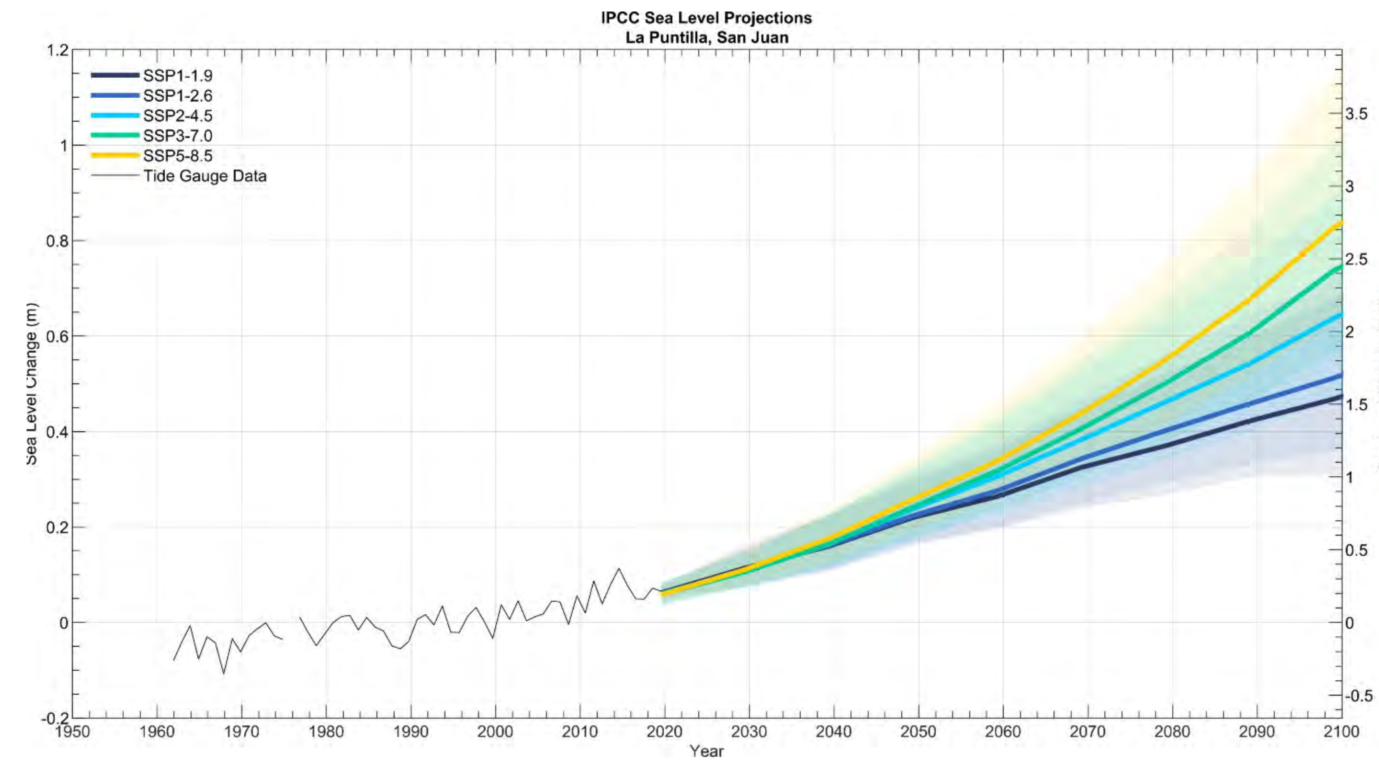


Figure 19. The likely ranges of sea level change in La Puntilla, San Juan for IPCC GHG emissions scenarios. Thick lines show the ensemble means. Shaded ranges show the 17th - 83rd percentile ranges for each scenario. The black line shows tide gauge historical data. (Source: Kemper-Fox et al., In Press)

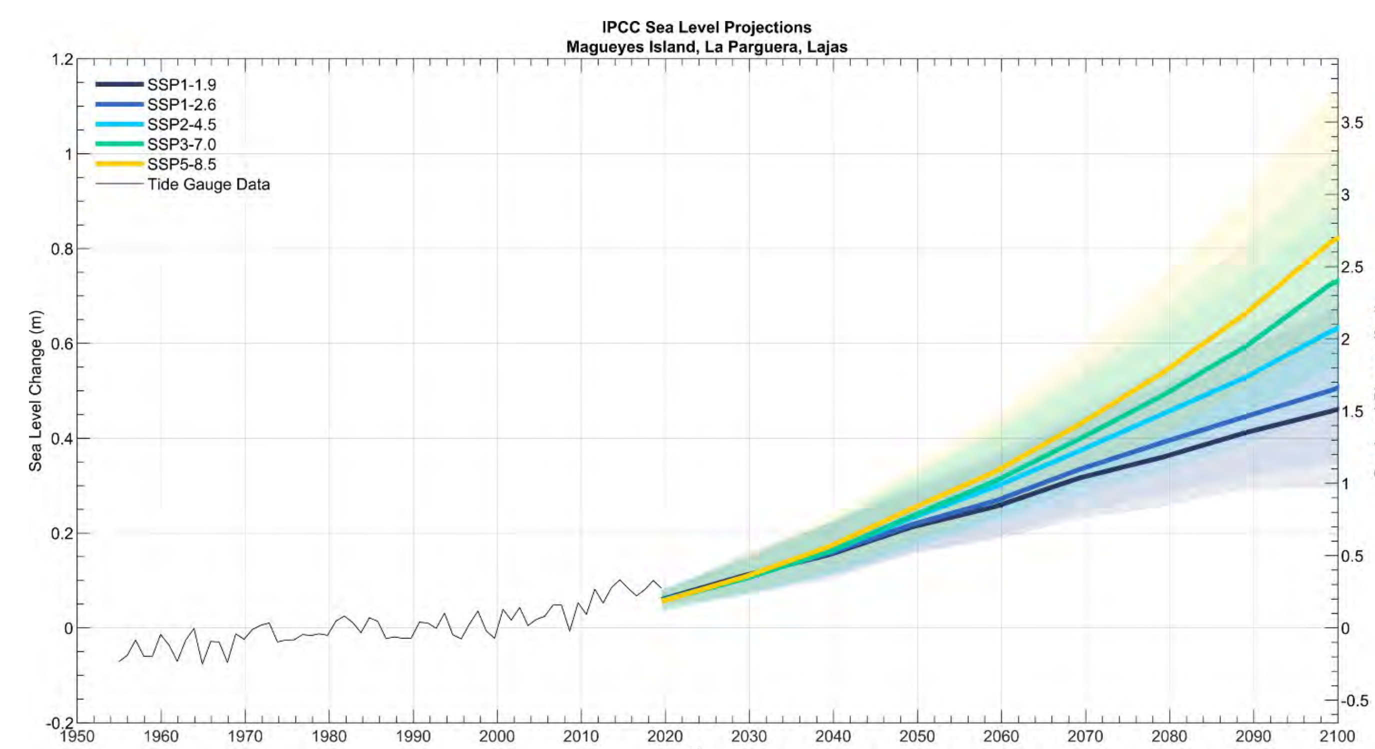


Figure 20. The likely ranges of sea level change for Magueyes Island, La Parguera, Lajas for IPCC GHG emissions scenarios. Thick lines show the ensemble means. Shaded ranges show the 17th - 83rd percentile ranges for each scenario. The black line shows the tide gauge historical data. (Source: Kemper-Fox et al., In Press)

SECTION 07
Ocean Acidification and Other Ocean Changes

KEY MESSAGES

In Puerto Rico, atmospheric CO_2 levels have continued to increase, reaching 415 ppm in June 2021. Oceans have taken up about 26-30% of all CO_2 emissions from human activities causing a regional decrease in seawater pH of -0.017 ± 0.0002 units/decade. Caribbean surface waters are 12% more acidic than in 1988.

Since 2009, coastal reef areas in the southwest of Puerto Rico have experienced a decadal increase of 3% in seawater CO_2 concentration and 2% in acidity. Conditions favorable for coral reef carbonate sediment dissolution have continued to increase since 2009 and persist by as much as 90% of the year. Moreover, the seawater concentration of calcium carbonate minerals has decreased by about 1.7% in the last decade, making calcification more difficult for marine organisms (e.g., corals) and weakening marine carbonate structures.

The sustained warming trend (0.26±0.006 °C/decade) in regional coastal and ocean waters poses a major threat to corals and their ecosystem thus compromising the services these provide including their role as coastal barriers, food source and tourism attraction. Caribbean waters are 2.3% warmer than in 1992, which provide for rapid intensification of cyclones, a particular threat for a region well embedded in the Atlantic hurricane alley.

The rapid anthropogenic increase of atmospheric carbon dioxide (CO_2) has dramatically altered the upper ocean's pH and heat content (Sixth Assessment Report of the IPCC (AR6; IPCC 2021). Warming has fundamentally impacted the global marine ecosystem health, food security, coastal protection and human socio-economic activities such as tourism. Surface pH has declined globally causing reductions in the saturation state of calcium carbonate – a constituent of skeletons or shells of a variety of marine organisms (IPCC, 2021). Experimental studies have not only demonstrated that ocean acidification (OA) could be a further threat to marine ecosystems in coming decades, but that its adverse impact to on biodiversity and socio-economic activities are further complicated by ocean warming (Anthony, 2016).

This section presents the current trends in atmospheric and seawater CO_2 concentration, seawater pH and temperature in Puerto Rico coastal and ocean waters. Knowledge of OA and warming conditions is critical to advance the 2030 Sustainable Development Goals (SDGs) of the United Nations (UN) in Puerto Rico [3]. Moreover, the information provided in this section is relevant for tracking progress towards achieving mitigation by the global community and adaptation activities in the Island.

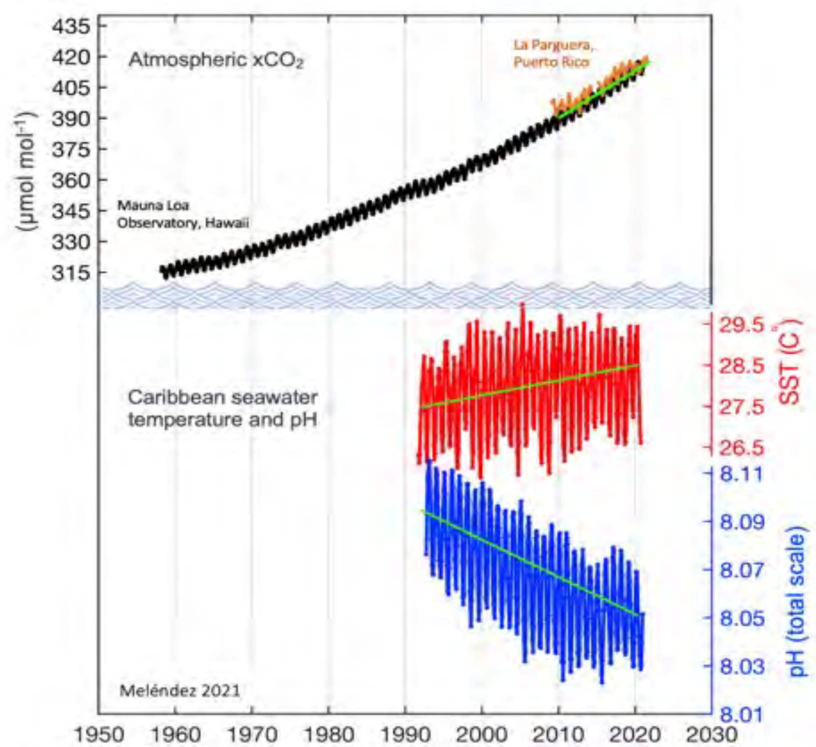


Figure 21. Time series from 1958 to March 2021 show the monthly atmospheric CO_2 mole fraction (xCO_2 µmol mol-1) at the Mauna Loa Observatory, Hawaii (www.esrl.noaa.gov/gmd/ccgg/trends/) and from 2009 to June 2021 at La Parguera (LP), Puerto Rico (https://www.caricoos.org/oceans/acidification/atmospheric). Time series from 1988 to 2020 of surface seawater pH (red) for the Puerto Rico Exclusive Economic Zone [-68 ˚W -65 ˚W 21 ˚N 15 ˚N] and sea surface temperature (red, SST). SST values were obtained from the NOAA Optimum Interpolation (OI SST) V2 data (17.625 ˚N 67.125 ˚W). Information about the Ocean Acidification Product Suit (OAPS) model can be found at https://www.coral.noaa.gov/accrete/oaps.html.

[3] https://ods.estadisticas.pr/es

ATMOSPHERIC CO_2 LEVELS IN PUERTO RICO

In Puerto Rico, atmospheric CO_2 levels have increased ~20 parts per million (ppm) since 2009 (Figure 21). This atmospheric CO_2 level exceeded 415 ppm in June 2021 or ~50% above pre-industrial levels (278 ppm). This represents an average annual growth rate of ~2 ppm/year (Figure 21) in the last decade (2010-2020). Globally, the CO_2 emissions decreased by 6.4 % in 2020 relative to 2019 due to the COVID-19 global pandemic (Liu et al., 2020). However, modeling studies suggest a modest or negligible impact of the reduction of CO_2 emissions on global atmospheric temperature (Fyfe et al., 2021) and ocean pH (Lovenduski et al., 2021).

REGIONAL OBSERVATIONS OF OCEAN pH AND TEMPERATURE

Over the last four decades, scientists have documented increases in surface ocean temperature, acidity (i.e., pH), and CO_2 at different oceanic settings using various techniques and long-term observations. To understand the rate at which these conditions are changing within our region, the methods described in Meléndez and Salisbury (2017) and the PRCCC Working Group 1 Report (2013) were used. Data considered for the analysis includes modeled ocean pH from the Ocean Acidification Product Suit (OAPS), remotely sensed monthly sea surface temperature anomalies (NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) v2) and in-situ high-frequency observations from two buoys off the south coast of PR - the CO_2 buoy in the mid-shelf off La Parguera (LP) and the CARICOOS PR-1 buoy in the outer insular shelf off Ponce.

Available historic observations and proxies evidence ocean warming is occurring at a global scale at a rate not consistent with natural cycles alone such as El Niño–Southern Oscillation (ENSO) or Atlantic Decadal Oscillation. The IPCC (2014) reported a global near surface warming rate of 0.11 °C/decade. Previous calculations of warming rates in the region's surface waters include an assessment using 1966 to 1995 SST data from La Parguera tide station which yielded a 0.25 °C/decade warming rate (Winter et al., 1998) and a later report by Morell (2008), using over a decade (1993 - 2003) of in-situ Conductivity, Temperature, and Depth (CTD) observations at the Caribbean Time Series Station (CATS) south of Puerto Rico (17.63 N, 67.00 W), yielded a warming rate of 0.26 °C/decade. An updated analysis using remotely sensed sea surface temperature data from 1992 to 2020 (Figure 21) at an open ocean location off the southwest Puerto Rico (17.5 N 66.5 W) returned a warming rate of 0.26 ± 0.006 °C/decade. The above estimates indicate a sustained warming rate for open ocean Caribbean waters south of the island. Said rate, which is double the global rate, has resulted in a 2.3% higher surface ocean temperature than in 1992.

Surface seawater pH levels from 1988 to 2020 using OAPS within the Puerto Rico Exclusive Economic Zone show that pH significantly (t-test, p-value<0.001) decreased at a rate of -0.017 ± 0.0002 units/decade (Figure 21). The current surface ocean is 12% more acidic (based on H+ concentration) than in 1988. These values agreed with values reported across the Caribbean (Gledhill et al., 2008) and Atlantic regions (Bates et al., 2012) using regional and global numerical marine carbonate system models and in-situ observations, respectively.

COASTAL OBSERVATIONS OF SEAWATER CO_2, pH AND TEMPERATURE

Measuring the impact that OA and warming have on marine ecosystems is challenging, partially due to the magnitude of the natural variability within coastal habitats. However, in the last decade, it has become apparent that the anthropogenic OA effects surpass the natural variations at LP (Sutton et al., 2018, Meléndez et al., 2020).

At LP, the surface seawater CO_2 has increased at a rate of 11.8 ±2.1 µatm/decade, and pH has declined -0.009 ± 0.002 units/decade. This is a decadal increase of 3% in CO_2 and 2% in acidity. Even though longer-term observations are needed to resolve the regional and large-scale controls on these rates, both trends were statistically significant (p-value<0.05). These trends show that water chemistry has changed rapidly over the last decade at LP. It is likely that the rate of acidification is driven by enhanced respiration at the site (see Meléndez et al., 2020). Approaches to improving the primary productivity of the system could help reverse these local trends.

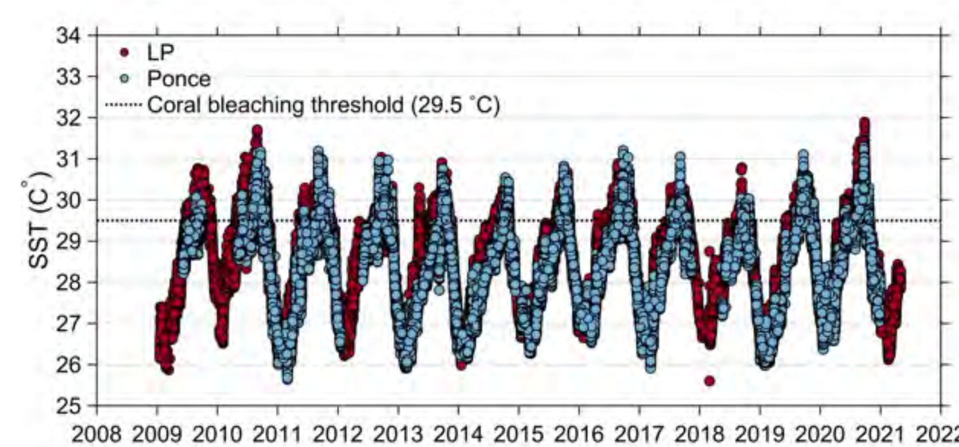


Figure 22. See Surface Temperature (°C) at the CARICOOS PR-1 buoy in the outer shelf off Ponce and the CO_2 buoy in the mid-shelf reef off LP from 2009 to 2020

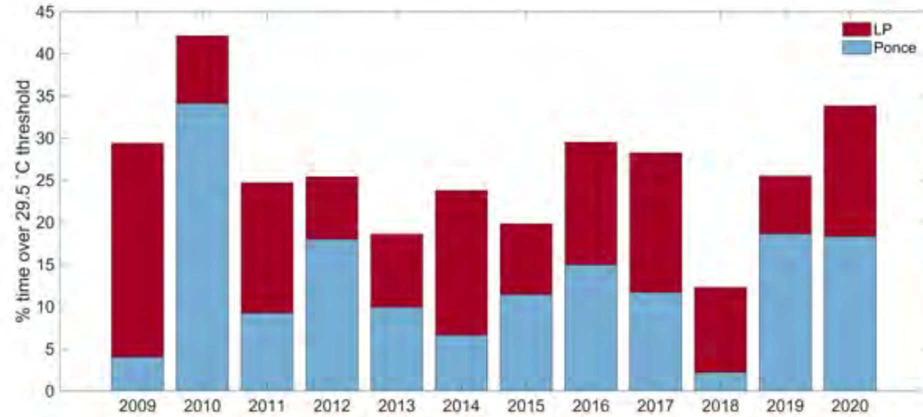


Figure 23. Percent of time above the threshold for coral bleaching (29.5 ˚C) at the CARICOOS PR-1 buoy in the outer shelf off Ponce and the CO_2 buoy in the mid-shelf reef off LP from 2009 to 2020.

In shelf waters south of Puerto Rico, where sea surface temperature is not modulated by heat transfer to waters below the mixed layer or to vertical advective processes (i.e., mesoscale eddies) the above regional ocean warming rate has resulted in frequent seasonal occurrence of temperatures well above the threshold for coral bleaching (29.5 ˚C). Sea surface temperature observations from the last decade collected at the CO_2 buoy off LP and the CARICOOS PR-1 buoy off Ponce (Figure 22) evidence the frequent seasonal occurrence of temperatures well above 29.5 ˚C. An average 25% of the observations off LP and 13% of those off Ponce exceeded said threshold (Figure 23). Temperatures above the bleaching threshold are frequent in both outer and inner shelf waters.

OTHER OCEAN ACIDIFICATION PROXIES - CORAL REEFS

Despite the high natural variability in coral reef systems, anthropogenic effects in water chemistry are more apparent at LP CO_2 buoy than other Atlantic reef areas (Sutton et al., 2018). This is of concern because OA may compromise the reef's ability to recover through reduced calcification rates (Anthony et al., 2008), enhanced bioerosion rate (Enochs et al., 2016) and reduced coral larvae recruitment (Doropoulos et al., 2012). This affects the ability of corals to serve as coastal barriers and threatens the livelihoods of many low-income and minority communities.

Understanding the extent to which the saturation state of the aragonite carbonate mineral Ω_{arag} is changing in Puerto Rico can help in the planning management strategies to ensure calcareous organisms, carbonate structures, and sandy beaches persist in future climate conditions. The Ω_{arag} is a chemical measure that can tell how much energy is demanded of the organism to build carbonate skeletal structures or shells. The higher the number (>1), the easier it is to calcify, and the more strongly the shells are built. However, carbonate minerals begin to dissolve at values that are less than 3.7 (Yamamoto et al., 2012). It has been shown that the physical strength of carbonate skeletons can be adversely affected by Ω_{arag} values higher than one (Cohen et al., 2009).

The Ω_{arag} in the Caribbean region is decreasing faster (-0.09 units/decade) than other Atlantic areas (Friedrich et al., 2012). Observations at LP coral reef system show a significant (p-value<0.001) decline of -0.06 ± 0.01 units/decade (Figure 24). A decadal decrease of 1.7 % suggests that marine calcifiers in this system need to invest more energy to maintain calcification and build strong shells than 10 years ago. Observations from LP reef system show that surface waters can be under the 3.7 threshold for carbonate sediment dissolution by as much as 90% of the year (Figure 24). Furthermore, the time under Ω_{arag} conditions in which dissolution of calcium carbonate is favorable has increased over the time series.

Recent new methods use the LP time series to better understand ecosystem changes (Meléndez, 2020). The observations indicated that dissolution processes dominate the calcification throughout the year, with higher rates during late summer and fall (Meléndez et al., submitted). This can have profound implications for calcareous organisms at larvae stages and highly soluble minerals (Kroeker et al., 2013). The combination of stressors (high temperature + acidity + CO_2 + dissolution + low Ω_{arag} are co-occurring with more frequency during late summer and fall.

There is high confidence that warming and OA are extremely likely to affect coastal and marine resources. Caribbean coral reefs in

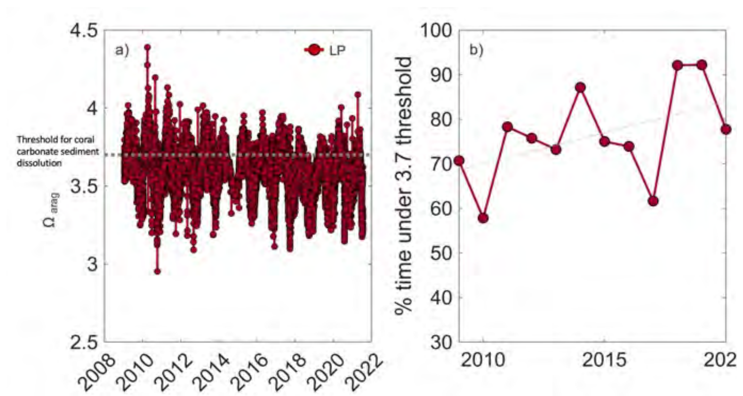


Figure 24. Time series Ω_{arag} observations (a) and % of time under the 3.7 threshold for carbonate sediment dissolution (b) at the LP CO_2 buoy from 2009 to 2020.

SECTION 08
Tropical Cyclones

KEY MESSAGES

The number of tropical cyclones impacting Puerto Rico has increased over the past 25 years (1996-2021).

Warmer sea surface temperatures and a warmer atmosphere likely contributed to the intense and large rainfall totals associated with Hurricane Maria, which is the highest average rainfall observed from a tropical cyclone in the last 60 years for the island. Climate model projections indicate that rainfall intensity will continue to increase as the climate warms. Additionally, there is high confidence that the number of intense tropical cyclones reaching categories 4 and 5 is likely to increase as the climate warms.

Tropical cyclones encompass tropical depressions (a closed circulation with average one-minute wind speeds less than 39 mph), tropical storms (wind speeds 39-73 mph) and hurricanes (wind speeds of at least 74 mph). In addition to strong winds, these storms favor intense rainfall and flooding; however, the rainfall can be beneficial during periods of drought. There is large variability in the frequency of tropical cyclones within the northern Caribbean Basin, especially between decades such as the relatively quiet period between the 1970s until the mid-1990s in comparison to prior and more recent decades. From 1855 to 2019, there were on average 2.9 tropical cyclone events recorded within 60 nautical miles of Puerto Rico in each five-year period (Figure 25). It has now been 25 years (as of 2021) since a below-average five-year period of tropical cyclone activity has been observed. August and September are the peak months of hurricane season and when most storms typically impact the island, including Hurricane Maria that devastated the island in September 2017.

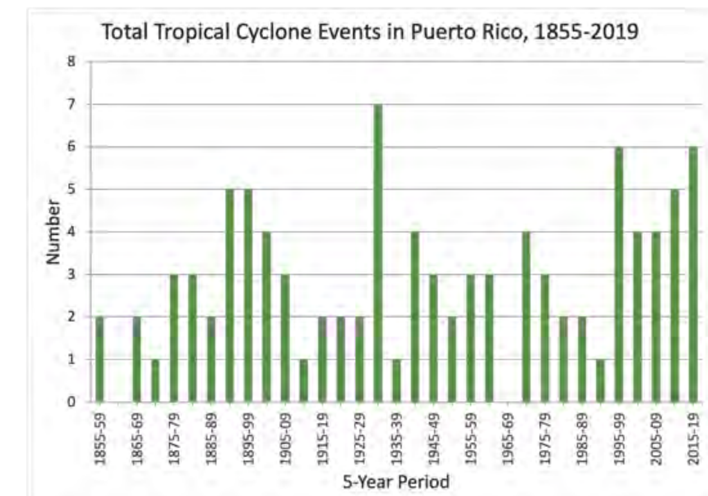


Figure 25. Total number of tropical cyclone events within 60 nautical miles of Puerto Rico, summed over 5-year periods from 1855-2019. Adapted from the state climate summary for Puerto Rico and updated through 2019 https://statesummaries.ncics.org/chapter/pr.

Currently, a precise detectable trend in tropical cyclone activity due to human-caused warming cannot be established based on historical data (Knutson et al., 2019). Key uncertainties include the relative contributions of human factors and natural variability, such as the influence of ENSO on cyclone formation in the tropical Atlantic, and uncertainties in the historical record of cyclone frequency and intensity prior to the satellite era. This does not imply that increases haven't occurred over the historical record, but the available data limit the ability to determine this with confidence (Kossin et al., 2017). Attribution studies are another means to help identify the relative contribution of human caused warming on prior extreme events. For instance, there is increasing evidence that warmer sea surface temperatures and a warmer atmosphere contributed to record rainfall totals for notable recent hurricanes, including Maria (Keelings & Ayala, 2019), Harvey (Risser & Wehner, 2017), and Florence (Reed et al., 2020). Additionally, warmer sea surface temperatures have been associated with other atmospheric parameters that influence hurricane development and intensity. For instance, an optimal environment for hurricane development requires an atmosphere with little vertical wind shear, which is more typical when sea surface temperatures are warm within the Caribbean (Kossin & Vimont, 2007).

Climate model projections are used to better understand potential changes in tropical cyclone frequency, intensity, and precipitation rate that occur as the climate warms. Figure 26 (adapted from Knutson et al., 2020) summarizes model-projected changes in tropical cyclone characteristics for a global warming level of 2°C. Projected changes in the total number of storms remains uncertain, but tropical cyclone intensity is projected to increase, which includes increases in the longevity of associated surface winds, and the proportion of tropical cyclones that reach the most intense status (category 4 and 5 levels; Knutson et al., 2020). Climate model simulations also depict heavier precipitation associated with tropical cyclones, similar to many attribution studies, as both sea surface temperatures and the atmosphere warms, providing the heat and energy needed to produce more intense and longer lasting rainfall. Projections of tropical cyclone precipitation rate show global mean increases of 14% for 2 °C of global warming. The combined effects of increases in tropical cyclone intensity (wind speeds and rainfall rates) with rising sea levels will lead to increases in storm surge and coastal flooding (Knutson et al., 2020).

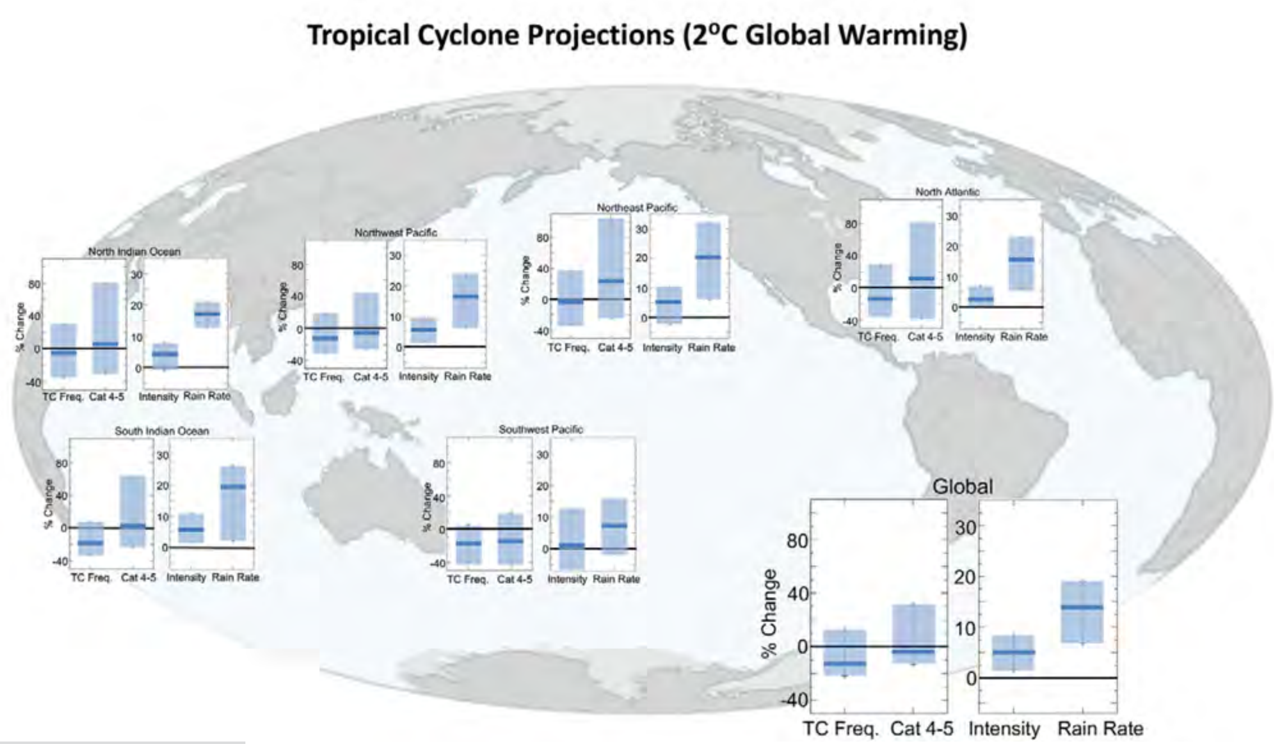


Figure 26. Projections of tropical cyclone frequency, frequency of category 4 and 5 storms, tropical cyclone intensity and rain rates for a warming of 2°C. Shown are the median and percentile ranges. Note the ranges are different for frequency compared to intensity and rain rate. Figure is adapted from Knutson et al., (2020) and provides additional details.

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WORKING GROUP 2

Ecology and Biodiversity

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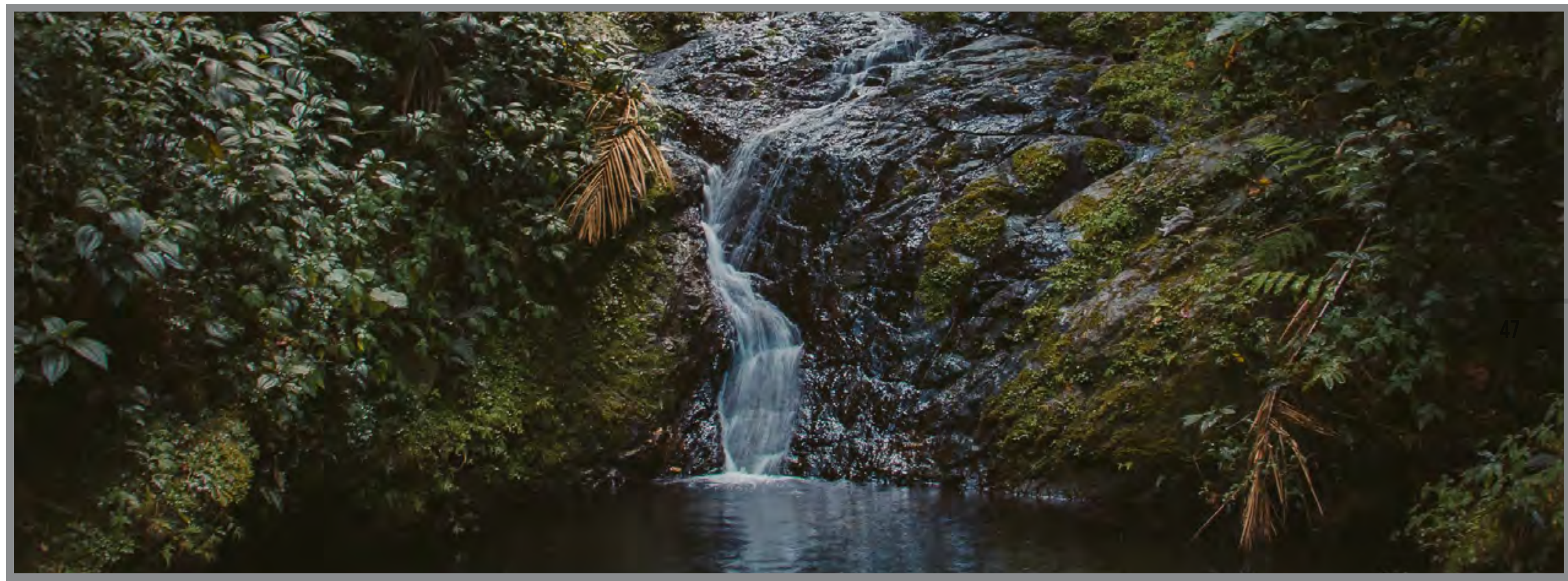


EXECUTIVE SUMMARY

This chapter explores climate change effects from the ridge to the reef throughout the Puerto Rico archipelago. Climate change effects will likely influence each ecosystem type, as well as the interrelationships between these systems.

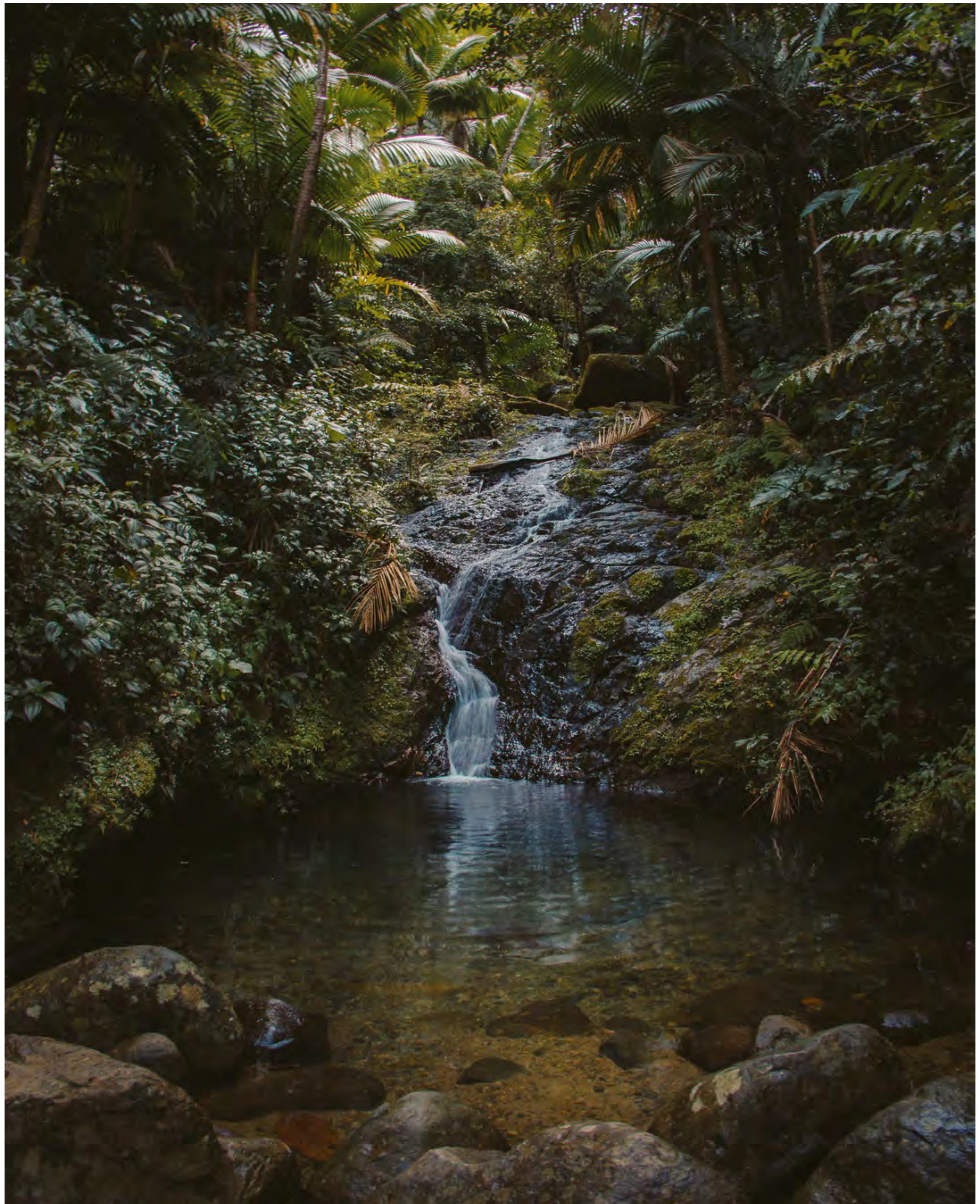
The effect of ocean chemistry and circulation on coastal and marine ecosystems in Puerto Rico is also included in this chapter. Ocean chemistry affects acidification, which has significant consequences for calcifying organisms. Ocean circulation can have significant effects on ecosystems, including the transport of sargassum to the Caribbean and anticyclonic eddies.

New information on the effects of climate change on freshwater, coastal, and marine ecosystems of Puerto Rico, are grouped based on:

- changes in water quality and quantity;
- sea level rise and saltwater intrusion;
- predicted changes temperature;
- increases in CO_2 and other greenhouse gases;
- changes in the ozone layer leading to fluxes in ultraviolet (UV) radiation; and
- changes in the intensity and frequency of storm events.

For each of these ecosystems, adaptation and management strategies are suggested for responding to climate change.

Reactive strategies, such as habitat restoration, and proactive strategies, such as the creation and adaptive management of conservation corridors and reductions in land-based stressors, are provided as recommendations to improve the adaptability and resilience of Puerto Rico's ecosystems to climate change. The importance of planning and monitoring management strategies is emphasized to evaluate ecosystems' conditions and the effectiveness of the recommended strategies. Finally, the chapter concludes with the recommended approaches for obtaining the information required to build strong adaptation strategies for freshwater, coastal, and marine ecosystems, as well as the resources that depend on them.



RESUMEN EJECUTIVO

Este capítulo explora los efectos del cambio climático desde las montañas hasta los arrecifes alrededor de todo el archipiélago de Puerto Rico. Es probable que los efectos del cambio climático afectarán cada tipo de ecosistema además de las interrelaciones entre estos sistemas.

El efecto de la química y la circulación oceanográfica sobre los ecosistemas costeros y marinos de Puerto Rico también se incluyó en este capítulo. La química del océano afecta la acidificación, la cual afecta significativamente los organismos calcificadores. La circulación del océano puede tener efectos significativos sobre los ecosistemas, incluyendo el transporte del sargazo al Caribe y los remolinos anticiclónicos.

La nueva información sobre los efectos del cambio climático en los ecosistemas de agua dulce, costeros y marinos de Puerto Rico está agrupada basándose en:

- los cambios en la calidad y cantidad de agua;
- el aumento en el nivel de mar y la intrusión de agua salina;
- los cambios en temperatura anticipados;
- los aumentos en el dióxido de carbono y otros gases de invernadero;
- los cambios en la capa de ozono causantes de variaciones en la radiación ultravioleta (UV); y
- los cambios en la intensidad y frecuencia de las tormentas.

Para cada uno de estos ecosistemas, se sugieren estrategias de adaptación y manejo para responder a los cambios climatológicos.

Se proveen estrategias reactivas, como la restauración de hábitat, y estrategias proactivas, como la creación y manejo adaptivo de corredores de conservación y la reducción de estresores de origen terrestre, como sugerencias para mejorar la adaptabilidad y la resiliencia de los ecosistemas de Puerto Rico al cambio climático. Se enfatiza la importancia de las estrategias de planificación y manejo para evaluar las condiciones de los ecosistemas y la eficacia de las estrategias recomendadas. Finalmente, el capítulo concluye con una descripción de los métodos recomendados para obtener la información requerida para construir estrategias robustas para la adaptación de los ecosistemas de agua dulce, costeros y marinos además de los recursos que dependen de ellos.

INTRODUCTION

KEY POINTS

- *Watersheds in Puerto Rico present a gradient of physical conditions that influence the aquatic communities within the watershed, as well as the coastal and marine communities at the mouth of their rivers and outlets. Thus, climate change effects upstream will also have downstream consequences.*
- *Coastal and marine construction, unsustainable agricultural practices, and other human activities adversely affect Puerto Rico's ecosystems. Climate change will likely exacerbate these effects, affecting the functioning of these ecosystems, including their resilience and ability to continue providing services to the archipelago.*
- *Hurricanes Irma and Maria in 2017 significantly changed the land and seascape, including coastal wetlands (Branoff et al. 2018), and coral (NOAA 2018b) and seagrass habitats (Hernández-Delgado et al. 2018). The predicted increase in the frequency and intensity of storms as climate change continues are likely to be a critical driver affecting the form and function of natural systems in Puerto Rico.*

The members of Working Group 2: Ecology and Biodiversity took a ridge-to-reef approach, analyzing connections between ecosystems within watersheds (freshwater, karst, wetlands) to the coast (estuarine wetlands, lagoons, including bioluminescent bays, beaches, and rocky shores) and within the nearshore marine environment (coral reefs and other coral habitats, seagrass, cays and islets, fishery resources, and marine mammals) in the discussion of climate change and its effects. Some systems, such as freshwater and karst, were not highlighted in the 2013 State of the Climate report, so more information is provided for them.

In Puerto Rico, 134 watersheds have been identified (DNER 2016; Figure 1), the majority of which begin in the central mountain region. The major watersheds correspond to the main rivers around the island, while the smaller watersheds are related to stream systems near coastal areas. The geological variability of the island influences surface runoff and associated transport of contaminants through the watershed and into marine waters. Due to the steep slopes in mountainous areas, the relatively small extension of the coastal plain, and the rapid rate at which water levels in streams and rivers rise during rainfall events, storms rapidly convey runoff downhill and streams and rivers quickly send pulses of freshwater into the nearshore environment. Thus, land-based pollutants, including terrestrial sediments and other contaminants, are quickly transported to the marine environment.

The River Continuum Concept (RCC) describes general parameters that represent a "continuous gradient of physical condition changes along the watershed, including width, depth, velocity, flow, temperature, and inputs of organic matter, among others" (Vannote et al. 1980). The changes in structure and function of communities from the headwaters to the river mouth are due to predictable variations in parameters that also allow the prediction of the distribution of functional feeding groups along a river's course. For example, the RCC predicts changes in the composition of available resources transported through the trophic food web. As available resources change, the functional groups that rely on them vary. It has been shown that this concept applies to rivers in tropical islands (Greathouse, 2006), so the RCC was applied to predict possible consequences of climate change to freshwater systems in Puerto Rico, as well as coastal communities at river mouths.

Because climate change is expected to increase the frequency and intensity of storms and cause sea level rise, the ridge-to-reef connection (through the watershed to ocean waters) will become more critical. The effects of climate change coupled with human activities are likely to cause shifts in the freshwater, coastal and marine ecosystems of Puerto Rico such as through increases in streambank and coastal erosion, contaminated floodwater, and debris transport. There may also be shifts in coastal habitat due to climate change effects and potential loss of habitat because of the lack of unoccupied areas for these systems to migrate. These shifts will affect the ability of coastal and marine ecosystems to provide services to the human population such as storm buffering, coastal protection, and food sources like fisheries.

Observed trends and modeling predictions have shown that rapid, anthropogenic-driven (due to increasing CO_2 concentrations) climate change will continue and could have unprecedented impacts on terrestrial and marine communities with associated negative socioeconomic consequences across regional scales. This is of particular concern for small islands with rapidly growing human populations, most of which are in coastal areas that are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion, as well as experiencing marine disease outbreaks (Bonan 2008; Ward and Lafferty 2004; Bellard et al. 2012; Hoegh-Guldberg et al. 2017; Veron et al. 2009; Chindarkar 2012; Lane et al. 2013; IPCC 2014; Hernández-Delgado 2015; Gould et al. 2018).

Thermal anomalies are now more frequent, widespread, and intense, affecting freshwater, coastal and marine ecosystems, and human populations. In Puerto Rico, coastal and marine development, human activities in these areas, as well as agricultural practices in watersheds, have led to adverse effects to coastal and marine ecosystems that are likely to be exacerbated by climate change.

In 2017, when Hurricanes Irma and Maria, categories 5 and 4, respectively, reached Puerto Rico, they significantly changed the landscape as intense winds, heavy rainfall, storm surge, and riverine flooding damaged vegetation and infrastructure throughout the archipelago. Hurricane Maria was the strongest storm to hit Puerto Rico since 1992, bringing maximum sustained winds of 135 knots, 38 inches of rain, flooding up to 5 feet above ground level, and 9 feet of storm surge. The storms also led to high levels of damaged coral, particularly along the northeast (including Culebra and Vieques), north, and west coasts of the island (NOAA 2018b), where the strongest waves occurred. Severe damage to nearshore coral and seagrass habitats also occurred due, in part, to the debris and contaminants generated by the storm and transported to nearshore waters (Hernández-Delgado et al. 2018).

Figure 1. Watersheds, reservoirs and lagoons and rivers and streams in Puerto Rico

General overviews of the ecosystems within the watersheds of Puerto Rico are provided below. Refer to the appendices for details on the freshwater (Appendix A), forests and karst (Appendix B), wetlands and bioluminescent bays (Appendix C), shorelines (Appendix D), and marine ecosystems of Puerto Rico (Appendix E).

Freshwater
Freshwater ecosystems were not included in the original State of the Climate report and are therefore emphasized later in this report. Puerto Rico's freshwater ecosystems are the source of waters, and in many cases of organisms, that influence downstream ecosystems, including the effects of riverine flooding during storms.

Forests
In the previous State of the Climate report (PRCCC 2013), forest cover (from headlands to coast) was categorized into four broad groups to discuss the composition, structure, and evaluation of climatic stressors in forests.

Because the previous State of the Climate report (PRCCC 2013) did not contain information on karst landscapes, we focus on the effects of climate change on northern karst forests and subtropical dry forests of the southern karst in this report. Coastal and moist lowland forests, which are mainly wetland habitats, are discussed further in the wetland section.

Karst
The karst landscape is a distinctive topography created by the dissolution of underlying soluble rocks by surface or groundwater. Karst is commonly associated with carbonate rocks such as limestone or dolomite. In Puerto Rico, the limestone region covers approximately 244,285 hectares (ha) or 28% of the island with 218,692 ha in the North, 21,022 ha in the South, and 4,571 ha dispersed throughout the rest of the island (Lugo et al. 2000).

The Río Encantado, located in the northern karst, runs 9.6 miles underground and is one of the longest underground sections of river in the world. The aquifer of the northern karst region contains one of the largest freshwater supplies of the island. On the south coast, distinctive karst features are less notable in the dry environment due to the lower rainfall that inhibits the rate of solution. In addition, much of the southern limestones are buried under deep alluvial soils.

WETLANDS AND LAGOONS, INCLUDING BIOLUMINESCENT BAYS

Palustrine and Estuarine Wetlands
In Puerto Rico and the Caribbean in general, palustrine and estuarine ecosystems are vulnerable to the effects of climate change because of the relationship between hydrology and wetland structure and function. Most wetlands in Puerto Rico are found along the coast with palustrine wetlands largely found abutting estuarine or shoreline ecosystems, creating interactions between the different systems.

A recent analysis of changes in land cover and the dynamics of coastal wetlands around Puerto Rico for the period from 1977 to 2010 estimated changes in wetland resources. The U.S. Fish and Wildlife Service (USFWS) employed the National Wetland Inventory (NWI) process to produce the NWI maps for Puerto Rico (USFWS 1983) utilizing imagery gathered in 1977. Since its draft publication in 1983, the NWI for Puerto Rico has not been updated. Recently, the Coastal Change Analysis Program (C-CAP; NOAA 2017) completed a landscape classification of the island based on 2010 imagery. Because C-CAP and NWI use the basic Cowardin et al. (1979) wetland categories, a coverage comparison between the two map products was possible (see Appendix C for more details). This comparison found that large acreages of estuarine and palustrine wetlands were transformed (15 and 30%, respectively) from 1977 to 2010 due largely to conversion to agriculture, negative transformations to more degraded wetlands, and conversion to developed land to a less extent (Figure 2 and Table 1).

Bioluminescent Systems
Bioluminescent bays and lagoons in Puerto Rico are unique, rare ecosystems where the accumulation and retention of bioluminescent dinoflagellates result in the display of light. Most bioluminescent systems are small, shallow (average depth: approximately 3.5 m), and with narrow inlets to the sea (approximately 100 – 150 m wide), leading to long water residence times and abundant populations of dinoflagellates (Margalef and González 1958; Coker and González 1960; Margalef 1961; Smayda 1970; Seixas 1988). Other factors, such as wind and water circulation patterns, may be important for maintaining high abundances of species within these ecosystems (Seliger at al. 1970 and 1971; Seixas 1983, 1988; Soler-Figueroa and Otero 2015, 2016). Bioluminescent systems are surrounded by mangroves, dominated by red mangrove, *Rhizophora mangle*, which provide nutrients and organic materials required for the growth of dinoflagellates and other phytoplankton species (Burkholder and Burkholder 1958; Prakash and Rashid 1968; Seliger et al. 1971). Bioluminescent systems function as a buffer zone between land and the open ocean because the mangroves protect the coast during major storms and hurricanes, buffering the wind and wave energy, and their roots serve as traps of land-based sediments.

Shorelines
Sandy beaches were a focus of the previous State of the Climate report for Puerto Rico (PRCCC 2013). This version includes other coastline types around the island (Figure 3; Barreto 2010). The most common coastline types around the island are beach (30%) and vegetated coastlines are dominated by mangroves (28%), but other plants, particularly in dune areas, are also common. Rocky shorelines constitute 10% of coastlines around the island and include volcanic, sedimentary, and metamorphic rock, while alluvial coastal plain is the least common coastal type and is mainly found along the southeast (Barreto 2010).

Many coastal modifications occurred during the transition from an agricultural to an industrial economy from 1950 to 1970 with the arrival of new industries, refineries, and heavy manufacturing that required the construction of port facilities, different types of breakwaters, and other concrete structures along the coast (Barreto 1997). Ongoing urbanization and residential

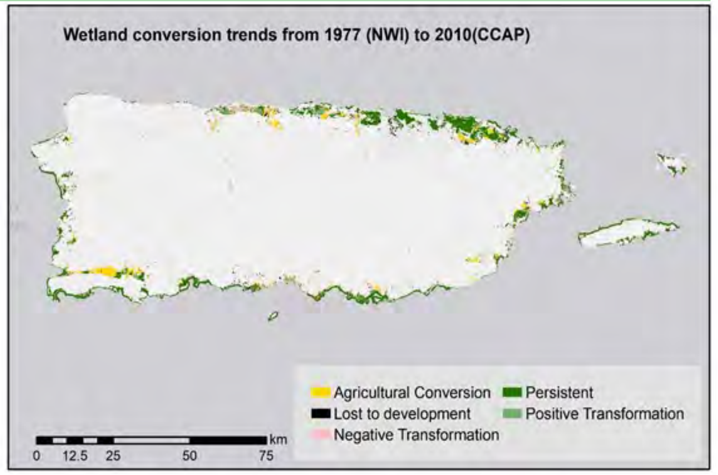


Figure 2. Trends in wetland conversion based on a comparison of NWI 1977 and C-CAP 2010 maps (NOAA 2017).

Table 1: Trends in wetland conversion, loss, and other changes or persistence from 1977 to 2010.

TREND	INSTANCES	ACRES	HECTARES
AGRICULTURE CONVERSION	26	23,257.10	9,411.81
LOST	58	8,703.25	3,522.08
NEGATIVE	138	34,487.71	13,956.68
PERSISTED	39	95,006.65	38,447.83
POSITIVE	76	15,213.47	6,156.67

development in coastal areas also contribute to shoreline hardening and changing patterns in sediment transport that affect natural coastlines. The proliferation of hardened shorelines represents a significant modification because these structures reduce natural coastline protection and promote erosion. These effects will be exacerbated by climate change, including increased storm intensity and frequency and sea level rise.

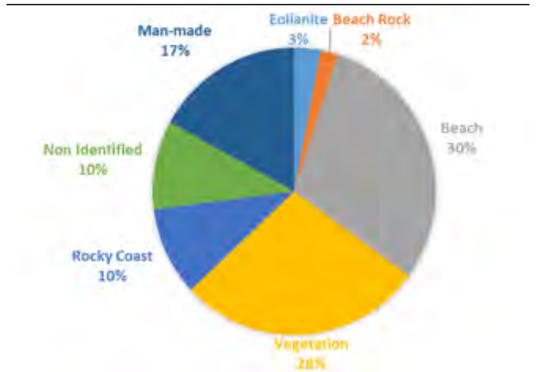


Figure 3. Coastal Types in Puerto Rico (Barreto 2010)

Marine Systems

Marine systems of Puerto Rico include coral and seagrass habitats, and cays and islets, as well as resources that depend on these habitats, such as fisheries and marine mammals.

Coral Habitats

Coral reefs aid in the establishment and protection of productive seagrass beds and mangrove forests and provide habitat, refuge, and resources to millions of species, including many that are commercially important. Many types of hard substrate are often colonized by corals, sometimes making the substrate hard to distinguish from structures that have been built entirely by corals and other calcifying organisms. Reefs provide protection to coastlines, and areas for research, recreation, and education. The annual value of flood risk reduction provided by coral reefs in the U.S. is estimated at $1.805 billion (2010 U.S. dollars) and 18,000 lives (Storlazzi et al. 2019).

Seagrass

Seagrass meadows provide essential services for coastal ecosystems, including sediment stabilization, reduction of water column turbidity, and reduction of wave energy. They serve as critical habitat for commercially and recreationally important fisheries including grunts, snappers, and lobsters in the Caribbean (Nagelkerken et al. 2000). Seagrass meadows aid in the remove of CO_2 by trapping organic carbon from the water column, from plant production in the sediment, known as "blue carbon" (Greiner et al. 2013), and by promoting the dissolution of carbonate sand (Burdige and Zimmerman 2002; Burdige et al. 2008; Burdige et al. 2010). In addition, it has been suggested that seagrass meadows adjacent to coral reefs contribute to reductions in coral diseases by controlling pathogenic bacteria (Lamb et al. 2017).

Cays and Islets

There are over 750 islands, islets, and cays within the U.S. Caribbean (Puerto Rico and the U.S. Virgin Islands [USVI] USFS-IITF 2015). The diversity of these islands is influenced by geology, location (windward, leeward), ocean bathymetry, proximity to a larger land mass, elevation and area, accessibility, and historical use. In Puerto Rico, an islet can refer to any small island, whereas a cay is a small, low island or bank composed of sand and coral fragments. Generally, four island types can be identified in the U.S. Caribbean according to their formation: (1) sand and coral cays; (2) mangrove cays; (3) volcanic and volcaniclastic; and (4) limestone. Because of their isolation, offshore islands provide valuable refuges for flora and fauna, including sea turtles, seabirds, and Nearctic and Neotropical migrating birds, where threats from invasive species and human uses are reduced. These islands also often serve as coastal barriers protecting the shoreline where they occur.

Fisheries

Puerto Rico's commercial fishery is a multi-species, multi-gear, small-scale artisanal fishery [1] where harvest is mostly for local consumption and is an important source of income and sustenance to many coastal communities.

Many reef fish species targeted by commercial and recreational fishers are vulnerable to overfishing because they are long-lived and grow slowly, and, because they gather in spawning aggregations, large numbers of individuals can be easily captured. Declines in commercial catch attributed to overfishing affect the local economy. Climate change affects different fishery species in different ways. Some species may benefit from climate change by expanding their range into waters that become suitable as temperatures rise, while others, such as reef fish that rely on different marine habitats during different stages of their lives, may decline with sea level rise, increasing temperatures, and increased frequency and intensity of storms. These subsequent effects of climate change can lead to declines in mangrove, seagrass, and coral habitat quality and availability.

Marine Mammals

Approximately 27 marine mammal species have been reported in the Caribbean Sea and Atlantic Ocean, some of which are residents and migrants around Puerto Rico (Rogríguez-Ferrer et al. 2019). Marine mammals have been affected by anthropogenic activities including overfishing and declines in water quality that have an effect on their prey and health, as well as hunting, which still occurs for some species as allowed by certain countries in the Caribbean.

1 According to FAO, artisanal fisheries are defined as "Traditional fisheries involving fishing households (as opposed to commercial companies), using relatively small amount of capital and energy, relatively small fishing vessels (if any), making short fishing trips, close to shore, mainly for local consumption. Artisanal fisheries can be subsistence or commercial fisheries, providing for local consumption or export. They are sometimes referred to as small-scale fisheries."

SECTION 02

Ocean Processes and Effects to Coastal and Marine Ecosystems in Puerto Rico

KEY MESSAGE

Ocean acidification adversely affects calcification and may lead to the displacement of calcifying species by non-calcifying species.

Ocean Chemistry

Ocean chemistry, while related to and affected by climate change, is not part of the climate system. Anthropogenically driven global change is the causal agent for climate change, as well as for changes in ocean acidification, which is discussed in Working Group 1. Below is a discussion of ocean acidification as it relates to calcifying marine organisms, particularly corals.

Ocean Acidification

The process of ocean acidification (details in Working Group 1: Section 7) has potentially detrimental consequences for marine life. It is certain that ocean acidification caused by anthropogenic activities is currently in progress and will increase in accord with atmospheric carbon dioxide (CO_2) emissions (IPCC 2021). The effect of ocean acidification on coastal zones, where most of the affected marine organisms reside can be several times higher and faster than typically expected for oceanic waters due to processes other than CO_2 uptake (e.g., respiration, discharge of riverine waters). Ocean acidification decreases the availability of the carbonate ion, CO_3^{2-} (the principal building block of most marine skeletal material), adversely affecting calcification and increasing dissolution processes. This leads to slow growth rates and malformed and less dense carbonate shells and skeletons (Cohen et al. 2009). As a result, species that undergo calcification may become displaced by species that do not. This will likely continue deteriorating reef conditions and can cause ecological regime shifts from coral to algal reefs (Anthony et al. 2011). A decline in calcifying species (e.g., corals, crustose coralline and calcareous algae, conch, and urchins) increases the potential for shoreline erosion, decreases the potential for carbonate island formation, and decreases beach and reef-based tourism and economic activities. Ocean acidification will likely lead to ecological regime shifts from coral to algal reefs (Hoegh-Guldberg et al. 2007; Anthony et al. 2011). Seagrass beds and macroalgae could benefit because they utilize CO_2 during growth (Palacios and Zimmerman 2007). This could cause non-calcifying species to outcompete calcifying organisms (Fabricius et al. 2011), resulting in changes to ecosystem services. For example, ocean acidification could affect the food web dynamics at lower trophic levels and have physiological effects at larval stages that would likely cascade upwards through the food web impacting coral and fish recruitment.

In addition to the effect on calcification of living organisms, ocean acidification is likely to increase biological (bioerosion) and chemical (dissolution) erosion of carbonate structures, shells, and sediments (Andersson et al. 2009; Andersson and Gledhill 2013; Enochs et al. 2015). Any decline in calcification or increase in net dissolution could compromise many reef systems and associated cays because rates of accretion on healthy, undisturbed reefs only slightly outpace rates of reef loss due to physical and biological erosion (see Glynn 1997 for review). The combination of erosion, dissolution, and bioerosion processes in shallow reef habitats could accelerate the loss of calcium carbonate sediments and decrease the stability of the reef skeletal framework (Eyre et al. 2014), potentially leading to a collapse of reef structures (Hoegh-Guldberg et al. 2007). This is of particular concern in cay and island environments considering the vital habitat the reef framework provides for marine organisms and the coastal protection it affords to human populations through dissipation of wave energy (Storlazzi et al., 2021).

Ocean acidification also leads to a decrease in ocean sound absorption (Hester et al. 2008). As the ocean becomes more acidic, decreases in pH-dependent charged molecules such as carbonate ions that absorb acoustic waves will allow low frequency sound to travel much further. Because marine mammals use sound to communicate and are very sensitive to other sources of noise, these impacts could affect reproductive success if it becomes more difficult for males and females to locate one another. Decreases in sound absorption could also lead to behavioral and injurious impacts to marine mammals, thus decreasing their fitness.

Effects on Calcification

Friedrich et al. (2012) concluded that calcification rates may have already dropped by approximately 15% in the Caribbean with respect to pre-industrial values. However, this decrease in calcification has not been attributed to ocean acidification (Carricart-Ganivet et al. 2012). It is more likely that changes in calcification are due to the decreasing carbonate production rates (Perry et al. 2013, 2015), hard coral cover (Gardner et at. 2003), and reef complexity (Alvarez-Filip et al. 2009), and changes in reef diversity and community composition (Alvarez-Filip et al. 2013) throughout the Caribbean region over the last decades. Observations of the chemistry of net ecosystem calcification (NEC) in La Parguera, Puerto Rico suggest that calcium carbonate dissolution can play a large role in reef-scale NEC in areas with low live coral (<10%). In La Parguera, ecosystem calcification dominated during a short window of time, approximately four months in 2014 decreasing consistently to 2.5 months in 2017. Saturation state (Ω) appears to have decreased (1.7%) in La Parguera, Puerto Rico from 2009 to the present (see Working Group 1: Section 7).

The effects of ocean acidification on calcification are species-specific and the ecological consequences vary depending on the benthic community dominating the reef. For instance, *Porites* spp. invest increased calcification in extension and under stress conditions this may reduce their ability to compete for space. Other key reef-building species such as *Orbicella* spp. use increased calcification to construct denser skeletons. Reductions in calcification would therefore make *Orbicella* spp. more susceptible to both physical and biological breakdown (Carricart-Ganivet et al. 2012).

Ocean Circulation

KEY MESSAGES

The bloom and decay of *sargassum* species can produce anoxic conditions, resulting in mass mortality of important marine species.

Anticycolonic eddies cause variability in the mean current, affecting deep light penetration in visible and UV spectra, and possibly influencing coral bleaching events.

Sargassum

A recent threat to bioluminescent bays and lagoons is the accumulation of the brown macroalgae *Sargassum* spp. *Sargussum* blooms have recurred annually since 2011 and appear to be from the tropical Atlantic Ocean east of Brazil (Langin 2018). Blooms are thought to be related to weather fluctuations, nutrient inputs from the Amazon River, changes in ocean currents, and increased iron fertilization from airborne dust that settles in the ocean (Wang and Hu 2016; Langin 2018). The first widespread accumulation of *Sargassum* spp. in the Caribbean was reported in 2011, but the areal coverage of the 2015 event was four times larger than in 2011 (Wang and Hu 2016).

In August 2015, the decay of a high biomass of these algae in Laguna Grande, Fajardo, produced anoxic conditions (i.e., 0 mg/L oxygen concentrations in the water; F. Aponte and DNER pers. comm.) resulting in mass mortality of bony fishes, rays, and other species, and the disappearance of bioluminescent *Pyrodinium bahamense* populations and other phytoplankton species (B. Soler-Figueroa, unpublished data). *Sargassum* blooms also affect shoreline communities and estuarine wetlands, as well as shallow reef and seagrass areas. The effects of *Sargassum* brown tides on the Mexican Caribbean coast included reductions in light, oxygen (hypoxia or anoxia), and pH, as well as high monthly influxes of nitrogen and phosphorus leading to eutrophication (van Tussenbroek et al. 2017). This led to impacts on the trophic dynamics of the long-spined sea urchin, *Diadema antillarum*, a keystone herbivore in the coral reef ecosystem (Cabanillas-Terán et al. 2019), as well as the replacement of turtle grass meadows with algal communities and total or partial mortality of nearshore corals (van Tussenbroek et al. 2017).

Anticyclonic Eddies

Oceanographic conditions of calm seas and warm, clear waters are typically associated with anticyclonic eddies entering the northern Caribbean Sea. Anticyclonic eddies are mesoscale systems that travel across the Caribbean Sea introducing an important source of variability to the mean current (Gordon, 1967; Molinari et al. 1981; Carton and Chao 1999; Andrade and Barton 2000). Anticyclonic eddies are convergent systems that tend to depress thermoclines and associated pycnoclines. Because of the downwelling motion, nutrients remain stratified deep in the water column below the pycnocline resulting in a highly oligotrophic surface mixed layer that allows for a deep light penetration both in the visible and UV spectrums. The number of anticyclones increases significantly south of Puerto Rico and Hispaniola during August through December, which contributes to a slowing of the northern Caribbean current.

One relatively large anticyclonic eddy entered the northern Caribbean and remained almost stationary during a period of more than two months between 16 to 18 degrees North and 69 to 67 degrees West from August through September 2005. Although direct optical/chemical/physical oceanographic data do not seem to be available to relate the 2005 mass coral bleaching event with the passing of this mesoscale anticyclonic eddy, both phenomena coincided in time and space (Figure 4).

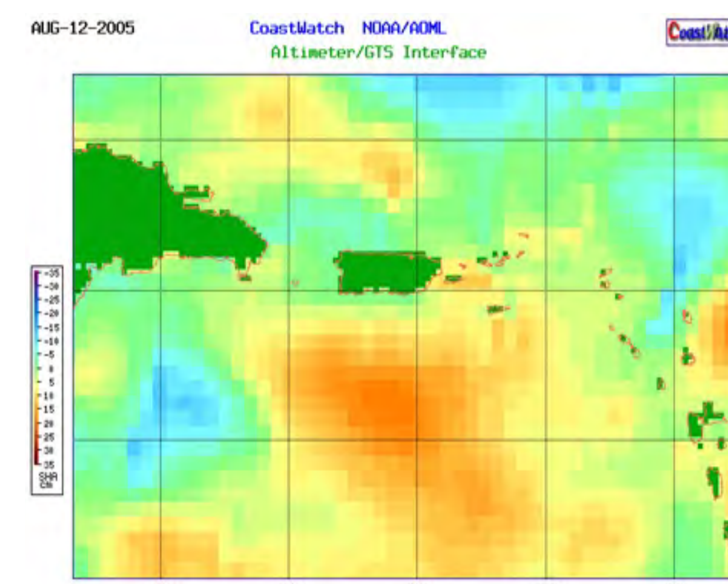


Figure 4. Geographic range of a mesoscale anticyclonic eddy affecting the northern Caribbean during the late summer and fall of 2005 as inferred from altimetry (ocean height) data.

Linking Coral Bleaching and Disease to Climate and Oceanographic Processes

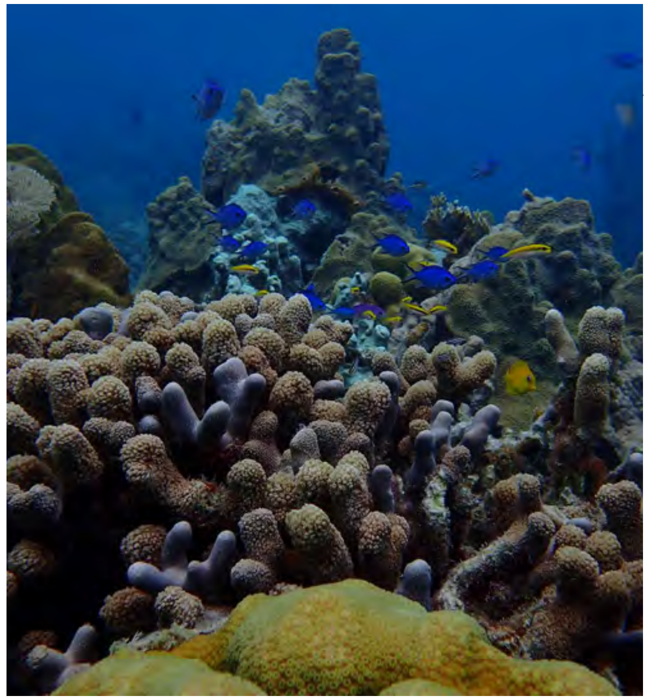
KEY MESSAGE

Coral disease outbreaks and bleaching events have been increasing in frequency and intensity, which are positively and significantly correlated with high thermal anomalies.

Coral bleaching is the process by which zooxanthellae endosymbionts are expelled from the coral host due to oxidative stress in the symbiont chloroplasts, resulting in photosynthetic system degradation and breakdown of the symbiosis (see Lesser 2007 for review). The symbionts are obligate for their hosts because of their contribution to their host's energy budgets through the provision of photosynthates, as well as by facilitation of the calcification process in skeleton-forming taxa (Baker et al. 2008). Bleaching weakens corals and, in combination with other secondary stressors, may lead to a series of problems that result in an overall decline in coral health, including increased incidence of disease and mortality (Glynn 1996; Lesser 2007).

Small scale coral bleaching events have been linked to both anthropogenic and natural stressors such as extreme water temperatures and solar irradiance, subaerial exposure, sedimentation, freshwater dilution, contaminants, and diseases, whereas elevated sea temperatures and high solar irradiance may act synchronously to induce large-scale bleaching events (Glynn 1996). Increased solar radiation, both in the visible (400 – 700 nm) and the ultraviolet (UV; 290 – 400 nm) regions of the spectrum, has been implicated in mass coral bleaching (Hoegh-Guldberg and Smith 1989; Brown 1997; Lesser and Farrell 2004; Baker et al. 2008), reduced growth rates and photosynthetic pigments (Torres et al. 2007), and reduced coral fecundity (Torres et al. 2008; Torres-Pérez and Armstrong 2012). The combined effects of high water temperatures and acute exposure to UV radiation have been shown to affect the photosynthetic efficiency of scleractinian coral species (Ferrier-Pagés et al. 2007; Shick et al. 1996; Lesser 2000). The fact that differential mortality of corals was observed from reefs distributed within the surface mixed layer (0 – 50 m) and from reefs at similar depths within the Puerto Rico insular shelf suggests that water temperature was not the only trigger of the 2005 regional coral bleaching, and García-Sais et al. (2017) propose that a synergistic effect with UV radiation was more likely responsible for the observed patterns of coral loss.

As discussed in the PRCCC (2013), the most severe coral bleaching event was observed during the fall of 2005 when thermal stress in Caribbean surface waters exceeded any observed from the region in the previous 20 years, and regional averaged sea surface temperatures (SST) were the highest on

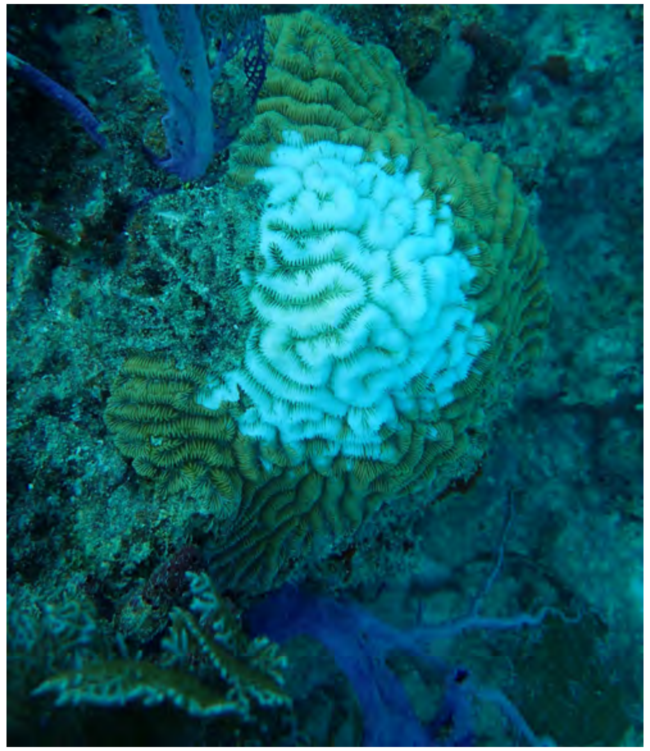


El Negro Reef, Cabo Rojo (2016). Source: Puerto Rico Coral Reefs Monitoring Program.

Coral diseases and subsequent mortality have been linked to bleaching events in the Caribbean (Hughes et al. 2003; Aronson et al. 2002). During the 2005 event, white plague disease (WPD) outbreaks, occurrence of Caribbean yellow band disease (CYBD), and intensive bleaching caused an average 53% loss in live coral tissue in La Parguera (Cróquer and Weil 2009). Centennial colonies of mountainous star coral died within months as they were further infected by what appeared to be a cyanobacterium (Torres-Pérez pers. obs.). Together with the bleaching-associated mortalities, white band disease (WBD), WPD, and CYBD were responsible for the largest ever recorded loss of live coral cover in the Caribbean. Between 50 - 80% of live coral cover disappeared from reefs in La Parguera, Culebra, Mona, and Desecheo, Puerto Rico, and other important reef localities in the northeast and the southern Caribbean between 2005 and 2011 (Hernández-Pacheco et al. 2011; Bruckner and Hill 2009; Cróquer and Weil 2009; Bastidas et al. 2012).

White Band Disease (WBD). Source: Dr. Ernesto Weil

Overall, most of Puerto Rico's reefs have been affected by disease outbreaks and bleaching events in the last decades and these are incraeasing in frequency and intensity, leading to partial and complete colony mortality on many reefs. These events are positively and significantly correlated with high thermal anomalies. Diseases are affecting the most important reef-building species, as well as many other stony corals and other organisms that are part of the coral reef community such as hydrocorals, octocorals, zoanthids, sponges, and crustose coralline algae. Between 25-60% of live coral tissue has been lost from coral reefs around Puerto Rico and recent evidence indicates that diseases are also affecting the natural recovery of coral communities by significantly reducing coral fecundity and reproductive output.



Stony Coral Tissue Loss Disease (SCTLD). Source: Stacey Williams

KEY MESSAGES

Average streamflow is projected to decrease.

Changes in the hydrologic regime will affect freshwater, wetland, and marine systems.

The climate has a strong influence over processes, such as evaporation and precipitation, that govern the amount and distribution of water. Van Beusekom et al. (2015) used statistically downscaled global-scale general circulation models for two scenarios, one for high future greenhouse gas emissions and one for low future emissions and applied them to a hydrologic model to address changes in water resources in Puerto Rico. Under scenarios of low and high greenhouse gas emissions, streamflow around the island is projected to decrease, which will also affect downstream systems. Changes in the hydrologic regime in Puerto Rico will affect freshwater, wetland, and marine systems.

The Comprehensive Plan for Water Resources (DNER, 2016) recognizes the following possible consequences of climate change on water resources in Puerto Rico: a reduction in rain; a reduction in surface water availability; impacts to riparian, estuarine and wetland diversity; higher human pressure on water sources; an increase in saline intrusion into aquifers; increased demand for groundwater; changes in evapotranspiration; changes in relative soil moisture; increases in the probability of urban and coastal floods; and potential increases in the sedimentation of lakes, rivers and streams. Some of these potential consequences, such as increases in flooding and sedimentation, will also lead to increased transport of land-based pollutants and debris to marine systems, affecting the health of these resources.

The compromised host hypothesis (sensu Rosenberg and Ben-Haim 2002) suggests that rising ocean temperatures associated with climate change may increase the number and prevalence of diseases by making corals, octocorals, and other marine invertebrates more susceptible to ubiquitous pathogens, or by causing shifts in resident microbial communities, making some of them pathogenic or more virulent. Results from 15 years of disease research in Puerto Rico show a positive and significant relationship between increasing seawater temperatures and increases in numbers, prevalence, and virulence of diseases (Cróquer and Weil 2009). A recent example of the compromised host hypothesis in Puerto Rico is the arrival of stony coral tissue loss disease (SCTLD), which causes mass mortality of over 22 species of scleractinian corals. SCTLD was first reported in 2014 on the southeastern coast of Florida (Precht et al. 2016) and has since spread to sites in the Caribbean, including to Puerto Rico in November 2019 (Kramer et al., 2019).

Sabana River mouth in the Atlantic Ocean. Source: Wanda I. Crespo

Changes in Water Quantity and Quality

Global climate change predictions suggest a generalized change in precipitation patterns around the world (IPCC 2014). Projections of future rainfall for the Caribbean suggest a 25-50% reduction in mean annual rainfall (Campbell et al. 2011). As rainfall patterns change, droughts could be more frequent and severe. Droughts increase the amount of carbon in the soil, which can be drawn into streams and cause a decrease in pH due to the formation of carbonic acid (H_2CO_3), a weak acid which deprotonates easily to produce hydrogen (H+) and bicarbonate (HCO^{3-}) ions. This mechanism and its effects on aquatic biota have already been demonstrated in other tropical regions (Ramírez et al. 2006; Small et al. 2012). In Puerto Rico, an experimental addition of CO_2 has shown a reduction in stream pH and a negative effect on macroinvertebrate abundance (Klem and Gutiérrez-Fonseca 2017) with potential negative consequences for aquatic ecosystems.

Hydrological drought occurs when surface water flow is reduced and surface and groundwater levels fall as a result of dry weather patterns (meteorological drought). There is a lag in response between meteorological and hydrological drought. Watershed characteristics, like geology and land use, can play an important role in the persistence of hydrological drought (Van Loona, 2015).

Reductions in water availability can affect instream flows. Decreases in streamflow may disconnect surface waters from groundwater as the water table reduces, affecting aquatic organisms. Changes such as mortality of vegetation can favor the establishment of invasive species or the expansion of terrestrial vegetation into the aquatic environment. Reductions in riparian vegetative cover could cause increases in the temperature of stream water in headwaters and midsections of streams. As headwater pools become shallower and warmer, decapod growth and reproduction could be affected, making them more susceptible to drought and low dissolved oxygen caused by high inputs of organic matter (Pérez-Reyes et al. 2015). In midsections and lower portions of streams, a hostile environment for organisms can develop due to concentrations of pollutants and reductions in oxygen concentration. Lower water availability will intensify intra- and interspecific interactions among the biota. At the lowest elevations, reductions in streamflow could result in greater saline intrusion to areas further inland during periods of drought. It is possible that, as inflow from major tributaries decreases, less water will be available in the lower portions of the watershed, including wetlands.

Droughts stress the inhabitants of rivers because isolated pools or water holes gradually dry due to declining groundwater, become more concentrated with solutes like salt and often have lower dissolved oxygen concentrations than flowing water. Most species of native shrimp cannot cope with high sedimentation and accumulation of organic matter, low dissolved oxygen levels and a reduction in the pool volume that leads to disconnection between pools, preventing migration and ultimately causing death. The 2015 drought went on for so long that there were major concerns for shrimp; the pools in Quebrada Prieta reached the anoxic stage (W.H. McDowell of Luquillo LTER pers. comm.).

Droughts also allow the buildup of organic material, both living and dead, in the dry parts of rivers. This contributes to the energy of rivers when water returns, although drying will also change the biogeochemical makeup of the accumulated material and sediment (Pérez-Reyes et al. 2015). In the last decades, Puerto Rico has experienced two droughts, one in 1994 and the most recent in 2015. During these extreme drought events, the impact on the freshwater biota was the same: 1) an increase in densities of shrimp as a result of a reduction in pool volume; 2) downstream migration of filter feeders and shredders; 3) an increase in the number of predators (e.g., *Macrobrachium*) in the headwater pools where they are not observed during normal conditions (Covich and McDowell 1996); and 4) an increase in insect densities as a result of the accumulation of organic matter in the pools. In addition, an increase in the abundance of macroinvertebrates, particularly of Collector-Gatherers, has been found because of increased fine organic matter deposited in the bottom of the pools and an increase in litter fall from riparian vegetation, possibly due to water stress in plants and a decrease in chlorophyll (Gutiérrez-Fonseca et al. 2020).

In Puerto Rico during the 2015 drought, the effluent of the tertiary regional wastewater treatment plant in Caguas discharged approximately 12 million gallons per day (MGD) to one of the headwater streams of Rio Grande de Loíza. This was the main water supply to the Carraizo reservoir during the low instream flow due to the drought. Even when effluent receives advanced treatment, some metabolic compounds can persist in the water, like pharmaceutical products (such as antibiotics, analgesics, antiinflammatory drugs), personal care products, and even endocrine disruptors (caffeine, aspirin, steroids, hormones, among others; Pal et al. 2010). These compounds are considered endocrine disruptors because they can interfere with the endocrine system of humans and other organisms, even at low concentrations (Soler Llavina 2015). Therefore, the release of treated wastewater during droughts, when mixing and dissolution capacity of streams is drastically reduced due to low flows, can lead to a mixture of multiple compounds persisting in the water and posing risks to the biota and the human population.

Increased drought frequency and intensity will likely favor tolerant, exotic fishes over native species and may cause exotic species that are currently present at low levels to become highly abundant. In a long-term monitoring study, Ramírez et al. (2018) demonstrated that the 2015 drought caused a shift from a native-dominated to an exotic-dominated fish assemblage in the Río Piedras. However, it is possible that with droughts of sufficient magnitude, duration or frequency, native species may not be able to recover and systems could remain in exotic-dominated states.

Reduced instream flows related to drought conditions could further exacerbate the negative effects of instream barriers on migratory fauna. During the water year of 2015, many rivers in Puerto Rico experienced drastically reduced flows, leading to new records of low instream flows. During low flow conditions, barriers can become impassable (Cooney and Kwak, 2013), restricting the migratory patterns of aquatic fauna.

Droughts may also affect native fishes and entire aquatic ecosystems by negatively affecting amphidromous migrations (Covich et al. 2006). It is likely that both downstream transport of larvae and upstream migration of postlarvae are more successful during periods of high river discharge. This is evidenced by the overlap between spawning and recruitment cycles with periods of high rainfall in Puerto Rico and positive relationships between daily river discharge and postlarval recruit abundances (Engman, 2017). Moreover, strong droughts of long duration have the potential to fully interrupt amphidromous life histories. In Puerto Rico, under normal low flow conditions, sand berms form at the mouths of many rivers (Figure 5). These berms are formed by wave action and can build to sufficient mass that they physically block the entire river mouth, creating a barrier for the dispersal of larvae to the ocean and recruitment from the ocean of postlarvae that will stay in place until a freshwater surge from heavy rains dislodges it (Negrón-Gonzalez and Cintrón 1979; Engman 2017). Thus, changes in drought and rainfall patterns will change berm formation with associated impacts on aquatic communities.

Decreased success of amphidromous recruitment will challenge the viability of amphidromous fish populations because recruitment determines population dynamics in species with marine larval phases (Caley et al. 1996). Moreover, nutrient dynamics may be altered if amphidromous migrations are diminished by drought. Amphidromous fish postlarvae have been shown to be a marine subsidy because they transport marine nutrients to estuarine and freshwater ecosystems during recruitment. Reduced migrations of amphidromous species will also decrease the available food resources for ecologically and economically valuable predatory and sport fishes because shrimp and fish postlarvae are important components of the diets of estuarine and riverine fishes (Engman 2017).

In 2014 and 2015, three massive fish die-offs occurred in La Plata Reservoir as a result of reductions in dissolved oxygen concentrations. Tributaries that supply water to the reservoir, namely Guadiana and La Plata Rivers, had drastically reduced flows resulting in the accumulation of large amounts of sediment at the outlets of the tributaries. Low water levels also resulted in the exposure of fish nests.

These conditions persisted for 93 days (Figure 6, Left) until a heavy rain event that moved accumulated sediment into the reservoir causing an increase in water turbidity and reductions in dissolved oxygen. These unfavorable conditions caused a massive fish die-off in La Plata Reservoir. In 2015, water levels in La Plata Reservoir were reduced again for 153 days (Figure 4, Right) once more leading to a fish die-off and effects on reproductive success. Accumulated sediment

Figure 5. River mouth of Rio Sabana. Left without sand berm from May 24, 2014. Right with sand berm formed from July 17, 2014 (Photos: A. Engman)

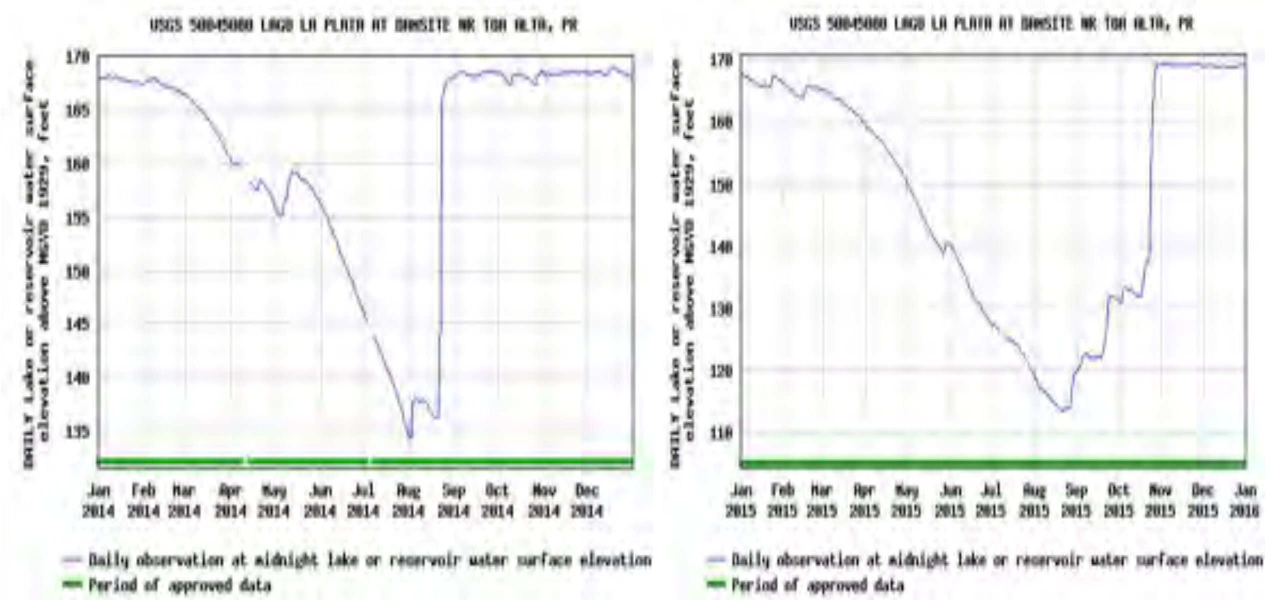


Figure 6. Levels in La Plata Reservoir in 2014 (left) and 2015 (right). Information obtained from USGS Surface-Water Daily Data for Puerto Rico.

along the border of the reservoir was extracted and placed in downstream areas of the watershed, which likely led to further impacts to aquatic organisms from sediment transport.

Henareh Khalyani et al. (2016) examined the climate change implications for tropical islands through the interpolation and interpretation of downscaled general circulation model projections. Under all scenarios, there was a shift from subtropical moist and wet forest in the northern limestone region to tropical moist forest and then tropical dry forest. In the southern limestone region, the subtropical dry forest shifts to tropical dry forest and subsequently to tropical very dry forest. They indicate that these new ecological conditions may result in new ecosystems and new communities, with the loss of tree species that require soil moisture throughout the year and associated impacts to fauna.

In subtropical dry forests such as those of the Guánica Forest, as well as the subtropical moist forests of the northern karst, tree mortality may increase by increasing length and intensity of drought. Trees may respond in differing ways to moisture stress, either through stomatal control to maintain leaf water potential or through maintaining a water supply from the soil. The former reduces the risk of hydraulic failure but increases the risk of mortality by "carbon starvation." Other studies indicate that the major cause of mortality in seasonally dry forests is hydraulic failure (Meir and Pennington 2011). Shifts in species' composition may occur because of this increased mortality (PRCCC 2013).

Laskey et al. (2016) found that dry forest flowering and fruiting diversity is associated with diverse strategies for dealing with seasonality of moisture availability. Upon extreme drought events, however, these strategies or responses may be limited, thus limiting successful flowering, fruiting, and subsequent germination and survival.

Increases in temperature and increased drought periods have been shown to result in the increased potential for more frequent and intense wildfires. While in Puerto Rico most wildfires are human-related, an extended and more severe drought can create conditions conducive to more intense and larger fires (Gould 2013). High intensity fires may lead to significant loss of woody vegetation and, if seed sources are not available, regrowth of native woody vegetation may be restricted (Meir and Pennington 2011). This often permits the dominance of invasive species and, in dry forests of Puerto Rico such as Guánica, these include African forage grasses (Miller and Lugo 2009). With successive burning these grasses expand into intact forest. Germination and survival of native forest seedlings and saplings is low due to high water deficit, high temperatures and high light levels (Wolfe and Van Bloem 2012; PRCCC 2013) leading to natives being outcompeted by invasive species.

One of the most important effects of climate change for Caribbean wetlands is the alteration in rainfall patterns. In short, rainy seasons are expected to become shorter, with less frequent average annual rainfall, but more intense events. Intense rainfall events can provide greater runoff, erosion, and sedimentation, which in turn can increase nutrient, sediment, and pollution loads into estuaries[2] . On the other hand, prolonged dry periods can exacerbate the effect of sea level rise on coastal palustrine wetlands (Colón-Rivera et al. 2014). This occurs because the natural saltwater exchange that occurs at estuaries will travel further inland due to sea level rise if there are no steady freshwater inflows to counter the effect.

[2] https://www.epa.gov/arc-x/climate-adaptation-and-estuaries

Precipitation patterns (i.e., wet vs. dry seasons) are the primary factor controlling the abundance and composition of phytoplankton species and bioluminescence (Soler-Figueroa and Otero 2015, 2016). Thus, expected changes in precipitation due to climate change and the resultant environmental conditions will govern the fate of bioluminescent systems. Changes in precipitation patterns and storms can modify the vertical structure of natural waters and the salinity regimes, nutrient inputs, sediment loading, and pollutant transport that may alter oxygen balance, light penetration, and the overall productivity in bays and lagoons, thus potentially changing the capacity of these systems to sustain the extant biological assemblages. These environmental changes are accentuated in bioluminescent systems due to their small size, narrow entrances, shallow depths, and long water residence and by the short generation times of the bioluminescent organisms.

Changes in salinity may also occur with changes in rainfall patterns and associated freshwater discharges to the marine environment. Marine mammals are adapted to tolerate certain fluctuations in salinity (Fiedler, 2002) but it has been reported that in low temperature and salinity zones, species such as the bottlenose dolphin (*Tursiops truncatus*), demonstrate increases in skin lesions. These lesions could affect the health of dolphins (Wilson et al. 1999) and other marine mammals if they are similarly affected. Decreasing water quality is associated with coastal development, inland and coastal erosion, sewage, and increasing precipitation and associated transport of terrestrial pollutants to nearshore waters and further exacerbates the stress of climate factors on corals and other marine organisms.

Changes in water quality under certain climate change scenarios (e.g., increases in storms or extended periods of drought) will result in rapid shifts in the phytoplankton community, compromising the stability of these ecosystems. Alterations at the base of the trophic food webs will result in cascade effects to upper trophic levels. Thus, the structure and function of bioluminescent systems are potentially at risk, affecting other marine systems because phytoplankton contributes to half of the global primary production (Falkowski et al. 1998) and is at the base of the trophic food webs, mediating the transfer of energy to higher trophic levels (Field et al. 1998; Cloern and Jassby 2010).

Bottlenose dolphin. Source: NOAA Photo Library.

Sea Level Rise and Saltwater Intrusion

KEY MESSAGE

Projected sea level rise and saltwater intrusion into sensitive freshwater and coastal ecosystems can cause habitat transitions with negative ecological consequences to species that use these *ecosystems.*

Dryer conditions can lead to greater saltwater intrusion into freshwater ecosystems. The marine currents and waves can favor the accumulation of sediments in river mouths and restrict the entrance of migratory fauna into streams. As a result, nutrients of marine origin, transported by migratory fauna, will be eliminated from stream ecosystems. Furthermore, river predators that consume postlarvae during migrations will lose an important food source. Increases in saline concentration at river mouths can favor the establishment of saline-tolerant species that can increase in abundance and outcompete freshwater species.

Saltwater intrusion into the limited freshwater lenses from rising sea levels has the potential to alter the vegetation in those areas (Saha et al, 2011). This will also affect water resources in an area that is an essential source of freshwater and is already being affected by the introduction of other contaminants from terrestrial sources.

Hydrologically, saltwater intrusion is an important effect that can trigger state transitions in coastal wetlands (PRCCC, 2013). The magnitude of this effect will depend on changes in rainfall patterns, but estuarine basin mangrove stands that experience increased tidal exchange, for instance, can quickly become stressed and convert to salt flats if there is not enough freshwater inflow to lower extreme salinities. On the other hand, freshwater forested wetlands such as *Pterocarpus officinalis* or *Anona glabra* stands are sensitive to all levels of saltwater intrusion. Historical land use in Puerto Rico has forced these freshwater forested wetlands to almost exclusively coastal settings, thus increasing their vulnerability to sea level rise and saltwater intrusion. For example, increased soil water salinity affects growth, flowering, and recruitment in *Pterocarpus* forests (Rivera-Ocasio et al. 2007).

It is anticipated that rising seas will affect coastal morphology, causing mangroves to move inland and encroach on dry forest, with consequences for the species that depend on dry forest habitat. Resident and migratory birds that rely on dry forest for breeding and overwintering, respectively, could be particularly vulnerable if dry forest does not expand into new areas at the same rate it is converted to estuarine habitats. For example, Rodriguez Colón (2012) investigated North American migrant songbirds that depend simultaneously on interconnected mangrove and dry forest habitat in the south coastal region of Jobos Bay National Estuarine Research Reserve, and concluded that these populations will be imperiled by sea level rise if dry forest habitat is reduced, degraded, or eliminated. Avian populations in other coastal dry forest areas in Puerto Rico may face a similar threat (PRCCC, 2013).

Sea level has been rising steadily in Puerto Rico over the last decades, with an observed acceleration starting around 2010. Increased sea level causes beach erosion, exacerbates storm surges, and causes saltwater intrusion into coastal wetlands and aquifers.

Sea level rise translates into magnified coastal erosion on sandy beaches, but it also means increased sediment deposition on some coastal areas. These events can be particularly problematic for estuarine and coastal wetlands. In the Northeast Ecological Corridor Natural Reserve (NECNR), several river and lagoon outlets were blocked by sand deposition during the swells associated with winter storm Riley during March 2018. For example, Laguna Cholí, a small estuarine lagoon in the NECNR, was permanently blocked from the ocean when the swells, which caused severe erosion in nearby Luquillo beaches, deposited enough sediment to fill the outlet channel, the culvert pipe that supported lagoon drainage and even palm trees and the lagoon itself (Ricardo Colón pers. obs.). Given the small area of the lagoon drainage basin, the lagoon overflows into nearby access roads and non-wetland ecosystems (Figure 7).

Figure 7. Extreme sediment deposition caused by 2018 winter storm Riley in the Northeast Ecological Corridor Natural Reserve permanently disconnected Laguna Cholí (area to the right) from the ocean (area to the left). This is an unexpected management issue related to sea level rise.

Sea level rise may alter the depth and width of shallow coastal ecosystems. This could result in changes in their relative bottom area, potentially modifying their hydrodynamics (Kennedy et al. 2012). Due to the shallow depths of bioluminescent systems, the coupling between the pelagic and benthic compartments is essential for the proper functioning of these ecosystems. For example, during periods of low precipitation, turbulent mixing events could result in internal nutrient pulses triggering the growth of phytoplankton species (Fisher et al. 1982; Guadayol et al. 2009; Cornwell et al. 2014). This was observed at Bahía Fosforescente when *P. bahamense* and *C. furca* populations increased, followed by increments in nitrate+nitrite and ammonium concentrations not related to precipitation (Soler-Figueroa, 2015).

The pelagic-benthic interactions also play a major role in the dynamics of *P. bahamense*. This dinoflagellate, as part of its life history, produces a resting cyst which settles into the sediments and serves as a seed population to initiate blooms (Anderson 1989; Corrales et al. 1995; Morquecho et al. 2014; Onda et al. 2014). Increases in wind forcing and in bottom current velocities induce the resuspension of the cysts (Corrales et al. 1995; Azanza 1997), suggesting that physical processes coupled with water depth are essential for the advancement of *P. bahamense* populations. Therefore, changes in the depth and bottom areas due to sea level rise could have ecological consequences on the dynamics of bioluminescent systems.

Bioluminescent systems can also be indirectly affected by sea level rise due to the possible impacts to mangrove ecosystems. Mangroves are an essential component of the bioluminescent bays and lagoons providing nutrients, vitamin B-12, and organic materials required for the growth of phytoplankton organisms (Burkholder and Burkholder 1958; Seliger et al. 1971; San Juan and González 2000). Therefore, the impacts of climate change on mangrove ecosystems, such as their inland migration (Scavia et al. 2002) and plant death due to changes in flooding patterns and subsequent salinity increases (reviewed by Ward et al. 2016), may be devastating to bioluminescent systems.

Expected effects of sea level rise on seagrass beds will occur due to increased water depth; reduced light attenuation; changes in the tidal range, current velocity, and circulation flow patterns; and increased saline intrusion. All these elements will affect structure, distribution, growth, and reproduction of seagrass beds. The amount of light reaching the bottom decreases exponentially with depth; therefore, increases in water depth may limit seagrass photosynthesis. In Puerto Rico, the rate of sea level rise is increasing 1 cm per year since 2000 in San Juan and La Parguera (Mercado 2016). This means that in 50 years, the distribution of turtle grass, which has an average depth limit of approximately 8 m (Duarte 1991), would be affected due to changes in the location of the maximum depth limit of this species that dominates many seagrass beds in Puerto Rico. Sea level rise may provide new shallow water habitat for seagrasses to occupy, but this retreat is not possible in areas of shoreline hardening. Sea level rise may also cause saline intrusion in estuaries resulting in the possible displacement of aquatic vegetation with a limited salinity tolerance as seagrasses.

Danylchuk (2015) used acoustic tracking to define preferred shoals for bonefish and the associated recreational catch-and-release fishery around Culebra, Puerto Rico. The study shows how this depth-associated recreational fishery that is important commercially for fishing guides and associated businesses could be affected by changes in sea level.

An increase in sea level is likely to increase the construction of flood control structures or channels. This can affect species, such as manatees, through changes in freshwater inputs and sediments and associated impacts to foraging habitat, including altered distribution of seagrass.

Sea level rise has mostly been studied on its own. However, increased saltwater flooding on offshore cays (Cayo Ratones and Cayo Diablo in La Cordillera Natural Reserve) has been observed due to tropical storm/hurricane surges, which is thought to be exacerbated by SLR. For the Virgin Islands tree boa (*Chilabotrus granti*), a dramatic loss of habitat (56-75 %) has been predicted for Cayo Diablo, an important habitat for the boa, when projecting the combined effect of strong hurricane surge (Category 3 through 5) at high tide under a 0.91 cm SLR scenario (FWS, 2018). A similar situation is expected for other low elevation cays in the region.

Temperature Change

KEY MESSAGE

Projected increases in sea surface and terrestrial temperatures are expected to affect the distribution and composition of many species that are sensitive to temperature changes.

Increasing sea surface temperatures affect important metabolic pathways impacting physiological functions and responses that impair growth, reproduction, and immune responses of important foundation and keystone marine species.

The temperature of rivers can be regulated by different factors such as solar radiation, size of the stream, near-stream soil heat and groundwater (Caissie, 2006). Other anthropogenic factors, such as reductions in instream flow due to water extractions or dams, and thermal pollution can alter the temperature of the streams (Caissie, 2006). All the factors regulating the temperature of streams are expected to interact with climate change. Warmer temperatures will reduce the water's capacity to retain dissolved oxygen in the water column that is necessary for processes like respiration and degradation of different compounds like organic matter and contaminants (Carpenter et al, 2011). Water quality of rivers can deteriorate as the capacity of the rivers to manage pollutants diminishes (Caissie, 2006). Higher temperatures and changes in flow are expected to cause excessive macrophyte (aquatic plant that can be emergent, submergent or floating) growth that could result in trapping of sediments and eutrophication (Jennings et al, 2014). Other aquatic organisms are expected to be affected in terms of their growth rate and distribution. Changes in the size of organisms is recognized as the third ecological response to increases in temperature due to climate change and can result in reductions in the size of adults (Kindlmann et al. 2001). In addition, increases in metabolic rates are expected. Microbial and invertebrate cycling will be mediated faster but could be less efficient in terms of carbon retention (Mas-Martí et al, 2015).

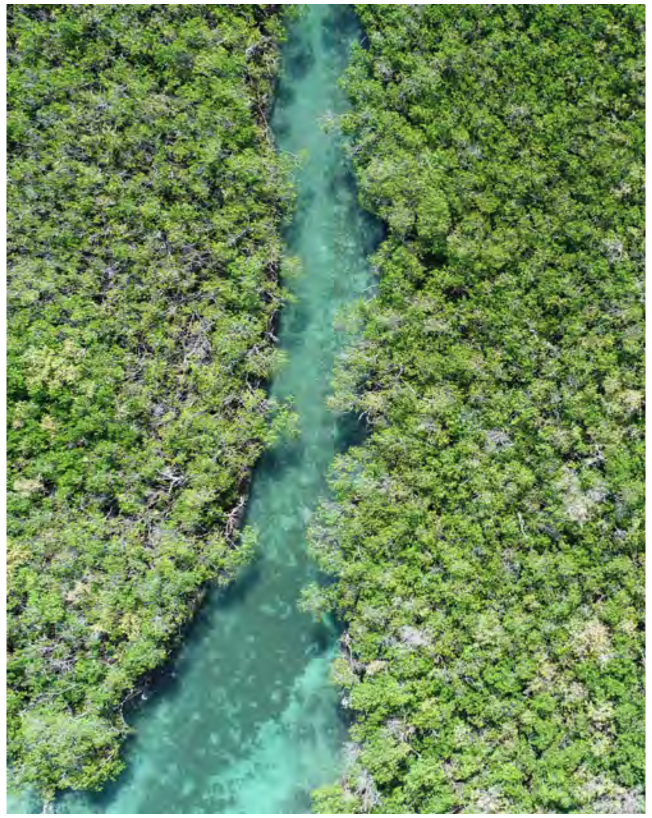
The principal climate-related stressors or threats to the dry forests in Puerto Rico include those associated with precipitation and increased temperature. While it is not necessarily clear what the changes in precipitation will be, there is consistency in the predictions concerning increases in temperature. The areas containing seasonally dry tropical forests are expected to receive increases in temperature from between 2 to 4°C by 2100. Even in the absence of changes in precipitation, this warming will result in a reduction in soil moisture availability, or in other words, increasing drought (Meir and Pennington, 2011). Dry forests in Puerto Rico typically are subject to a primary dry season from December to April. The severity and extension of this dry season is of particular concern in that it may affect phenology (flowering and fruiting patterns) and the successful establishment and survival of seedlings (PRCCC, 2013). Shifts in phenology will likely affect the associated species' composition of faunal assemblages.

While it varies among species, there is general agreement that in dry forests the availability of moisture plays a major role in the successful establishment of seedlings. Seeds from most dry forest tropical species mature in the dry season and are dispersed at the beginning of the wetter season when moisture is available for germination and growth (Ewel 1980; Singh and Singh 1992). Vegetative regeneration is an important mechanism in disturbed dry forest sites and would become even more important when regeneration by seed is affected by changes in the seasonality of precipitation (Murphy and Lugo 1986). This sensitivity to changes in moisture will make dry forests particularly vulnerable to climate change, potentially eliminating the more drought sensitive species and resulting in shifts in species composition in these forests (Condit et al. 1996). The increased dependency on vegetative regeneration or coppicing will likely cause shifts in species composition to species with greater ability to resprout (PRCCC, 2013).

In the Caribbean, the SST showed a warming trend over the past 30 years where the Atlantic Warm Pool (a large body of warm water that comprises the Gulf of Mexico, the Caribbean Sea, and the western tropical North Atlantic) has increased in size, reaching Puerto Rican waters (Glenn et al. 2015) As described by the WG 1, ocean temperature is increasing and the pH of the ocean is lower (more acidic) due to the increased CO_2 concentration in the atmosphere and the subsequent increase of the amount of CO_2 absorbed by the ocean. Feedbacks between these physical and chemical factors could have severe consequences for estuarine biodiversity. Intertidal wetland fauna are predominantly vulnerable, as they are simultaneously subjected to increasing temperature and increasing water alkalinity.

Temperature is a key parameter controlling the growth and metabolic processes of phytoplankton organisms (Morris, 1980). Therefore, it is anticipated that the warmer temperatures expected due to climate change will have a strong effect on the dynamics of the phytoplankton community of bioluminescent systems. For example, increases in temperature have been linked to shifts in phytoplankton size structure, resulting in the dominance of small-sized cells (review by Guinder and Molinero, 2013) and in decreases in the transfer of energy to higher trophic levels (Suikkanen et al., 2013). However, the temperature tolerance of each species will also play an important role in their responses (Wells et al. 2015). For instance, the high temperature tolerance of *P. bahamense* (temperature range: 20 – 25 °C; review by Usup et al. 2012), and the fact that their blooms only occur when temperatures are greater than 25 °C (Phlips et al. 2006), suggests that the warmer temperatures may favor its growth.

Increases in water temperatures also result in decreases in dissolved oxygen concentrations, which in shallow and semi-enclosed ecosystems, such as the bioluminescent systems, may lead to severe hypoxia conditions (Anthony et al. 2009). Furthermore, increased temperatures could potentially alter the water circulation patterns of bioluminescent systems due to changes in the water density gradients (J. González, University of Puerto Rico-Mayagüez pers. comm.), thus modifying the distribution and abundance of bioluminescent dinoflagellates.



For seagrass, elevated temperature effects depend on the species' thermal tolerances and their optimal temperatures for processes including photosynthesis, respiration, and growth (Short et al. 1999). Tropical seagrasses have a reduced temperature tolerance compared with temperate seagrasses. For example, the temperature range for optimal growth of turtle grass is between 23-31°C (73.4- 87.8°F; Barber and Behrens 1985).

Many studies demonstrate that photosynthesis and respiration are sensitive to changes in temperature with turtle grass exhibiting higher photosynthetic rates during warmer months (Herzka and Dunton 1997), although respiration rates eventually surpass photosynthetic rates with increased temperature. This leads to changes in the photosynthesis to respiration ratio, which affects the ability of seagrass to maintain the positive carbon balance needed for growth (Zimmerman et al. 1989). It also increases light requirements for carbon production (Bulthuis 1987), which affects seagrass' photosynthetic capacity and contributes to mortality and reduced growth (Evans et al. 1986; Marsh et al. 1986). Greater increases in water temperature reduce dissolved O_2 causing water column anoxia and stimulating anoxia in the shoot meristem, which results in negative impacts on growth and survival (Greve et al. 2003; Borum et al. 2005).

Seagrass flowering and reproduction are directly controlled by water temperature. Therefore, changes in temperature alter shoot abundance and distribution (McMillan 1982; Van Vierssen et al. 1984). Flowering in turtle grass occurs between 24-26° C (75.2-78.8° F), lower temperatures can delay flower maturation and cause splitting of immature fruit, resulting in the loss of reproductive potential in affected plants (Phillips et al. 1981; McMillan 1982; Durako and Moffler 1987). During warm months, high water temperatures and their impacts to seagrass can be exacerbated by interactions with high salinity resulting in die offs of turtle grass (Zieman et al. 1999).

Increased ocean temperature enhances the growth of competitive algae and epiphytes reducing light and carbon availability at leaf surfaces (Sand-Jensen 1977; Sand-Jensen and Revsbech 1987). Additionally, increased ocean temperatures may allow the extent of pathogens to increase, and seagrasses may be more vulnerable due to weakening of plants associated with stressors related to climate change (Harvell et al. 2002).

Increases in the temperature of ocean waters are expected to affect the distribution of marine mammals. Marine mammals are adapted to and tolerate certain temperature ranges. Any change in temperatures outside these ranges can cause the movement of populations to areas where they can tolerate the temperatures. Calves may be more susceptible to temperature increases because they have less capacity to thermoregulate than adults. Similarly, large whales may be less affected than small cetaceans because large whales are capable of long-distance migrations and could, therefore, have a greater capacity to change distribution. Small cetaceans are less capable of thermoregulation and long-distance migrations. Changes in temperatures could also affect marine mammals indirectly by affecting water circulation patterns that influence the abundance and distribution of prey species (Sadykova et al. 2020; Pepin 1991). Changes in temperature could affect the embryonic or larval stages and age at sexual maturity (Klaich et al. 2006) of prey species, as well as the migration of plankton, fish, and cephalopods (squid, octopus) consumed by different marine mammal species. These changes could lead to a decrease in prey and affect the reproductive condition of mammals. Marine mammals need a certain amount of body fat so ovulation can occur (Boyd 2000); therefore, if females do not get the necessary nutrients to create enough fat, they will not be fertile.

Trichechus manatus manatus.
Source: Jorge E. Saliva. USFWS National Digital Library.

Increases in CO_2 and other Greenhouse Gases

KEY MESSAGE

Increased CO_2 concentrations and subsequent decreases in pH are expected due to climate change leading to species' distribution, growth, and composition changing in terrestrial, coastal, and marine ecosystems.

Day (2010) discussed the possibility of changes in karst processes occurring because of changes in levels of soil CO_2. Implications for dissolution rates may be serious because the soil is the primary source of CO_2 dissolved by percolating rainwater. This may result in changes in karst topography, particularly in northern Puerto Rico, thus resulting in a shift in vegetation structure and composition.

Species' composition may be affected by differing growth rates because of decreasing moisture availability and increasing concentrations of CO_2. One study has indicated that growth of a dry forest tree may be reduced by 12% under a medium emissions scenario and as much as 21% under a high emissions scenario (Brienen et al. 2010). If all species exhibited similar effects, the carbon sequestration capacity by this forest type will be reduced. This is particularly important due to the aerial extent of dry forests in the tropics. If tree species exhibit differing rates of growth reduction, then species composition in those forests may be affected (Brienen et al. 2010; PRCCC 2013). Because it is anticipated that northern karst forests will shift over time from subtropical moist to subtropical dry forest (Henareh Khalyani et al. 2016), these differing growth rates are also likely to affect the species composition of the northern karst forests.

The increases in CO_2 concentrations and the resulting pH decreases expected under climate change scenarios may also affect the growth and physiology of phytoplankton species, but the responses of these organisms are species-specific. For instance, CO_2 increases (Wells et al. 2015) and changes in the chemical forms of nitrogen towards reduced forms (i.e., ammonium and organic nitrogen) due to decreases in pH (Fu et al. 2012) could potentially benefit the growth of dinoflagellates intensifying their blooms. On the other hand, CO_2 enrichment could alter the elemental composition and the C-to-nutrient ratios of bioluminescent systems, with significant modifications in the phytoplankton composition and, thus, in the pelagic food webs (Guinder and Molinero 2013). Additionally, decreases in pH may impact several transmembrane cellular processes that influence cell metabolism (Wells et al. 2015). For example, the flagellar motion (Manson et al. 1977) and the bioluminescence chemical reaction (reviewed by Valiadi and Iglesias-Rodríguez 2013) are controlled by transmembrane proton gradients. Therefore, decreases in pH could potentially impact the physiology of bioluminescent organisms and, hence, bioluminescent systems.

Source: Wanda I. Crespo

As discussed in the previous report (PRCCC 2013), the anticipated changes in dissolved inorganic carbon species associated with increasing carbon dioxide may have a positive effect on seagrasses because they evolved in a high CO_2 atmosphere and nutrient rich sediment conditions (Den Hartog 1979; Hemminga and Duarte 2000). As a result of climate change, increasing CO_2 availability will increase seagrass photosynthesis and leaf sugar content (Beer 1989; Durako 1993; Zimmerman et al. 1995; Beer and Koch 1996) and decrease their light requirements, increasing productivity and helping them survive high temperatures (Björk et al. 2008; Zimmerman and Mobley, 1997; Zimmerman et al. 1997, 2015; Touchette and Burkholder 2000; Palacios and Zimmerman 2007). Additionally, seagrass can increase flower production, shoot numbers, and below-ground tissues, and alter leaf chemical composition (Palacios and Zimmerman 2007; Campbell and Fourqurean 2013; Zimmerman et al. 2017). Turtle grass has shown a more positive response to increases in CO_2 and decreases in pH than shoal grass (*Halodule wrightii*) and manatee grass (*Syringodium filiforme*; Campbell and Fourqurean 2013). The differing response between species can provoke shifts in species' distributions in seagrass systems associated with elevated CO_2 concentrations (Short and Neckles 1999).

In the tropics, seagrasses play a significant role in controlling biogeochemical cycles in shallow waters providing oxygen through roots and rhizomes and consequently increasing alkalinity and sequestering carbon in the bicarbonate pool (Burdige and Zimmerman 2002; Burdige et al. 2008; 2010). Furthermore, seagrasses are a source of organic matter promoting carbonate dissolution and the deposition of organic and inorganic suspended material (Burdige et al. 2008). The production of CO_2 takes place during remineralization of sediment organic matter in the presence of oxygen yielding CO_2 and water. The dissolution of carbonates then occurs as calcium carbonate reacts with the water and carbon dioxide to produce calcium ions and bicarbonate. These processes are affected by seagrass density (Burdige and Zimmerman 2002). The impact of climate change on these processes is unclear.

Coral habitats in Puerto Rico are facing the impact of rapidly increasing environmental stressors associated with the increasing accumulation of CO_2 and other greenhouse gases in the atmosphere. Increasing sea surface temperatures and acidification are direct consequences of higher CO_2 levels. See the sections on ocean acidification and temperature for more information regarding the effects to corals.

It will be necessary to study the impacts of multiple factors on the response of freshwater, coastal, and marine ecosystems to future climate change in order to determine how ecosystem services and the distribution of organisms will be affected by changes in carbon dioxide availability.

Source: Juan L Torres-Pérez, PhD

Ultraviolet Radiation

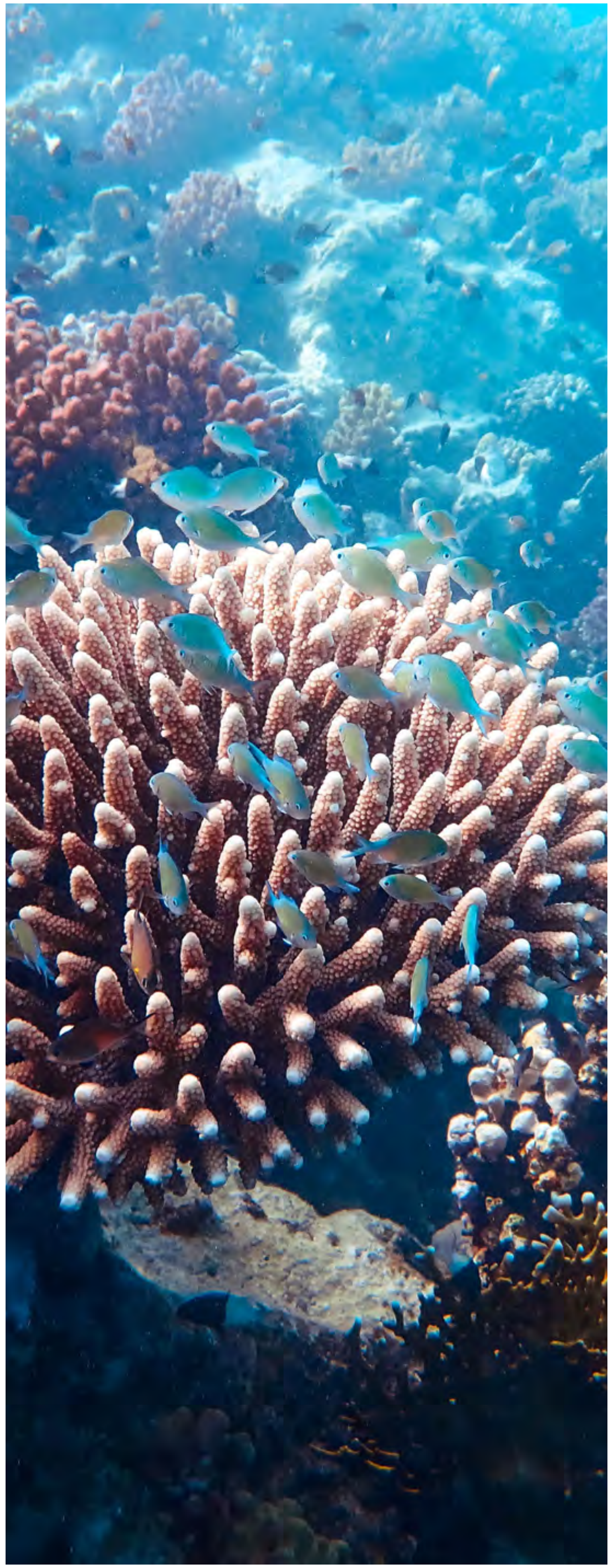
KEY MESSAGE

Seagrasses already live near their UV radiation threshold. Intense fluxes in UV radiation can cause coral bleaching and a reduction in zooxanthellae photosynthetic pigments.

Although the Montreal Protocol has been considered highly successful, it will take several years for the ozone hole to return to its size in 1980 (McKenzie et al. 2011). The ozone layer filters out most of the shorter wavelengths from the sun, UV-C (100-280nm), while longer wavelengths such as UV-A (315-400nm) penetrate the atmosphere and do not vary with changes in the ozone layer. Some UV-B (280-315nm) wavelengths can reach the Earth's surface and lead to adverse impacts on plants and animals.

Changes in the ozone layer are most significant at the poles; however, any increases in UV radiation due to global climate change will affect species' photosynthetic processes, potentially having repercussions on the distribution of seagrasses. In Puerto Rico, seagrasses live near their threshold of UV radiation and temperature tolerance where 17% of the UV-B and 35% of UV-A from incident surface UV radiation can reach a water depth of 1.5 m from summer to fall (Detrés et al. 2001). Experiments with turtle grass have demonstrated changes in pigments and modifications to compounds that absorb UV-B (Detrés et al. 2001; Torres-Pérez et al. 2014). Seagrasses in the intertidal zone are more prone to changes in UV, being more tolerant to increases in UV-B than deep water seagrasses (Larkum et al. 2007).

Coral bleaching has also been related to intense fluxes of ultraviolet (UV) radiation, which are in turn associated with periods of extremely calm and clear waters. In the tropics, clear waters such as those usually found surrounding coral reefs are notably transparent to UV radiation (Booth and Morrow 1997; Tedetti and Sempéré 2006). Despite this, reef-building corals dominate shallow tropical waters. This may be attributed to their tolerance of UV radiation thanks to the production of UV-absorbing compounds (commonly known as mycosporine-like amino acids or MAAs) in the cells of zooxanthellae (Banaszak et al. 2006; Singh et al. 2008). The coral-zooxanthellae symbiosis is still susceptible to bleaching during prolonged periods of intense UV radiation (Gleason and Wellington 1993; Torres et al. 2007). The onset of coral bleaching episodes due to UV radiation may activate different mechanisms than those activated during a temperature-related bleaching episode. Findings in La Parguera (Torres et al. 2007; Torres-Pérez and Armstrong 2012), for instance, indicate a reduction in zooxanthellae photosynthetic pigments despite non-significant changes in zooxanthellae densities within the coral tissues. Similar results have also been found in Pacific corals (Ferrier-Pagès et al. 2007) and in the gorgonian *Eunicea* (Drohan et al. 2005).



Storms

KEY MESSAGE

Increases in extreme events and temperature can cause coral bleaching and disease outbreaks, shifts in fisheries, declines in coastal dry forests, and the spread of invasive species.

Puerto Rico is in the path of Atlantic and Caribbean hurricanes. While most models indicate that storm frecuency may not increase, they do agree that storm intensity will increase. Increased storm intensity has been associated with climate change, as well as recurrent coral bleaching events and disease outbreaks. Global warming predictions suggest an increase in the average hurricane intensity of approximately 25–30% per °C in all ocean basins (Holland and Bruyère 2014). The 2017 hurricane season was particularly active, and between September and October, Puerto Rico felt the direct and indirect impacts of storms and hurricanes, particularly Hurricanes Irma, Jose, and Maria.

Climate change is expected to result in an increase in extreme events. If these events increase in their intensity, inland flooding and landslides are expected. Heavy downpours and intense hurricanes can result in increased erosion and sedimentation in waterways (Jennings et al. 2014), with an increased downstream transport of dissolved and particulate material. The effects of hurricanes on freshwater biota depend on the amount of precipitation associated with this natural disturbance. In 1988 and 1998, Hurricanes Hugo and Georges, respectively, hit the island and had a direct effect on the freshwater biota. Precipitation was twice the normal level and the amount of organic matter that reached the streams was massive (Covich et al. 1991; 1996). A direct effect of the precipitation and high flow conditions observed during both hurricanes was a decrease in shrimp densities in the upper pools in comparison with years prior to the massive hurricanes (Covich et al. 1991; 1996). Before Hugo, the shrimp density observed at Quebrada Prieta in El Verde ranged from 6.9 to 7.4 shrimp/m², but two months after the hurricane the density decreased to 3.1 to 5.0 shrimp/m². Two years after Hugo, the densities of shrimp returned to pre-hurricane densities (Covich et al. 1991). Post-Hurricane Maria, the number of native shrimp species collected in 20 river sites throughout El Yunque was greater than or equal to the number collected prior to the hurricane, indicating that the hurricane did not have a negative effect on these species (Krause et al. 2019). This demonstrates the direct effect of hurricanes on shrimp and how fast their populations recover from disturbances.

Hurricane-related flooding has been shown to cause mortality and displacement of native stream fishes (Smith and Kwak 2015). Although the study by Smith and Kwak (2015) demonstrated resiliency in these species related to recruitment and recolonization, it is not known if these mechanisms will be sufficient in the face of more frequent and intense storm events. In 2017, after Hurricane Maria, scientists discovered that only non-native fish species that were adapted to survive drought rather than extremely high river flows and flooding, were flushed far downstream or into the ocean during the hurricane where many died from blunt force trauma or saltwater exposure (Kwak and Ramírez 2019). However, exotic fish, particularly the Mozambique tilapia (*Oreochromis mossambicus*) and non-native guppies were found in eight new sites post-Maria, and the population density and biomass of native fish remained depressed one year post-hurricane (Krause et al. 2019).

Similar to stream communities, the physical impacts of increased storm intensity on forests due to increased damage from high winds and increased landslides and flooding may result in changes in species' composition and structure. The structure of Caribbean dry forests is shorter and contains a larger proportion of multi-stemmed trees than other neotropical dry forests. Following disturbance such as hurricanes, dry forests resprout near the base. Studies in the Guánica dry forest have shown that hurricane-induced tree sprouts have the longevity and growth characteristics to contribute to the structure of the forest (Van Bloem et al. 2007). More intense hurricanes may result in a structure that is comprised of a greater proportion of multi-stemmed species and, in addition, the species composition may shift towards a greater proportion of species able to sprout. Day (2010) emphasizes that in areas such as the northern karst of Puerto Rico, a major impact is likely to be a dramatic increase in flooding. Heavy or prolonged rains from intense tropical storms will cause increases in overland flow when surface and epikarstic infiltration capacities are exceeded.

Modelling conducted by Holm et al. (2017) of the impacts on biomass and net primary productivity in subtropical dry forests from increased storm frequency and intensity appear to indicate that these forests will respond with some resilience. Increased hurricane intensity did not cause a large shift in above-ground biomass or net primary productivity. An important difference in results between wet and dry forests of Puerto Rico was that, even after increasing hurricane regimes in terms of both intensity and frequency increasing by 100%, the dry forest did not experience high basal area or biomass loss whereas these came close to zero in the wet forests (meaning vegetation loss). This resiliency appears to be due to the ability to resprout following these events. However, this modeling effort does not take into consideration any shifts in vegetation to a much drier type because of increased drought periods and increased temperature.

Hurricane Maria provided a clear perspective of the impact of extreme events to coastal wetlands. While most of Puerto Rico's herbaceous wetlands survived the hurricane, forested wetlands were not able to withstand the event with such resilience. Most red mangrove fringes and basins subject to tidal flooding suffered mortality events that were noticeable even one year after the event (Figure 8). The major cause of mortality for red mangrove stands was snapping at the main trunk, followed by prolonged inundation in the areas closest to direct tidal influence. Recovery in these stands is predicated on the seedlings that survived the hurricane and have begun to create a mangrove understory in some affected sites (Figure 9).

Freshwater forested wetlands such as the *Pterocarpus* forests in the Humacao Natural Reserve and the Palmas del Mar *Pterocarpus* Forest suffered 100% defoliation, with trunk rupture being the main structural effect, followed by total or partial uprooting (Colón-Rivera et al., Unpublished manuscript).

Seagrass beds grow in shallow environments where the high light and low energy habitats needs are met, thus increased runoff rates and turbidity associated with runoff from heavy rainfall events result in less light availability for photosynthesis. Furthermore, increased freshwater input from heavy precipitation changes to river flow regimes, increased sediment loading, and changes in salinity substantially affect seagrass growth in estuarine environments. Experiments on turtle grass have found a salinity tolerance of 12 parts per thousand (ppt), and below this value both leaf number and biomass decrease, which can alter distribution and species' composition in seagrass beds (Doering and Chamberlain 2000).

Large turbidity plumes and freshwater pulses were identified during the active 2017 hurricane season (NOAA 2018a). The increase in water movement from storms and tidal surges can uproot or bury seagrass and sediment plumes can also lead to seagrass burial. After hurricanes Irma and Maria, seagrass communities in Culebra were impacted largely by sediment burial (Hernández-Delgado et al. 2018). Turtle grass survival response after moderate burial and erosion is to increase vertical growth and increased leaf production (Marbà et al. 1994). However, due to differences in growth rates, turtle grass takes many years to recover from storms while other seagrasses such as *Halophila decipiens* (paddle grass) and the invasive *H. stipulacea* recover rapidly. Consequently, a shift in species structure due to changes in storm intensity might occur (Patriquin 1975; Williams 1988; van Tussenbroek 1994; 2006; 2008). Studies have shown no difference in leaf area index after Category 4 hurricanes in well-protected areas (Dierssen et al. 2003) so changes in seagrass area and composition due to changes in storm frequency and intensity will depend on the location of the beds and light availability.

Increases in temperature because of climatic change are expected to increase the intensity and potentially frequency of hurricanes, storms, and weather patterns such as El Niño and La Niña. These changes will have a negative impact on the marine community, causing decreases in habitat, prey abundance, and salinity, affecting species and their survival.

Coral reef composition and structure in the late 1970's reflected adaptation to storms, with shallowest reef environments (0-8 m) dominated by storm-resistant, branching corals like elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) coral. Even though branching corals suffered fragmentation and dispersion when hurricanes hit, environmental conditions after

Figure 8. Red mangrove (Rhizophora mangle) mortality due mainly to snapped trunks from Hurricane Maria on a fringe of the Aguas Prietas Lagoon, Northeast Ecological Corridor Natural Reserve in Fajardo. December 2018. Photo by RJ Colón-Rivera.

Figure 9. Ground view of a red mangrove (Rhizophora mangle) old-growth stand affected by Hurricane Maria in the Northeast Ecological Corridor Natural Reserve in Luquillo (Juan Martín River outlet). February 2019. Photo by RJ Colón-Rivera.

the disturbance always allowed for fragment survival and the reestablishment of populations. However, good environmental conditions for rapid recovery are usually no longer present and detrimental conditions generally affect nearshore marine communities synergistically with disturbance preventing recovery (Weil and Rogers 2011).

In the 2018 Puerto Rico Coral Reef Monitoring Program (PRCRMP) report, Dr. García-Sais reported a decline in fish density and general decline in species richness relative to previous surveys, suggesting that it is the result of small fishes unable to withstand the extreme surge and abrasion effects caused by the hurricanes and other storm and surge events of that year. This includes a historical swell event from March 4 to 7, 2018, which affected the north and northeast coasts of the island, causing further damage to shorelines and coastal reefs. An average of 11% of Puerto Rico's corals were damaged by hurricanes Irma and Maria, with some sites experiencing up to 100% damage (NOAA 2018b). East coast fishers, particularly those from the southeast region where Hurricane Maria made its entrance, reported significant changes to benthic habitats and fishing grounds, such as seagrass beds, where fishermen would fish conch, became barren sandy bottoms. Productive fishing grounds where fishers previously frequented no longer produced catch, and as a result, fishers began to move further out at sea in search of new fishing grounds (Carlos J. Velázquez, pers. comm.; Seara et. al 2020).

Anecdotal evidence from commercial fishers around the island provides insight to the potential effects climate change is having on fisheries. Fishers have been observing a shift in seasons, specifically with changes in seasonal currents, water temperature, and spawning seasons. A study on the perceptions and socioeconomic effects of climate change on commercial fisheries revealed that pre-Hurricane Maria fishers were more familiar and concerned with the impacts of coastal pollution, and although they felt that climate change was responsible for many of the changes observed (i.e., decline in fish stocks, habitat changes, needing to fish further out to sea), fishers have historically attributed these changes to coastal pollution and mangrove destruction (Seara et al. 2020). However, the aftermath of Hurricane Maria brought new focus on the threats and impacts of climate change on fisheries. In their survey, Seara et al. (2020) found that fishers have been making modifications to fishing practices over the years: targeting different species, using multiple fishing gears, and fishing further out in search of better fishing grounds.

Increases in precipitation will cause an increase in nutrient influx to ocean waters that may lead to eutrophication. Increases in algae that may be toxic or produce toxic products that affect marine mammals and their prey could lead to changes in the distribution and fitness of marine mammals. An increase in freshwater influx due to increased precipitation will also increase pollutant concentrations in ocean waters, affecting the health of marine mammals due to ingestion of pollutants in prey or absorption through the skin or other tissues.

Invasive Species

Another effect of tropical storms and hurricanes is the spread of invasive species, such as the aquatic non-native water hyacinth (*Eichhornia crassipes*) in the Northeast Ecological Corridor. According to the USGS, the presence of the water hyacinth in pond apple swamps of the reserve after Hurricane Maria constituted the first report of this species in its corresponding watershed (pers. comm. to R. Colón; Figure 10). This is an example of how runoff can propagate invasive aquatic species into coastal wetlands during extreme weather events.

(a)

(b)

Figure 10. A "cayur" or pond apple swamp (Annona glabra) before (a) and after (b) hurricane María runoff dispersed the invasive water hyacinth (Eichhornia crassipes) throughout the habitat.

SECTION 04 Climate Change Adaptation and Management Strategies

KEY MESSAGE

Reactive strategies concentrate on the restoration of affected ecosystems while proactive strategies address potential climate change impacts and implement activites before impacts occur.

Based on work looking at climate change and river ecosystems, there are two types of management strategies: reactive and proactive (Palmer et al. 2009). Reactive strategies are implemented before the problem becomes severe and can include measures such as bank stabilization, habitat restoration, construction or redesign of stormwater infrastructure, wetland creation, construction of fish passages and planting of drought resistant vegetation. Proactive strategies anticipate change and adapt to it through management before climate change impacts become evident. Proactive strategies include stormwater management, ensuring floodplains are free of infrastructure, allowing the growth of riparian vegetation, increasing physical habitat heterogeneity, replanting and widening riparian buffers, managing groundwater and surface water together, defining environmental flows and implementing water use permits.

REACTIVE STRATEGIES: Restoration

Restoration of both degraded dry and moist karst forests may become more difficult. Dry forests that have been cleared or degraded often develop into exotic grassland communities that are maintained by fire and are difficult to reforest. Areas that are replanted are subject to high mortality from fire, but also from increased moisture stress and temperature (Wolfe 2009). Studies have shown that successful restoration projects can be high maintenance and therefore costly, requiring mulching, irrigation, or both. The application of such treatments can increase survival significantly (Martínez-Rodríguez and Van Bloem 2009). Increased temperatures and more intense and prolonged droughts can therefore make restoration a more costly endeavor (PRCCC 2013).

Various types of fences have been used to accelerate dune formation in North America, Europe, and, recently, Puerto Rico. Snow fences are the most common alternative for this purpose on the Atlantic coast of the U.S., including New Jersey and North Carolina. These fences are usually made of 35mm wide vertical wooden flat slats, 1.2 m tall, with 50% porosity (Grafals-Soto and Nordstrom 2009). In Puerto Rico the NGO Vida Marina has proven that biomimicry is effective in dunes restoration.[3]

Other management strategies for dunes include the installation of educational signs, installation of boardwalks to establish paths and avoid trampling vegetation, planting of native species, and control of invasive species such as the Australian pine (*Casuarina equisetifolia*) and Devil's tongue (*Sansevieria trifasciata*). Similarly, for seagrass, management strategies include implementing codes of conduct for boat anchoring and dock installation to reduce physical disturbance and shading effects and implementing education and outreach to raise awareness of the services and threats to seagrasses.

Over the last 15 years, a variety of groups in the US Caribbean and elsewhere have been using coral population enhancement techniques such as stabilizing live coral fragments after physical disturbances like groundings or storms, as well as active culture, growth, and restocking of fragments or larva. Many *in situ* efforts led by local agencies and non-government organizations (NOAA

[3] https://coast.noaa.gov/digitalcoast/training/puerto-rico.html

Restoration Center, DNER, HJR Reefscaping, Sea Ventures, Sociedad Ambiente Marino, The Nature Conservancy) are actively engaged in culturing fragments with a high degree of success. Field nurseries established around the islands of Puerto Rico and the USVI are generating thousands of colonies each year for restoration activities. Cultured colonies provide a continual source of material for outplanting through successive re-fragmentation.

Cays that are identified as vulnerable due to loss of ramparts could be candidates for coral reef restoration efforts, such outplanting colonies of elkhorn corals to increase the buffer to wave energy and provide a source of ramparts in the future. These corals have the fastest growth rates of the Atlantic/Caribbean coral species and asexual fragmentation is the dominant form of reproduction. This last characteristic makes it an ideal species that can be efficiently propagated using low-tech in-situ nurseries. The outplanting of elkhorn corals may provide an important source of ramparts for the stabilization of cays in face of sea level rise. The loss of cay ramparts is a concern that needs to be addressed as the impacts of climate change may increase the rate of cay erosion that will alter coral reefs, back-reef and inshore environments, as well as shorelines (Williams et al. 1999). These environments are critical for many habitats that support ecological functions for threatened and endangered species.

Source: Juan L Torres-Pérez, PhD

PROACTIVE STRATEGIES:

Conservation Corridors and Protected Areas

Protection strategies in the northern karst should take into consideration east-west and north-south gradients, as well as topographic gradients within mogotes or hills, and the different ecological communities that are found because of these gradients. In the absence of such strategies, the loss of biodiversity because of not only climate change but other drivers such as encroachment of development and invasive species will be increased (Aukema et al. 2011; Day 2010). Protection strategies in the southern karst must take into consideration the potential need for expansion of protected areas such as the Guánica Commonwealth Forest, due to climate-related factors such as sea level changes and coastal erosion due to more intense and/or possibly more frequent tropical storms.

Similarly, for coastal and marine systems, coastal zone management or land use policies and plans should address potential climate change impacts to seagrass and corals and be proactive in terms of managing activities in areas with seagrass and corals. To enable cays and islets to better respond to climate change, it is of upmost importance to restrict development in all coastal zones, and impose additional restrictions based on island-specific vulnerabilities. The sustainable use of bioluminescent bay ecosystems should be promoted to reduce and eliminate non-climate related impacts (e.g., boat speeds, anchorage, full moon visits, and light pollution).

Limited, short-term studies have shown that marine protected areas (MPAs) with diverse fish assemblages have significantly lower numbers of coral diseases and lower disease prevalence compared to unprotected areas nearby (Raymundo et al. 2009). MPAs also benefit other species and habitats. The number and spatial extent of MPAs around Puerto Rico should be expanded using scientific information and advice to establish new MPAs and strengthen current ones while also implementing education programs and management of human activities incorporating multiple stakeholders.

MPAs should include coral populations with the highest genetic variability possible because disease outbreaks and other selective pressures (pollution, thermal anomalies, etc.) usually eliminate susceptible genotypes. The surviving genotypes will hopefully repopulate areas with genotypes that are resistant to particular agents or drivers of mortality. Other important considerations for the establishment of MPAs include selecting suitable areas (which should consider the characteristics of nearby watersheds), specific species to be protected or to use in cultures working to create more resilient genotypes, and connectivity with other MPAs. Not all species are foundation or keystone species that contribute significantly to the development, function, and stability of a coral reef community. Control of local stressors like land-based sources of pollution, effective enforcement of existing regulations, and establishment of MPAs are promising tools for protecting all the interconnected zones and the processes that link them together. It is currently very difficult to prevent or successfully manage disease outbreaks and/or temperature-induced bleaching events. Natural coral ecosystems will be impacted, sometimes at catastrophic levels, like the *Diadema* and Atlantic acroporid mass die-offs of the early 1980's in the Caribbean, and the gorgonian mass mortalities in some Caribbean localities, the Mediterranean, the Eastern Pacific, and more recently, SCTLD throughout Florida and in many islands in the Caribbean. Disease and/or bleaching-related mortalities (and other stressors) will continue and only species with high genetic variability have high probability of surviving in particular areas. For these modular, long-lived organisms in particular, a few survivors could be enough to restart population recovery if there are favorable conditions for sexual reproduction, recruitment, and growth.

Source: Luis Jorge Rivera Herrera

MPA locations should also consider where connectivity patterns are present between seagrass beds and adjacent habitats (i.e., mangroves and coral reefs) to prioritize these areas for protection, as well as identifying and protecting seagrass in areas where the risk of anthropogenic impacts are low that can help to seed the recovery of damaged areas. MPAs should be established/expanded to protect multiple sites within a wide geographical area where the full range of seagrass communities is present.

Vulnerable species that would benefit from the protection afforded by being located on a cay or islet should be translocated. This requires completion of extensive vulnerability assessments across the region to determine which areas are apt for which species, including consideration of potential habitat change due to climate change impacts.

PROACTIVE STRATEGIES:

Reducing Land-Based Stressors

In addition to management actions responding to impacts of climate change through promotion of resilience, concurrent and active management of other human stressors affecting marine habitats is also needed. There should be a concerted effort between governments, researchers, and managers to restore and maintain water quality and environmental conditions that promote healthy corals and seagrass habitats, as well as coastal habitats.

Protection of important coastal and marine habitats, particularly those that demonstrate resilience to climate change impacts, should be done by improving water quality by:

- Redirecting and/or improving stormwater drain traps to decrease nutrient load; and
- Installing and/or improving terrestrial erosion control systems.

Source: Wanda I. Crespo

Planning and Monitoring Management Strategies

It is important to implement monitoring programs to evaluate the conditions of the ecosystem and to provide information to see if the management strategies meet their objectives.

Compared to other marine ecosystems in Puerto Rico, bioluminescent systems have been less studied. Recent events of drastic reductions in *P. bahamense* populations, such as that observed in Laguna Grande due to the decay of *Sargassum* spp., should warn managers of the susceptibilities of these ecosystems to any environmental change. This highlights the necessity for conducting systematic and continuous monitoring to gain a deeper understanding of responses of *P. bahamense* and other phytoplankton organisms to alterations in their environment and to accurately predict the possible impacts of climate change. Furthermore, long-term studies will improve our ability to separate the effect of natural patterns from anthropogenic influences (Hays et al. 2005; Anderson 2014) and will provide information for the development of the best science-based management approach to guarantee the role of this ecosystem as an important habitat for protected species and for tourism.

The Caribbean region lacks a comprehensive islands' management plan. A comprehensive inventory of cays in the US Caribbean was recently completed (USFS-IITF 2015), however it has yet to be adequately ground-truthed. Management plans exist for several of the main islands and archipelagos, but most plans are old (Table 2) and few (if any) implicitly include consideration of climate change impacts. There is a clear and critical need for the development of a regional islands' management plan focused on the vulnerabilities and threats associated with climate change. The Caribbean Landscape Conservation Cooperative (CLCC) launched a multi-agency/organizational Conservation Action Team (CAT), called the Cays Systems CAT Group, to work collaboratively to address this need. Although the CLCC is no longer funded, the Cays CAT continued with its efforts toward designing a management strategy for cays in Puerto Rico under the leadership of the U.S. Fish and Wildlife Service, including examining management scenarios based on climate change predictions.

Table 2. Existing and available management plans for Puerto Rican cays.

REGION	PLAN
MONA AND MONITO ISLANDS	DNER (no date, draft). Plan for the Management and Conservation of Mona and Monito Islands Natural Reserve. Prepared by: Mía Sued Jiménez, Myrna Aponte Reyes, María del Mar López. Commonwealth of Puerto Rico. 352 pages.
CORDILLERA ISLANDS, FAJARDO/CULEBRA	DNER (2009). Plan de Manejo de la Reserva Natural Arrecifes de La Cordillera, Fajardo. Commonwealth of Puerto Rico. Consultores Educativos Ambientales, C.S.P. (revised 2009). 94 pages.
JOBOS BAY, SALINAS	DNER (2016). Jobos Bay National Estuarine Research Reserve Management Plan 2017-2022. Final Plan. Commonwealth of Puerto Rico. 193 pages.
NORTHEASTERN, PR	NOAA. Coral Reef Conservation Program. 2020. Plan estratégico para el manejo de los usos recreativos en el corredor marino del noreste de Puerto Rico. 132 pages.
ENTIRE PR REGION	DNER (2015). Puerto Rico State Wildlife Action Plan: Ten-year review September 2015. DNER, Commonwealth of Puerto Rico. 178 pages.
CULEBRA	U.S. Department of the Interior, Fish and Wildlife Service (2012). Comprehensive Conservation Plan, Culebra National Wildlife Refuge, Culebra, Puerto Rico. Atlanta, Georgia. 174 pages.
DESECHEO	U.S. Department of the Interior, Fish and Wildlife Service (2012). Comprehensive Conservation Plan, Desecheo National Wildlife Refuge, Ma-yaguez, Puerto Rico. Atlanta, Georgia. 132 pages.
ENTIRE PR REGION	Ventosa-Febles, E.A., M. Camacho Rodríguez, J.L. Chabert Llompart, J. Sustache Sustache, and D. Dávila Casanova (2005). Puerto Rico Critical Wildlife Areas. DNER, Commonwealth of Puerto Rico.

Needs for Climate Change-Related Adaptation in Puerto Rico

Each of the following sections include approaches that should be used to address the effects of climate change and design adaptation strategies for the respective ecosystems.

Freshwater

- Studies on the impact of introduced fish on native fish of Puerto Rico to develop a program to eradicate exotic species that negatively affect the native aquatic fauna of Puerto Rico.
- Prioritization of the removal of dams that are no longer in use, or are unsafe, to reestablish river connectivity for the benefit and conservation of the native aquatic fauna. In addition, the replacement of road crossing structures that are directly affecting the physical habitat of streams and disrupting the species' migration pattern should be prioritized.
- Development of a systematic survey program to gather more information and gain a better understanding of the status of the aquatic fauna in Puerto Rico to effectively develop conservation and management strategies.
- Development and implementation of a comprehensive instream flow study that can be used to establish water extraction rules.
- Development of a comprehensive streambank restoration and maintenance protocol to effectively guide agencies (state and municipal) in preventing streambank habitat modifications and degradation.

Bioluminescent Bays

- Perform experimental studies on the ecophysiology of *P. bahamense* to better understand the responses of this dinoflagellate to changes in temperature, salinity, and nutrient concentrations. These experiments should be conducted on the individual species and with natural communities to produce ecologically realistic climate change response scenarios.
- Increase ecosystem-wide monitoring efforts after weather perturbations to strengthen understanding of phytoplankton community responses.
- Develop models that integrate the ecology and hydrology of watersheds with bioluminescent systems. These models should include the watershed land use and coverage, transport of nutrients and sediments due to runoff, water quality changes, and the possible responses of bioluminescent organisms and the entire plankton community to runoff and water quality.

Submerged Aquatic Vegetation

- Develop detailed maps of seagrass meadows to allow monitoring of changes in distribution and abundance over time.
- Modeling should be used to predict seagrass distribution through assessments of the correlation between different stress factors, including light availability, temperature, and ocean acidification.
- Understand how seagrass connectivity affects ecosystem services and vice-versa, including the influence of seagrasses on sediment biochemistry.
- Develop studies of seagrass response to climate change that integrate plant physiology and 'omics' (genomics, proteomics, and/or metabolomics) should be developed and implemented.
- Conduct studies of the clonal growth and development of turtle grass and the sexual reproduction of manatee grass.
- Conduct studies of the seagrass food web interactions to understand consumer control in this ecosystem should be developed and implemented.

Source: Juan L. Torres-Pérez, PhD

Cays and Islets

- Development of an integrated and adaptive database with GIS capacity containing data on the cays, islets, and islands in PR/USVI to determine priority areas for management, research, restoration, recovery, and conservation action plans, and describing jurisdiction, designation, management plans, research results, critical habitat, native species inventory (including threatened, endangered, and candidate species), seabird colony status, plant and vegetation communities, vulnerability, and resource use, among others.
- Development of a better understanding of coastal processes (i.e., rates of bio-erosion, sedimentation, sediment transport and other sources of changes in sediment budget that may restrict the depositional processes and shoreline accretion rates) in relation to sea level rise and storm surge impacts on habitat distributions and functionality. The implications of seawater temperature, water quality, and ocean acidification on the degradation of coral reef organisms that buffer cays from wave energy and subsequent coastal erosion processes (reduced beach building materials and loss of size and height of outer reefs) also need to be studied.
- Assess vanishing seafloor rates in our region (Yates et al. 2017).
- Predictive models to forecast where invasive species that may still be unknown in the Caribbean are most likely to originate (e.g., using global socio-economic models, goods transportation), and the likely invasion pathways within the Caribbean.
- Innovative and improved tools and techniques to successfully eradicate invasive species, including from larger and higher cays, islets, and islands to prepare habitat for future species translocations.
- Extrapolation of vulnerabilities from observed data sets to all the cays in U.S. Caribbean to estimate/predict vulnerability and perform inundation mapping.
- Assessments of species' capacities to survive under future scenario predictions (e.g., increased drought and changes in habitat on cays).
- Translocations as an adaptation strategy requires completion of extensive vulnerability assessments across the region to determine the safe places to which different species can be moved.
- Improved and innovative ecosystem restoration tools to restore degraded habitats on high islands that may be suitable for future species translocations.
- Update seabird colony status for islets and cays and develop an integrated data management system among agencies and researchers.
- Model the optimal location and size of additional marine protected areas.
- Improved understanding of nutrient flow mechanisms between terrestrial and near-shore marine environments, and the disruption of these mechanisms with climate change.
- Importance of cays, islets, and islands as stop-over and wintering sites for migratory shorebirds and land birds.
- Determine carrying capacity of humans on cays based on available area to protect the integrity of habitats that are necessary for ecosystem functions that are particular to the cays.
- Assess the load of marine debris and impacts to the habitats from solid waste pollution and the effect on critical habitats and threatened and endangered species.
- Model the combined effect of SLR and tropical storm/hurricane surges on offshore cays to predict habitat loss due to saltwater inundation.

Coral Reefs and other Coral Habitats

- Conduct more research on anticyclonic eddies, which are recurrent phenomena affecting the Caribbean Sea, to establish their potential influence on coral bleaching events.
- Development and implementation of additional research to fully understand the differences related to how UV radiation versus high SST that lead to bleaching affect the coral-zooxanthellae symbiosis.
- Development and implementation of studies to determine the synergistic effects between suspended and dissolved matter on reef corals' growth and resiliency; and additional synergistic effects of sedimentation with other critical environmental factors, such as increased temperatures and ocean acidification.
- Obtain more information regarding the presence/absence of specific zooxanthellae clades within the Puerto Rico shelf, particularly those that have shown some resistant to some of these stressing factors.
- Conduct studies that can address species and ecosystem vulnerability, resilience, and adaptive capacity. Further understanding on the expected ocean acidification effects of the species and habitats in the Caribbean and Puerto Rico is based on evidence tested elsewhere, so there is a need for empirical species' response data for Puerto Rico. Corals situated in areas with high natural variability may be naturally conditioned to low pH conditions; therefore, will potentially be less vulnerable to ocean acidification. However, the stress response mechanisms are currently not well understood and there are only a few studies on ecosystem and organismal responses to climate stressors (e.g., ocean warming) that consider ocean acidification.

Fishery Resources

- More research is needed to assess direct and indirect effects of climate change on Puerto Rico's fisheries for both commercial and recreational sectors. Changes in water temperature and seasonal currents will have effects on traditional fishing seasons, both commercial and recreational.
- Understanding how recurrent storm events and storm surges, warming waters, eutrophication, and coastal erosion, etc. will continue to put pressure on fishery habitats and how these changes and variables will affect the fisheries industry and local economy is critical for management and adaptation strategies.

Marine Mammals

Wells (2010) explored the effects of climate change on bottlenose dolphins and noted three responses to climate change: redistribution, or move to areas where changes in temperature are subtler and within dolphin temperature tolerance ranges; stay in the same habitat and adapt to the new conditions through ecological, physiological, or behavioral changes; or go extinct. These responses also apply to other cetacean species, especially smaller ones and should be considered when designing adaptation strategies that address the first and second response.

The following approaches should be used to address the effects of climate change and design adaptation strategies for fishery resources around Puerto Rico:

- Priority should be given to collection of baseline data on marine mammal stock assessments to enable scientists and managers to determine the effect of climate change on species. Population assessments are also needed to determine the genetic structure of marine mammal coastal species such as manatees and bottlenose dolphins.
- Marine mammal health assessments and species' habitat characterizations are needed to evaluate potential changes and effects on pathogens and food sources due to climate change.
- A GAP analysis of stranding events over the past 30 years is needed to determine whether there have been changes or possible trends that could be linked to climate change.
- The stranding program needs to be enhanced with resources to increase its capacity to conduct additional analyses to identify possible emerging diseases, outbreaks, and/or unusual mortality events that might be related to climate change.

Source: Juan L. Torres-Pérez, PhD

SUMMARY

Overall, it is expected that, due to climate change, increases in average temperature and an increase in the magnitude and frequency of rain and drought events will occur. Extreme events are expected to have a higher magnitude, frequency, and intensity. Changes in the environment will be uneven and sudden. There will be key ecohydrological impacts changes in the physical climate and impacts on stream ecosystems (Quesne et al. 2010). The Comprehensive Plan for Water Resources (DNER 2016) recognizes the following consequences of climate change on water resources: a reduction in rain; a reduction in surface water availability; impacts on riparian, estuarine and wetland diversity; a greater water use demand; saline intrusion in aquifers; increased demands on groundwater; changes in evapotranspiration; changes in relative soil moisture; increases in the probability of urban and coastal floods; and potential increases in sedimentation of lakes, rivers and streams. Due to increases in the magnitude, frequency and intensity of extreme events, there will be a greater amount of dissolved and particulate material transported downstream. Changes in drought patterns will lead to reductions in water availability, instream flow and base flow. There will also be changes due to the interrelationship between surface and groundwater and reductions in dissolved oxygen, including increases in contaminants in the water column with extreme events. Life cycles and migratory patterns of aquatic species will change as habitat quality and availability change, and as community composition shifts to more tolerant species.

Sea level rise is expected to lead to a greater penetration by saltwater, leading to more saltwater intrusion. Warmer temperatures reduce the capacity of water to retain dissolved oxygen in the water column that is necessary for processes such as respiration and degradation of organic matter and pollutants (Carpenter et al. 2011). Carbon dioxide decreases pH, leading to reductions in pH in freshwater systems making the environment more acidic.

Increases in metabolic rates are expected. Microbial and invertebrate-mediated cycling could be faster, but less efficient in terms of carbon retention (Mas-Martí et al. 2015). Increases in UV can have negative impacts on primary producers (i.e., cyanobacteria, phytoplankton, macroalgae and aquatic plants) and aquatic consumers (i.e., zooplankton, crustaceans, amphibians, and fish; Häder et al. 2011). Changes in the size of organisms is recognized as the third ecological response to global warming and can result in reductions in the size of adults (Kindlmann et al. 2001).

Seagrasses are considered important habitats due to the numerous services they provide such as sediment stabilization, marine organisms nursery grounds, and carbon storage, among others. Climate change impacts such as sea level rise and increases hurricane intensity and precipitation, in addition to anthropogenic activities, affect light penetration into the water column producing threats to seagrass survival that result in habitat degradation. Additionally, increases in temperature stress affect seagrass growth and reproduction, altering the photosynthetic process and causing changes on the structure and distribution depending on species tolerance. The increase in temperature and the combination of factors may result in widespread seagrass damage in Puerto Rico. However, high CO_2 availability due to climate change is predicted to decrease seagrass light requirements and help seagrass to tolerate temperature stress. Differences in performance among species may alter species compositions. Moreover, seagrass beds may aid in coral reef survival by ameliorating ocean acidification and decreasing disease levels. Therefore, effective management requires a comprehensive understanding of seagrass life history to protect these ecosystems, as well as an increase of scientific involvement and public awareness.

It is estimated that coral reefs reduce wave energy by an average of 97% (Ferrario et al. 2014) with most of the energy absorbed at the shallower point (reef crest). In order for coral reefs to continue to provide coastal protection, corals will need to grow upward rapidly enough to keep pace with the rising sea level (Sheppard et al. 2005). Ocean acidification is likely to diminish the structural integrity of coral reefs through reduced skeletal density, loss of crustose calcareous algae, and dissolution of high-Mg carbonate cements, which help to bind the reef. Emerging evidence suggests that effects of ocean acidification on the reef's structural integrity and ecosystem function are strongly related to effects on net community dissolution (Andersson et al. 2009) and bioerosion rates (Enochs et al. 2015), decreases in calcification rates of crustose coralline algae (Johnson and Carpenter 2012), and fertilization and recruitment success (Albright et al. 2010). Such effects could compromise reef resiliency in the face of other acute threats, such as thermal stress, diseases, increasing storm intensity, and rising sea level. This will make coastal areas increasingly vulnerable to waves and storm surge with associated effects on the tourism sector, fisheries, and coastal infrastructure.

During the period in which biomass is increasing, marine plants can sequester carbon, reducing the concentration of seawater CO_2. There have been studies (e.g., Florida Reef Tract) suggesting seagrass meadows may attenuate ocean acidification effects creating "refugia" for calcifying organisms and coral reefs downstream (Manzello et al. 2012). Further studies are needed regarding the potential ocean acidification management alternatives these ecosystems can offer the coastal zones of Puerto Rico.

Climate change will continue to affect top marine predators both directly and indirectly. The effects on these populations could be detrimental to the species, as well as fishery-dependent communities, and should be taken into consideration when new management plans are developed. Marine mammals are vulnerable to toxics, changes in temperatures and noise levels, potentially to a greater extent than other species, and should be protected, including through strategies to decrease such effects.

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WORKING GROUP 3

Society and Economy

03

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EXECUTIVE SUMMARY

Climate change is one of the most serious threats our present generation currently faces, as it directly and indirectly affects every aspect of our society and livelihoods. This paramount challenge has forced nations and communities re-evaluate their existing conditions and identify opportunities to move forward in our global pursuit of progress and well-being. As such, global voices are pushing towards strengthening our social, economic, and ecological resilient capacity in the face of current and projected climatic changes. Particularly on the most vulnerable countries and communities where adaptation actions can make a difference on the continuity of their livelihoods and ways of life.

Since the publication of the previous State of the Climate in 2013, Puerto Rico has faced multiple series of climatic events that prompted disaster responses to cope with the human and economic losses experienced. Most notably, hurricanes Irma and Maria in September 2017 served as a crude reminder of the vulnerabilities our society and economy faces as the climate crisis continues to manifest across the globe. Yet, it also exposed the strength of families and communities to move forward in the face of difficult challenges and ignited stronger voices demanding action to be better prepared for future events.

The initiative of Working Group 3 for this updated version of Puerto Rico's State of the Climate report showcases a diverse array of information to better understand the manifestations of the climate crisis in Puerto Rico. The summary works from the authors include topics ranging from: climate policy; economic conditions, including insurance, tourism, and agriculture; social context, including cultural heritage; critical infrastructures; water resource management, and land use planning. An overview of the main opportunities for adaptation and climate action are also included in the concluding remarks of this document.

RESUMEN EJECUTIVO

El cambio climático es una de las amenazas más graves que enfrenta las presentes generaciones ya que afecta directa e indirectamente todos los aspectos de nuestra sociedad y sus medios de vida. Este desafío primordial ha obligado a las naciones y comunidades a reevaluar sus condiciones existentes e identificar oportunidades para avanzar en nuestra búsqueda global de progreso y bienestar. Como tal, las voces globales están presionando para fortalecer nuestra capacidad de resiliencia social, económica y ecológica frente a los cambios climáticos actuales y proyectados. Particularmente en los países y comunidades más vulnerables donde las acciones de adaptación pueden marcar la diferencia en la continuidad de sus medios de subsistencia y formas de vida.

Desde la publicación del anterior Estado del Clima en 2013, Puerto Rico ha enfrentado múltiples eventos climáticos que provocaron respuestas a desastres para hacer frente a las pérdidas humanas y económicas experimentadas. En particular, los huracanes Irma y María en septiembre de 2017 sirvieron como un crudo recordatorio de las vulnerabilidades que enfrenta nuestra sociedad y economía a medida que la crisis climática continúa manifestándose en el mundo. Sin embargo, también expuso la fuerza de las familias y comunidades para avanzar frente a desafíos difíciles y encendió voces más fuertes que exigían acción para estar mejor preparados para eventos futuros.

La iniciativa del Grupo de Trabajo 3 para esta versión actualizada del informe Estado del Clima de Puerto Rico presenta una diversa gama de información para comprender mejor las manifestaciones de la crisis climática en Puerto Rico. Los trabajos resumidos de los autores incluyen temas que van desde: política climática; condiciones económicas, incluidos seguros, turismo y agricultura; contexto social, incluido el patrimonio cultural; infraestructuras críticas; gestión de recursos hídricos y planificación del uso de la tierra. En las observaciones finales de este documento también se incluye una descripción general de las principales oportunidades para la adaptación y la acción climática.

INTRODUCTION

The unequivocal changes to Earth's climate are a direct outcome of human activities, more specifically due to the rate of greenhouse gas (GHG) emissions resulting from social and economic activities (IPCC, 2021). From energy production technologies to agricultural production and urbanization, the business-as-usual model of development has led societies to generate far greater GHG emissions than at any other point in recorded human history.

Puerto Rico, as other Small Island Developing States (SIDS), is expected to continue receiving some of the most adverse impacts of these global climatic changes, despite their limited contribution to GHG emissions (Mycoo and Donovan, 2017). The consequences of such global and regional changes bring enormous challenges in the form of a climate crisis, that require assertive actions from us all: from leaders across intergovernmental institutions to family members in households and communities. For insular territories, the need to adapt and become more resilient to present and future climate impacts is paramount to securing the wellbeing of present and future generations (United Nations, 2015).

Since the publication of the first State of the Puerto Rico Climate report (PRCCC, 2013), there have been great challenges to advancing climate change adaptation and mitigation initiatives stemming from the environmental, social, public health, economic, and financial arenas. The Archipelago of Puerto Rico has experienced changing demographic patterns due to a continuous outward migration for the past decade, a reduction in birth rates, the increase in life expectancy which have caused and increase in the proportion of elderly population, and a decrease in working age population percentages (IEPR, 2017). Puerto Rico has experienced a sharper recession than the rest of the United States: since the economic contraction began in 2006, it shrank by more than 10% and the employment was reduced by 14% (U.S. Department of the Treasury, 2018). In addition, a Financial Control Board through US Legislative action (PROMESA Act), is currently overseeing the limited powers of the Puerto Rico's Executive and Legislative government branches to administer its finances. All these events have brought unprecedented challenges to operate and maintain the development of the Commonwealth, including the provision of a comprehensive government response to the effects and impacts of climate change.

After the publication of its first state of the climate report, Puerto Rico had to confront and overcome a string of extreme climatic events including droughts and major hurricanes. Between 2014 and 2016, the archipelago experienced the most severe drought event affecting the Caribbean region in 66 years, whose intensity has been linked with climate change due to increased atmospheric temperatures observed (Herrera and Ault, 2017). In 2017, hurricanes Irma and María catalyzed one of the greatest disaster events experienced on Puerto Rico in a generation. With over 2,975 excess deaths (Milken Institute School of Public Health, 2018) and economic losses estimated at $ 42.3 billion (JPPR, 2018), the aftermath of these events decimated the archipelago and tested Puerto Rico's capabilities to withstand the effects of extreme weather events.

The devastation caused by these events was met with unprecedented actions from a myriad of communities and non-governmental organizations, leading their local recovery and reconstruction efforts and demanding better responses and accountability from our government institutions. These recovery and reconstruction efforts have been tested with other non-climatic disaster events: earthquakes along southwest Puerto Rico (December 2019-January 2020), and the ongoing SARS-CoV-2 virus causing the COVID-19 pandemic present in Puerto Rico since March 2020.

Yet, multiple opportunities have appeared for Puerto Rico to develop and promote sectoral community-based adaptation. Non-governmental organizations are proposing innovative initiatives and showing positive results for the economic and social development of the island. This report highlights the need to create more knowledge about these phenomena and to develop a more coordinated response to emergencies in the future, collective and community based (Rivas, 2018). Recent post-disaster recovery efforts prompted a national conversation about the concept of 'resilience' (DNER, 2018) and a myriad of initiatives across Puerto Rico to strengthen their adaptive capacity in the face of extreme events (RPRAC, 2018).

The initiative of Working Group 3 for this updated version of Puerto Rico's State of the Climate report builds on the main findings presented in the 2013 edition (PRCCC, 2013), as well as from the information presented in the Working Group 1 (Geophysical and Chemical Knowledge) and Working Group 2 (Ecology and Biodiversity) chapters. It exposes a diverse array of information to better understand the manifestations of the climate crisis in Puerto Rico. The summary works from the authors include topics ranging from: climate policy; economic conditions, including insurance, tourism, and agriculture; social context, including cultural heritage; critical infrastructures; water resource management, and land use planning. An overview of the main recommendations presented across different sections of the chapter are discussed as part of the concluding remarks of this document.

SECTION 01

Climate Change Impacts

KEY MESSAGE

The United States of America have enacted different views on climate policies since 2013.

Climate Policy and Governance

Recent information documented by the United Nations Intergovernmental Panel on Climate Change (IPCC) has made States and humanity more aware of the devastating effects faced by all as a result of the atmospheric emissions of carbon dioxide and other greenhouse gasses produced since the Industrial Revolution (IPPC, 2018). Moreover, as previously stated, Puerto Rico is witnessing firsthand the resulting effects of global warming and climate change, phenomena that currently are wreaking havoc on the planet.

For many, the international community has not moved fast enough nor forcefully enough in light of the predicted increase in temperatures for the next decades, and the catastrophic and irreversible nature of devastation expected by said increases in temperature. However, progress has been achieved with the development of an international law regime specifically addressing climate change.

The United Nations Framework Convention on Climate Change (UNFCCC) was negotiated and opened for signature in June 1992, during the Earth Summit held in Rio de Janeiro, Brazil. Today, the UNFCCC has 197 parties, making it one of the most widely accepted environmental treaty regimes in existence (UNFCCC, 2017). The UNFCCC parties agreed that their actions would be guided by the following principles: intergenerational equity; common but differentiated responsibilities; the precautionary principle; sustainable development; and the right to development (United Nations, 1992). However, as a framework treaty, the 1992 UNFCCC does not impose upon parties any specific reduction levels for greenhouse gases. The intent was to agree on such reduction levels in subsequent meetings through protocols.

In 2015, during the 21st UNFCCC Conference of the Parties held in Paris, France, the Paris Agreement was adopted to strengthen the global response to climate change by maintaining the global temperature rise during the 21st Century below 2˚C above pre-industrial levels, and by pursuing actions that could limit the temperature increase even further to 1.5˚C (United Nations, 2015). Since November 2016, 191 parties have ratified the Paris Agreement (United Nations, 2021).

During the past decades, small island developing states (SIDS) have effectively raised awareness regarding the particular vulnerability of SIDS to climate change, climate variability, and sea level rise featured prominently in the Barbados Programme of Action (United Nations, 1994), which identified priority areas and indicated the specific actions needed to address the special challenges faced by the governments of these countries. The forty-one SIDS signatories of the UNFCCC have vehemently called for a heightened sense of urgency by the international community towards climate change as more than 60% of humanity lives in coastal areas, thus making a majority of the world's population vulnerable to climate change and sea level rise. Moreover, many SIDS countries are presently at risk of becoming uninhabitable – a catastrophe that would directly impact the more than 50 million people that live in these countries.

CLIMATE POLICY IN THE UNITED STATES OF AMERICA

The United States of America have enacted different views on climate policies from 2013 to date. President Joseph Biden issued at least three Executive Orders associated with a response to the climate crisis: Executive Order 13990 of January 20, 2021; Executive Order 14008 of January 28, 2021; and Executive Order 14013 of February 4, 2021. These initial actions showcased a drastic shift in policies from its predecessor, seeking to regain traction on its international and domestic roles and responsibilities. President Donald Trump, who did not support the UNFCCC nor the Paris Agreement, issued Executive Order 13783 on 2017 to revoke actions previously taken by President Barack Obama, as well as reports adopted by the Executive Branch, directed to implementing climate change policies in the United States.

Presidential Executive Orders and Rulemaking

PRESIDENTIAL EXECUTIVE ORDERS FROM PRESIDENT TRUMP'S ADMINISTRATION:

EXECUTIVE ORDER 13783:

Promoting Energy Independence and Economic Growth

Revoked by President Biden (White House, 2017).

PRESIDENTIAL EXECUTIVE ORDERS FROM PRESIDENT BIDEN'S ADMINISTRATION:

(updated to March 2021):

EXECUTIVE ORDER 13990:

Protecting Public Health and the Environment and Restoring Science to Tackle Climate Crisis (Federal Register, 2021[a]).

EXECUTIVE ORDER 14008:

Tackling the Climate Crisis at Home and Abroad (Federal Register, 2021[b]).

EXECUTIVE ORDER 14013:

Rebuilding and Enhancing Programs to Resettle Refugees and Planning for the Impacts of Climate Change on Migration (Federal Register, 2021[c]).

CLEAN AIR ACT AND OTHER FEDERAL POLICIES

The Clean Air Act, 42 U.S.C. §7401 et seq. (1963), and its subsequent amendments, is the comprehensive federal law regime that regulates air emissions from stationary and mobile sources. Among other things, this law authorizes the United States Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS) to protect and enhance the quality of the United States' air resources in order to promote the public health, welfare, and productive capacity of its population as well as to regulate emission of pollutants.

Implementing the air quality standards is a joint responsibility of states and the EPA (National Primary and Secondary Ambient Air Quality Standards, 1971). In this partnership, states are responsible for developing enforceable state implementation plans to meet and maintain air quality that meets national standards, including enforceable emissions limitations and other control measures. The EPA reviews those state plans to ensure that they comply with the Act, and if a state fails to adopt or implement an adequate plan, EPA is required to issue a federal implementation plan (National Primary and Secondary Ambient Air Quality Standards, 1971).

According to EPA reports, between 1990 and 2016, national concentrations of air pollutants improved 99% for lead, 77% for carbon monoxide, 85% for sulfur dioxide (1-hour), 56% for nitrogen dioxide (annual), and 22% for ozone. Fine particle concentrations (24-hour) improved 44% and coarse particle concentrations (24-hour) improved 40% between 2000 -when trends data begins for fine particles- and 2016 (EPA, 2017).

Another piece of federal legislation is the American Recovery and Reinvestment Act signed in 2009. This Act authorized a stimulus package that incentivized existing renewable energy, increased allocations of new clean renewable energy bonds and qualified energy conservation bonds, extended the credit for electricity produced from renewable sources, among others. It allocated $16.8 billion for "Energy Efficiency and Renewable Energy" (American Recovery and Reinvestment Act of 2009).

UNITED STATES SUPREME COURT RULINGS

One of the most important Supreme Court opinions addressing climate change is Massachusetts v. EPA, 548 US 497 (2007). A group of private organizations petitioned the EPA to begin regulating the emissions of greenhouse gases, including carbon dioxide, under §202(a)(1) of the Clean Air Act. The Court held:

> *The harms associated with climate change are serious and well recognized. The Government's own objective assessment of the relevant science and a strong consensus among qualified experts indicate that global warming threatens, inter alia, a precipitate rise in sea levels, severe and irreversible*

changes to natural ecosystems, a significant reduction in winter snowpack with direct and important economic consequences, and increases in the spread of disease and the ferocity of weather events (Massachusetts v. EPA, 2007).

Ultimately, the Court held that the Clean Air Act authorizes the EPA to regulate greenhouse gas emissions from new motor vehicles in the event that it forms a "judgment" that such emissions contribute to climate change. The only way the EPA can avoid taking regulatory action with respect to greenhouse gas emissions from new motor vehicles is if it determines that greenhouse gases do not contribute to climate change, or if it provides some reasonable explanation as to why it cannot or will not exercise its discretion to determine whether they do.

CLIMATE POLICY AND ITS ENFORCEMENT IN PUERTO RICO

The Puerto Rico Constitution provides that: "It shall be the public policy of the Commonwealth to conserve, develop and use its natural resources in the most effective manner possible for the general welfare of the community" (P.R. Const. art. VI, § 19). The Puerto Rico Supreme Court has interpreted this clause as establishing a "double mandate" to achieve the most effective conservation of Puerto Rico's natural resources, while also striving to use and develop said resources in the community's best interest and welfare (Misión Industrial v. Junta de Calidad Ambiental, 1998). These mandates prevail over any laws, regulations or ordinances. Unfortunately, this constitutional clause has not been interpreted in the context of climate change to date. Nonetheless, over the years there have been several initiatives in Puerto Rico aimed at climate change mitigation, adaptation to its effects, the promotion of sustainable development, and the conservation of natural resources.

PUERTO RICO GOVERNORS' EXECUTIVE ORDERS

EXECUTIVE ORDER NO. OE-2013-16

Puerto Rico's Governor called for the development of a study on the vulnerability of public infrastructure related to climate change, and the adoption of adaptation plans to confront the study's findings (Governor of Puerto Rico, 2013). A total of 17 government agencies initiated the development of climate change vulnerability studies. Only 3 agencies managed to complete their adaptation plans (AAA, 2015; CTPR, 2016; DRNA, 2016).

EXECUTIVE ORDER NO. OE-2013-18

Puerto Rico's Governor ordered the quantification of emissions of greenhouse gases (GHG) in Puerto Rico, and the elaboration of a plan for the reduction of these emissions to approach the neutral carbon target (Governor of Puerto Rico, 2013). The GHG report was concluded in 2014 (Center for Climate Strategies, 2014). The climate change mitigation plan to approach a carbon neutral target has not been completed at present.

EXECUTIVE ORDER NO. OE-2018-045

This executive order creates the Multisectoral Working Group to Mitigate Climate Change to establish and recommend public policy initiatives aimed at reducing the effects of climate change and protecting the environment (Governor of Puerto Rico, 2018).

PUERTO RICO LEGISLATION AND LOCAL POLICIES

ACT NO. 82-2010, AS AMENDED

"Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico Act"

While specifically acknowledging that Puerto Rico's current energy policy significantly contributes to climate change, Law 82 of 2010 orders the Executive Branch to create the necessary conditions to allow future generations an opportunity to progress and develop within a healthy environment through the stabilization of the price of energy and new economic development sources. It also establishes the standards to promote the generation of renewable energy pursuant to short, medium, and long-term mandatory goals known as Renewable Portfolio Standards, among others (Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico Act, 2010).

ACT NO. 17-2019,

"Puerto Rico Energy Public Policy Act"

This act establishes Puerto Rico's new public policy on energy setting the parameters for a resilient, reliable, and robust energy system. An amendment to Act No. 82-2010 (known as the "Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico Act"), Act No 17-2019 increases the Renewable Portfolio Standard until 100% energy production from renewable sources is achieved by 2050 (Objective No. 7); eliminates the use of coal as an energy source as of 2028 (Objective No. 3); among other measures.

ACT NO. 33-2019,

"Mitigation, Adaptation and Resilience to Climate Change of Puerto Rico Act"

This law is Puerto Rico's first climate change public policy. This act provides mitigation, adaptation and resilience processes by sectors; establishes an inventory of greenhouse gas emissions; orders the approval of a Climate Change Mitigation, Adaptation and Resilience Plan by sectors; sets specific initial reduction objectives; creates the Committee of Experts and Advisers on Climate Change and the Joint Commission on Mitigation, Adaptation and Resilience to Climate Change of the Legislative Assembly; among other measures. As of April 2021, the implementation of mandates associated with this policy have yet to showcase results, having yet to secure funding for its execution.

PUERTO RICO COURT RULINGS

As stated before, the Supreme Court of Puerto Rico has not expressed its stance on the impact, mitigation, or adaptation measures related to climate change. However, in the Dissenting Opinion in Lozada Sánchez v. JCA, Supreme Court Judge Liana Fiol-Matta cited language pertaining to climate change from the United States Supreme Court opinion discussed above, Massachusetts v. EPA (Lozada Sánchez v. JCA, 2012). Thus, we trust that in the future our Supreme Court will be open to developments in federal and international courts about climate change.

Social and Economic Context

KEY MESSAGES

Puerto Rico confronts several challenges due to its high vulnerability, its fiscal situation, economic contraction, and socioeconomic constraints.

Low-income and moderate-income households exposed to natural hazards may be disproportionately affected by climate change.

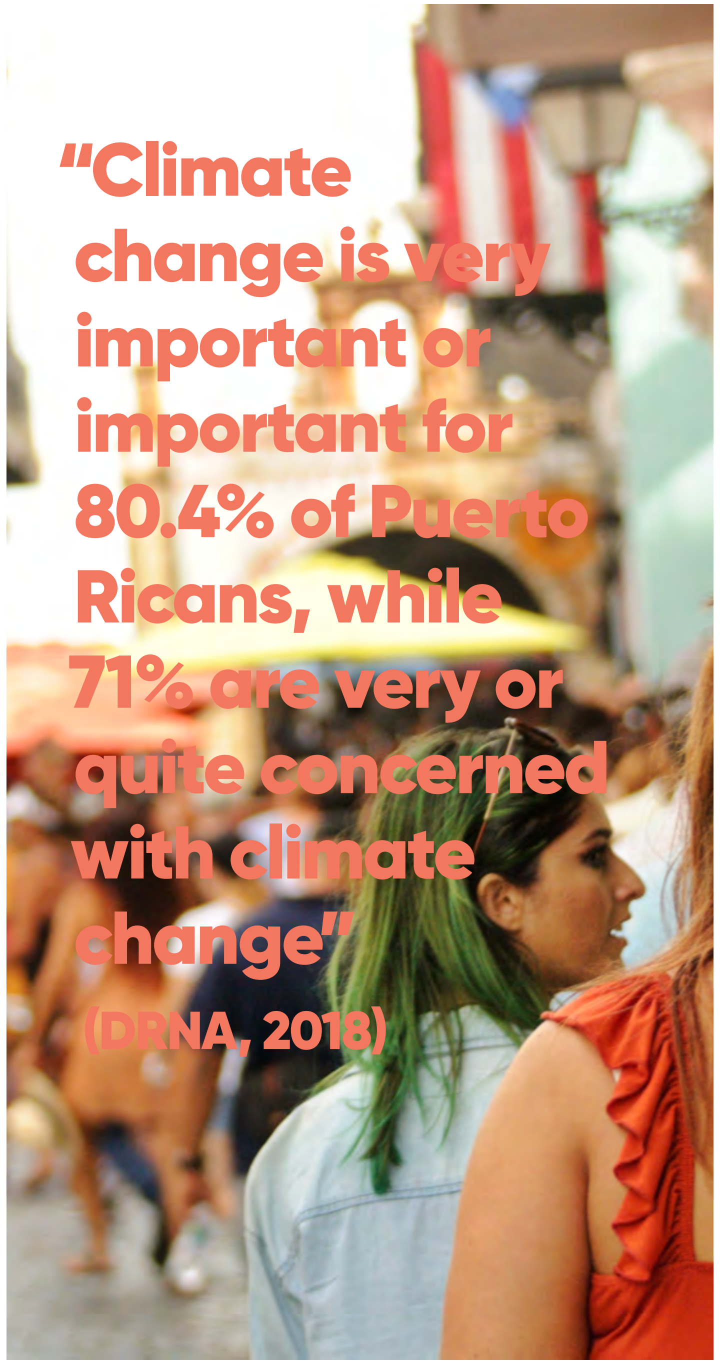
Puerto Rico has undergone a major transformation in the last two decades with a prolonged and deep contraction of the economy, a major loss of population, various natural disaster declarations, and more recently the SARS-CoV-2 pandemic. Several challenges are perceived to influence Puerto Ricans ability to adapt to a changing climate, such as a critical fiscal situation, an increase in social demands, and a downside projection of the economy, even though this is an issue of importance and concern to most residents (DRNA, 2018). Climate change is very important or important for 80.4% of Puerto Ricans, while 71% of Puerto Ricans are very or quite concerned with climate change (DRNA, 2018).

FISCAL SITUATION

In late February 2020 the Government of Puerto Rico submitted a revised Fiscal Plan for the next five years, providing a projection of fiscal and economic matters and a glimpse of the serious fiscal issues still to be resolved (Government of Puerto Rico, 2020[a]). The Fiscal Plan incorporates major cuts in several social services, including budget reductions to the Health and Education Departments, further termination of agencies, and cutbacks in payroll.

The Fiscal Plan projects the population to be 3.0 million by 2025 and estimates a negative growth in real Gross National Product (GNP) of 1.5% and 0.7% in fiscal years 2021 and 2022. Growth rates for the upcoming years will be positive but modest; based on the continued inflow of federal reconstruction funds and their investment in construction activity. It is estimated that around $36.3 billion will enter the economy during those years. What proportion will be invested and thus, have an impact on the economy, is uncertain.

The overall picture for Puerto Rico drawn by the Fiscal Plan suggests that there will not be a significant improvement in fiscal matters and that the island's social problems could very well worsen due to fiscal constraints and the impacts of the 2017 hurricanes, the recent earthquakes, and the SARS-CoV-2 pandemic.



POPULATION

According to the US Census Bureau, Puerto Rico has a population of 3,318,447 inhabitants for the 2015-2019 period, with approximately 60% concentrated in coastal municipalities (Instituto de Estadísticas, 2021). Population has decreased during past years for various reasons, including outward migration and a reduction in the number of births. Studies estimated that 24,189 residents live in areas that would be flooded if sea level rises by three feet (DRNA, 2019).

The elderly

The elderly population (65 years or older) is the only age group that shows growth, while the rest of the population groups continue to decline. Older adults face higher risks from climate change compared to the rest of the population, as they tend to have fewer financial resources to take adaptation measures. It is estimated that there are 37,820 elderly renter and owner households in Puerto Rico with severe cost burdens (housing costs >50% of income) (Government of Puerto Rico, 2020[b]). In addition, their risks from health conditions are greater, especially due to higher land surface temperatures (Méndez-Lázaro et.al., 2018). Moreover, the proportion of people who indicated that they were experiencing periods of intense heat that made it difficult for them to carry out their daily activities increased with age (DRNA, 2018).

Puerto Ricans living on the Archipelago are more likely to suffer from hypertension and diabetes (Pérez & Ailshire, 2017). These conditions increase their risk of heart failure during heat waves. A recent study focused on residents of San Juan and Bayamón, urban cites in Puerto Rico, found a significant increase in the effect of high temperatures on mortality during the summers of 2012 and 2013, being strokes and cardiovascular diseases the primary causes of death (Méndez-Lázaro et al., 2016).

Population under the poverty level

Poverty is another social indicator that has a very high prevalence in most of Puerto Rico. Approximately 44.1% of Puerto Rico households live below poverty level (Instituto de Estadísticas, 2021). Many of these are a single person household and/or elderly households.

Inequality has increased in Puerto Rico in past years, becoming the US jurisdiction with the highest economic inequality [Gini index US: 0.485; PR: 0.542] (Guzmán, G. 2019). According to international studies, a high degree of inequality implies greater difficulties in achieving economic growth (Instituto de Estadísticas, 2016). In Puerto Rico, the lack of economic resources, combined with the lack of knowledge about proper adaptation options are the main barriers that limit residents from implementing climate change adaptation actions in their households (DRNA, 2018).

Table 1. Selected characteristics of Puerto Rico's population. Sources: American Community Survey 2010-2014 and (five-year estimates); American Community Survey 2015-2019 (five-year estimates).

PUERTO RICO'S POPULATION: SELECTED CHARACTERISTICS

POPULATION	2014: 3,638,965 (ACS, 2014) 2019: 3,318,447 (ACS, 2019)
MEDIAN AGE	2014– 38.1 years (ACS 2014) 2019 – 41.7 years (ACS 2019)
POPULATION 65 YEARS OR OVER	2014: 582,130 (16.0%) 2019: 653,736 (19.7%)
HOUSEHOLDERS 65 YEARS OR OVER LIVING ALONE	2014: 138,956 (11.2%) 2019: 107,711 (9.0%)
UNEMPLOYMENT RATE (CIVILIAN LABOR FORCE)	2014: 18.3% 2019: 16.1%
POPULATION UNDER POVERTY LEVEL	2014: 45.2% 2019: 44.1%
INEQUALITY	Gini index US: 0.485; PR: 0.542

COMMUNITIES AT RISK

The effects of climate change do not impact all people and communities equally. Climate change could exacerbate current flooding conditions as precipitation patterns continue to change and sea level rise continues to progress (Gould et. al., 2018), thus prompting changes in flood risks and impacts to communities across Puerto Rico.

There are 84,233 housing units in Puerto Rico located in 100-year flood zones, whose estimated value is $8.388 million (DRNA, 2019). These flood zones are based on historical rainfall records. As climate change increases the risk of heavy rainfall, it is expected that flooding of houses in flood zones will be more frequent and more severe, and that additional areas will experience flooding. A three-foot increase in sea level would expose at least 14,570 housing units in Puerto Rico; the added value of these houses was $ 1,606 million in 2019 (DRNA, 2019).

Low-income and moderate-income households exposed to natural hazards may be disproportionately affected by climate change. According to the Climate Change Risk and Resilience Public Perception Study, most Puerto Rico residents who reported experiencing coastal flooding during storm and hurricane events, and from overflowing rivers, streams, and sinkholes, are among the population with the lowest income ranges (DRNA, 2018). For instance, many of the residents in flood prone areas in Puerto Rico cannot afford flood insurance to repair or replace their property when the next flooding event occurs (Kousky & Lingle, 2018). In Puerto Rico, an estimated 408,279 housing units are occupied by low- and moderate-income households in areas that could be permanently inundated by 0.9 meters rise in sea level. These constitute 46% of all Puerto Rico's housing units (Government of Puerto Rico, 2020[b]).

Higher sea levels will result in more frequent nuisance flooding, especially in low lying coastal communities. Nuisance flooding occurs with high tides due to climate-related sea level rise, land subsidence, and the loss of natural barriers (NOS, n.d.) Oftentimes these are not immediately destructive but can cause substantial negative socioeconomic impacts, compromising infrastructure and posing public health risks (Moftakhari, AghaKouchak, Sanders & Matthew, 2017). In Puerto Rico, flooding is of concern and peaks during the high-water stance in August through October (Mercado, 2016). Communities in the southwest coast of Puerto Rico are facing a complex situation as result from the earthquakes and aftershocks occurred in the region since January 2020, which caused permanent changes to the ground surface that appeared to shift downward and slightly to the west, according to a recent study (Smith, 2020).

Source: Ruperto Chaparro, Sea Grant Program

Critical Infrastructure at Risk

KEY MESSAGE

Future investments in infrastructure must consider adaptation to climate change in design, but also in operation and maintenance.

Most of Puerto Rico's critical infrastructure such as airports, electric power generating facilities, roads, and water infrastructure is located on coastal areas. The problem with the infrastructure is not so much of capacity since the island has a smaller economy and population, but of maintenance and improvements in the condition of existing facilities.

Puerto Rico's infrastructure is in poor condition and was graded a "D" by the American Society of Civil Engineers (ASCE, 2019). According the 2019 Puerto Rico Infrastructure Report Card, the island needs to increase investment by $1.3 billion to $2.3 billion annually – or $13 to $23 billion over 10 years – to update infrastructure to support economic growth and competitiveness (ASCE, 2019). Much of this infrastructure, which is obsolete or severely deteriorated, is in areas exposed to natural hazards.

AIRPORTS

Puerto Rico has 10 main airports, all located in the coastal municipalities (Figure 1). Currently, the runways of all airports, except Aguadilla and Vieques, are in areas susceptible to coastal and/or riverine flooding. At only 2.7 meters above sea level, the runways at the main international airport, Luis Muñoz Marín, and Isla Grande airports could be severely impacted by sea level rise (DRNA, 2019).

MARITIME PORTS

There are 12 seaports in Puerto Rico, being the Port of San Juan the main cargo port. In 2016, it occupied the 14th position among all ports in the United States (including Hawaii and Alaska) in terms of total cargo handled (U.S. Army Corps of Engineers, 2016). This port

Figure 2. Sea level rise impacts in the Port of San Juan (0.9 m sea level rise and 1.8 m sea level rise

is also important for cruise ships. In 2018, the port was visited by 1,658,822 tourists on cruise ships, of which approximately 453,367 tourists used it as a home port and 1,205,455 were visitors in transit (Puerto Rico Tourism Company, 2019).

At present, about half (51.5%) of the Port of San Juan is susceptible to flooding (DRNA, 2019). In the scenario of 0.9 meters sea level rise, at least 10% of the terrestrial port area (0.49 km^2) would be permanently flooded. In a 1.8 meters sea level rise scenario, about 30% (1.6 km^2) would be impacted (DRNA, 2019).

AIRPORTS AND HEIGHT ABOVE SEA LEVEL

Figure 1. Airports in Puerto Rico and runway heights above sea level in feet.

ROADS

According to the USGS National Transportation Dataset (2018), Puerto Rico has approximately 33,787 km of roads (DRNA, 2019). It is estimated that 208 km of roads, whose value is $101.8 million, would be affected by a 0.9 meters sea level rise (DRNA, 2019). Approximately 874 km of roads with an estimated value of $427.6 million would be impacted by an increase in 1.8 meters sea level rise (DRNA, 2019).

Figure 3. Electric power infrastructure in Aguirre,Salinas Puerto Rico.

ENERGY

There are 13 power plants on the island, nine of which are located in coastal municipalities (DRNA, 2019). The electric power infrastructure, including power plants, transmission towers, transmission centers, switchyards, substations and power lines, that is located in the areas projected to flood permanently by a 0.9 meters sea level rise is valued in $171.7 million, as of 2019 (DRNA, 2019). This includes the AES plant in Guayama, the Aguirre Complex, Costa Sur and Palo Seco. With 1.8 meters sea level rise, electric power infrastructure valued at $404.7 million would be impacted (DRNA, 2019).

WATER AND WASTEWATER INFRASTRUCTURE

There are 139 filtration plants, 1,493 pump stations and 2,170 drinking water storage tanks in Puerto Rico (DRNA, 2019). Additionally, there are 61 wastewater treatment plants and 1,065 wastewater pump stations. An estimated 51% (2,504 structures) of this infrastructure is in coastal municipalities.

The estimated value of the selected water and wastewater infrastructure that could be directly impacted by a 0.9 meters sea level rise is $19.6 million (DRNA, 2019). The estimated value of selected infrastructure located in areas that would experience a 1.8-meter rise in sea level is $93 million. These estimates do not consider the pipes located in these areas, which result in a higher value and losses under these scenarios.

WASTE MANAGEMENT INFRASTRUCTURE

The proper integration of diverse alternatives into Puerto Rico's waste management plan (WMP) requires understanding the service and value chains involved. Further details on the assessment performed is included in the Appendix section. Moreover, the importance of an Integrated Solid Waste Management Plan (ISWMP) is considered a priority, particularly considering increasing non-compliance and limited lifespan of disposal facilities and currently limited alternatives or infrastructure for diversion. Most recent impacts to the solid waste industry such as the 2017 Hurricane Season, earthquakes in 2020, and the current COVID-19 Pandemic, must be evaluated and seriously considered upon addressing the industry's path forward.

ASSESSING THE CAPACITY OF OUR INFRASTRUCTURE IN THE FACE OF CLIMATE CHANGE

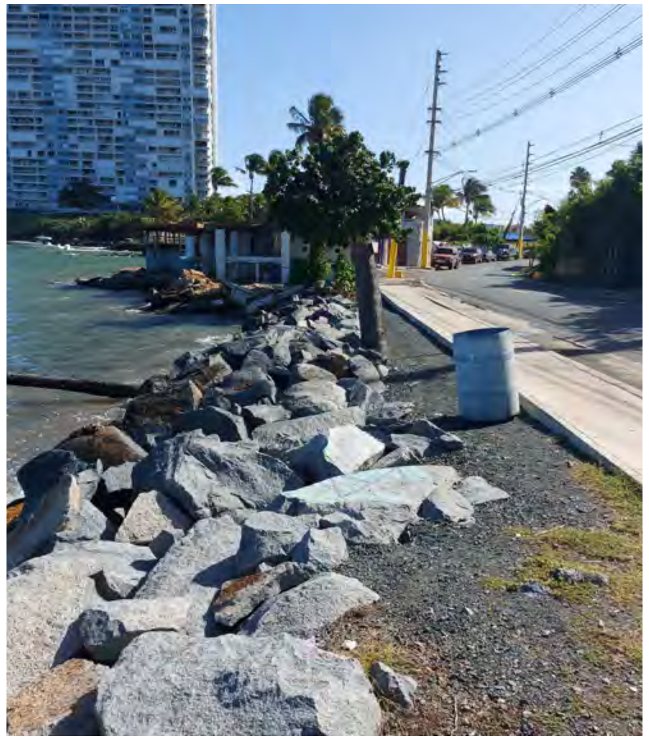
As previously described by Working Group 1, Puerto Rico is already experiencing an increase in average temperatures and altered rainfall patterns, and an increase in tropical cyclone intensity is projected. Consequently, these events are forcing an urgent conversation to address how to plan, design for, and operate critical infrastructure in a changing climate. Confronting the more acute challenges and climate risks that influence the strategic and operational management of such infrastructure is becoming ever more challenging. Infrastructure evaluated by specialists from the Puerto Rico Professional College of Engineers and Surveyors ("CIAPR" for its acronym in Spanish) is critical to economic performance, social behavior, and other aspects of the population's livelihoods.

The analysis performed on early 2017 followed the framework for risk management described in the International Organization for Standardization's document ISO 31000 Risk management – Principles and guidelines (International Organization for Standardization, 2009). The Risk Assessment Process considered common assets for all infrastructure analyzed, including: management, physical, financial, regulatory, supply chain, legal, response, product/service and reputation.

The risk assessments focused on healthcare and waste management infrastructures (see WG3 Appendix for results). The following are common needs identified:

- **Need of baseline criteria.** For most of the infrastructure evaluated, there was found to be a lack of information. Baseline criteria, information, and statistics must be generated to begin to prioritize areas for immediate action and long-term strategies.
  - *Enhance data on Puerto Rico specific factors: understand local transportation conditions and context, infrastructure age, and impacts from past weather events and how these can impact the infrastructure analyzed.*
- **Need of improved governance regarding climate change.** Part of this would mean reducing greenhouse gas emissions and integrating sustainable development into management objectives and organizational responsibilities.
- **Need for proper risk management.**
  - *As stated in a recommendation from CIAPR, there is a need to define, characterize, and evaluate critical infrastructure systems to highlight the major interdependencies between energy, water, telecommunications, transportation, public facilities, flood protection, hospitals, and other critical infrastructure systems (CIAPR, n.d.).*
  - *Risk management: recognize, monitor, anticipate, communicate, and prepare for changing climate-related risks.*
  - *Need to identify and assess infrastructure risk in relation to the communities served and impacted.*
  - *Adapt operations to changing risk conditions: prevent, respond to, manage, and cope with uncertainty, adversity, and sources of risks.*
- **Need for improved quality standards regarding climate change.** Without sustainable infrastructure, the quality of service becomes compromised. Therefore, part of assuring a reliable quality of service/product in the future is addressing the impacts of climate change on infrastructure now. This should be incorporated in the quality management program of the organization managing the infrastructure.
- **Need to adopt a strategy of adaptation to minimize the consequences and maximize the opportunities of addressing climate change impacts.**
- **Need to promote green building designs and integrate them into the organization's management system.**
- **Analysis tools for climate related risks should be included in the organization's risk profile.**
- **Need for responsible urban planning.**
- **Need to educate management and staff on climate related risks and how it impacts their ability to deliver their service/product.**

It is important to view these evaluations as a foundation on which to work toward continuous improvement. Puerto Rico's resilience and adaptation capacity can improve with more accurate and complete data and information, properly executed risk assessments, and the commitment of organizational leadership to incorporate these ideas into planning and policies.



Source: Wanda I. Crespo

Insurance and Reinsurance

KEY MESSAGE

Threats from climate change may also affect those who obtain insurance, as premiums are likely to increase with more weather-related disasters.

Insurance companies are an important part of economies and protect many of our most valued assets. Insurance helps cover a covered loss (e.g., damage to your home or car) contingent on the terms of a policy contract.

INTEGRATING CLIMATE CHANGE

Historically, companies in the United States have been slow to integrate climate change into business practices (Schiller, 2012), which not only puts the companies at risk, but their policy and shareholders as well. Climate change effects pose a threat to the insurance industry due to increased costs of damages from threats like increasing intensity of storms and increased amounts of precipitation. Sea level rise increases the vulnerability of coastal homes and infrastructure to flooding and more intense storm surge. Experts predict an 80% increase in flood losses along tropical Atlantic coastlines with 0.3 meters of sea level rise by 2030 (Torres George, 2013). Damages from floods will result in more financial losses and insurance claims, potentially causing the cost of insurance in coastal zones to rise and become more difficult to acquire.

Within the last 38 years, losses from disaster events have increased in the U.S. (Munich Re, 2019). In 2017, the second costliest year for global natural disasters, total losses were $330 billion, of which 41% was insured (Löw, 2018).

2017 ATLANTIC HURRICANE SEASON - THE HARVEY, IRMA AND MARIA TRILOGY

The atypical 2017 Atlantic Hurricane Season has its own-similar denomination according to the largest reinsurance companies. Swiss Re for example, names it the HIM trilogy (as per the initials of hurricanes Harvey, Irma and Maria) while Munich RE refers to it as the "hurricane trio". Harvey, with enormous levels of rainfalls and subsequent floods in Houston, Irma and its category 5 intensity level during three full days (a record considering landfalls and associated effects over the Caribbean islands); and Maria and its rapid-developing process (from category 1 to 5 in a 15 hours lapse) combined with the unprecedented impact over Puerto Rico, meant massive economic damages and a strike to the insurance industry.

Source: Ruperto Chaparro, Sea Grant Program

Source: Ruperto Chaparro, Sea Grant Program

The HIM trail of destruction caused economic damages of $217 billion and insured losses $92 billion (Swiss Re, 2018). This is equal to 0.5% of US GDP, making the 2017 season, the second costliest in the North Atlantic since 2005 (Swiss Re, 2018). For Puerto Rico, the overall economic losses due to Hurricane Maria were around $65 billion (Munich Re, 2018). Insurance proceeds have made a significant contribution to recovery efforts, but a substantial proportion of these losses were uninsured (<4% of households have flood insurance [Kousky & Lingle, 2018]). These costs will ultimately have to be borne by government, businesses and individuals (Swiss Re, 2018). For the risk management industry, the 2017 season represents an opportunity to develop loss scenarios considering the events frequency, rainfalls, storm surge, wind and the potential exacerbation of these characteristics due the global warming. Scenarios and modeling exercises for Puerto Rico would benefit from using the best available data and the integration of local construction codes.

Threats from climate change can also affect those who obtain insurance, as premiums are likely to increase with more weather-related disasters. For example, an increase in wind intensity can cause more wind damage claims and eventually make insurance premiums more expensive or harder to obtain (EPA, 2016).

Tourism and Recreation

KEY MESSAGE

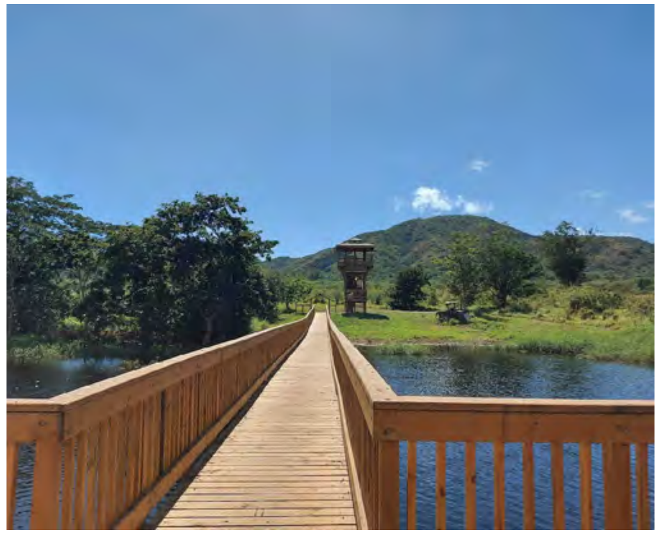
The tourism industry of Puerto Rico can be affected by multiple climate related threats including land temperature increase, the frequency and extent of wildfires, increase in extreme weather events, changes in precipitation, and sea level rise.

Climate is an essential part of tourism, particularly for beach, nature, and sport tourism. Changing climate and weather patterns at tourist destinations and on tourist generating countries can significantly affect tourists' comfort and their travel decisions. Like other destinations within the Caribbean region, Puerto Rico's rainforests, mangroves, coral reefs, and many miles of coast provide outdoor tourism opportunities to visitors and residents alike. C. R. De Freitas establishes three aspects where climate can influence outdoor recreation: thermal aspects, physical aspects, and esthetical aspect (De Freitas, 1990). As prognosticated, climate change will have an impact on all three aspects in Puerto Rico.

The Puerto Rico Comprehensive Outdoor Recreation Plan 2020-2025 (SCORP) recognizes that climate change directly affects how people spend their leisure time, reducing options and/or making it unsafe to engage in some outdoor activities (PRDSR, 2020). Climate change can affect infrastructure and natural resources that sustain outdoor recreation activities, as well as the population's willingness to participate in certain outdoor recreation activities (Askew and Bowker, 2018). Increases in surface temperatures and heat waves could limit recreation options, particularly in urban areas (Dolesh, 2017). To successfully manage these challenges, the recreation sector will need to adapt with comprehensive planning efforts and robust methods of outreach and education.

According to the World Travel and Tourism Council (WTTC) (2020), in 2019, travel and tourism in Puerto Rico contributed $4,617 million to GDP (4.2% of total economy). The sector supported 100,000 jobs (10% of total employment) (WTTC, 2020). Puerto Rico, tourism is currently an important economic sector that shows signs of continuous growth, even during this time of continued economic contraction and fiscal uncertainty.

The economic drivers of tourism in Puerto Rico (i.e., natural features like beaches, coral reefs, mangroves, rainforests, etc.) are extremely vulnerable to climate change, as reflected in the PRCCC Working Group 2 analyses. An economic valuation study revealed that visitors who made use of coral reefs as part of their stay in Puerto Rico spend over $1.9 billion dollars annually between 2016 and 2017 (Leeworthy, et. al., 2018).



Source: Wanda I. Crespo

The tourism industry of Puerto Rico can be affected by multiple climate related threats: warmer summers, increase in extreme weather events, water scarcity, marine biodiversity loss, coastal erosion, and increase in disease outbreaks, among others (PRTC, 2016). Table 2 summarize possible implications for tourism due to climate stressors.

Table 2.General implications of climate stressors on the tourism industry.

CLIMATE STRESSOR	IMPLICATIONS FOR TOURISM
WARMER TEMPERATURES	Heat stress on tourists Increased cooling costs Health impacts such as infectious and vector-borne diseases Aesthetic degradation of marine resources in diving destinations
MORE FREQUENT AND LARGER WILDFIRES	Loss of natural attractions Damage to tourism infrastructure
INCREASING INTENSITY OF EXTREME STORMS	Damages to tourism facilities Increased insurance costs/loss of insurability Business interruption costs Flooding damage to natural, historic and cultural assets
REDUCED AVERAGE PRECIPITATION AND INCREASED EVAPORATION	Water shortages Increased wildfires threatening infrastructure and affecting demand
SEA LEVEL RISE	Coastal erosion Loss of beach areas Higher costs to protect and maintain waterfronts and sea defences

Source: Adapted from Simpson et al., 2011; and UNWTO/UNEP/WMO, 2008.

According to Puerto Rico Tourism Company (PRTC), 4,984 (34.8%) of the 14,306 endorsed accommodations are currently in a high-risk flood zone (1% chance of flooding or greater); and 3,080 endorsed accommodations (21.5%) were in the VE flood zone, which is a zone at increased risk of storm surge (PRTC, 2014). The Porta Antillas (East Region)[1] have 73% of the hotels in flood zones, Porta Caribe[2] (south region) have 42% and Metro Region[3] 36% (PRTC, 2016).

The 2017 hurricane season caused an estimated loss of 826,100 visitors to the Caribbean, compared to pre-hurricane forecasts. These visitors would have generated US $741 million and supported 11,005 jobs (WTTC, 2018). According to PRTC the estimated job losses in the sector was approximately 5,436 (PRTC, 2021).

Natural disasters have dramatically increased in frequency and magnitude, also, outbreaks have been on the rise, in numbers and diversity of the diseases. The implications of crises increasingly require governments to engage with the private sector to improve crisis preparedness[4], management and recovery plans (WTTC, 2019).

1 Caguas, Canóvanas, Ceiba, Culebra, Fajardo, Gurabo, Humacao, Juncos, Las Piedras, Loíza, Luquillo, Maunabo, Naguabo, Río Grande, San Lorenzo, Vieques and Yabucoa.
2 Arroyo, Coamo, Guayama, Guayanilla, Juana Díaz, Patillas, Peñuelas, Ponce, Villalba, Salinas, Santa Isabel, and Yauco.
3 Bayamón, Carolina, Cataño, Guaynabo, San Juan, Toa Baja, and Trujillo Alto.
4 "Must focus on building trust-based coalitions, assessing readiness & developing emergency action plans as well as enhancing education." (WTTC, 2019).

Cultural Heritage

KEY MESSAGE

Climate change and its impacts presents a direct threat to the material evidence of Puerto Rico's cultural history. Assessing the vulnerability of cultural heritage sites and creating appropriate adaptive management plans is imperative to the preservation of Puerto Rico's cultural heritage.

Source: Wanda I. Crespo

Puerto Rico has a long and rich cultural history that is apparent throughout the island and reflects more than 5,000 years of social processes. Aside from its expected physical, economic, and social impacts, climate change will also have severe impacts on the material evidence of this cultural history. Heritage is the physical basis for social identity, which supports the community of investment for action and protection of natural environments. It also provides a significant means of revenue linked to cultural tourism.

Heritage can be natural or cultural, tangible or intangible. Tangible cultural heritage, also known as material heritage, evokes a strong sense of place and belonging and supports community recovery after disasters (Maldonado et al. 2021). Geographic location shapes one's community and culture. Heritage is what connects a person with their community, home, and past (Altman and Low, 1992), linking today's societies with past traditions.

Archaeology can recover forms of material heritage, which inform and expand narratives from the past. Public archaeologists work alongside communities to record, preserve, and interpret the past, aiding in the incorporation of public input into cultural heritage management plans (Richardson & Almansa-Sánchez, 2015, Rivera-Collazo et al. 2020). Environmental archaeology is also an important branch of the study of climate change. Studying past societies provides useful information on how past societies adapted to and altered a changing natural environment. It also informs the magnitude of hazards and threats in the present, as current geomorphology is the product of both social and natural dynamics (Rivera-Collazo et al. 2021).

The International Council on Monuments and Sites (ICOMOS) (2019) has identified a series of climate drivers expected to impact tangible and intangible cultural heritage in various ways. These drivers include sea level rise, acute and / or chronic flooding, coastal erosion, increased ocean temperatures, increased storm intensity and/or frequency, more extreme rainfall, increased humidity, increased wind or changes in wind direction, drought, aridification, heatwaves, changes in water table, saltwater intrusion, changes in seasonality, and changes in species distribution driven by climatic changes. In addition to these stressors, there are secondary stressors triggered by human activity itself, which also impact communities and their heritage in the context of changing climate. These include pollution, climate driven development, and damage from mitigation and adaptation strategies. These hazards have the potential to directly impact moveable heritage (including museums and collections), archaeological resources on land and underwater, buildings and structures, cultural landscapes (including submerged cultural landscapes, historic landscapes, parks and gardens), associated and traditional communities, and intangible cultural heritage. Puerto Rico is already feeling the impact of these drivers in multiple ways (Boger et al. 2019). For example, coastal archaeological sites are intensively eroding, archaeological collections and historic buildings have been lost or damaged during recent hurricane events, especially Hurricane Maria, traditional knowledge has been lost as elders die or migrate after catastrophic events, and archaeological sites have been impacted or totally destroyed during projects designed to mitigate future climate impacts (Rivera-Collazo, 2021).

TYPES OF CULTURAL HERITAGE IN PUERTO RICO

Law 112 of July 20, 1988 (amended) declares as public resource and heritage of the people of Puerto Rico all sites, objects, deposits, artifacts, documents or archaeological materials that are on or beneath the surface of the earth in the jurisdiction of the Commonwealth of Puerto Rico. Puerto Rico has one World Heritage Site (the San Juan Spanish Defense System), hundreds of sites and places registered in the National Register of Historic Places (NRHP), which list is managed by the United States Department of the Interior, and an unknown number of sites that remain to be registered, studied and documented, and could qualify for inclusion in the NRHP. The Institute of Puerto Rican Culture and the State Historic Preservation Office keep separate lists of known archaeological sites of historic and pre-Columbian cultural affiliation. In addition to these places, other cultural heritage contexts include museums, archaeological collections in non-standardized or regulated deposits (under the oversight of diverse governmental, non-governmental or private organizations, or individual archaeologists that conduct contract archaeology), personal collections of archaeological and historic objects and documents, archives, places of traditional cultural practices, ritual landscapes and placenames, and traditional knowledge, among others. Background research demonstrates that there is no comprehensive study on the potential impacts of climate change to Puerto Rico's cultural heritage, but the impacts are already evident, and are expected to continue increasing in severity.

According to the digital database of the Program of Archaeology and Ethnohistory of the Institute of Puerto Rican Culture[1] , there is a total of 1,185 known coastal archaeological cultural heritage sites in Puerto Rico between 0 – 20m in elevation, as shown in Figure 4. Of the overall sites, 555 are historic, 534 are indigenous, 48 are multi-component, and the remaining 48 are of unknown cultural affiliation. There are multiple issues with this database that affect the quality of any analysis. First, the number of sites is biased because the definition of "site" has not been systematic. For example, individual buildings within Old San Juan are registered as individual sites, when they are components within one larger context. Second, the register is the product of reported sites based on contract archaeology and not generated by systematic survey. Therefore, not all municipalities have been equally studied, not all reported sites have been confirmed, and it is not possible to know how statistically representative of reality is this dataset. Field surveys of portions of the coast demonstrate that the register is incomplete, and this number is massively conservative. The real number of coastal archaeological sites could be as much as 300% higher than that registered (Rivera-Collazo 2019). Therefore, the desk-based assessment of the state of hazard for cultural heritage on the island is extremely conservative because the databases are incomplete and not systematic.

The discussion that follows looks only to sea level rise and coastal erosion as drivers of impact of tangible cultural heritage. Similar evaluations must be performed for other climate drivers.

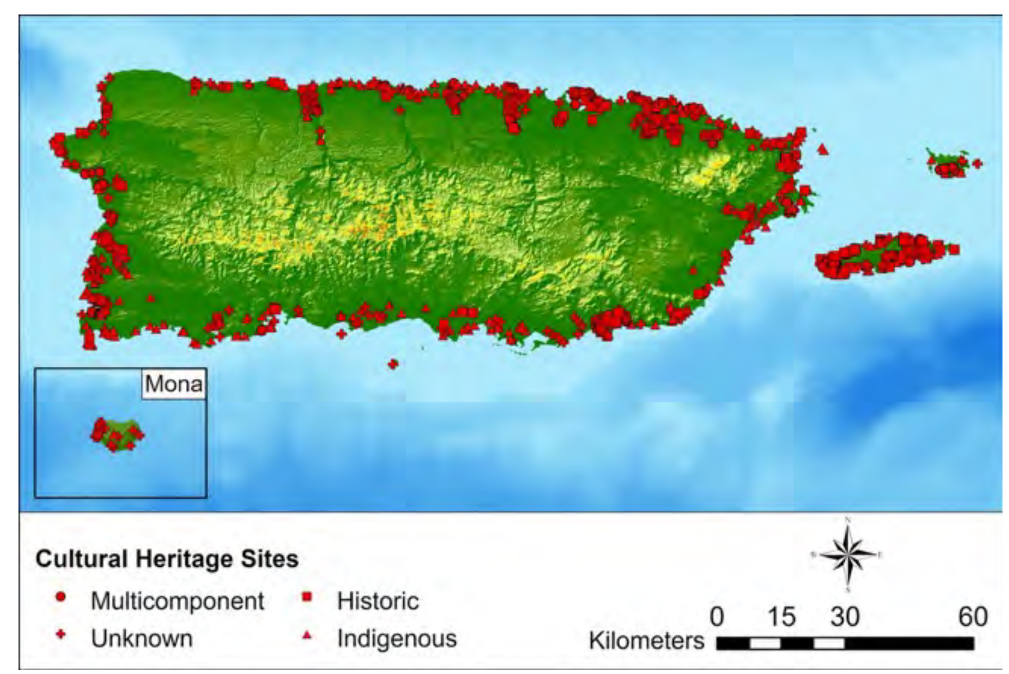


Figure 4: Map of the 1,185 known cultural heritage sites in Puerto Rico that lie below 20 meters in elevation. Sites are broken down into era (historic, indigenous, multicomponent, or unknown). Data sources: Archaeological data provided by the Instituto de Cultura Puertorriqueña.

1 Note from author: Raw data of all sites between 0 – 20m in elevation provided by the Director of the program in 2017.

IMPACTS IN THE PRESENT

So far, the field observations along the north and east coast of Puerto Rico have demonstrated that all sites on the current shoreline are being impacted in some manner, some more rapidly than others, and the archaeological contexts are washing away to sea. There have not been any systematic surveys of Vieques, Culebra, Mona, other cays and islets, or of the south and west coasts of the largest island. Additionally, there is more information on pre-Columbian archaeology (from Archaic to Late Ostionoid or Taino sites) than on historic period archaeology (from the 16th to the 20th Centuries). Even though maritime culture and navigation are central to our Puerto Rican identity, most of the places that register those activities have not been explored or studied, and are washing away.

FUTURE / EXPECTED IMPACTS

A simple bathtub flooding analysis (that does not consider coastal dynamics or erosion) suggests that almost 300 of the 1,158 coastal sites registered in the ICP database are under threat of flooding or impact by a sea level rise of 1.8m (Ezcurra & Rivera-Collazo 2018). The field survey demonstrates that this estimate is grossly conservative and the scenario is significantly more dire (Rivera-Collazo 2019). This number will be even higher when other climate change variables are included in the assessment.

Aside from the obvious threat of erosion, rising seas will lead to the formation of a new intertidal zone, exposing formerly dry regions to periodic wetting and drying, thereby increasing the rate of degradation of materials buried in that zone. Additionally, some coastal sites may become permanently flooded or submerged. This will limit access to sites and can lead to complete destruction or loss of a site. Further, saltwater intrusion will lead to the deterioration of material, due to changes in the chemistry to surrounding soil and water. This deterioration can include corrosion, salt deposits, and rusting. Ocean water encroachment along the coastline will also increase the height of the water table, damaging stratigraphy, and buried artefacts, and increasing rot of organic materials. Finally, intrusion of salt water will alter the chemistry of the soils surrounding sites, increasing deterioration of artefacts from corrosion and rusting. In addition to these physical impacts, other risk factors include - among others - coastal development, community relocation, dredging, river channeling, and installation of hard mitigation measures to temporally curtail coastal flooding. Underwater cultural heritage – which has not been researched in Puerto Rico – is also at risk of many impacts, including decomposition, reworking, bioturbation, burial under more sediments, rusting, and secondary impacts from dredging, pollution, and others.

ACTION PLANS AND SUGGESTED WAYS FORWARD

Assessing the vulnerability of these sites and creating appropriate adaptive management plans is imperative to the preservation of Puerto Rico's cultural heritage. Prioritization of intervention must include effective community engagement to ensure preservation of tangible heritage of importance for local community identity.

Source: Wanda I. Crespo

The society in general must prepare for loss of heritage, which is already happening. It will not be possible to save everything. Therefore, it is critical to start working to identify what are the most severe risks, what should be saved and how can it be saved. It is particularly urgent to remember that, on its own, tangible cultural heritage is inanimate and has no intrinsic adaptive capacity. It is the society that produces, uses, and values the heritage the one that provides totality of the adaptive capacity that mitigates the potential impacts in order to reduce overall vulnerability. Without social engagement and proactive action, cultural heritage vulnerability to climate impacts is absolute and measured only by exposure and sensitivity. Therefore, mitigation of risks requires proactive social engagement, prioritization, planning, monitoring and agile response. Specific adaptive management strategies that will increase the resilience of cultural landscapes (Beagan & Dolan, 2015) and the adaptive capacities of cultural heritage sites (Phillips, 2015) are imperative. Management strategies must also include early identification of sites at risk of total loss to create historic records and collections from these sites, improving the official databases and management of collections.

6 Irreplaceable materials were lost in several archives and cultural institutions by Hurricane Maria (September 2017), including the Archivo General, Instituto de Cultura Puertorriqueña main offices, the National Gallery, the University of Puerto Rico (UPR), the Museum of the Americas, the National Guard Museum, La Casa del Libro, and the Castillo San Cristóbal.

7 There are two regions with important heritage sites for which there is no sea level rise data: Isla de Mona, containing 21 of these sites (4 historic and 17 indigenous), and Isla Caja de Muertos, containing 1 historic site. These locations were not included in this assessment but must be evaluated as soon as possible.

Table 3.Selected list of climate stressors and their effects on the cultural heritage of Puerto Rico.

CLIMATE STRESSOR	MUSEUMS, COLLECTIONS, AND MOVABLE HERITAGE	ARCHAEOLOGICAL RESOURCES
INCREASING TEMPERATURE EXTREMES	Increased stress	Increase deterioration rates of recently exposed artifacts and an increased rate of decay of organic material. Materials may suffer additional stress (heat stress) from sudden thermal expansion or shock. Accelerated rusting in submerged resources.
DROUGHT EVENTS	Cause heaving or cracking, leading to a loss of stratigraphic integrity. Increased vulnerability to the effects of fire. Wild-fires, fed by drying of vegetation, and higher temperatures pose a threat to historic jíbaro and manor houses, tobacco and agricultural sheds, haciendas, ballcourts and shell middens, and many other cultural contexts.	
EXTREME PRECIPITATION EVENTS	Cause erosion and soil destabilization, threatening structural stability of historic sites. Are a severe risk for heritage sites along rivers and on floodplains, particularly for those in and near urban areas where the draining infrastructure has demonstrated to be very poor.	
INCREASE IN HURRICANE INTENSITY	Cause stronger storm surges, which exacerbate the erosion of coastal sites. Underwater sites will also be impacted, often in the form of destabilization or damage from movement of sediments. Finally, stronger winds cause direct damage to materials and structures, as well as secondary damage from wind-blown debris that may collide with site structures. [6]	
SEA LEVEL RISE [7]	An increase of 0.6 meters in sea level will cause 56 sites to be flooded at the highest high tide in Puerto Rico, Vieques, and Culebra. An additional 69 sites lay within 1 meter above the high tide line. 140 sites will be impacted by a 1.8-meter projection in sea level rise. An additional 148 sites lay within 1 meter above the high tide line.	

Agriculture and Food Production

KEY MESSAGE

Climate change stressors are exacerbating an already fragile agricultural sector. Total agricultural product and infrastructure loss from the 2017 hurricanes was over $2 billion.

Agricultural trends in Puerto Rico are largely influenced by the region's vulnerability to external factors such as economic forces (e.g., international trade, food dependence, etc.) and exposure to climatic events. Comas (2009) describes the vulnerability of Puerto Rico's food supply chain as being affected by "a high dependence on imported food, oligopolies in maritime transport logistics, maritime routes coinciding with the hurricane route, and the food reservoir is not clearly defined." The islands' food production is highly vulnerable to climate change because sea level rise may affect prime agricultural lands located in coastal areas; saltwater intrusion may affect aquifers upon which agricultural coastal lands have relied for generations and thus aggravating access to water problems; new pests and introduced species may affect livestock, wildlife, and plants; and farmers do not have the capacity or access to specialized expertise, information or equipment to adapt to climate change (Gould et al., 2015; Gould et al., 2017). Today's agricultural economy often forces farmers to make decisions that may be necessary for the survival of their business but are less protective of soil and water resources.

PRECIPITATION

Agriculture in Puerto Rico is heavily influenced by spatial and temporal rainfall patterns (Harmsen et al., 2008). Yields are reduced whenever a growing crop receives less than or greater than the crop water requirement (i.e., the cumulative potential crop evapotranspiration).

In general, the northwest region and El Yunque Forest receives greater than 2,000 mm of rainfall per year, while the southern coast receives less than 1,000 mm per year. The low rainfall conditions on the southern coast expanded northward between longitudes -66.4 and -66.0 degrees during drought years. The 2015 rainfall distribution (NOAA Advanced Hydrologic Prediction Service; Figure 5) may become the new normal for the region and use of irrigation will spread to areas outside of the current reach of the four irrigation districts if water can be made available.

The rainy season is expected to become wetter and the dry season to become drier between 2000 (average of 1990-2010) and 2090 (average of 2080-2100) (Harmsen et al., 2009). September rainfall is predicted to increase by 73%, 82%, and 95% between 2000 and 2090 at Adjuntas, Mayagüez, and Lajas, respectively (Harmsen et al., 2009). Under current conditions, during the months with the greatest rainfall (Aug, Sep, Oct), western Puerto Rico already experiences unacceptably high levels of soil erosion. Increased soil erosion from extreme rainfall events will further reduce soil fertility, degrade water quality of streams, coastal waters and reefs, and threaten sensitive ecosystems. A potentially positive finding from Harmsen et al. (2009) was that annual aquifer recharge may increase since most recharge occurs during the rainy season. In addition to increasing groundwater supplies, this may have a positive effect on streamflow and quality, since stream base flow would be expected to increase. Potential gains in aquifer recharge may be offset by inadequate water infrastructure and the potential growth/expansion of agriculture.

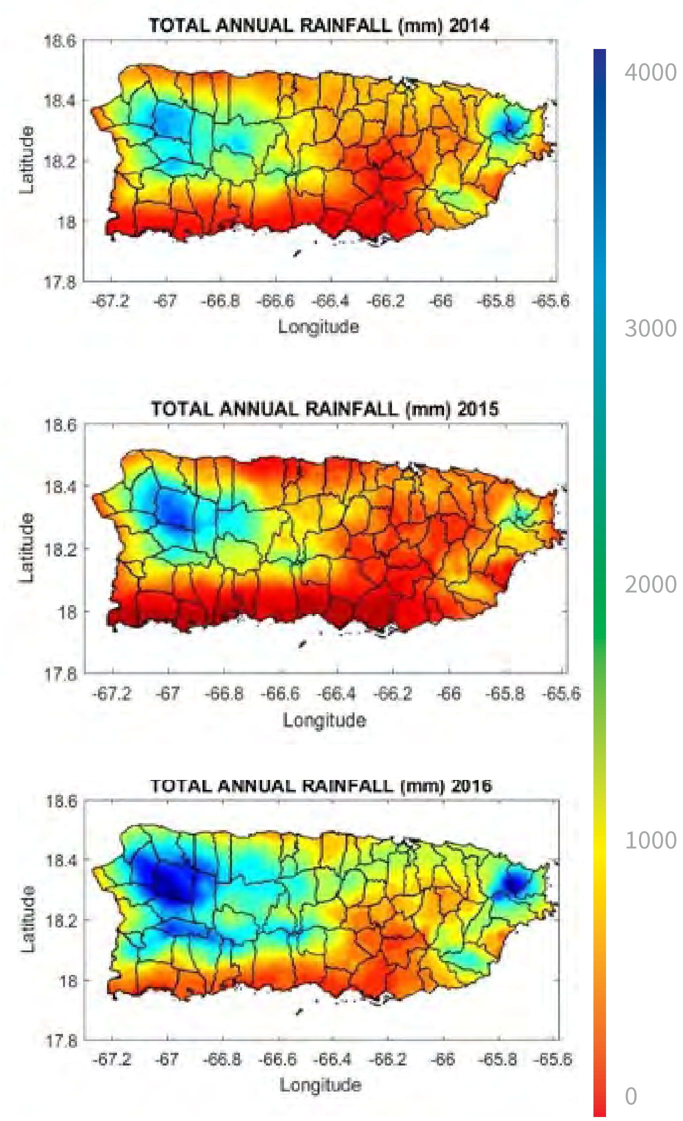
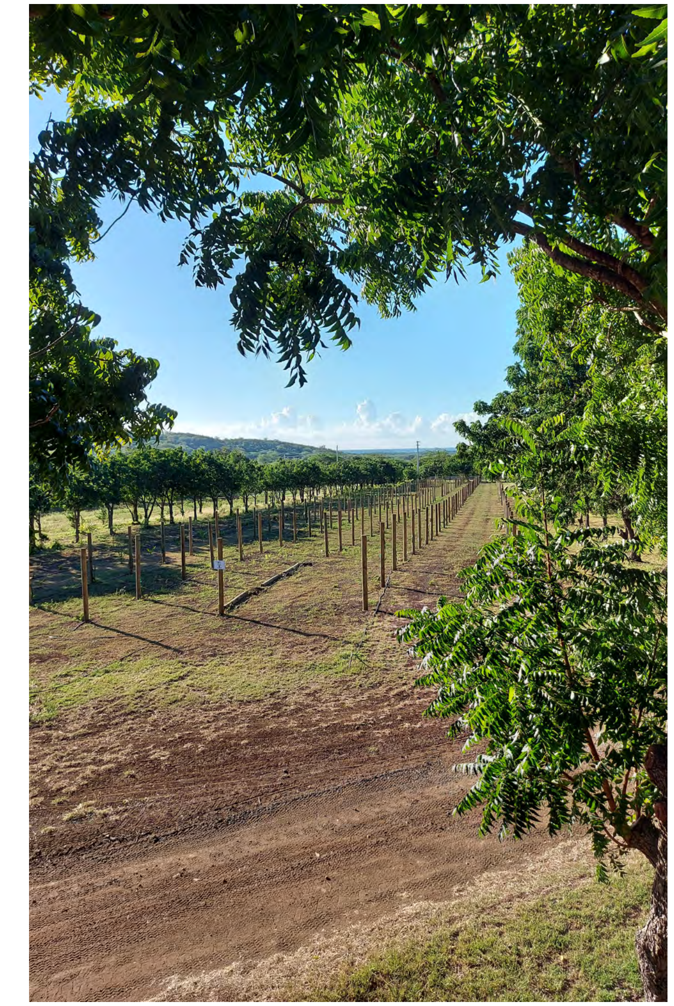


Figure 5. 2014, 2015 and 2016 total rainfall depth for Puerto Rico. Source: NOAA Advanced Hydrologic Prediction Service.

DROUGHTS

Recurrent droughts across the island have highlighted the agricultural vulnerability to these hazards and the increasing need for adaptation mechanisms such as best management practices to support agricultural production. Since 1950, Puerto Rico has experienced seven major periods of meteorological droughts. The drought of 2014-2016 covered 64% of Puerto Rico at its peak and resulted in agricultural losses of over $13.8 million, affecting mainly the livestock and farinaceous sectors, particularly plantains and bananas (Álvarez-Berríos et al., 2018). The Puerto Rico Department of Agriculture reported that in 2015, the drought caused losses of $8.6 million in forage (62.2% of all reported losses) and $750,000 in livestock due to malnutrition or death (5.4%) (Figure 6). Approximately 28% of livestock farms experienced damages and increased costs associated with imported feed to compensate for the reduced availability of hay due to the drought, particularly in 2014 (Gould et al., 2015). Of the total losses, 22% was attributed to plantains, a staple food on the island. The remaining 10% of the losses were attributed to a variety of 21 crops, including farinaceous crops, herbs, fruits, and coffee (Alvarez-Berrios et al., 2018).



Source: Wanda I. Crespo

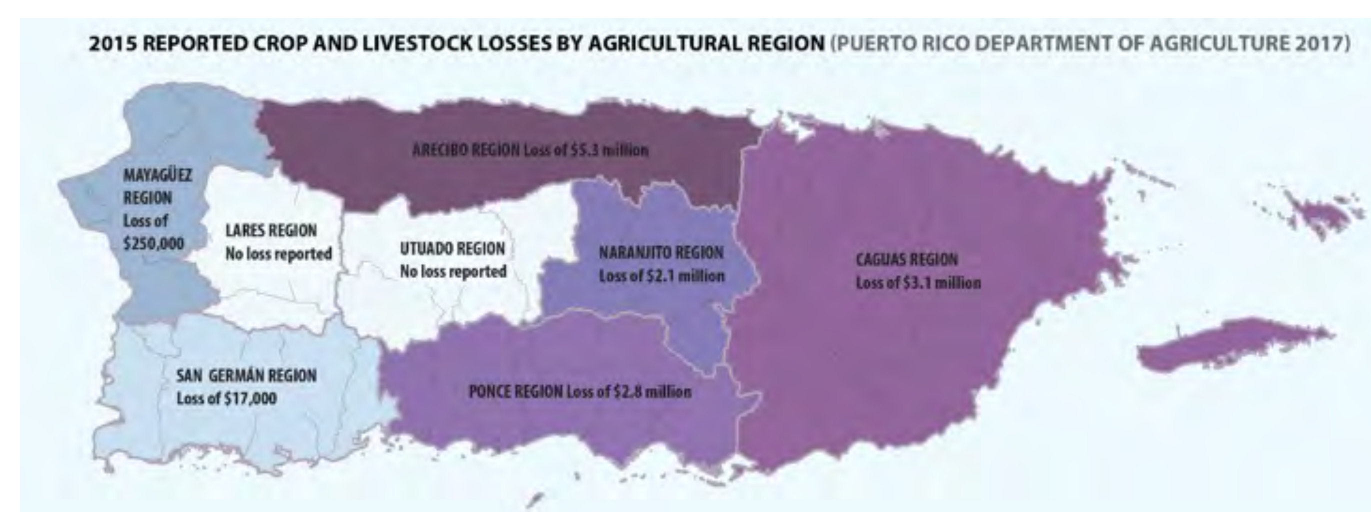


Figure 6. Drought losses by municipality in 2015 based on Puerto Rico Department of Agriculture data.

TROPICAL CYCLONES

In September 2017, hurricanes Irma and María caused losses of over $2 billion, including crops, ornamental plants, livestock, and other animal products (Puerto Rico Department of Agriculture, 2017). Over 1,016 mm of rainfall were measured from hurricane María, causing flooding on 210.4 km² of farmland. Moreover, about 40% of the poultry production infrastructure and over 90% of dairy industry structures were damaged by the hurricane (ASD, 2018). Agricultural production and infrastructure were also significantly damaged by hurricanes Irma and María, amounting to $1.8 billion in losses. In 2019, the Jacksonville port in Florida, where 90% of Puerto Rico's supplies come from, shut down from September 2 to September 5 due to Hurricane Dorian's path, generating a complicated logistics shift to get vessels in and out of Puerto Rico prior to the shutdown (Caribbean Business, 2019). Hurricane Dorian never arrived at the Jacksonville Port, remaining stationary over the Bahamas for more than 24 hours.

Agricultural advisors interviewed by the USDA Caribbean Climate Hub identified the damage to technology related infrastructure such as power outages (71%), communications (58%) and impassable roads (52%) as devastating to the agricultural sector, exacerbating the direct impact the hurricanes had on agriculture itself (Álvarez-Berríos et al., 2021).

Source: Ricardo Burgos

Table 4. Total agricultural product losses and losses to infrastructure related to 2017 hurricanes Irma and María. (Puerto Rico Department of Agriculture's Office of Agricultural Statistics, 2018).

CATEGORY	AGRICULTURAL PRODUCT LOSSES RELATED TO IRMA AND MARÍA	LOSSES TO INFRASTRUCTURE PER AGRICULTURAL SECTOR
POULTRY AND EGGS	$11,349,473.69	$34,984,001.52
CROPS	$159,099,607.58	$1,030,958,212.13
CATTLE	$16,441,708.51	$694,884,739.54
ORNAMENTALS	$40,715,363.01	-
ANIMAL PRODUCTS	$365,420.70	-
AQUACULTURE	-	$64,903,155.12
GRAND TOTAL	$227,971,573.49	$1,825,730,108.31

Freshwater Resource Management

KEY MESSAGE

Climate change continues to pose challenges for Puerto Rico's freshwater management and sustainable use of water resources and infrastructure.

As previous works detailed in Working Group 1 suggest, Puerto Rico will continue to experience multiple changes on precipitation patterns, temperature, extreme climate events and median sea level; all of which have direct impacts on its freshwater resources. As global changes continue to alter the hydrological cycle trends, Puerto Rico's water resources are expected to be affected in both quantity and quality, and thus are major concerns from an adaptation and resilience-building perspectives (AAA, 2014; DRNA, 2016[a]). The Integrated Water Use Plan has documented and identified several climate-change impacts to freshwater resources including projected reduction in mean precipitation; reduction in superficial freshwater availability; changes in riverine, estuarine and wetland biodiversity; saline intrusion to aquifers; changes in sedimentation loads to reservoirs, rivers and streams; changes in evapotranspiration; and changes in soil humidity (DRNA, 2016[b]).

Source: Wanda I. Crespo

Projected changes in precipitation patterns across Puerto Rico can generate considerable impacts to freshwater resources (Hayhoe, 2013; Van Beusekom et al., 2015; Khalyani et al., 2016). Despite uncertainties associated still embedded into latest downscaled climate models, drier conditions are expected for Puerto Rico and the Caribbean basin. These projections also denote regional and seasonal variability, pointing towards longer dry periods and increased precipitation reductions particularly along the south portion of Puerto Rico.

Reductions in mean precipitation along the southern coast have contributed to affected vulnerable groundwater resources, including aquifer systems that are currently under critical condition. While coastal freshwater resources, such as those of the South coast aquifers, are vulnerable to climate change impacts, intensive groundwater extractions continue to pose a greater threat to these freshwater resources than climatic factors alone (Ferguson & Gleeson, 2012; Unsal et al., 2014). Additional research is needed to better analyze climate change impacts on Puerto Rico's groundwater resources.

Tropical cyclones have brought significant challenges to freshwater resources in Puerto Rico, affecting water quality, natural and built infrastructure conditions, and compromising watershed integrity. Devastation caused by hurricanes Irma and María in 2017 resulted in an estimated 40,000 landslides Island-wide (Bessette-Kirton et al., 2019), severe damages and tree mortality for an estimated 23-31 million trees (Feng et al., 2018), prompting extraordinary sediment discharges to rivers, streams, reservoirs and coastal ecosystems (Miller et al., 2019). In the aftermath of these hurricanes, water quality was severely affected due to high turbidity, high bacteria count, and chlorinated volatile organic compounds (Brown et al., 2018), placing greater environmental and public health concerns.

Runoff along watersheds during hurricane María caused disastrous pluvial flooding, generating casualties, and causing severe infrastructure losses in Puerto Rico. Most notably, flood events along La Plata watershed caused significant damages and deaths on communities in Comerío and Toa Baja (RPRAC, 2018).

WATER RESOURCE MANAGEMENT VULNERABILITIES AND CHALLENGES

Overall, Puerto Rico's challenges for freshwater management and sustainable use of water resources and infrastructure are expected to worsen as consequence of climate change. Particularly for storing, distributing and maintaining the quality of freshwater for human and ecosystem uses, as identified by PRASA and DRNA climate change adaptation plans (AAA, 2014; DRNA, 2016[a]). Main challenges to freshwater resource management to consider include:

1. *Deficiencies in watershed conservation and, reservoir management* – Increased sedimentation rates have been documented along multiple reservoirs, (Soler-López, 2012; Soler-López, 2014; Soler-López, 2016; Gomez-Fragoso, 2016[a]; Gomez-Fragoso, 2016[b]), resulting in reduced storage capacity of these reservoirs, and thus reducing the useful life of these critical freshwater infrastructures for freshwater provision and hydroelectric energy generation. There are still uncertainties as to how sediment dynamics will change across watersheds given projected changes in precipitation patterns, yet current trends are already pressing challenges to secure water distribution for the future.

2. *Limitations for projected water needs for agriculture sector* – Increased agriculture production along the southwest and southeast regions of Puerto Rico could be affected as water demands might not be met with existing availability (DRNA, 2016[b]). The agricultural sector can see greater benefits from investments in innovative water management techniques and from irrigation systems that optimize the water from underground and superficial sources.

3. *Water conflicts over projected water use limitations across sectors* –Public Law 136-1976 asserts that all Puerto Rico waters are a public good, and as such, domestic human consumption prevails over other uses. The implementation of existing water policies can bring conflicts with energy and agriculture sectors on areas with current and projected water scarcity issues. Water demands for Puerto Rico are currently being met with present productions, attributed to the population decline –mostly due to outward migration- and continuous actions to reduce water losses by PRASA. Nonetheless, projected water demand across water users in 2030 will not be met across different regions of the Island, most notably across the southern region (DRNA, 2016[b]). A strong enforcement of existing public policies will be needed to address and assert potential conflicting uses, as climate change continues to alter Puerto Rico's freshwater resources.

Source: Wanda I. Crespo

Land Use Development and Planning

KEY MESSAGE

Land use development and planning processes are instrumental to promote greater greenhouse gases reductions, and to facilitate climate adaptation actions.

Puerto Rico is exposed to multiple natural hazards that should guide land use planning and developments. According to the most recent flood data derived from FEMA and the Puerto Rico Planning Board, it is estimated that 1,186 km² (13%) of the island is susceptible to coastal and riverine flooding (A, AE, AO and VE) (Government of Puerto Rico, 2020). Puerto Rico is also susceptible to landslides which range from nuisances to deadly events. A recent study identified that 30% of the island has a high, very high or extremely high susceptibility to landslides that are likely to initiate during or soon after intense rainfall (Hughes and Schulz, 2020). Exposure to these and other geologic hazards such as coastal erosion and liquefaction are increased with extreme weather events and sea level rise.

Figure 7. Percentage of area affected by 0.91 m in sea level rise per coastal municipality.

Coastal municipalities such as Loiza, Cataño, Ceiba, Carolina and Barceloneta have a substantial number of lands that would be permanently flooded by rising sea levels, and should be carefully planned (DRNA, 2019).

Planning processes aimed to utilize and protect limited land resources have presented solutions and actions for improved social and economic development, reduced vulnerabilities to major climatic hazards and protected critical natural resources. Land use development and planning processes are instrumental to promote greater GHG reductions, and to facilitate climate adaptation actions across the Globe (Smith et al., 2014; IPCC, 2019). Examples of these initiatives include the National Determined Contributions (NDCs) and climate change adaptation plans (UNFCCC, 2021). The 2015 Puerto Rico Land Use Plan showcased an initial planning response to climate change emphasizing the need to promote urban development that minimizes GHG emissions while fostering protection against climate related disasters. It also included guidelines for mitigation and adapting climate change.

In 2019, with the approval of the Puerto Rico Climate Change Mitigation, Adaptation and Resilience Act, Law No. 33 of 2019 a public policy on climate change mitigation, adaptation and resilience was established. Section 11 of this law, provides that the government entities and municipalities have to incorporate the following in their territorial plans: (1) climate policies, (2) steps to manage the varied effects of climate change, (3) strategies for mitigation, adaptation and resilience to these events with broad objectives and measures related to the minimum percentage of reduction in water consumption, the mitigation of greenhouse gases in all generating sectors and adaptation to the impacts of climate change on the natural systems, and socioeconomic sectors.

The Puerto Rico Municipal Code, Law Num. 107 of 2020 is another instrument that can be used as a climate change adaptation tool. Section 6.010 provides that municipalities, in the development of their land use plans (Territorial Plans), can identify areas that require to be carefully planned due to its exposure to natural hazards. Although the Municipal Code does not expressly mention climate change, municipalities interested in adaptation planning could coordinate with the PRPB the development of Area Plans for such purposes. Adaptation Action Areas are a useful approach that have been used in some US cities (DRNA, 2017).

However, adaptation actions through land use planning can also promote increased inequality and increased vulnerability within their territory if the recommended actions place greater burden on vulnerable communities, socially disadvantaged and politically underrepresented population groups. These adverse consequences of adaptation planning have been documented across several cities in both developing and developed countries (Bulkeley, et al., 2014; Anguelovski, et al., 2016). Strengthening stakeholder participation and greater inclusion in decision-making processes for land use planning are instrumental to limit these adverse impacts for adaptation planning efforts (Anguelovski, et al., 2016).

SECTION 02
Opportunities for Adaptation and Climate Action

KEY MESSAGE

The United States of America have enacted different views on climate policies since 2013..

Previous sections have presented an update on the impacts of climate change on Puerto Rico's social and economic attributes, from cultural and historic heritage to critical infrastructure. This last section highlights several opportunities to enhance resilience and promote adaptation actions in Puerto Rico, summarizing some of the most relevant messages brought by the authors and collaborators of the Puerto Rico Climate Change Council.

CLIMATE POLICY AND GOVERNANCE

There have been considerable advancements on climate change policies since 2013, both in Puerto Rico and at the international arena. The Paris Agreement was an important milestone to advance stronger and more resolute global actions towards limiting a global temperature increase of over 1.5˚C (2.7˚F). The commitments presented by world nations will require more ambitious actions to curb GHG emissions to achieve this critical target. In Puerto Rico, most prominent achievements in climate policy and governance are in Law 33-2019. The effectiveness of funding, enforcing, and monitoring the progress implementing international, US federal and national policies will help determine the increased severity of changes on climatic stressors that vulnerable regions will experience over coming decades. The allocation of $68.5 billion of US federal disaster funds for recovery efforts to Puerto Rico presents an important opportunity to better prepare the island nation adapt and thrive in the face of the climate crisis.

SOCIAL AND ECONOMIC CONTEXT

Puerto Rico confronts several challenges due to its high vulnerability. Its fiscal situation, economic contraction, and socioeconomic constraints require a cross-cutting policy with strategies to address the situations and underlying causes of vulnerability. On the positive side, many communities are working to strengthen their adaptive capacity and resilience to climate change. However, communities need government support to be resilient. In that sense, there is an extraordinary opportunity through reconstruction processes to address some of the challenges and improve the socioeconomic condition and livelihoods of Puerto Rico residents. The resilience and adaptation of Puerto Rico's society also requires sustainable land use policies in place and robust fiscal and economic development strategies.

CRITICAL INFRASTRUCTURE AT RISK

The exposure of critical infrastructure located near coastal zones to sea level rise can increase Puerto Rico's vulnerability to ongoing and future climatic changes. Investments to 'climate proof' critical infrastructure aligned with proper planning, enforced by responsible permitting, would benefit from further risk and vulnerability assessments that consider additional stressors beyond sea-level rise; to guide reconstruction and ensure it can meet 21st century demands and challenges for the Archipelago. The use of international standards for assessing risk, including ISO 31000 and ISO 14080 and others, can prove an important tool to analyze current and future impacts of climate change on critical infrastructure. Particularly for infrastructure within the energy, transportation, health, water, waste management, financial services, chemical manufacture, communications, commercial facilities, and emergency services sectors.

Opportunities arise towards greater community integration for the management and operation of infrastructure and the provision of key services, including energy, water, and waste management. The examples of community aqueducts (Non-PRASA) and the emergence of rural electric cooperatives should be further evaluated to showcase their capacity to overcome the challenges posed by climate change on Puerto Rico. The need for sound data to support risk assessments and evaluate conditions of critical infrastructure continues to be a major opportunity to strengthen local and national resiliency.

INSURANCE AND REINSURANCE

Hazard mitigation and adaptation strategies can not only make people and communities more resilient, but also may reduce the amount and value of losses. A reduction in financial losses helps keep insurance premiums low for everyone and reduces risk for insurance companies.

The rising cost of flood and home insurance can also help limit future development in hazardous areas like floodplains. Potential buyers may look elsewhere outside of flood-prone areas if costs of construction or insurance are too high due to natural hazard risk in the area. For those that already live on areas threatened by floods or other hazards, participating in the Community Rating System (CRS) of the National Flood Insurance Program (NFIP) can reduce the cost of flood insurance premiums and promote more resilient building design and construction. The CRS offers insurance discounts to communities who implement regulations that exceed the minimum requirements of the NFIP. Currently, Ponce is the only municipality in Puerto Rico that participates in the CRS. For many communities, this option may be a good start to incorporating climate change into building codes and design and to reducing personal and financial damages from future floods and storms.

TOURISM AND RECREATION

The tourism industry of Puerto Rico can be affected by multiple climate related threats: warmer summers, increase in extreme weather events, water scarcity, marine biodiversity loss, coastal erosion, and increase in disease outbreaks, amongst others. Several approaches are presented to spur adaptation actions on the tourism sector, based on guidelines developed by United Nations and other relevant intergovernmental agencies. According to the World Travel and Tourism Council, "the travel and tourism sector must continue building an all-hazards approach to resilience, to navigate through and operate" within this global and local risk landscape (WTTC, 2019). Opportunities arise to strengthen and implement the existing climate change adaptation plan of the Puerto Rico Tourism Company (PRTC) to advance the resilience of this important economic sector. The goals included in the PRTC Plan to increase the adaptation capacity, includes (PRCT, 2016):

- *Awareness of the tourism sector stakeholders about adaptation to climate change.*
- *Implement and create programs that promote resilience of the tourism sector to climate change.*
- *Establish strategic alliances to address the challenges of climate change to tourism sector.*
- *Determine the degree of vulnerability of the tourism sector based on its particularities.*
- *Develop metrics and technical material to promote adaptation to Climate Change in the tourism sector.*
- *Promote transportation and urban systems that are energy efficient and low carbon.*
- *Financing Mechanisms.*

Also, PRTC recommends a review of their Climate Change Adaptation Plan to update vulnerabilities, socioeconomic information and implement strategies to promote the resilience of tourism sector in the face of climatic events such as hurricanes and the challenges posed by change climate (PRCT, 2021).

CULTURAL HERITAGE

As the section on historic and cultural sites presented, climate change impacts pose a threat to material cultural heritage across Puerto Rico. Opportunities for action to protect our cultural and historic heritage from the impacts of climate change are primarily focused on two main areas: public engagement and improved management practices. On the public engagement component, citizen science and public archaeology are viewed as options to integrate more people into documenting and preserving important historical sites. Additional studies and more detailed climate change vulnerability assessments are recommended to facilitate improved management practices, along with public participation. Methodologies used by the National Parks Service and the SCAPE trust can serve as models to move forward actions for protecting our cultural and historic sites from climate change impacts. See WG3 Appendix for more examples of adaptative strategies in cultural heritage.

Source: Wanda I. Crespo

AGRICULTURE AND FOOD PRODUCTION

Food production and agricultural practices in Puerto Rico continue to denote serious vulnerabilities that threaten their production and sustainability. Considering the Island's high dependence on food imports, other global climatic and non-climatic drivers are still dominant forces pressing on the vulnerability of this sector. However, changes in precipitation patterns and extreme events are projected to continue exerting pressures to food production, soil health and water availability for irrigation across the island. The challenges posed by climate change to agricultural production, particularly to food supply, would benefit from greater attention and coordinated response of federal and Puerto Rico government agencies, private industry, and academia. Recommended adaptation actions for improving resilience in agriculture range from the use of locally adapted, pest resistant and drought tolerant crops and diversification strategies to improved water & soil conservation management and improvements to socio-ecological diversification of crops and their uses to offset agricultural losses.

FRESHWATER RESOURCE MANAGEMENT

On water resource management, there are three main recommendations to enhance their resilient capacity, building on existing adaptation efforts. First, government agencies should move towards implementation and evaluation of recommended adaptation action, as presented in their climate adaptation plans and the Integrated Water Management Plans. The southern region of Puerto Rico can be greatly benefited from more immediate actions to restore aquifers and improve water infrastructure. Second, sound evaluation and monitoring systems should be implemented, to measure and understand how existing actions are providing desired results and outcomes. Third, updated climate adaptation plans for water resource and infrastructure management should be based in a comprehensive quantitative analysis that include a risk-based approach that monetizes benefits and impacts, as well as the cost of inaction. Additional opportunities to expand resilient approaches on water sector exist in assessing existing stormwater and flood control infrastructure capabilities under climate change.

LAND USE DEVELOPMENT AND PLANNING

One of the main opportunities for land use planning activities to support adaptation actions and enhance the resilient capacity in Puerto Rico is mainstreaming climate change into land use planning and into disaster recovery and mitigation planning processes. Following the experiences of cities and local governments worldwide, municipalities have the potential to identify the main vulnerabilities of climate change stressors on their territories as part of their revision to existing Land Use Plans; as well as to assess the main critical infrastructure, sensitive ecosystems, vulnerable population groups cultural and historic heritage sites and industrial sectors under threat from climate stressors. In this aspect, land use planning can continue to serve as a tool to spatially represent and organize the future development of our communities and economy. Thus, incorporating the new challenges to prepare our present and future inhabitants towards becoming more resilient societies.

Climate change is one of the most serious threats our present generation currently faces, as it directly and indirectly affects every aspect of our society and livelihoods. This paramount challenge has forced nations and communities re-evaluate their existing conditions and identify opportunities to move forward in our global pursuit of progress and well-being. As such, global voices are pushing towards strengthening our social, economic, and ecological resilient capacity in the face of current and projected climatic changes. Particularly on the most vulnerable countries and communities where adaptation actions can make a difference on the continuity of their livelihoods and ways of life. As Puerto Rico continues to navigate through its recovery and reconstruction from the aftermath of hurricanes Irma and María, land use planning activities - and overall disaster recovery and mitigation planning - need to take a more prominent and urgent role to secure a resilient future.

Source: Wanda I. Crespo

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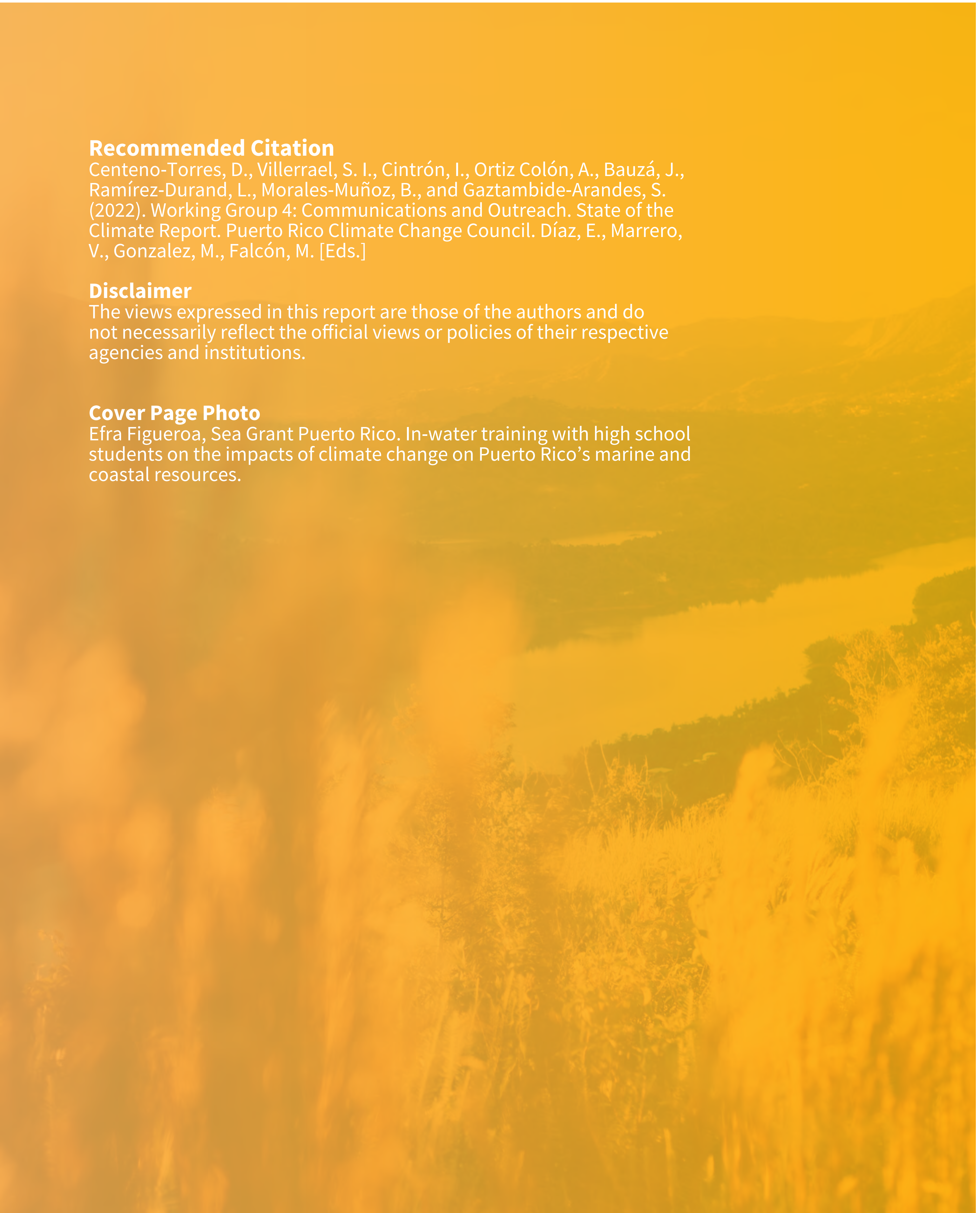
WORKING GROUP 4

Communications and Outreach

04



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Cover Page Photo
Efra Figueroa, Sea Grant Puerto Rico. In-water training with high school students on the impacts of climate change on Puerto Rico's marine and coastal resources.

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Case studies in Puerto Rico

SAN JUAN BAY ESTUARY PROGRAM CLIMATE CHANGE ADAPTATION PLAN: A PARTICIPATORY PROCESS TO COMMUNICATE AND A CALL TO ACTION
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THE CENTER FOR THE EDUCATION ON ENVIRONMENTAL CLIMATE CHANGE (CENECCA), PUERTO RICO SEA GRANT CASE STUDY: CLIMATE AWARENESS AND EDUCATION THROUGH FIELD EXPERIENCE FOR MIDDLE AND HIGH SCHOOL STUDENTS
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EXECUTIVE SUMMARY
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FRAMEWORK FOR EFFECTIVELY COMMUNICATING
CLIMATE CHANGE: COMMUNICATION FOR DEVELOPMENT COMMON BARRIERS AND OPPORTUNITIES

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EXECUTIVE SUMMARY

Climate change communications are key to develop sound adaptation and mitigation strategies. The messages used must take into account the audience to increase citizen's interest and participation in planning, decision-making, and implementing proactive climate change actions. The Working Group 4: Communications and Outreach chapter highlights the importance of keeping citizens informed about the science of climate change and its environmental, social, and economic implications. Throughout this chapter, the use of the communication for development (C4D) approach is proposed, which allows multi-directional communication and empowers individuals and communities to take sustainable and solution-based actions.

As explained by the United Nations Organization: "Communication for Development is a social process that promotes dialogue between communities and decision makers at local, national and regional levels. Its goal is to promote, develop and implement policies and programs that enhance the quality of life for all." When developing effective communications, it is important to take into account the common barriers for communicating climate change, including depending solely on traditional mass media, not translating scientific data into accessible information, omitting examples of local risks, and not considering the framing or context of the audience.

In Puerto Rico, there are several conditions that can be leveraged as opportunities for communicating climate change. These opportunities include the increased concern about environmental issues, the existing network of community organizations and groups, the increase in access to social media and alternate ways of consuming content, and a media industry that needs inexpensively produced content as well as new ways of engaging local audiences.

This chapter also presents several case studies that demonstrate effective communication approaches to educating and involving citizens in actions to mitigate or adapt to climate change. Further, it provides a series of recommendations for a community-based, participatory approach, including: 1) learning, listening and integrating community diversity; 2) recognizing that communities possess relevant knowledge about their reality; 3) not assuming that audiences will interpret numerical information and figures as experts do; 4) defining terms clearly; 5) identifying clear samples when presenting data; 6) using vivid images to engage emotional processing; 7) using specific and concrete examples of future outcomes; and 8) explaining how actions to mitigate global warming will lead to the avoidance of large losses.

RESUMEN EJECUTIVO

Las comunicaciones sobre el cambio climático son fundamentales para el desarrollo de estrategias de adaptación y mitigación. Los mensajes utilizados deben considerar la audiencia para aumentar el interés y la participación ciudadana en la planificación, la toma de decisiones y la implementación de acciones proactivas ante el cambio climático. El capítulo del Grupo de Trabajo 4: Comunicación y Divulgación destaca la importancia de mantener a la ciudadanía informada sobre el cambio climático y sus implicaciones ambientales, sociales y económicas. A través del capítulo, se propone el enfoque de la comunicación para el desarrollo (C4D, por sus siglas en inglés), el cual permite una comunicación multidireccional y empodera a las personas y a las comunidades para llevar a cabo acciones sostenibles y orientadas a soluciones.

Según la Organización de las Naciones Unidas "La comunicación para el desarrollo es un proceso social que promueve el diálogo entre las comunidades y las entidades responsables de la toma de decisiones a nivel local, nacional y regional. Su objetivo es promover, desarrollar e implementar políticas y programas que mejoren la calidad de vida de todos y todas". Al desarrollar comunicaciones efectivas, es importante considerar las barreras relacionadas a las comunicaciones del cambio climático, incluyendo el depender únicamente de los medios de comunicación tradicionales, no traducir los datos científicos en información accesible, omitir ejemplos de riesgos locales, y no considerar el contexto de la audiencia.

En Puerto Rico existen distintas condiciones que presentan oportunidades para comunicar los asuntos relacionados al cambio climático. Estas oportunidades incluyen el aumento de la preocupación por los problemas ambientales, la red existente de organizaciones y grupos comunitarios, el aumento en el acceso de las redes sociales y otras alternativas de consumir contenido, y una industria de medios de comunicación que necesita contenidos producidos de forma económica, así como nuevas maneras de atraer al público local.

El capítulo también presenta varios estudios de caso que demuestran enfoques de comunicación efectivos para educar e involucrar a la ciudadanía en acciones para mitigar o adaptarse al cambio climático. Además, ofrece una serie de recomendaciones con un enfoque participativo, orientado en la comunidad. Entre las recomendaciones se incluye: 1) aprender, escuchar e integrar la diversidad comunitaria; 2) reconocer que las comunidades tienen conocimiento importante sobre su realidad; 3) no suponer que el público interpretará las cifras y figuras como lo hacen los expertos; 4) definir los términos con claridad; 5) identificar ejemplos claros al presentar los datos; 6) utilizar imágenes vívidas para capturar el procesamiento emocional; 7) utilizar ejemplos específicos y concretos de los escenarios futuros; y 8) explicar cómo las acciones para mitigar el calentamiento global llevarán a evitar pérdidas significativas.

INTRODUCTION

This is the first time the **State of Climate Report for Puerto Rico** includes a section about communicating climate change in Puerto Rico. This chapter highlights the importance of keeping citizens informed about the science of climate change and its environmental, social, and economic implications —like coastal erosion, rising sea levels, disruptive heat and rain patterns, among others. Most importantly, though acknowledging the relevance of mass media, the communications team behind this chapter recognizes the role of citizens' intervention in planning processes, so that effective adaptation and mitigation strategies are built from a collaborative and locally based perspective that fosters sustainable planning practices.

There is no official climate change communications policy for Puerto Rico, although different government agencies and municipalities have made some efforts, particularly the Department of Natural and Environmental Resources. Thus, for this chapter we asked several organizations to share their communications tactics regarding climate and environmental issues, as to identify best practices and how to integrate them into a concerted, participatory communications strategy about climate change.

Some of the cases presented here are more closely related to climate change than others, since the organizations' missions are diverse. Nevertheless, we consider these initiatives very valuable, as they have kept the communication lines open regarding climate and environmental issues and have been able to engage citizens in conversations and activities around environmental topics. We consider them a stepping stone to the robust, coordinated and locally based communications policy that should be developed in the near future.

We thank the organizations for sharing their strategies and knowledge, and look forward to further systemic collaboration towards engaging more informed and proactive citizens as we face together the challenges generated by climate change.

SECTION 01

Framework for Effectively Communicating Climate Change: Communication for Development

Communication for development (C4D) allows multi-directional communication and empowers individuals and communities to take sustainable and solution-based actions.

Climate change communications are key to address and develop sound adaptation and mitigation strategies, and have become an increasingly important topic among both scientists and society. The UN General Secretary Ban Ki Moon described climate change as the "moral challenge of our generation" (The Guardian, 2007). Well-informed decisions move society towards healthy democracy and prosperity. Efficient science communications, by distilling all the complex and technical information to key points that are understandable to several audiences, can help strengthen and advance science-based solutions by working as an aid to policy-makers and other stakeholders. Existing theories often lack a clear connection with how people learn (Morey et al., 2000).

Learning is an active process (Vyhotsky, 1978). Learners build knowledge by engaging with the world and others around them as they struggle to explain and connect new ideas and prior understanding. Enriching, building on and changing existing mental models or prior knowledge is key for all future learning (Alexander, 1996). Deeper understanding emerges from situated and complex environment occurring learning (Greeno, 2006; Bransford et al., 2006). Learning complex ideas deeply involves considerable mental effort that can only be sustained by motivation and cognitive engagement through multi-faceted, concrete and malleable strategies (Fredricks et al., 2004).

Social learning is the collective action and reflection that takes place amongst both individuals and groups when they work to improve the management of the interrelationships between social and ecological systems. This type of learning has been widely deemed an effective approach to tackle climate change. This tactic is rooted in the fact that learning occurs through situated and collective engagement with others (Collins & Ison, 2009).

Social marketing is adapting marketing tactics and strategies to generate changes in individual attitudes and behaviors that impact society. It has been applied for decades to public policy issues, like promoting the use of a seatbelt when driving, reducing teenagers' initiation as smokers and deterring teen pregnancies. As a spin-off of traditional advertising and marketing, social marketing lacks the systemic and participatory perspective that is key to widespread, long-term social change. It is based on the same principles that propose unidirectional messaging geared at enticing, convincing or frightening an individual into doing (or not doing) something.

On the other hand, there are a wide range of participatory approaches to communications, which were once seen as an alternate way of communicating with specific audiences, but now are used as sustainable ways to develop social projects. These approaches have been strengthened with the rise and expansion of social media to more than just entertainment. Social media have helped in rebalancing the voices of society´s sectors, downplaying the usual voices of institutional powers and giving people and communities a different role in the dynamics that rule public communications processes.

When selecting a communicational approach to climate change, it should be taken into account that climate change has a multi-systemic origin and is a very complex issue. Thus, social marketing strategies and traditional mass media advertising fall short in the process of communicating what is climate change and generating appropriate responses.

The communication for development (C4D) approach appears more adequate and current, as it allows for a multidirectional flow of communication, validates and leverages the audience's knowledge on the topic, and its ultimate goal is to empower individuals and communities into taking sustainable actions that will either solve the problem at hand or generate new options for the social system.

Research and experience suggested that fear-based arguments had run their course as effective tools for inspiring action (CRED, 2009). A movement toward solution-based communication eases participants into talking about climate change. This does not mean that advertising or social marketing tactics are obsolete. In fact, some are very useful and can be more effective with a participative twist, as participation promotes engagement - a fundamental for behavioral change. There is no one-size-fits-all approach to enable behavioral change and learning because the process needs to take into consideration all the dynamics of individual communities. It all boils down to targeting strategies to specific audience. Active public engagement is a communication form that draws from a wide array of disciplines including anthropology, psychology, economics, history, environmental science, policy and climate science. Over the last decade or so this strategy has morphed into combining science with narrative storytelling. Key elements include the showcase of vivid visual imagery, the use of appropriate language (avoiding jargon), metaphors, analogies, and trusted messengers (CRED, 2009).

AS EXPLAINED BY THE UNITED NATIONS ORGANIZATION:

"COMMUNICATION FOR DEVELOPMENT IS A SOCIAL PROCESS THAT PROMOTES DIALOGUE BETWEEN COMMUNITIES AND DECISION MAKERS AT LOCAL, NATIONAL AND REGIONAL LEVELS. ITS GOAL IS TO PROMOTE, DEVELOP AND IMPLEMENT POLICIES AND PROGRAMS THAT ENHANCE THE QUALITY OF LIFE FOR ALL."

"IT PRIORITIZES COMMUNICATION SYSTEMS AND PROCESSES THAT ENABLE PEOPLE TO DELIBERATE AND SPEAK OUT ON ISSUES IMPORTANT TO THEIR OWN WELL-BEING"

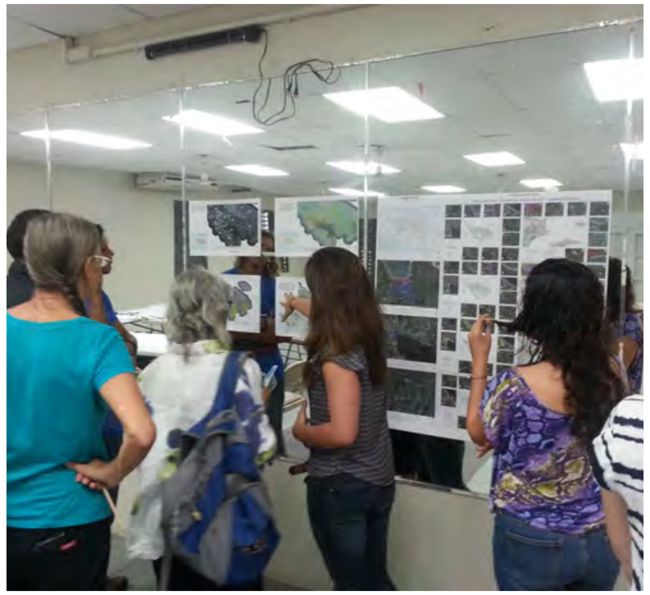
"ITS ROLE IN EMPOWERMENT PROCESSES HELPS DISTINGUISH COMMUNICATION FOR DEVELOPMENT FROM OTHER FORMS OF COMMUNICATION, FOR EXAMPLE, CORPORATE AND INTERNAL COMMUNICATIONS, AND MAKES IT AN ESSENTIAL PART OF PROGRAMS AIMED AT ACHIEVING THE MILLENNIUM DEVELOPMENT GOALS (MDGS) AND OTHER DEVELOPMENT PRIORITIES IN AN EQUITABLE AND SUSTAINABLE MANNER" (MC CALL, 2011).

For Schmitz, "community" refers to intended beneficiaries and their families, friends, neighbors and the leaders of small community-based or faith-based groups who work most closely with them in the place they live. Without them and without considering their knowledge, skills and experiences, even the best data or evidence will be incomplete and ineffective.

Community outreach programs can use traditional communications tools (like advertising, documentaries, posters and others) to generate group discussions and other locally based activities, which in turn can foster community engagement.

"COMMUNITY ENGAGEMENT IS ABOUT ENSURING THAT THOSE MOST IMPACTED BY SOCIAL CHALLENGES HAVE A SAY IN DESIGNING AND IMPLEMENTING SOLUTIONS. THE PARTICIPATION OF INTENDED BENEFICIARIES AND THEIR FAMILIES, NEIGHBORS, AND TRUSTED LEADERS CAN BE AN INTEGRAL PART OF DATA-DRIVEN PROCESSES TO ACHIEVE BETTER RESULTS. AND A SHIFT IN POWER WHERE COMMUNITY MEMBERS OWN AND HELP PRODUCE THE RESULT WILL LEAD TO GREATER IMPACT"

(Schimtz, 2017).



SECTION 02

Common Barriers to Communicating Climate Change

KEY MESSAGE

Frequently, barriers for communicating climate change include depending solely on traditional mass media, making an emphasis on scientific data, local risk perceptions and framing.

Traditional mass media

Traditional mass media communication can become a barrier as it is based on the vertical dynamics of institutional powers (Figure 1). When talking about climate change, the phrase 'institutional power' refers to government, academia and scientific sources that do not always know, or ask for, a community´s experience and knowledge about the topic.

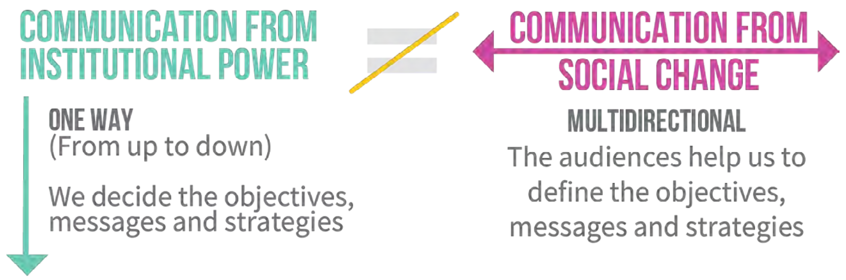


Figure 1: Conceptual frame of communication from institutional power versus development and social change.

Since it works from a standpoint of authority, mass communication emits unidirectional messages. In addition, as it needs to reach vast masses, it tries to homogenize audiences and sends generic or impersonal messages using the most basic and common language and other cultural references. Because people and communities are not homogeneous, these messages reach their audiences at different levels depending on interest and contexts (Figure 2). Some of these practices are frequently changing because of the segmentation opportunities provided by social media, cable TV and the Internet.

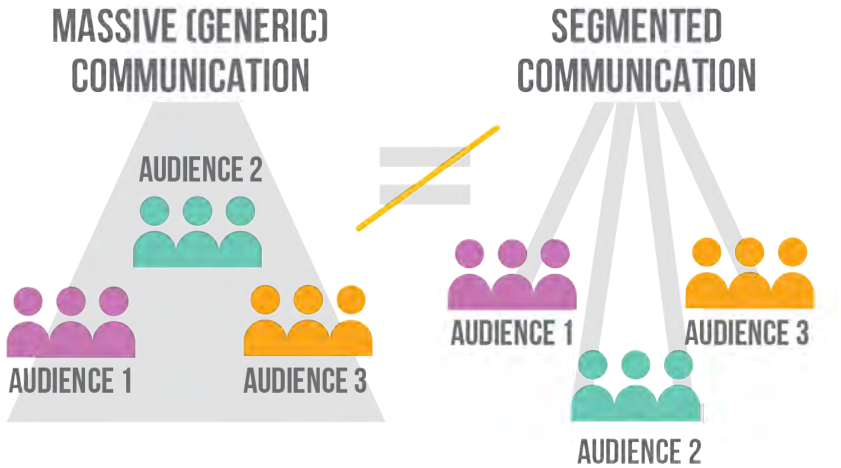


Figure 2: Conceptual frame from a massive (generic) communication vs. segmented communication.

On the other hand, communication for development and social change acknowledges audience differentiation by demographic and psychographic characteristics. It recognizes the breadth of interests and realities for diverse audiences and creates relevant messages for each one, using channels that those audiences prefer or have access to.

In addition, communication for development leverages multidirectional communication opportunities by including opinion leaders and community representatives in the process of choosing the messages and the media, and sharing content with the intended audiences. Mass media messages are not kept out of the equation, but are used to support locally based tactics in a broader way.

EMPHASIS OF SCIENTIFIC DATA

As for the "**data barrier**," even though climate change facts are crucial to educate citizens, an emphasis on scientific evidence can turn into an obstacle if facts are not translated into relatable information. Perception of scientific agreement greatly influence people's support for mitigation and action. This is important in communicating both to the general public and to decision makers. A profile of uncertainties surrounding scientific results can be communicated to provide a better understanding on where the disagreement or gaps of knowledge are within the science. An example of this is the confidence terminology adapted by the IPCC (Figure 3).

All science research has uncertainty. In order to provide a robust message of change in trends, it is important to incorporate various model predictions that can give a better picture of the direction of change rather than specific seasonal shifts or magnitude of events. Another important challenge in climate data is the level of detail. While climate scientists are more focused in systematic changes globally, regionally and locally, the audience is more interested in how the projected climatic changes will impact specific systems on the ground. Hence, the importance to establish a specific outline of information required for a group of stakeholders. This needs to be done by building understanding of how their specific field will be affected by the projections and providing a framework on how the data available can be incorporated into planning and procedure (Leal Filho, 2012).

LOCAL RISK PERCEPTION

Motivating local adaptation strategies must be addressed as a priority and with adequate institutional support. Climate change is a global problem, but risk is a local issue. To develop a constructive response, the messaging should be built on local, immediate and concrete risks. For example, stories about the melting of icebergs and the disappearance of polar bears as consequences of climate change will not appeal to tropical island residents like Puerto Ricans, neither to the neighbors of Caño Martín Peña, unless the message links those stories to their experiences with rising sea levels and flooding. Providing communities with the chance to discuss a recent flooding and what might have caused it could result in better understanding of the issue than presenting neighbors with a chart about rising water levels. The same can be said for climate change mitigation strategies. Providing examples of local concrete activities can promote a more effective approach. In fact, 68.4% of Puerto Ricans surveyed in 2018, indicated that the main barrier or limitation for carrying out activities or actions to address the impacts of climate change is the lack of specific information on available measures or actions (Estudios Técnicos, 2018).

Local risk perception is an important driver of response. The same fact will lead to a different shape of risk for each person. Emotions and social processes determine the response to risk. Effective climate communications strategies recognize the importance of attention and better understanding of how communities, with their subdivisions, understand and respond to risk (Harvey et al., 2012). When working at a grassroots level, communicating, translating, and disseminating climate change to diverse communities requires an analysis of their background experiences, their attitudes toward related topics and how their culture prepares them to deal with menacing issues. In **The Psychology of Global Warming, Improving the Fit between the Science and the Message,** Ben R. Newell and Andrew J. Pitman (2010) states:

"How humans interpret evidence, how they react to evidence, and how they form views based on evidence is not related merely to the quality of the evidence. Psychologists, especially those with an interest in judgment and decision-making, explore precisely these issues and can therefore provide insights into the impediments confronting the communicators of climate science. The role that psychology can and should play in the climate change debate was heralded almost 30 years ago (Fischhoff, 1981) and since then there has been an increasing amount of research at the intersection of psychology and climate science, especially in the last decade (e.g., Budescu et al. 2009; Fischhoff 2007; Fischhoff and Furby 1983; Hardisty and Weber 2009; Leiserowitz 2006; Moser and Dilling 2004; Nicholls 1999; Ster- man 2008; Stern 1992; Weber 2006)."

Additionally, local knowledge provides the base to explain relationships between particular climatic events and livelihood activities. It also gives some insight in the strengths and pitfalls of past dialogue attempts. Climate change communicators should consider, for example, how Puerto Ricans deal with natural disasters, how they learn to prepare for hurricane seasons, and how the culture manages concepts like urban planning and natural resource protection.

Schmitz offers a valuable tool to define audiences (Table 1).

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes: Early 21st century	Likelihood of further changes: Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely*	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely* (nights only)	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia {2.6} *Medium confidence* in many (but not all) regions *Likely*	***Likely*** {10.6} Not formally assessed *More likely than not*	Not formally assessed {11.3}	*Very likely* {12.4} *Very likely* *Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	*Likely* more land areas with increases than decreases {2.6} *Likely* more land areas with increases than decreases *Likely* over most land areas	***Medium confidence*** {7.6, 10.6} *Medium confidence* *More likely than not*	*Likely* over many land areas {11.3}	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions {12.4} *Likely* over many areas *Very likely* over most land areas
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely* changes in some regions {2.6} *Medium confidence* in some regions *Likely* in many regions, since 1970	***Low confidence*** {10.6} *Medium confidence* *More likely than not*	*Low confidence* {11.3}	***Likely*** (*medium confidence*) on a regional to global scale {12.4} *Medium confidence* in some regions *Likely*
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes *Virtually certain* in North Atlantic since 1970 {2.6} *Low confidence* *Likely* in some regions, since 1970	***Low confidence*** {10.6} *Low confidence* *More likely than not*	*Low confidence* {11.3}	***More likely than not*** in the Western North Pacific and North Atlantic {14.6} *More likely than not* in some basins *Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) {3.7} *Likely* (late 20th century) *Likely*	***Likely*** {3.7} *Likely* *More likely than not*	*Likely* {13.7}	***Very likely*** {13.7} *Very likely* *Likely*

Figure 3: Extreme weather and climate events: Global scale assessment of recent observed changes, human contribution to the change, and projected further changes for the early (2016- 2035) and late (2081-2100) 21st century (IPCC, 2013).

Table 1: Guidelines to define audiences

GUIDELINES	PRIORITY AUDIENCE 1	PRIORITY AUDIENCE 2
DESCRIBE THE AUDIENCE *(geographic location, age, gender, educational level, race, cultural background, etc.)*		
WHAT IS THEIR CONCERN REGARDING THE ISSUE?		
WHAT DO YOU WANT THEM TO DO?		
HOW HAVE YOU ENGAGED THIS GROUP BEFORE?		
WHAT IS THE BEST WAY TO APPROACH AND ENGAGE THEM?		
WHAT BARRIERS MIGHT EXIST BETWEEN YOU AND THIS AUDIENCE?		

Source: Adapted from Community Engagement Toolkit, Paul Schmitz (2017).

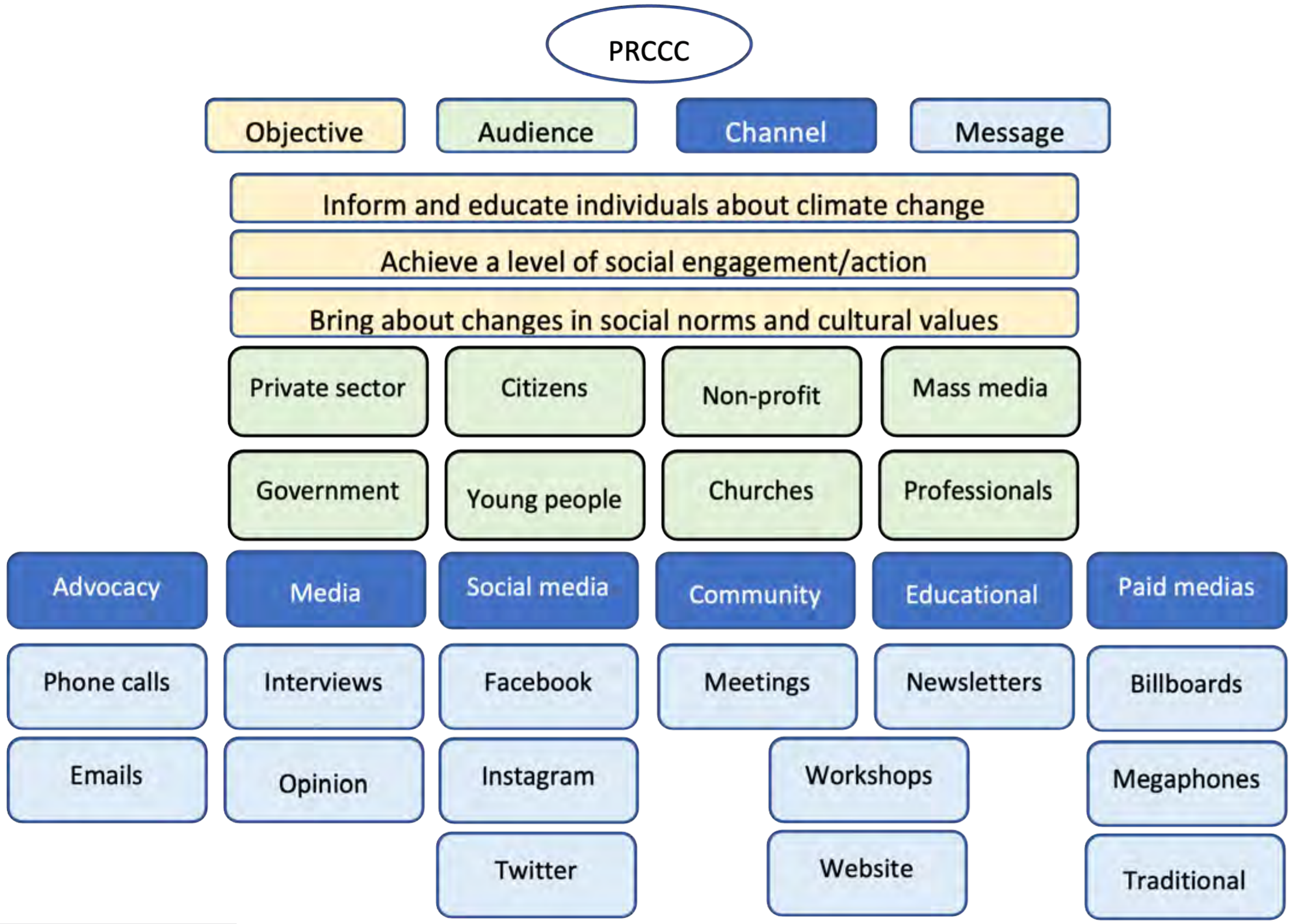


Figure 4: The basic elements of communications (Harvey et al., 2012).

In addition to analyzing the audiences, the process requires a look into what media or communications processes they prefer, who are the opinion leaders, and what messages are relevant to them. Figure 4 shows the relationship between these components of the communications process.

FRAMING

Framing is setting a relevant context for the desired communication aim. The way we talk about climate change affects the way people think about it. Cultural, political or religion affiliation, occupation, sexuality, past experiences, and even intuitive perception shape people's interpretation of new information. These are called mental models and are crucial when framing the issue of climate change. Mental models serve as filter, as people tend to pick up only the information that matches their mental model. This poses a great challenge for climate change communicators. People constantly use mental models to decide whether to welcome or reject an idea. For example, when talking about risk people will refer to past experiences and decide if the risk is threatening or manageable.

Mental models are not static, but in order to update them the information must be tailored to address misconception and insert new blocks in a non-threatening way. Thus, communicating climate change should be done using narrative with characters they can identify with in order to build an emotional involvement with the issue. Moreover, trustworthiness is essential to engage your audience. This is a combination of perceived warmth and competence. Regularly scientists are very cautious to share data numbers; however, people may also be interested in knowing why they, as scientists, find the issue fascinating. There has to be a conscious effort in building trust and establishing resonance with the target audience. It is important to be sensitive to concern of power dynamics. Ignoring the specifics of climate change impact on each community, and invalidating how neighbors experience such impact are additional barriers we impose on ourselves when we use the unidirectional approach.

We present a portfolio of five different frames that can help build the communications strategy to resonate with people:

1. *Local vs Far* – keep the message close to home so that people perceive the threat to themselves and their families. Communicators can highlight the current impacts of climate change on the regions using local instead of national examples. This can be done using extreme weather events as "teachable moments". Since they are dramatic and easily understood, it will help connect individual experiences to potential impacts of climate change. An additional consideration for this issue is that when "discussing extreme events…communicators should bear in mind that while it is correct to say that climate change is increasing the odds of an extreme weather event, climate scientists cannot yet make the claim that climate change is causing such events. This important distinction often gets lost or is misunderstood, causing confusion and undue skepticism". For example, we can link the severity of Hurricane Maria to observed increased ocean temperatures, however, since it is difficult to attribute how much of the warming is due to human activity, it is incorrect to state that climate change caused the hurricane. However, it did provide a powerful example of how disrupting, costly and dangerous extreme weather events can be. Sometimes it is encouraged to disentangle facts from people's identities and talking about a specific issue (i.e., fishing, faith, flooding, farming, etc.) brings the issue home and serves as an entry to discuss climate change. This gives the person an opportunity to understand the relevance of scientific data to themselves instead of opposing their mental models.

2. *Future vs Now* – Time frame is important when communicating how climate change is occurring and its impacts. In general, immediate threats appear more urgent than future threats. Nonetheless, social psychologists Matthew Baldwin and Joris Lammers found that dismissive conservatives shifted their beliefs to be more pro-environmental after they were exposed to past-focused passages and visuals. Their liberal counterparts felt more inclined towards the forward-looking message, but this didn't affect their attitudes.

3. *Prevention vs Promotion* – Goals are always a useful tool to craft a message. Are they pro-solution or against an impact? People with a prevention focus are concerned with maintaining a status quo and are motivated by minimizing losses. On the other hand, people with a focus on promotion are concerned with maximizing gains and the advancement of an ideal. Columbia's CRED Guide states that, "Research shows that tailoring messages to people's natural promotion and prevention orientations increases the level of response for both groups, regardless of whether their response was positive or negative." These findings support the concept of framing messages from multiple perspectives to accomplish environmental goals. For example, if a local city wants people to increase their recycling, city officials should explain options in various ways, some with a promotion focus and some with a prevention focus. A promotion message would emphasize "going the extra mile" (e.g., going out of one's way to recycle, how recycling benefits the community). A prevention message would encourage "dotting the i's and crossing the t's" (e.g., being careful to recycle, how not recycling hurts the community)."

4. *Gains vs loss* – People tend to avoid losses more than to seek gains. Commonly, this frame is combined with the now vs future to motivate tackling future risks. If a person perceives that climate inaction would result in greater loss, they may be more likely to adopt environmentally responsible behavior and support costly mitigation efforts. Communicators can frame actions to show savings in the present as well as in the future, such as with electricity bill savings when switching to energy efficient appliances. In this strategy the message has to include both current and future potential losses. Changes in behavior can be achieve when the idea of "losing less now instead of losing more in the future" is presented (CRED, 2009).

5. *Interconnection frame* – Climate change is not only an environmental problem, its intersectionality makes it an incredibly relevant consideration in poverty, food security, inequalities, education, human health, water access, development, gender equality, peace and sustainability. The conversation should be centered in the co-benefits for community well-being and the economy in order to gain support and understand the positive impacts of climate action in other socio-economic issues.

SECTION 03

Opportunities for Communicating Climate Change

An increased concern about environmental issues, existing network of community groups, social media, and a revenue-challenged media industry provide opportunities that can be leveraged for communicating climate change in Puerto Rico.

Currently there are several conditions in Puerto Rico that can be leveraged as opportunities for communicating climate change, for example:

1. A SLOWLY INCREASING CONCERN ABOUT ENVIRONMENTAL ISSUES – *still budding, but promising.*

2. THE EXISTING NETWORK OF COMMUNITY ORGANIZATIONS AND GROUPS, EACH WITH THEIR OWN INFORMAL COMMUNICATION AND DECISION-MAKING CULTURE.

3. AN INCREMENT IN ACCESS TO SOCIAL MEDIA AND ALTERNATE WAYS OF CONSUMING CONTENT *(both entertainment and educational).*

4. A REVENUE-CHALLENGED MEDIA INDUSTRY THAT NEEDS INEXPENSIVELY PRODUCED CONTENT AS WELL AS NEW WAYS OF ENGAGING LOCAL AUDIENCES.

Regarding **opportunities #1 and #2**, it must be said that there are many environment-related efforts in Puerto Rico, mostly coordinated by non-profit organizations in communities highly exposed (sometimes unbeknownst to them) to the impact of climate change. Some of these efforts are funded by the Puerto Rico Coastal Zone Management Program (PRCZMP) of the Department of Natural and Environmental Resources.

The general perception of Puerto Ricans was put to the test in a perception poll commissioned by the PRCZMP. The majority of the respondents (82.6%) indicated that they know what climate change is, however 59.3% indicated that they had a low to medium level of understanding of climate change (Estudios Técnicos, 2018). For 80.4% of the respondents, climate change is very or considerably important and 91.6% expressed interest in getting more information associated with climate change. This poll sheds some light on the openness of Puerto Ricans to receive information; audiences that can be considered for climate change communication; and the preferred media to receive this information, television and social media (Estudios Técnicos, 2018). Furthermore, a local study on community risk and planning showed that environmental conservation organizations perceived community engagement and education as necessary for a more resilient and livable city in the face of extreme weather events (Santiago, Flores & Hong, 2018).

In addition, current environmental crises (like localized flash flooding, droughts or coastal erosion) are calling citizens' attention towards what phenomena might be causing these environmental changes and what can be done about them. For example, given the recent Hurricanes Irma and María, 62% of Puerto Ricans identified hurricanes and tropical storms as events with great potential of impacting the Island. This new awareness creates an opportunity for educating about climate change. Such interest in the manifestations of climate change and its impact on one's community does not necessarily translate into an interest in scientific details. Wonderful communications opportunities are sometimes wasted by focusing the conversation on scientific data instead of the community's need and the actual measures at their disposal.

Source: Dr. Pablo Méndez Lázaro

The Center for Research on Environmental Decisions, part of the Earth Institute at Columbia University, provides a useful guide for engaging communities in conversations about climate change, based on eight principles[1]

1. KNOW YOUR AUDIENCE: KNOW THEIR CONCERNS AND THEIR MENTAL FRAMES.
2. GET YOUR AUDIENCE'S ATTENTION: ALWAYS PROVIDE A LOCAL FRAME.
3. TRANSLATE SCIENTIFIC DATA INTO CONCRETE EXPERIENCE: TIE SCIENTIFIC EVIDENCE TO FACTS AND INCIDENTS RESIDENTS HAVE ALREADY PERCEIVED AND EXPERIENCED. THEY KNOW MORE THAN YOU THINK, EVEN IF THEY DO NOT USE THE SCIENTIFIC JARGON.
4. BEWARE THE OVERUSE OF EMOTIONAL APPEALS: AVOID GENERATING ALARM WITHOUT PROVIDING OPTIONS OF ACTIONS THAT CAN BE TAKEN BY COMMUNITIES WITH LIMITED RESOURCES.
5. ADDRESS SCIENTIFIC AND CLIMATE UNCERTAINTIES BY PROVIDING PROBABLE PROJECTIONS, CONTEXT AND EXAMPLES.
6. TAP INTO SOCIAL IDENTITIES AND AFFILIATIONS TO GENERATE ALLIANCES.
7. ENCOURAGE GROUP PARTICIPATION FOR GENERATING ACTION PLANS.
8. MAKE BEHAVIOR CHANGE EASIER BY SUGGESTING MEASURES ACCESSIBLE TO YOUR AUDIENCE.

Opportunity #3, the increment in access to social media and alternate ways of consuming content, comes with caveats. It is true that Internet penetration in Puerto Rico has increased significantly in recent years, as well as the use of smartphones. Also, social media platforms are great for sharing entertaining and educational low-cost content regarding almost any topic. However, social media have their nuances, as audience demographics and psychographics vary from Facebook to Instagram, for example. Again, messages need to be tailored to users. On the other hand, communities and groups have their own ways of adapting the use of social media and the Internet according to their knowledge, their socioeconomic level (considering the cost of data plans), and their own informal communication practices and culture. Along these lines, it is also important to note that Internet access varies across the Island. According to the Puerto Rico Statistics Institute (2020), the metropolitan region, the east and south are home to the majority of municipalities with the highest percentage (50-74) of households with broadband Internet access. On the other hand, in some municipalities of the western region (Lajas, Cabo Rojo, Maricao, and Las Marías) less than 35% of the homes have Internet access. Although the report references data at the municipal level, it should be pointed out that it may vary throughout communities within municipalities.

Opportunity #4, a media industry that needs content as well as new ways of engaging local audiences, also represents a challenge. Reduced production budgets might open the door to community-provided content like stories about climate change impact, but it also means less locally produced programming able to air such content. It should be noted that content aimed for mass media use must follow production criteria and values that are not always affordable for government agencies, environmental organizations or community groups. These are not insurmountable obstacles, only challenges that should be taken into consideration when approaching mass media for climate change communications efforts in order to take advantage of whatever opportunities rise for using mass media.

Multiple opportunities apply in the case of disasters, where it is key to communicate and translate preparation, warning, response, and post-response messages to at-risk communities and the public. San Juan, Puerto Rico's early warning system is classified as hierarchical, where scientists send a unified message to decisionmakers across sectors who are trained in disaster preparedness and response (Bui, 2018). This information is then translated to the public, however gaps for communication to local, at-risk communities, such as language barriers; audience's ability to translate scientific information into actions for preparation; and availability of preparedness training during non-disaster periods may limit the effectiveness of this system. Addressing these gaps can improve response and resilience of these communities.

After hurricane Maria in 2017, mortality reports from news and social media contributed to negative public perceptions, as the mortality undercount caused the public to criticize the government for mishandling mortality reporting and lack of transparency (Andrade et al., 2020). The collapse of critical infrastructure, lack of a written communications plan for multiple failures in critical infrastructure, information gaps, and inconsistencies and lack of clarity about death tolls all contributed to a discrepancy in reports of mortality caused by Hurricane Maria. Recommendations from Andrade et al. (2020) to improve communications include determining catastrophic crisis and emergency risk communication (CERC) guidelines to address messaging and response in an evolving environment, and emphasizing communication personnel training in mortality surveillance processes and morality communications to the public.

1 http://guide.cred.columbia.edu/guide/principles.html

SECTION 04
Case Studies

The cases presented in this chapter show various effective approaches to educating and involving citizens in actions to mitigate or adapt to climate change. As described below, the San Juan Bay Estuary Program, the Center for the Education on Environmental Climate Change and Para La Naturaleza use creative initiatives to engage young students with the natural resources around them and teach about the impacts of climate change. The fourth case presents the work done to generate a community-based communications plan for Loíza.

CASE STUDY 1

The San Juan Bay Estuary Program Climate Change Adaptation Plan:
A Participatory Process to Communicate and a Call to Action

BY DR. JORGE BAUZÁ, SCIENTIFIC DIRECTOR

The San Juan Bay Estuary (SJBE) is an estuarine system located in the north coastal plain of Puerto Rico and it is composed of water bodies interconnected by channels and canals. The water bodies of the SJBE includes San Juan Bay, the Condado Lagoon, the San José Lagoon and Los Corozos, the Torrecilla Lagoon, and the Piñones Lagoon, plus the channels that interconnect these bodies of water, such as the San Antonio Channel, the Suárez Canal, and the Martín Peña Channel. The SJBE system is also defined by small, isolated creeks and canals as well as upland areas that drain into the estuary waters described above. The watershed or drainage basin is relatively small (< 97 square miles (251 km²). It extends above a broad, flat coastal plain and consists of 83 square miles (215 km² of land) and 14 square miles (36 km²) of water. Mudflats, marshes, mangroves, submerged aquatic vegetation, coral communities, rocky shorelines, and sandy beaches are some of the types of habitats found within the SJBE system, supporting very rich and diverse biological communities (Figure 5).

Figure 5: Map of the San Juan Bay Estuary. The orange line is the delimitation of the watershed while the blue lines are water bodies (rivers, streams, canals and lagoons).

All of these ecosystems are susceptible to the effects of climate change, which include extreme climatological events, coastal erosion (Figure 6), coastal flooding (Figure 7) and ocean acidification, some of which are already causing evident changes in its systems. These impacts compromise and may endanger the goals of the SJBE Program (Estuario) to enhance, restore and conserve the SJBE through the implementation of 68 specific actions and strategies presented in the Comprehensive Conservation and Management Plan (CCMP). We briefly discuss one of several projects regarding climate change that the Estuario leads encompassing public engagement and participation initiatives.

Figure 6. Coastal erosion in the San Juan Bay Estuary.

The SJBEP developed a climate-change adaptation plan to implement specific actions to reduce the vulnerability of the estuary system to climate change risks, as well as to communicate climate change topics to the public. The first step was to launch a communications and consultation campaign with the objective to engage and identify citizens, groups, agencies and other interested parties in the development of the climate change adaptation plan. Citizens, groups, and agencies interested in the subject were invited to take part through email and the SJBEP Internet platforms. Not all invitees participated, but some of the participants preferred to take an active part during the entire process, while others just wanted to be kept informed. The first lesson learned was that not all people are interested in climate change because not everyone views it as an immediate risk when compared with other social, economic and domestic problems. From this audience of people with interest in climate change, SJBEP had approximately 50% participation.

Figure 7. Coastal flooding in Ocean Park.

The SJBEP then followed the steps set out in the workbook **Being Prepared for Climate Change: A Workbook for Developing Risk-Based Adaptation Plans** (hereafter, the Workbook), which is part of a pilot project designed by the Climate Ready Estuaries program (hereafter the CRE), under the U.S. Environmental Protection Agency's National Estuaries Program (NEP). The Workbook is a tool intended to help organizations such as the SJBEP identify climate change risks, carry out vulnerability studies, and develop and communicate a plan for adapting to the impacts caused by climate change. The CRE promotes participatory and interactive processes to bring together the members of a community. The final product of the CRE was the publication of a 2013 report titled "San Juan Bay Estuary Climate Adaptation Plan" (the Report, hereafter).

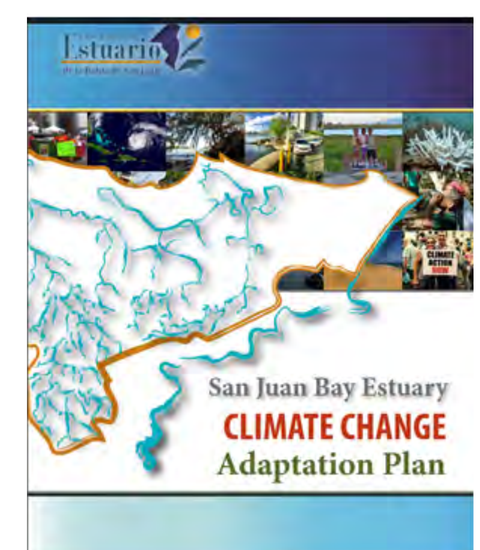


Figure 8. The cover of a 2013 report created by the San Juan Bay Estuary for Climate Change Adaptation.

In order to communicate effectively, the report was organized in four short chapters. The first chapter includes general background information about the Estuary, its waterbodies, and associated ecosystems and biological communities. The objective of this chapter was to put the topic of climate change in the context of the Estuary. The second chapter comments on climate changes in the Estuary, and stresses the tendencies foreseen for the Caribbean and Puerto Rico. This chapter discusses climate change vulnerability in an easy-to-understand language, so a person with minimal scientific background can easily understand it. The third chapter explains, step by step, how the Workbook was used to develop the SJBEP adaptation plan, which is discussed in the fourth chapter of the report. The report was published both in print and as an eBook (Figure 8). To be useful as a communication tool, this report was designed with simple graphics (Figure 9) and illustrated with full color images.

The Climate Change Adaptation Plan is used as the main communication tool to discuss climate change issues. It must be kept in mind that climate changes cannot be precisely predicted or foreseen, and that responses will not be linear. Thus, new information will emerge day by day, which will be taken into consideration in carrying out, updating, and amending this adaptation plan.

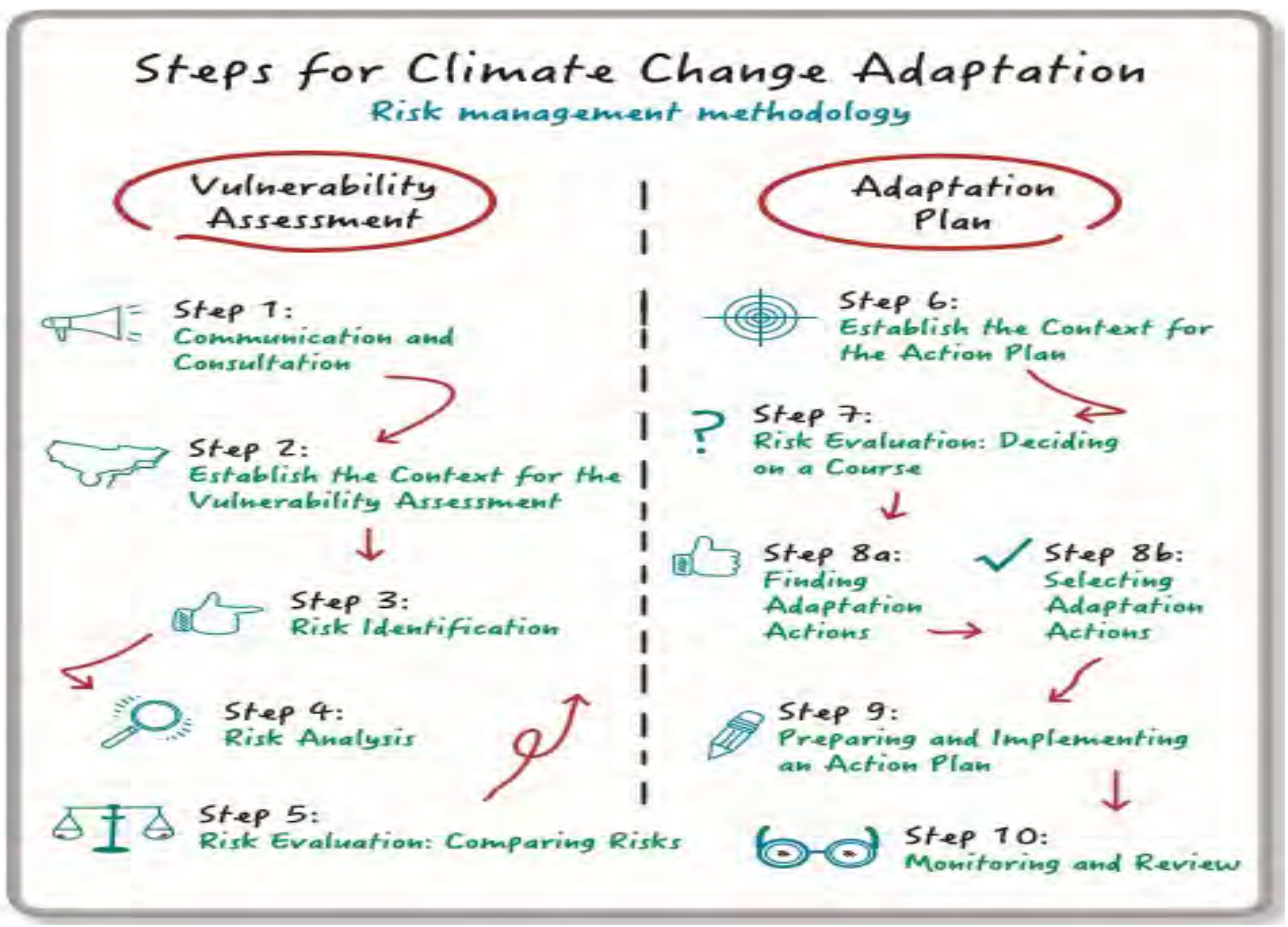


Figure 9. The step-by-step method used to develop the climate change adaptation plan.

CASE STUDY 2

The Center for the Education on Environmental Climate Change (CenECCA), Puerto Rico Sea Grant Case Study:

Climate awareness and education through field experience for middle and high school students

BY LILLIAN RAMÍREZ-DURAND AND BERLIZ MORALES-MUÑOZ, SEA GRANT

In 2014, Puerto Rico Sea Grant College Program (PRSGCP) signed a Memorandum of Understating with the Autonomous Municipality of Cabo Rojo to establish the Center for the Education on Environmental Climate Change (CenECCA, for its acronym in Spanish), located in historic Los Morrillos Lighthouse. The main goal of this project is to act as an Island-wide program that serves the need for scientific information aimed at the development of actions, programs, activities and adaptation policies related to climate change. This includes information related to natural hazards and sea level rise, among others, in order to minimize potentially adverse social and environmental impacts. CenECCA will disseminate the science of climate measurement and adaptation that can be used to develop tools of climate-relevant decision-making by focusing on increasing the availability, accessibility and utility of relevant scientific tools and data to respond to both long-term climate change impacts and short-term effects of extreme weather. CenECCA will serve as Puerto Rico's hub for climate change information, and will disseminate information to researchers, academia, the general public, and state and federal government agencies.

This Center is currently providing formal educational activities that include field trips for middle and high school students and teachers (Figure 10). During each activity, the facilities in the Los Morrillos Lighthouse are transformed into a hands-on scientific laboratory where students have the opportunity to experiment on and create awareness about ocean acidification, water quality, meteorology, coastal processes, fisheries, marine organisms and ocean and coastal ecosystems. Scientific instrumentation is provided on each station so students and teachers alike gather a deeper understanding of implementation and functionality of scientific instrumentation.

Figure 10. A field trip with students and teachers led by the Center for the Education on Environmental Climate Change.

Figure 11. Educational activities with students held by the Center for the Education on Environmental Climate Change and Puerto Rico Sea Grant College Program.

As part of their field trip, participants learn methodologies related to climate and conservation of marine and coastal resources.

The activities have been an enriching experience for students, teachers and the staff involved. Student and teacher evaluations for these activities received satisfaction scores averaging 75% or higher. Teachers can include the field trip to complement their curriculum of science classes. These education efforts are continued by giving talks at the schools with PRSGCP educators and extension specialists.

CenECCA and PRSGCP are engaged in providing formal and informal education to students, teachers, the public and private sector, and residents of coastal communities to further the conservation of Puerto Rico's coastal and marine resources (Figure 11). These educational activities create awareness of the impacts of climate change, to develop resilience and implement best available adaptation strategies. For additional information visit the following website: ***https://seagrantpr.org/outreach-program/center-for-the-education-on-environmental-climate-change/***

CASE STUDY 3

Puerto Rico Shines Naturally: Advocacy and Communications Strategies to Reduce Light Pollution

BY SOLEDAD GAZTAMBIDE ARANDES, PREVIOUSLY POLICY AND GOVERNMENT RELATIONS COORDINATOR, PARA LA NATURALEZA

According to the International Dark-Sky Association (2017), light pollution refers to any adverse effect of artificial light. Whereas "The Shining Star of the Caribbean" was a popular Puerto Rico tourism marketing slogan, the publication of the first global maps showing artificial nightlight cover (Cinzano et al., 2001) highlighted a different reading of this motto. Puerto Rico is indeed the "Shining Star of the Caribbean" but for the wrong reason: light pollution. A spatial analysis investigating the increase in light pollution from 1992 to 2000 showed that it was one of the most rapidly increasing threats to Puerto Rico's natural environment (Ramos, 2003).

Puerto Rico's addiction to light does much more than deprive us of admiring the night sky: it harms our wildlife and ecosystems, is a threat to human health, and is a waste of energy that contributes to climate change.[2] For over a decade, Para la Naturaleza has led an award-winning initiative to educate the public on controlling light emissions and protect the Cabezas de San Juan Nature Reserve's (CSJNR) bioluminescent lagoon and its habitats. Looking back at the program's impact shows that efforts have paid off: Sky Quality Meter (SQM) measurements of the night sky's magnitude of brightness per square arcsecond show a reduction in light pollution approaching 60% around the Nature Reserve: 19 sqm in 2006 vs 20 sqm in 2014 (the larger the number, the darker the sky). Readings for urban areas range between 16 and 21, with 22 being indicative of a truly dark site).

In 2005, the Conservation Trust of Puerto Rico, and later its unit Para la Naturaleza, embarked on an advocacy and education initiative named "Puerto Rico Shines Naturally" (Puerto Rico Brilla Naturalmente, in Spanish) [3] . As an organization established for the protection and management of Puerto Rico's natural areas and seeking to integrate society into the conservation of our ecosystems, the organization tackled this problem in and around protected areas. The CSJNR was chosen because light pollution imperils the recuperation efforts for the area's endangered sea turtles and the reserve protects one of three permanent bioluminescent lagoons (Laguna Grande) on the island.

Bioluminescent bays are fragile ecosystems containing microorganisms called dinoflagellates, which produce faint flashes of light with the slightest movement of the water that surrounds them. Light pollution is having an impact on the appreciation and enjoyment of visitors seeking to experience this magnificent natural phenomenon.

Furthermore, there are several sea turtle nesting areas in the reserve and its vicinity. Light pollution along coastlines severely reduces possible nesting sites as female sea turtles prefer dark beaches. In addition, sea turtle hatchlings crawl instinctively toward the relative safety of the ocean, attracted by the reflection of the moon and stars. Light pollution confuses the hatchlings and causes them to crawl towards roads or into communities where they are run over or become fatally exhausted or dehydrated.

A combination of planning, policies and programmatic strategies was required to effectively reduce the impact of this environmental problem. In 2006, the Light Pollution Advisory Committee (CACL, for its acronym in Spanish) was created. Scientists, architects, government officials, representatives of academic institutions and non-profit organizations joined this committee and formed a management task force to set out strategies for implementing the necessary measures to reduce light pollution in Puerto Rico.

LAWS AND REGULATIONS

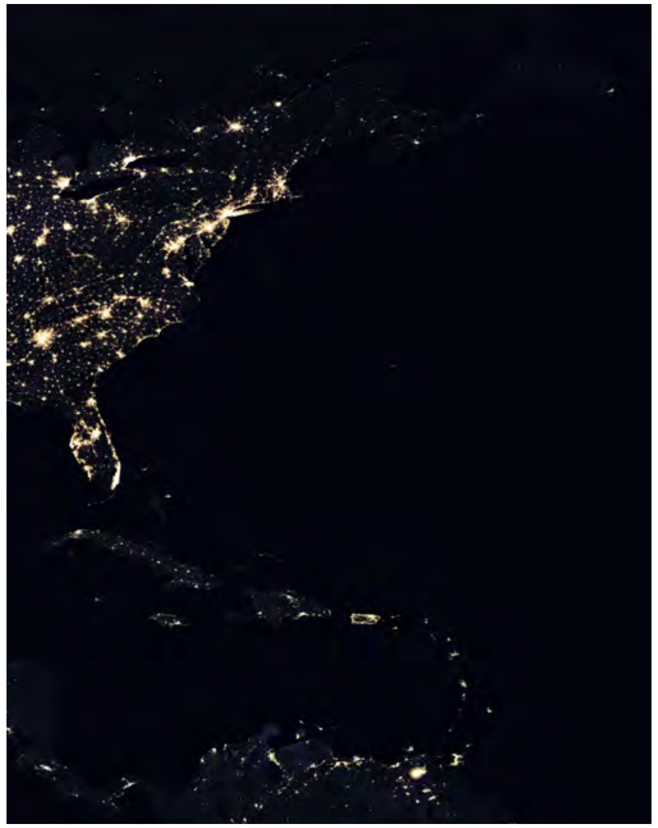
The advocacy and public policy component of this initiative involved the development of legislation to provide governmental parameters to organize human actions and behaviors related to light pollution. Our organization, with the support of the CACL, led the effort to pass Law 218 of 2008, known as the Light Pollution Control and Prevention Program.

The legislation tasked the Environmental Quality Board (EQB) [4] with developing regulations and instructed the Office of Permit Management (OGPe, for its acronym in Spanish) to incorporate rules and instructions into the Construction Code to prevent light pollution in new construction projects or

[2] (http://www.darkskyparks.org/light-pollution/problems#1).

[3] First Puerto Rico Brilla Naturalmente webpage - https://www.paralanaturaleza.org/prbrilla/

[4] Now ascribed to the DNER.



Source: NASA's Black Marble (2016).

in alterations for which a permit is required. The CACL played a crucial role in ensuring the implementation of the Light Pollution Control and Prevention Program and worked in unison with the EQB during the development and approval of the Regulations, which were completed in 2014 and revised in 2016.

In accordance to the law, the regulations set rules to prevent excessive and unnecessary light emissions and to keep artificial light intrusion away from properties and natural areas where it is unwanted. It includes outdoor classifications and designation of special areas, as well as requirements for outdoor light emitting sources, prohibitions, requirements for installation and operation of lighting systems advertisements (billboards), exclusions, transition period for both the public and private sectors, compliance plans and waivers (Microjuris, 2014).

PILOT STUDY

Together with the CACL, we initiated a pilot study to manage light pollution around the CSJNR and its surrounding neighborhood of Las Croabas. This pilot project site was purposely selected, as it surrounds one of the most visited bioluminescent bays of Puerto Rico. Permanent bioluminescent lagoons and bays exist in a very limited number of locations throughout the world, drawing thousands of tourists each year.

The project worked with the main sources of light pollution to modify lighting types so that instead of illuminating towards the sky in a dispersed way, it is efficiently directed downwards. As part of this effort, immediate neighbors were educated about the effect of light pollution in the area and this guided necessary changes in the residential areas, in addition to achieving changes in the lighting systems of other private entities and Governmental organizations. The first phase of the pilot project was a census to evaluate and replace light fixtures to reduce glare and unnecessary energy costs in surrounding communities. Fixtures were analyzed to determine if they were adequately located, if they were incorrectly illuminating the area and what type of replacement light fixture could be recommended to avoid the resulting light pollution.

The census identified over 427 light fixtures that needed to be replaced. Seven years later, with the support of neighbors and members of the CACL, 50% of the lighting system has been changed. The simple actions of education and outreach resulted in a quantifiable and noticeable reduction in light pollution.

OUTREACH AND AWARENESS

The second component or phase of the initiative was a public outreach and awareness campaign. The CACL worked together on the various light pollution topics (ecology, astronomy, human health and energy consumption) to create educational tools and strategies for the public. The specific strategies developed and actions taken were:

- *Development of educational materials such as brochures, posters, videos and presentations.*
- *Newspaper and magazine articles which included interviews and editorials.*
- *Lectures, presentations and workshops to community-based and local organizations.*
- *Collaboration with federal and state government agencies, tourism industry and private developers to reduce light pollution in their facilities or within their jurisdiction. Examples include:*
  - *Change light fixtures in the Seven Seas public beach in collaboration with the National Parks Program.*
  - *Replacement of street lighting in Las Croabas community in collaboration with the Electric Power Authority.*
  - *Coordination with the US Coast Guard to block the historic Fajardo Lighthouse on its landward side to reduce light pollution over the bioluminescent bay.*
  - *Change light bulbs in all north-facing rooms at El Conquistador Resort .*
  - *Incorporation of outdoor and balcony lighting fixture restrictions within the by-laws of a new housing development close the CSJNR (Ocean Club).*
- *Modified the most popular tour of CSJ to incorporate light pollution prevention as an interpretative objective and created new night tours focused entirely on light pollution. Since the program's launch, over 20,000 participants have attended the Bioluminescence and Light Pollution night tour and there have been over 230,000 participants in other related educational programming.*
- *Since 2014, organized annual light pollution forums in collaboration with EQB and the Department of Natural and Environmental Resources (DNER).*

LESSONS LEARNED

The main and most successful feature of the *Puerto Rico Shines Naturally* initiative was the participation of a multisector advisory committee, or task force. A demonstration project in a single geographic location enabled staff and volunteers to focus light pollution management efforts and engage local communities and stakeholders to be part of the transformative process. Para la Naturaleza was able to leverage funding to jumpstart the campaign and hire consultants to help manage the pilot project at Las Croabas. The education and outreach initiative must be carefully planned according to institutional needs as intense time and effort from Para la Naturaleza staff was required to reach out to residential and business owners.

As in all education initiatives, careful planning must go into the financing and marketing for them to be successful. In this case, citizens tended to be interested because some of the negative impacts of light pollution are related to topics they tend to value, such as endangered sea turtles, bioluminescent bays and reducing energy costs. Many citizens are not aware of these and other impacts of light pollution. Through this initiative, Para la Naturaleza learned that informed citizens take action. Outreach and education focused on summarizing the problem and offering concrete solutions. The initiative also had a 'trickle-down effect' as other community-based organizations began using the educational materials and information to do outreach and promote change in their own communities.

Para la Naturaleza is currently in the process of applying for a Dark Skies Certificate from the International Dark Skies Association. ***Visit http://www.paralanaturaleza.org/puerto-rico-brilla-naturalmente to learn more, see videos, and download educational brochures.***

FAST FACTS FOR REDUCING LIGHT POLLUTION:

TURN OFF THE LIGHTS.

USE MOTION DETECTION SENSORS TO CONTROL OUTDOOR LIGHTS.

USE AMBER OR YELLOW ENERGY-EFFICIENT BULBS THAT DON'T EXCEED 3,000 KELVIN (K).

ELIMINATE SOURCES OF LIGHT ALONG THE COASTLINE.

DIRECT LIGHT DOWNWARDS.

AVOID ILLUMINATING BUILDINGS OR TREES.

CASE STUDY 4
Sociedad Ambiente Marino
Community-based Coral aquaculture and reef rehabilitation
BY ISATIS CINTRÓN

Sociedad Ambiente Marino (SAM), or Marine Environment Society in English, has a long history of successful coral restoration along Puerto Rico's shoreline. Puerto Rico relies greatly on the coastline for goods and services, such as reef fisheries, tourism-related activities, which contribute 7.1% to island's GDP, and shoreline protection (Costa, 2016). Coral reefs can reduce wave energy by up to 97 percent and wave height by 86 percent (Ferrario et al., 2014). They also represent capital stock for future economic and political security of the archipelago, yet coral reefs are continually threatened by extreme climate events.

Changes in temperature and rainfall will likely increase coral heat stress leading to coral bleaching. Climate projections indicate that Caribbean temperatures will rise, as discussed by the Working Group 1. Given that actual sea temperature levels are close to the upper thermal limit for corals, it is predicted that bleaching is becoming an annual event for the Caribbean (Hoegh-Guldberg, 1999). Coral bleaching occurs because of the loss of endodermal symbiotic zooxanthellae living in coral tissue, usually due to elevated temperatures (Coles & Brown, 2003; Jokiel, 2004; Gates et al., 1992; Glynn, 1996; Glynn & D'Croz, 1990). Caribbean-wide 'mass' coral bleaching events, such as the ones observed in in 1982, 1995, 1998, 2002, 2005, 2010 and 2015, have caused loss of coral cover in Puerto Rico.

Focused on low-tech and low cost methodology, SAM has developed a series of restoration projects throughout the archipelago that include direct community participation. This way, the organization can promote the reintroduction of threatened coral species on reefs in Culebra, Vega Baja and Manatí. This project is co-implemented with the group Vegabajeños Impulsando Desarrollo Ambiental Sustentables (VIDAS) and the University of Puerto Rico's Center for Applied Tropical Ecology and Conservation (CATEC).

This project has spanned over 20 years and has been dedicated to the restoration of populations of coral species *Acropora cervicornis* and *Acropora palmata*. SAM has also spent over 15 years in growing and maintaining coral colonies in coral nurseries (Figure 12). This organization is dedicated to providing community outreach and has partnered with a variety of other organizations with the objective of reaching schools and other settings regarding topics of marine life, sustainability and climate change.

Figure 12. A coral structure with species Acropora cervicornis created and maintained by organization Sociedad Ambiente Marino. Photo: Grace Matos.

Figure 13. Community inclusion and engagement in coral reef restoration projects.

Outreach strategies used by SAM include hands-on activities, conferences, talks and informal education in various settings, including community-based meetings. Throughout these collaborations, communities recognize not only the ecological paybacks from these projects, but also the socioeconomic and cultural benefits to the local community. Community integration heightens community awareness and is also integral for behavioral change regarding mitigation of recreational impacts on coral reefs and marine wildlife. Overall, community-based projects broaden the sense of stewardship and help to build community capacity to address threats to coral reefs and at the watershed level.

LESSONS LEARNED:
Community inclusion and engagement in project planning and implementation were found to be critical to project success, especially in strengthening:

- *Buy-in from stakeholders in technical training and education in coral farming and reef conservation and restoration methods*
- *Capacity of rapid response during coral reef emergencies requiring restoration (e.g., following hurricanes or tropical storms)*
- *Communities' application of the guidelines developed for the management of adjacent shallow coral reef ecosystems, which provide an important defense system against storm swells and sea level rise.*

A further conclusion from the project was that in order to improve ecosystem conditions, restoration efforts need to take place alongside wider management efforts that address land use patterns, water quality issues and fishing activities.

CASE STUDY 5

Loíza

Community-based Communications Pilot

BY: SANDRA I. VILLERRAEL AND DAYANI CENTENO

Figure 14. Community meeting to discuss climate change. Loiza Climate Action.

In 2017, the PRCZMP commissioned the design of a communications strategy aimed at informing and educating the public about climate change. The plan was assigned to Voz Activa (a not-for-profit agency), using a communication-for-development approach.

PRCZMP and Voz Activa developed a pilot plan for the municipality of Loíza (about 25 km east from San Juan), leveraging existing community groups and other Program initiatives already in place there. The idea was to design a strategy to engage residents in the creation of communications tactics that could later be adapted to other communities.

Through a series of meetings, surveys and focus group sessions, participants were able to share their impressions on how climate change manifests itself in their neighborhoods, and how they perceive actions taken by government for mitigation or prevention purposes. Meetings and surveys also explored residents' preferred media for getting news as well as staying in touch with neighbors and community organizations (Figure 14).

These efforts revealed that participants are already aware of climate change issues, their causes and the consequences for their neighborhoods. They expressed feeling undermined by what they described as "the government not taking them into consideration when making decisions for mitigation plans," since they want to be part of the solution.

Some of the participants expressed frustration because authorities do not enforce protections against human activities that accelerate the effects of climate change. From their perspective, the government undervalues their issues and properties. Nevertheless, they acknowledged some progress in this matter due to the intervention of a non-profit organization commissioned by the PRCZMP to create a participative community-based action plan.

As for their media preferences, it should be noted that many low-income residents in Loíza (89% are under $50,000 annual income per household mark) do not have access to the Internet nor manage digital platforms (https://censo.estadisticas.pr/EncuestaComunidad). Also, nine out of ten are not fluent in English. This is relevant to a communications plan, as PRCCC is

FEBRERO 2017 VOL. 1 AÑO 1 EL CAMBIO CLIMÁTICO ES ASUNTO DE TODOS

#Loíza Acción Clima

LO PRÓXIMO: CITA CON LA ALCALDESA
17 DE MARZO: EXPONDREMOS LA URGENCIA DE QUE NOS PREPAREMOS PARA ENFRENTAR EL IMPACTO DEL CAMBIO CLIMÁTICO EN NUESTRO PUEBLO.

Juntos somos la fuerza

Somos residentes de Loíza organizados para prepararnos y educar sobre las amenazas que enfrentamos como pueblo costero ante el cambio climático. Contamos con recursos científicos y otros profesionales para documentar el impacto que tienen sobre nuestras vidas, propiedades y sobre nuestra economía las distintas manifestaciones del cambio climático. Y nos preparamos para convertir este riesgo en una oportunidad de unirnos para construir soluciones. Nos organizamos en grupos de trabajo como educación, cabildeo y comunicación.

Figure 15. Loiza Climate Action newsletter.

Figure 16. Printed T-shirts containing the logo for Loiza Climate Action.

active in several digital platforms like Twitter and a Facebook, and relies on a website written in English for sharing information with the general public.

Within this exercise in participative communications planning, participants generated: a) a logo as a visual identity for their work group, which was printed on t-shirts the participants wear when they gather data or share information with the community (Figure 15); b) a print newsletter with basic information about climate change and about the group's efforts (Figure 16); c) two short videos of neighbors sharing stories about the impact of climate change in Loíza.

As a pilot, the project's reach is limited yet successful in demonstrating that community engagement is possible and favorable to communicating climate change at a local level. Participants were excited to tell their neighbors, local authorities and other residents about their work as a group dealing with climate-related issues in Loíza. They were willing to share community stories, and were able to pinpoint crucial issues to be addressed with area residents and tourists –like dune protection.

Voz Activa strongly recommended that these stories and engaging experiences are adapted and replicated with other communities throughout the Island as a PRCCC unified effort to raise climate change awareness at local level. Principles discussed at the beginning of this chapter, including listening to your audience and facilitating participation in decision making indeed resulted in participation and engagement – even in a limited and short-timed pilot.

SECTION 05

Recommendations

From the standpoint of communication for development and social change, learning about, listening and integrating community diversity is a fundamental step when educating about the local impact of climate change.

This approach calls for an expanded range of skills from academics, government authorities, scientists and the media. Beyond pure and hard data or "expert voices", it requires social and community psychology and community development competencies. It also asks for humility to accept that each community possesses relevant knowledge about its reality and about the residents´ habits and priorities regarding the climate and environmental issues. Let people tell their own story; communicators are guides to facilitate the storytelling.

As suggested in **Climate Outreach: The Uncertainty Handbook**, when dealing with community-based groups it is better to have a conversation, not an argument; and, to tell a human story, not a scientific one (Corner et al., 2015).

In addition, Newell & Pitman (2010) recommend the following:

- *Do not assume that your audience will interpret numerical information and figures as you do.*
- *Always define terms clearly, even those that are commonplace within the discipline.*
- *When presenting data, identify samples clearly and choose reference points carefully.*
- *Use vivid images to engage emotional processing (images, we underline, related with your audiences; make it personal for them).*
- *Try to use specific and, when possible, concrete examples of distant future outcomes (e.g., the appearance of your audience's local environment in 30 years or the air quality that their children might face in Replace with: 2050).*
- *Capitalize on "loss aversion" (People tend to avoid outcomes framed as losses more than seek those framed as gains) by explaining how actions to mitigate global warming (e.g., better community planning) will lead to the avoidance of large losses (i.e., need for relocation).*

Most of these suggestions also apply when developing messages and campaigns for mass media.

Conclusion

Mass media communication alone cannot generate the behavioral and attitudinal changes needed for Puerto Rico to embrace adequate planning for climate change prevention and mitigation. A community-based, participatory approach is needed to engage at-risk sectors. In addition, both mass communication and communication for development efforts must use channels, messages and content tailored to specific audiences in order to maximize impact. Risk and mitigation approaches are different in mountain or coastal communities.

Education and engagement of communities in higher risk of suffering climate change impact is indispensable, particularly in light of Puerto Rico´s current fiscal and economic crisis and federal public policies – which will probably mean that citizens will need to come forward to protect their communities.

Any effort to communicate climate change and to promote preventive behaviors at community level must earn the community's trust and take advantage of their knowledge in order to appeal to neighborhood peers.

At times when budgets might be limited, leveraging community resources and engaging them in the communications strategy and decision-making process is not only the most sustainable course to provoke change, but also the most effective one.

Figure 17. Participants in an introductory workshop on green infrastructure for coastal resilience.

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APPENDICES

Puerto Rico's
STATE OF THE CLIMATE
2014–2021

WORKING GROUP 2

Ecology and Biodiversity

APPENDICES

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APPENDIX A
Freshwater Ecosystems

Freshwater ecosystems are classified as lentic or lotic ecosystems. Lentic refers to standing waters, such as lakes and ponds, while lotic systems are characterized by running waters, such as streams and rivers (Marsh 1999). Almost 71% of the Earth's surface is covered by water, and less than 1% is freshwater (4 million km²). Although a small fraction of global water, freshwater ecosystems are highly dynamic environments with complex interactions between biodiversity, topography, geology and climate (Neal et al. 2009; Mittermeier et al. 2010). These ecosystems are characterized by low salinity concentrations (less than 0.5g/l; Mittermeier et al. 2010) and associated biota have evolved to adapt to these conditions. Freshwater biota is highly diverse; over 126,000 species have been described worldwide (Balian et al. 2008) and new species are described annually. Moreover, freshwater ecosystems provide habitat for more than 10% of known animal and one third of known vertebrate species (Dudgeon et al. 2006; Mittermeier et al. 2010). Due to the connectivity that exists between adjacent ecosystems, including terrestrial and marine, the function of freshwater ecosystems can be impaired (Mittermeier et al. 2010), for instance, due to alterations to terrestrial ecosystems that affect hydrology. Baron et al. (2003) described freshwater ecosystems as *"…biological assets (that are) both disproportionately rich and disproportionately imperiled."* Some examples of these ecosystems are listed below.

Rivers are bodies of water that connect terrestrial, freshwater, and coastal marine systems in an open transport and migration route with unidirectional flow driven by gravity (Van Der Velde 2009). Rivers contain 0.0001% of the Earth's water (Wetzel 2001). The dissipation of energy due to the movement of water masses influences the morphologic, biotic and physicochemical parameters of rivers (Wetzel 2001).

Streams are small, shallow waterbodies that feed into larger water masses such as rivers. Streams may also be referred to as creeks, depending on size. They are considered perennial (continuous flow year-round), intermittent (normally cease flowing for weeks or months each year), or ephemeral (flow only for hours or days following rainfall; Svec et al. 2005). Rivers and streams are a predominant feature of freshwater ecosystems of Puerto Rico.

Springs represent a unique aquatic ecosystem characterized by high water clarity and relatively stable environmental characteristics. Groundwater is the principal water source for springs and is characterized by elevated concentrations of dissolved nutrients and gases (Knight 2008).

Ponds are water bodies that have relatively constant water temperature from top to bottom. These ecosystems are small and shallow, and the bottom is usually muddy. They are characterized by the presence of aquatic vegetation around the edges and throughout the water body, usually due to the lack of wave action.

Lakes are inland bodies of water that lack direct connectivity with the ocean (Hairston and Fussmann 2014). These ecosystems are characterized by the dynamic interactions between biological, chemical, and physical processes associated with their watersheds (Hairston and Fussmann 2014). As with other freshwater ecosystems, lakes can be categorized into shallow or deep, temporary or permanent. In Puerto Rico, ponds and springs are relatively rare, and no natural lakes exist. However, reservoirs were built to provide water for important activities, such as domestic use, hydropower, and irrigation. Reservoirs can behave similarly to natural lakes in terms of physical properties (like stratification) but are for designated uses.

Wetlands are among the most important ecosystems on Earth (Mitsch and Gosselink 2000; Delgado and Stedman 2004) and are sometimes referred as "the kidneys of the landscape" due to their function as downstream receivers of water and waste from natural and human sources (Mitsch and Gosselink 2000). They are characterized by three main features: presence of standing water or saturated soils, unique soil conditions different from adjacent uplands, and specialized flora and fauna adapted to very moist and humid conditions (Delgado and Stedman 2004). Coastal wetlands, lagoon systems, and bioluminescent bays are discussed separately in Appendix C.

FRESHWATER ECOSYSTEMS OF PUERTO RICO

There is a marked difference between slopes of watersheds around the island. The northern, western, and eastern watersheds tend to have larger areas, are longer and most of the waterbodies are perennial rivers, providing a continuous flow. In contrast, rivers and streams on the southern slopes are mostly intermittent (DNER 2016). In general, stream watersheds in Puerto Rico are typically steep, with a reduced distance between headwaters and coastal plains, and flashy hydrology. River and streambeds tend to be dominated by rocky substrates that can vary from gravel to boulders, but there are sandy and silty rivers and streams as well (Neal et al. 2009; DNER 2016).

There are no natural lakes in Puerto Rico, but there are 39 reservoirs, 15 of which are considered large reservoirs (DNER 2016). Most of the reservoirs were built in the main channel except the Fajardo and Río Blanco reservoirs, which were constructed off the main channel to reduce sedimentation and extend useful life. Reservoirs in Puerto Rico have been built for a variety of purposes including water supply, hydroelectric energy generation, agricultural irrigation, and flood control (DNER 2016). Cidra, Toa Vaca, Loíza, Fajardo, and Blanco, among others, were developed for water supply. Hydroelectric reservoirs generate 1.9% of the energy that is produced on the island. Agriculture on the island depends on water from Carite, Patillas, Guayabal, Luchetti, Loco, Guayo, Prieto, and other reservoirs in the Añasco River watershed, which is transported to fields through the irrigation canals.

There are two natural freshwater lagoons in Puerto Rico: Laguna Tortuguero and Laguna Cartagena. Laguna Guánica, another freshwater lagoon, was dredged in 1952 to increase agricultural production area in the Lajas Valley (DNER 2016).

Caño Tiburones is part of a coastal fringe where the aquifer of the northern karst region emerges from underground, forming an interface between freshwater and saltwater intrusion. This region was altered in the 1940's due to the construction of drainage channels to create additional areas for sugarcane cultivation. Water levels have increased during the past years to levels near those of pre-drainage due to failure of the pumping system.

Puerto Rico has three main irrigation districts located around the island (DNER 2016). The irrigation system of Isabela is located in the north, which consists of 4 canals: Guajataca, Isabela, Moca, and Aguadilla. This system receives water from the Guajataca Reservoir, which is gravity-fed through canals. The irrigation system of the South Coast is divided in two regions: the east, which is composed of the Patillas and Guamaní Canals, and the west, composed of the Juana Díaz Canal. The Patillas Canal is fed by the Patillas Reservoir, the Guamaní Canal receives water from the Carite Reservoir and the Juana Díaz Canal receives water from the Guayabal Reservoir. The Lajas Valley Irrigation System is located in the West. This is a complex system where water from the Loco and Yauco Rivers interconnect in the Lajas Valley to form an integrated system.

Puerto Rico has different geologic formations that function as aquifers (geological formations saturated with water with a volume and permeability that is enough to sustain a significant flow of freshwater; Driscoll 1986, Figure 1). Three main types of formations lead to aquifer formation: alluvial deposits, karst formations, and igneous rock. Four main aquifers have been identified in Puerto Rico: North Coast, Alluvial, South Coast, and Inland Valleys, each with different permeability and geological origin (DNER 2016; Figure 1).

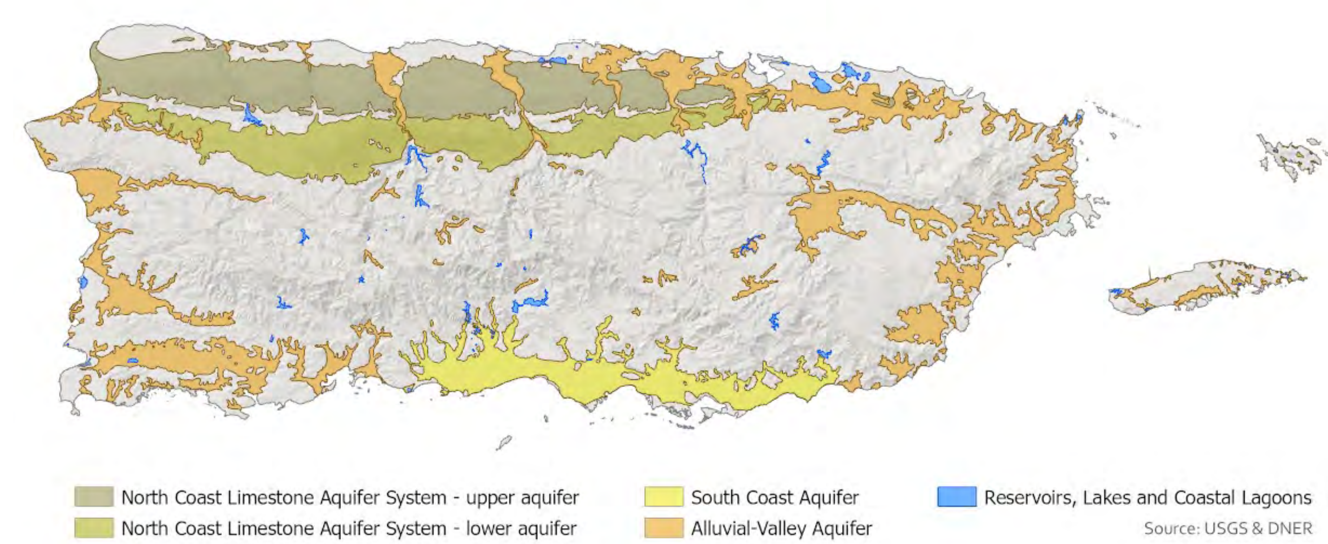


Figure 1. Map of the aquifers and reservoirs found in Puerto Rico.

PUERTO RICO'S AQUATIC BIOTA

Puerto Rico has a wide diversity of aquatic organisms. In this section, we present a general description of the biota present in freshwater ecosystems of Puerto Rico.

Nearly all of Puerto Rico's native freshwater fishes, snails, and decapods are amphidromous (life cycle that requires movement from freshwater to the marine environment). Amphidromous organisms have adults and juveniles that grow and spawn in freshwater stream ecosystems while larvae quickly hatch from benthic eggs and are carried with river currents to the estuary or ocean where they undergo a pelagic larval phase (Bauer 2009; Bauer 2011). Following the pelagic larval phase, postlarvae undergo return migrations to stream ecosystems where they mature into juveniles, then adults (McDowall 2007; Keith et al. 2008).

Algae

Primary production is dominated by the algae that grows over benthic substrate. Puerto Rican freshwater diatoms (a larger group of algae) are represented by over 580 species and morphospecies (taxonomic species based on morphological differences from related species). During low flow periods, some species can become very abundant and serve as a food source and habitat for some aquatic insects.

Macroinvertebrates

The aquatic macroinvertebrates represent the most diverse group of aquatic biota, composed of a variety of organisms from worms, leeches, mites, and snails to aquatic insects (Figure 2). An aquatic insect is an insect that spends at least part of its life cycle (i.e., larva, pupa or adult) associated with an aquatic environment. In Puerto Rico, 68 families of aquatic insects have been reported, versus 60 and 63 families reported in Cuba and Hispaniola, respectively (Gutierrez-Fonseca et al. 2015). The habitats where they can be found range from marine, brackish or freshwater; freshwater habitats are rivers, streams, lakes, ponds or phytotelmata (water-filled reservoirs created by leaves, flowers, inflorescences or trunk crevices of certain plants).

Aquatic macroinvertebrates play an important role in aquatic ecosystems. For example, the breakdown of organic matter is mediated by specialized macroinvertebrates that fragment large pieces of leaves into smaller pieces. In general, their ecological function is best described by their feeding activity. The most common classification is feeding functional groups (FFG), which is based on morphological structures and behavioral mechanisms of food acquisition. The FFG classification played a key role in the development of the River Continuum Concept (RCC; Vannote et al. 1980).

The major FFG are: 1) Scrapers that consume algae and associated material that grow over substrates by removing them with their mouthparts, which are adapted to crop closely attached particles; 2) Shredders that cut or chew pieces of living or dead plant material, including all plant parts like leaves, roots, and wood; 3) Collector-Gatherers that have modified mouthparts to collect small particles (<1mm) accumulated on the stream bottom; 4) Filterers that consume small particles from the water column using a variety of strategies such as construction of nets and may have a large number of hairs and setae or fan-like structures; and finally 5) Predators that feed on other consumers. FFGs can be used as a tool to determine the ecological state of rivers in Puerto Rico. Changes in organic matter inputs, primary producers, and FFGs proportions may be key to understanding the risks and vulnerability of rivers on the island.

Aquatic insects and other macroinvertebrates have been used worldwide as indicators of the quality of aquatic ecosystems. Their sensitivity or tolerance to pollution has allowed the development of water quality indices. The Biological Monitoring Working Party (BMWP) and Family Biotic Index (FBI) are examples of two bioindicator tools that have been used effectively around the world to evaluate the environmental condition of streams. These two indices have been adapted for Puerto Rico (BMWP-PR and FBI-PR) by Gutierrez-Fonseca and Ramirez (2016). The BMWP-PR and FBI-PR indexes were compared to a more elaborate index developed by the EPA for Puerto Rico, the Macroinvertebrate Integrity Index (MII), and there was a good fit and performance between the indices (Kurtenbach 2017).

Figure 2. Images of examples of insects associated with freshwater ecosystems in Puerto Rico (from River Education Program, Luquillo Long-Term Ecological Research [LTER] Program)

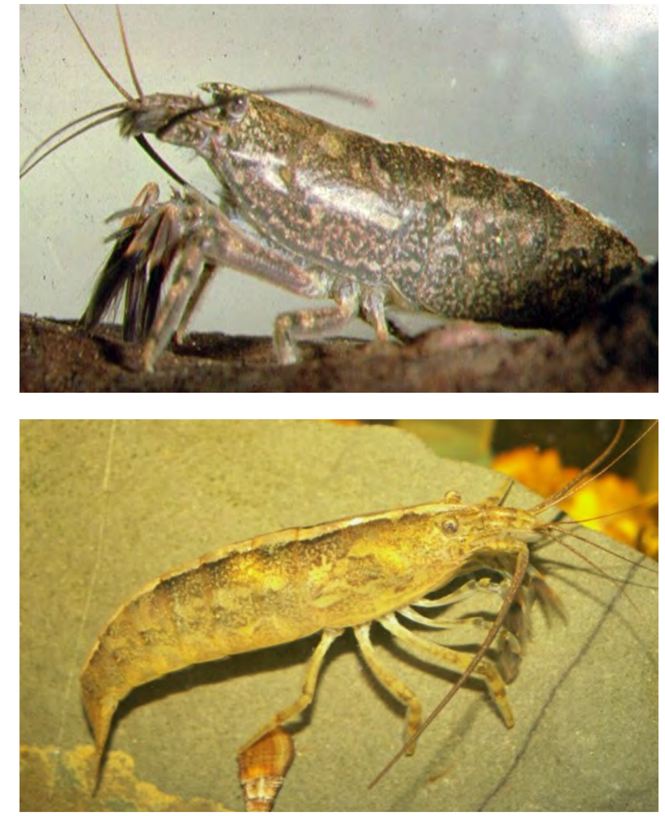


Figure 3. Image of the shrimp Atya lanipes (from O. Pérez Reyes, UPR-RP).

Crustacea

Freshwater ecosystems in the Caribbean are dominated by freshwater decapods in contrast with freshwater systems on continents which are dominated by insects (Covich and McDowell 1996; Crowl et al. 2012; Pérez-Reyes et al. 2013; Pérez-Reyes et al. 2016). On Caribbean islands, decapods are the major consumers and recyclers of organic matter. Besides their role as recyclers, freshwater decapods, as amphidromous species, have an extended life cycle with a marine phase.

A total of 18 species of decapods distributed among four families represent the native freshwater crustacean fauna of Puerto Rico (Pérez-Reyes et al. 2013; Wehrtmann et al. 2016). Members of the family Atyidae (shrimp) are filter feeders and scrapers (Figure 3). *Atya lanipes* is a species native to Puerto Rico with a wide distribution having been observed in 23 of 40 streams surveyed (Pérez-Reyes et al. 2013). The family Xiphocarididae (shrimp) is represented in Puerto Rico by the Caribbean endemic species *Xiphocaris elongata* (Wehrtmann et al. 2016). In freshwater ecosystems, this species is responsible for the removal of coarse organic matter and is catalogued as a shredder. In headwater pools, these shrimp are preyed upon by mountain mullet (*Agonostomus monticola*, Figure 4) resulting in changes in the size of the shrimp's rostrum (the forward extension of the carapace looks like a beak; Ocasio-Torres et al. 2014; Ocasio-Torres et al. 2015). Palaemonids (shrimp, Figure 5) and Pseudothelphusids (crabs) are the primary invertebrate predators in Puerto Rico streams. Palaemonids are represented by six species that feed on shrimp from other families, snails, insects, and juveniles of their species. The buruquena (*Epilobocera sinuatifrons*) is an endemic freshwater crab of Puerto Rico that represents the connection between riparian forest and streams. Adult crabs inhabit riparian forest where they feed on fruit, leaves, small invertebrates, and other organic matter and visit streams at night looking for water or when it is time to reproduce. These crabs will sometimes move their food from the forest to the stream and vice-versa (Chace and Hobbs 1969; Cook 2008; Cumberlidge et al. 2009). Studies on the densities of decapods in urban streams with forested headwaters demonstrated the importance of forested reaches for the conservation of sensitive species (Pérez-Reyes et al. 2015).

Freshwater decapods have an economic value to the local people (Kartchner 2003). Shrimpers capture shrimp and crabs in artisanal fisheries.

Figure 4. Image of the mountain mullet, Agonostomus monticola (from J. Almodóvar, UPRM).

Figure 5. Image of Macrobrachium spp., a primary predator in Puerto Rico (from B. Yoshioka, USFWS, retired).

Mollusca

Several freshwater gastropods (mollusks) are common around the archipelago including melanias, nerites, apple snails and other snails, and a pair of limpet species (Figure 6).

Neritids (snails) are native to the island and inhabit lower parts of the rivers. Their distribution is limited by calcium availability, which they obtain through predation on the shells of other individuals. Studies of the massive migration of these amphidromous snails on the island and how their movements are related to flow conditions were conducted by Blanco and Scatena (2005; 2007), who found that they tend to migrate in massive groups when waters recede after high discharge events, forming a long, tail-like aggregation pattern (Blanco and Scatena 2005; 2007).

Two snail species were introduced as biological control agents of a vector snail that is a carrier of the parasitic worms that cause schistosomiasis. One of the introduced snail species competes with the vector snail for the same microhabitat (Gómez-Pérez et al. 1991) while the other introduced snail consumes the vegetation where the vector snail deposits eggs (Seaman and Porterfield 1964). Two other snails were introduced to the island by pet shops (Williams, Jr. et al. 2001), where they were common in the aquatic vegetation used in aquarium tanks.

Fish

Puerto Rico's native freshwater fish assemblage is primarily composed of four families of diadromous fishes that utilize the marine environment during early life history stages (Figure 7).

Diadromous fishes typically make up almost all of the native freshwater fish fauna in streams without artificial barriers. These fishes are important components of Puerto Rico's freshwater ecosystems as they occupy multiple levels of the food web from detritivores and algivores to top-level predators. They also provide important ecosystem services to local people through recreational and artisanal subsistence fisheries that target multiple life stages of these fishes (Neal et al. 2009; Kwak et al. 2016).

Only one of the diadromous species, the American eel (*Anguilla rostrata*, family Anguillidae, see Figure 7), is catadromous, while the remaining species are amphidromous. American eels typically live as juveniles and adults in freshwater, but they may also inhabit estuarine and nearshore marine environments during these phases of their lives. At the age of anywhere from 3 to 30 or more years they migrate to the Atlantic Ocean for a terminal spawning event. American eels found in Puerto Rico are part of a panmictic (random mating within a breeding population) population that spans from Greenland in the north to Venezuela in the south; all of which aggregate and spawn somewhere near the Sargasso Sea. The American eel has long, thin, small-headed transparent larvae distributed by ocean currents and active swimming to coasts, then eels recruit to coastal rivers and estuaries at the glass eel stage (Williams et al. 2012).

Puerto Rico's amphidromous fish assemblage includes these species of Eleotridae (or sleepers): fat sleeper (*Dormitator maculatus*), smallscaled spinycheek sleeper (*Eleotris perniger*) and bigmouth sleeper (*Gobiomorus dormitor*, Figure 7). There are two genera of freshwater amphidromous Gobiidae (gobies) on the island: *Awaous*, which is represented by a single species river goby (*Awaous banana,* Figure 7), and Sicydium (Figure 7), a complex which includes up to four species-*S. plumieri, S. punctatum, S. buski,* and *S. gilberti,* of which the latter is a species

Figure 6. Images of examples of mollusks that spend at least a portion of time using freshwater ecosystems (from Luquillo LTER River Education Program).

Figure 7. Images of fish from the 4 diadromous fish families - clockwise from top left: bigmouth sleeper, American eel, two gobies of the genus Sicydium, river goby and mountain mullet (from Luquillo LTER, River Education

that was described by Watson (2000). The *Sicydium* species of Puerto Rico are only distinguishable as adults and juveniles through microscopic examination of the teeth of the upper jaw. Therefore, this species complex is often referred to under a single common name—sirajo goby. Finally, there is a freshwater amphidromous member of the family Mugilidae, the mountain mullet (*Agonostomus monticola*, Figure 7; Kwak et al. 2016).

In Puerto Rico, river goby and sirajo goby can be highly abundant as migrating postlarvae and are harvested in culturally significant artisanal fisheries from multiple rivers of the island (Erdman 1961; Kwak et al. 2016). Fishing of postlarvae occurs during mass-recruitment episodes or runs that reach peaks on the last quarter moon phase from June through January. Amphidromous postlarval fishes are an important component of the diets of predatory fishes such as the bigmouth sleeper and American eel in rivers receiving large postlarvae runs (Engman 2017). Although amphidromous species usually migrate between the oceans and freshwater during early life stages, infrequent deviation from this pattern does occur in Puerto Rico (Smith and Kwak 2014). The bigmouth sleeper is perhaps the most flexible of these species with respect to migratory life history. There appears to be a self-sustaining population of bigmouth sleepers in the Carite reservoir, while amphidromous fishes appear to be wholly extirpated from all other large reservoirs on the island (Bacheler et al. 2004; Cooney and Kwak 2013).

Riparian and aquatic vegetation

Riparian and instream ecosystems represent an interface between terrestrial and aquatic systems, encompassing an environmental gradient of ecological processes and communities (Naiman et al. 1993). The floral compositions and structural patterns of aquatic and riparian vegetation provide a connection across the terrestrial–aquatic interface. Additionally, aquatic and riparian vegetation can function as corridors and maintain fluvial processes (Ferreira and Aguiar 2006), habitat structure, water clarity, and food-web structure (Pusey and Arthington 2003); represent a source of food for stream biota (Cummins et al. 1988); and have been used by human communities as a source of food, medicine, fuels, and construction materials in tropical regions (Gichuki et al. 2001).

In the Caribbean region, riparian protection zones have been in place for over 260 years (Scatena 1990). The protection of headwater streams in Puerto Rico dates back to 1839 (Wadsworth 1950) although enforcement is sometimes weak. Anthropogenic disturbances, such as deforestation, agriculture, and urban development alter these important terrestrial-aquatic interfaces and can result in the elimination of native riparian plant species, colonization by invasive species, and overall alteration of the stream ecosystem (Heartsill-Scalley and Aide 2003). These alterations can result in restricted movement of organisms and can affect important features of stream ecosystems, such as temperature, light conditions, dissolved oxygen and habitat availability, all of which can lead to the local loss of plant and animal species (Gregory et al. 1991; Pusey and Arthington 2003).

There is little historical or current information regarding riparian and aquatic flora and the number of species is unknown. Studies indicate that riparian understory vegetation on the margins of perennially-flowing channels is dominated by successional-type species, mainly composed of shrubs, herbs and ferns (Scatena 1990; Heartsill-Scalley and Aide 2003). Vegetation transects along the Mameyes River in the Luquillo Forest revealed patterns that may represent typical vegetation composition along stream margins (Figure 8), river watershed, a mixture of herbaceous vegetation including grasses was found to be the dominant riparian vegetation (DNER 2016). During the same study, four floating species (three *Lemna* species and *Salvinia minima* Baker) and one submerged species (*Najas guadalupensis* [Spreng.] Magnus) of aquatic vegetation were identified (DNER 2016).

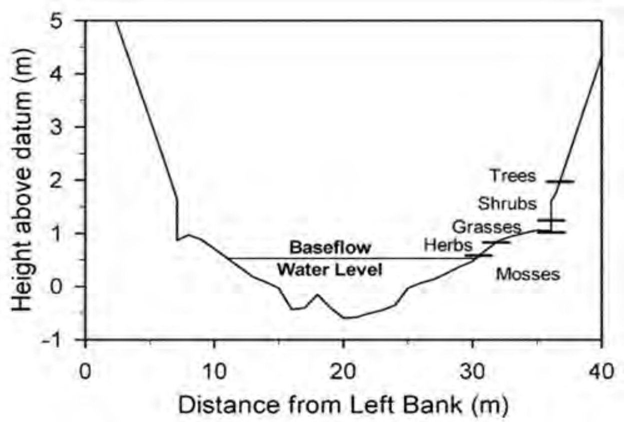


Figure 8. Cross-section at Mameyes River near Sabana, a mid-elevation site. Vertical zonation of vegetation types reflecting the flow regime of the stream (Source: Pike and Scatena 2010).

Phytotelmata

Water-filled reservoirs created by leaves, flowers, inflorescences or trunk crevices of certain plants provide a special type of aquatic habitat termed phytotelmata. Benzing (1998) described how epiphytes (organisms that grow on surface of a plant using it as a base) influence adjacent biota and whole-system processes, specifically those concerned with energetics, hydrology, and mineral cycling. Bromeliads and inflorescences of *Heliconia* harbor communities of aquatic organisms, even far away from any pond or river. Phytotelmata sustain a unique and poorly known fauna (Frank 1983; Frank and Lounibos 2009) including endemic insects and microcrustaceans (Richardson et al. 2000). Ongoing research in the neotropics focuses on the effects of climate change and deforestation on phytotelmata, but research on aquatic invertebrates focuses on mosquitoes that harbor known and emerging viruses. Recent research on fluctuations in dipterans (true flies) in phytotelmata in West Sumatra, Indonesia, showed that abundance of larvae was negatively correlated with temperature and rainfall, but positively correlated with humidity (Dahelmi and Syamsuardi. 2014).

VULNERABILITY OF FRESHWATER ECOSYSTEMS IN PUERTO RICO

Human actions across the landscape have been recognized as a principal threat to stream ecosystems, modifying the aquatic environment and thus, resulting in alterations in water quality and ecosystem processes (Townsend 2003; Strayer 2003). In Puerto Rico, for more than five centuries the economy depended almost entirely on agriculture (López et al. 2001). Agricultural activities, combined with timber cutting and development of forested land, resulted in the deforestation of 94% of the island (9,000 km^2) by the middle of the 20th century (Birdsey and Weaver 1987). As agriculture was replaced by manufacturing in the 1940's, the migrations of rural population to the towns and cities of Puerto Rico took place and forests gradually recovered on abandoned agricultural lands (Dietz 1986; Aide et al. 1996; Birdsey and Weaver 1987; Aide et al. 1995). Recovery of forested land lasted until the economic shift led to an increase in the demand for housing, industrial facilities, and roads in the coastal zone of the island (López et al. 2001). Hence, these aquatic ecosystems have been subjected to a wide variety of modifications due to changes in land use.

Land use influences aquatic ecosystems and may also lead to their degradation through sedimentation, nutrient enrichment, pollution and riparian clearing (Allan 2004). These mechanisms can ultimately affect water quality, modify ecosystem processes, and alter stream biota. For instance, in Puerto Rico, stream channels in previously agricultural areas that became urbanized are filled with sediments accumulated during past agricultural periods (Ramírez et al. 2009). Also, current agricultural practices (mostly from traditional monoculture practices) have been found to increase soil erosion (López et al. 1998), which has been linked to diminished water quality, increased water treatment costs and decreased photosynthetic activity of aquatic plants and algae (Estades Hernández et al. 1997). Aquatic macroinvertebrates have been shown to be highly sensitive to contamination, changes in hydrology, land use change and habitat disturbance. In Puerto Rico, aquatic ecosystems are particularly threatened by urban sprawl, water extraction, and the installation of dams. Macroinvertebrates in Puerto Rico have been found to respond negatively to urbanization (de Jesús-Crespo and Ramírez 2011), particularly due to the loss of riparian vegetation, which causes a decrease in the richness of families and an increase in the abundance of tolerant taxa.

The construction of dams associated with agriculture, hydroelectric activities, and municipal water use in Puerto Rico represents one of the greatest anthropogenic impacts to the island's freshwater ecosystems by reducing connectivity, degrading habitat, and affecting the ecological integrity of the ecosystem (Neal et al. 2009). Dams and other anthropogenic instream barriers, such as road crossing structures (examples shown in Figure 9) interrupt the migrations that fishes, shrimp and snails in Puerto Rico undergo as part of their diadromous life histories (Holmquist et al. 1998); and can alter natural hydrological variation affecting flooding and natural flow regimes downstream. While the impact of altered instream flows has not been evaluated for fish and aquatic macroinvertebrates in Puerto Rico, shrimp and mollusks are likely to be exceptionally vulnerable to the effects of water withdrawal leading to reductions in or elimination of stream flow, especially during times of low flow (Crook et al. 2009; Greathouse and Pringle 2006) because of the impacts on migrations as part of their diadromous life histories (Holmquist et al. 1998).

Cooney and Kwak (2013) completed an inventory of dams and other artificial barriers in selected rivers of Puerto Rico, the only known inventory of this nature for the Caribbean region. Their work integrated fish and dam surveys to get a better understating of the barrier effects on migratory species. The study identified the effects of instream barriers on the whole fish assemblage, as well as species-specific differences in the effects of barriers of differing height. Cooney and Kwak (2013) showed that the native fish assemblage is affected by instream barriers to migration in 75% of Puerto Rico's river lengths. Moreover, non-goby species are restricted or extirpated from 57% of the island's riverine habitat, while goby species, with their superior climbing ability, are restricted or extirpated from 36% of the river kilometers. This inventory serves as a baseline for future assessments in the Caribbean and can be used to prioritize the removal of barriers in Puerto Rico for the reestablishment or enhancement of river connectivity for the conservation of native aquatic species.

Figure 9. Examples of typical road crossing structures (Left: bridge; Right: round culvert). When structures are not properly designed, they disrupt river connectivity affecting the movement of migratory aquatic fauna (Photos: B. Yoshioka, USFWS, retired (left) and A. Galindo, USFWS (right)).

Urbanization in Puerto Rico has also been found to degrade streams by changing water quality and altering stream biota (de Jesús-Crespo and Ramírez 2011; Ramírez et al. 2014). For example, macroinvertebrate families and pollution-sensitive taxa are abundant in streams with less urban cover (de Jesús-Crespo and Ramírez 2011). Other studies indicate that, as the proportion of urban land increases, the assemblage of macroinvertebrate composition changes to dominance by pollution-tolerant taxa (e.g., snails, Chironomidae; de Jesús-Crespo and Ramírez 2011). Urbanization in Puerto Rico adversely affects native fish assemblages at the reach and catchment scale. Reach-scale alterations such as the construction of concrete-channelized reaches, a flood control measure, create highly homogenous and shallow habitats, which are less suitable for native fish species. Concrete channelized reaches in urban streams have been shown to have low native fish species' richness and abundance and a high abundance of tolerant and exotic species (Engman and Ramírez 2012). Although urbanization at the catchment scale does appear to negatively affect native fishes, urbanized streams without downstream barriers to migration or severe instream habitat alterations can harbor native fish assemblages at richness and density levels that are similar to streams with forested watersheds.

In addition to causing habitat loss, instream flow alterations may affect the recruitment of amphidromous postlarvae. In a recent study, Engman (2017) found positive relationships between the postlarval recruit abundances of multiple amphidromous fish species and river discharge. This study also revealed that reductions in river discharge on the days of the last-quarter moon phase during the months of June through January are likely to be especially detrimental to amphidromous fish recruitment (Engman, 2017).

Exotic species are a threat to the native freshwater fishes of Puerto Rico. In Puerto Rico, there are more introduced species of fishes than native species. Some of the species' introductions were conducted by management agencies to improve sport fishing in reservoirs that are inaccessible to native fishes. Other species have been incidentally introduced through aquarium releases. The introduced fish assemblage includes many taxa with high invasive potential such as sailfin catfish and cichlids (Neal et al. 2009; Kwak et al. 2016). However, in some instances, native species dominate even when these potentially invasive exotic species are present (Engman and Ramírez 2012; Ramírez et al. 2012).

The biota of rivers in Puerto Rico, and many other countries, have evolved in the context of extreme flow conditions (Lytle and Poff 2004). The ability of some species of shrimp, such as the river guábara (*Atya spp.*), the bocú shrimp (*Macrobrachium*) or the salpiche (*Xiphocaris elongata*), to migrate upstream or downstream is one example of a physiological and morphological adaptation to frequent changes in water flows (Covich et al. 1996). The life history of these species of decapods, which produce hundreds of thousands of eggs that have to be released during high flow conditions in order to reach the estuary quickly, and the massive migration upstream that happens during low flow conditions, is another example of an adaptation to take advantage of the good times, while biding time during the bad ones (Pérez-Reyes et al. 2016). Many species of native shrimp seem to breed during the high rain period (April-November), warmer months of the year and the hurricane season because the high flow conditions at these times move the larvae to the estuarine zone. The migration of thousands of juveniles to the upstream pools occurs during the low rainfall season. In this case, low flow conditions work to the animal's advantage reducing the possibility of being carried by the water to the lower reaches of the stream (Kikkert et al. 2009).

APPENDIX B
Forests

FORESTS

Forest cover in Puerto Rico (from headlands to coast) can be categorized into four broad groups: (1) Lower Montane forests of the Central Cordillera and Luquillo mountains; (2) Dry forests, including forests and bushes in the Holdridge dry subtropical life zone; (3) Karst forests, including the forests of the northern and southern limestone region; and (4) coastal lowland forests, including moist lowland forests and freshwater forests and swamps of *Pterocarpus* and mangroves.

Nearly 18% (158,000 hectares) of Puerto Rican forest cover can be classified as montane forests with elevations from above approximately 400 m in the Central and Carite Mountains, as well as above approximately 150 m in El Yunque National Forest (ENYF; PRCCC 2013). The EYNF includes 11,310 hectares in the Luquillo Mountains of northeast Puerto Rico and has a humid tropical maritime climate, with temperatures at high-elevation sites averaging 18.5°C and precipitation averaging greater than 4,000 mm annually, cooler and wetter than much of Puerto Rico (Jennings et al. 2014). The types of vegetation and community structure shift because of continuous changes in cloud cover, wind exposure, soil moisture, temperature, and precipitation across an elevational gradient. Four major vegetation and forest types are identified across an elevational gradient: lower montane wet and rain forests (elevations between 120 and 600 m); cloud forests (above 600m) with higher presence of epiphytes, shorter trees, and shrubs; montane wet and rain cloud forests (elevations between 600 and 900 m); elfin woodland montane wet and rain cloud forests (also known as dwarf forests) above 900 m, characterized by low canopy trees; and Sierra palm (*Prestoea montana*) montane wet and rain cloud forests (also known as palm breaks) in the east-facing slopes and ravines (in elevations above 450 m) (Jennings et al. 2014).

KARST

The northern limestone extends for about 140 km in an east-west direction from Loiza to Aguadilla with a maximum width of 22 km near Arecibo. Of the 218,692 ha in the northern part of the island, 142,544 ha or about 65% are considered to form the karst belt, defined as an area that exhibits surficial karst features such as cuestas, sinkholes, conical hills, tower karst and zanjones. The highest elevations in this region are along an escarpment at its southern edge, where the highest point is 530 meters (Lugo et al. 2001).

On the south coast, the limestone region is more fragmented, but extends from Ponce west to Guánica and covers approximately 21,022 ha. Distinctive karst features are less notable in the dry environment due to the lower rainfall that inhibits the rate of solution. An excellent example of subtropical dry forest over limestone and one that has been studied extensively is that of the Guánica State Forest (Lugo et al. 2001).

The primary difference between the vegetation in the northern and southern limestone regions is climate. About 88% of the limestone region falls within what has been described as subtropical moist forest, 7% in subtropical dry forest and 4.6% in subtropical wet forest. A very small percentage falls within the subtropical lower montane forest life zone (Lugo et al. 2001).

The karst region is of particular ecological importance and provides valuable ecosystem services. Its ecological systems are diverse, ranging from dry to wet forests, all of which are rich in species of plants and animals. Rare and endemic species occur through the region, with about 40% of all Federally-listed species (under the Endangered Species Act [ESA]) occurring in the region. The aquifer of the northern karst region contains one of the largest freshwater supplies of the island. The region provides high quality opportunities for recreation and tourism, containing a vast expanse of underground rivers, aquifers, and caves of unusual size and beauty (Lugo et al. 2001; Day 2010).

Puerto Rico Law 292 (August 21, 1999) provided for the protection and conservation of the Puerto Rico's karst area. It states that lands must be identified that should be restricted from commercial mining activities and other intensive uses. These lands were identified in a DNER (2008) Karst Study and is also a DNER Priority Conservation Area. The acquisition of high ecological value land is prioritized under the law through mitigation, donations and land transfers from other government agencies. Established land use rules explicitly prohibit mining and landfills within public and private karst lands, promote terrace cultivation and other sustainable agricultural practices, and promote reforestation projects in order to protect and conserve the natural resources, water quality, and the delivery of ecosystem services.

NORTHERN KARST

The forested areas present on northern limestone substrate occupy approximately 72,000 ha, or just over 8% of Puerto Rico, making them the largest continuous area of forest on the island. The steep topography of the haystack hills region and the underground drainage of the limestone affect both the hydrology and the human use of the landscape. However, in spite of the steep terrain, the land was heavily used for agriculture in the last century and nearly all forests in this region are secondary forests on abandoned agricultural land (Chinea 1980; Rivera and Aide 1998; Aukema et al. 2007). Climate of the northern karst region varies from east to west and from north to south within the region. The majority lies within the subtropical moist forest life zone. Temperatures vary from an average of 26.1°C in the coastal area to 23.8°C in the southern part of the northern karst (Chinea 1980). Rainfall varies from 1,000 mm to 2,000 mm annually (Ewel and Whitmore 1973).

Vegetation

Northern karst forests are characterized by high tree density and trees of small diameter and hard, thick leaves. Stands have a tendency to show signs of being exposed to frequent drought conditions. Even in the moist and wet forest karst belt, forests have a high proportion of deciduous tree species. This is likely due to the rapid rate of runoff and infiltration of rainwater, low water storage in shallow soils, and high sunlight and wind acting on the vegetation. An important characteristic is that the vegetation exhibits numerous gradients. There is an east-west gradient due to the trade winds and the decreasing rainfall from east to west as well as a north-south gradient with increasing rainfall due to increases in elevation. Wind exposure creates gradients within mogotes (solitary limestone hills), with more exposure on the northeast slopes and less on the southwest slopes but greater wind on the tops compared to bottoms and valleys (Chinea 1980; Lugo et al. 2001; PRCCC 2013).

Source: Wanda I. Crespo

Chinea (1980) identified three types of forests in the northern karst belt: mesic on the valley bottoms, mixed woodlands on the slopes, and dry woodland on the hilltops. Aukema et al. (2007) also found distinct plant communities across a topographic gradient in the northern karst and also found distinct plant communities within topographic positions. Their analysis separated hill tops and valley communities and found that communities on the slopes were intermediate and overlapped with both tops and bottoms. The mogote tops and slopes showed the most distinct plant communities, with higher species richness and lower non-native species richness. This would suggest that activities affecting these areas, such as mining, would result in a greater loss of native species than if vegetation in a valley were altered in any way. Aukema et al. (2007) recommended that conservation planning take into consideration the different communities that are present, in particular those found on the region's hilltops, where more native and often unique species may occur.

Fauna

A total of 51 species (17 families) of amphibians and reptiles have been reported from the northern limestone region. A list of these species can be found in Lugo et al (2001). Six additional species and two more families of amphibians are found in northern limestone region. Reptilian fauna has one less family and four species appear only the northern limestone, while eight species appear only in the southern limestone region. The Federally-listed Puerto Rico boa (*Epicrates inornatus*), while widely distributed throughout the island, is more common in the karst belt (Lugo et al 2001). Potential impacts to amphibians and reptiles due to climate change were discussed in depth in PRCCC (2013).

Source: Wanda I. Crespo

SOUTHERN KARST

About 40% of the tropics and subtropics are covered by open or closed forest, of which 42% is dry forest, 33% is moist forest, and about 25% is wet and rain forest. The dry forests account for about 22% in South America and 50% in Central America. Subtropical dry forest covers approximately 17% of Puerto Rico and its adjacent islands and cays, including the outlying islands of Mona, Desecheo, Culebra, Caja de Muertos, and the majority of Vieques. On the main island of Puerto Rico, it covers southwestern Puerto Rico from Santa Isabel to Cabo Rojo and a small area near Ceiba and Fajardo. Dry forests vary in species composition and structure depending on soil types, which vary across the life zone (Ewel and Whitmore 1973). Subtropical dry forest over a limestone substrate is best illustrated and most studied in the Guánica State Forest (Alvarez et al. 1990; Murphy and Lugo 1995).

Annual precipitation in the subtropical dry forest of Guánica ranges from 600 to 1,000 mm with an average of 860 mm, received seasonally with a peak during August to October and with periods of little to no rainfall between December and April. Because of the winds and high temperatures, water deficits may occur up to 10 months of the year (Miller and Lugo 2009; Ewel and Whitmore 1973). Temperatures range from an average of 24°C in January and February to 28°C between August and September (Medina and Cuevas 1990).

Vegetation
Generally, dry forests are smaller and less complex floristically and structurally than wet forests. The vegetation tends to form a complete ground cover and, on most soil types, is deciduous. Leaves are often small and succulent or coriaceous, and species with thorns or spines are common. Tree heights do not usually exceed 15 meters and the crowns are broad, spreading and flat. Plants are usually low in moisture content and the wood of most species is hard and durable. In these forests, the seasonality of rainfall is a dominant ecological factor and patterns of growth and reproduction are synchronized with the availability of water. In most tropical and subtropical dry forest, two dry periods are characteristic, a minor one in the summer months and a major one in the winter (Ewel and Whitmore 1973; Murphy and Lugo 1986; PRCCC 2013).

Substrates in the subtropical dry life zone include limestone, volcanic, alluvial, and ultramafic igneous and structure and species' composition varies depending on substrate types (Gould et al. 2008). The subtropical dry forest has been converted and fragmented in large part to agriculture (including grazing land), urban and rural development, and areas of tourism. The integrity of the remaining forested areas is threatened by encroaching adjacent development, invasive species, and fire; the latter two being exacerbated by impacts from climate change.

Fauna
More bird species are present in the Guánica Forest than in montane rain forests of Puerto Rico (31 species versus 20 species per 1,000 individuals) and there is almost four times the density of birds than in the rainforest (Miller and Lugo 2009). Kepler and Kepler (1970) compared the diversity and abundance of birds in the forests of the Luquillo Mountains and of the Guánica State Forest. They found greater diversity, and with respect to the more common species, larger populations.

CASE STUDY:
CLIMATE CHANGE EFFECTS:
Winter Migrant Bird Studies, Guánica

The Guánica Forest has been the site of one of the longest running studies of winter resident migrant birds, both those that are fully integrated into the fauna and those that are opportunistic and whose numbers vary from year to year. This mist-netting program, running for over 49 years, has documented dramatic declines in several species of year-round resident birds as well as the dominant set of winter resident migrants. Capture rates are 33% of what they were 20 years ago. Despite the dramatic declines, annual survival rates of the three more common species have remained constant indicating that declines in migrant captures are driven by declining recruitment into the Guánica Forest (Wunderle and Arendt 2017; Faaborg et al. 2013). While researchers continue to explore possible explanations for these significant declines, the diversity of the species involved and the complexities of their demographics make this a difficult task. Among possible causes are the long-term variations in rainfall associated with global climate change that might be affecting habitat quality at the breeding or wintering grounds, but further investigation is necessary (Faaborg et al. 2013).

Source: USFWS National Digital Library

Source: USFWS National Digital Library

CASE STUDY:
Puerto Rico Crested Toad

The Federally-listed endangered Puerto Rican crested toad (*Peltophyrne lemur*) historically occurred in the northern karst and presently occurs naturally in the southern karst in the Guánica Forest. Natural breeding ponds, seasonal in nature, lie close to the shoreline. With sufficient rainfall, breeding events occur in these fresh to brackish water seasonal ponds. Impacts to these ponds from saltwater intrusion due to sea level rise, flooding due to more frequent and intense storms, and lack of inundation or premature water loss due extended periods of drought may result in the elimination of these areas for breeding, affecting the long-term survival of the species. Conservation measures with multiple partners designed to recover the toad include protection and enhancement of habitat and natural breeding ponds, construction of artificial breeding ponds in both the northern and southern karst, and the introduction of captive-bred tadpoles or translocation from natural ponds, and education (Pacheco 2016). As of 2014, the species' status was improving, but the 2017 hurricanes impacted coastal habitats used by the species.

APPENDIX C

Figure 10. Wetland systems in Puerto Rico.

Recently, the Coastal Change Analysis Program (C-CAP; NOAA 2017) completed a landscape classification of the island based on 2010 imagery. Because the USFWS and NOAA efforts used the same standard classification scheme for wetlands based on Cowardin et al. (1979) wetland categories, a coverage comparison between the C-CAP and National Wetland Inventory (NWI; USFWS 1983; Figure 10) map products was possible, including a comparison based on the different years they were prepared.

Table 1. Classification of changes in wetland cover between NWI and C-CAP maps and conditions used to qualify change.

CHANGE CLASSIFICATION	CONDITIONS
POSITIVE	Unit increasing in complexity, unit decreasing in salinity.
NEGATIVE	Unit decreasing in complexity, unit increasing in salinity, loss of coverage. Some opportunities for enhancement/restoration.
LOST	Developed, converted to impervious soils, or filled in. Very little possibility of enhancement and/or restoration.
AGRICULTURAL CONVERSION	Unit converted to agriculture (cultivated crops, hay and restoration.
PERSISTED	Unit remained the same through period.

A specific change identifier was determined for each wetland polygon and a subjective "trend" classification was developed in order to determine the type of the change when comparing the results of the two maps (Table 1).

Based on the results of the comparison, palustrine wetlands have changed the most over time having been transformed between 1977 and 2010 (Table 2 and NOAA, 2017). Estuarine wetlands have been transformed but significant acreage of these wetlands remains in some parts of the island. Many of the areas where wetlands have persisted are around Culebra and Vieques and in areas with some level of federal or commonwealth government protection or management, such as the Cabo Rojo National Wildlife Refuge, Boquerón State Forest and Natural Reserve, Caja de Muertos Island, Hacienda la Esperanza in Manatí, and the San Juan Bay Estuary System. It is important to note that, while there are a number of wetland areas that have persisted and a small acreage of wetlands that showed a positive trend from 1977 to 2010, the majority of wetlands compared in this study (66,448 ha) were either converted to agricultural uses, lost completely, or negatively impacted (see Figure 11 and Table 1 in the main WG2 document). It is also important to note the NWI is poor at capturing inland, upstream wetlands, likely due to the difficulty of interpreting the 1977 images in mountainous areas and the small scale of wetland features such as riparian zones. The NOAA C-CAP effort is focused on the coast and therefore does not include any inland, upstream wetlands. However, based on other land use studies, such as those done for El Yunque, riparian and other wetlands associated with inland water bodies have been lost or altered by agriculture, residential and tourism development, and even industrial development in some mountain towns.

Table 2. Wetland types and areas that have been transformed versus persisting from 1977 to 2010.

SYSTEM	STATUS	ACRES	HECTARES	SHARE OF TOTAL
Estuarine	Transformed	27,308.68	11,051.43	15%
Estuarine	Persisted	42,392.91	17,155.80	24%
Lacustrine	Transformed	195.12	78.96	0%
Lacustrine	Persisted	196.43	79.49	0%
Marine	Transformed	1,595.53	645.69	1%
Marine	Persisted	29,818.89	12,067.28	17%
Palustrine	Transformed	52,326.79	21,175.90	30%
Palustrine	Persisted	22,429.31	9,076.82	13%
Riverine	Transformed	444.09	179.72	0%
Riverine	Persisted	169.11	68.44	0%

BIOLUMINESCENT SYSTEMS

In systems such as Bahía Fosforescente in La Parguera, Puerto Mosquito in Vieques (Figure 12), and Laguna Grande in Fajardo, the bioluminescence can be observed almost all year. Other places in Puerto Rico occasionally exhibit bioluminescence under favorable environmental conditions (e.g., Laguna Joyuda, Mar Negro, Monsio José, and Bahía de San Juan).

Pyrodinium bahamense var. *bahamense* is the main bioluminescent dinoflagellate in the bioluminescent systems of Puerto Rico (Margalef 1957; Figure 13A) and in other locations in the Caribbean (Seliger et al. 1970; Pinckney et al. 2014). Although this species has been characterized in other areas (e.g. Indian River Lagoon, Florida) as a potentially toxic dinoflagellate causing paralytic shellfish poisoning (PSP; Landsberg et al. 2006), no toxic events have been reported in Puerto Rico. In addition to *P. bahamense*, other bioluminescent dinoflagellates occurring in Puerto Rico include *Protoperidinium* spp., *Polykrikos* sp., and *Ceratium fusus* (Figure 13) (Pérez-Reyes et al. 2013).

The display of light has made bioluminescent systems an important tourist attraction, contributing significantly to the economy of the surrounding areas. Yet, their ecological significance is more important though commonly underestimated. Bioluminescent systems are areas of nutrient cycling and transport and excellent sources of primary and secondary productivity (Burkholder et al. 1967; Coker and González 1960; González 1965). Protected species, such as sea turtles, dolphins, and manatees, are seen regularly inside these systems looking for food and refuge. The bioluminescent bays and lagoons by themselves and the roots of the mangroves surrounding these areas provide nursery and habitat for several species, including commercially important fishes, mollusks, and crustaceans. Furthermore, the mangroves protect the coast during major storms and hurricanes, buffering the wind and wave energy, and their roots serve as traps of land-derived sediments. Thus, bioluminescent systems function as a buffer zone between land and the open ocean. Despite their economic and ecological importance, these ecosystems have been less studied compared to seagrasses, coral reefs, and other mangrove systems.

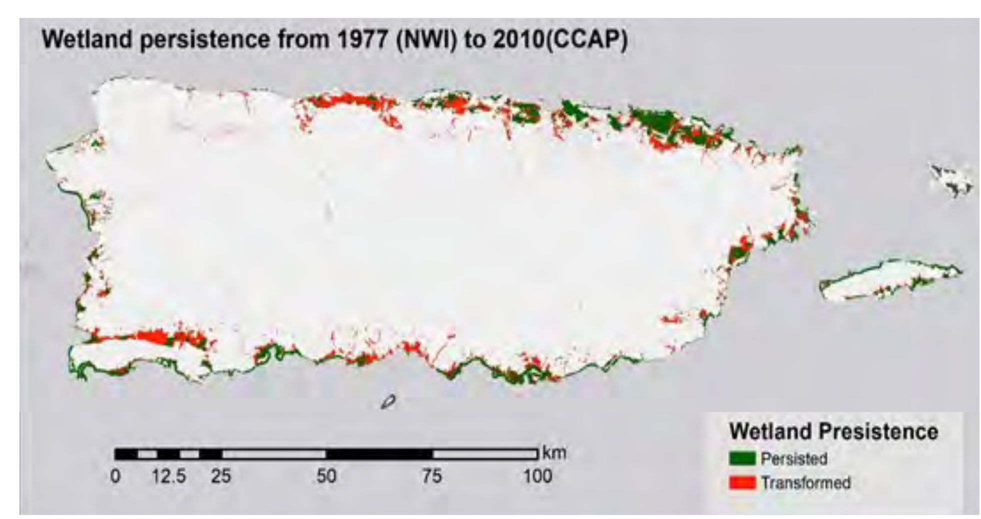


Figure 11. Overall persistence of wetlands in Puerto Rico based on a comparison of the 1977 NWI and 2010 C-CAP maps.

Bioluminescent systems are extremely sensitive to changes in watershed practices and to climate change. The vulnerabilities of these ecosystems to climate change are further aggravated by anthropogenic pressures such as habitat alteration, human-induced sediment inputs and resuspension, excessive boat traffic and anchorage, sewage wastes, agricultural fertilizers, chemical contaminants, trawl fishing, and marine debris. Increases in human populations and shoreline development in the surrounding areas (e.g., illegal houses in the Papayo area, close to Bahía Fosforescente) can result in discharges of wastewater and sediments affecting the water quality, with subsequent changes in the structure of these ecosystems. Shoreline development also results in light pollution (Hölker et al. 2010; Davies et al. 2014), which impairs the capacity of the naked human eye to discern the intensity of bioluminescence relative to the background.

Understanding and predicting the effects of climate change on bioluminescent systems can only be achieved by understanding the multiple environmental factors that control and regulate the abundance of phytoplankton organisms, including *P. bahamense*, and the phytoplankton community as a whole. Due to their short generation times (i.e., hours to days), phytoplankton organisms respond quickly to variations in temperature, salinity, light regimes, nutrients supply, and water column stability, all of which are driven by changes in climate conditions. As a result, these organisms are often the first ones to be impacted by climate change, and structural changes in their communities are the first indicator of ecosystem perturbations (Hays et al. 2005).

Phytoplankton contributes to half of the global primary production (Falkowski et al. 1998) and is at the base of the trophic food webs, mediating the transfer of energy to higher trophic levels (Field et al. 1998; Cloern and Jassby 2010). Therefore, any changes in community structure can severely impact and alter the ecosystem services and function (Paerl et al. 2006; Winder and Sommer 2012) of bioluminescent systems.

Blooms of *P. bahamense* have been linked to nutrient inputs after rainfall events (Phlips et al. 2004, 2006, 2011, and 2014; Soler-Figueroa and Otero 2015 and 2016) and to watershed and terrestrial runoff (Usup and Azanza 1998; Morquecho et al. 2012; Usup et al. 2012). Specifically, the relevance of rain appears to be related to increases in phosphorus concentrations that result in high abundances of *P. bahamense* (Seliger 1989; Azanza and Miranda 2001; Badylak et al. 2007; Phlips et al. 2006; Morquecho et al. 2012). Furthermore, the requirement for soil extracts to grow *P. bahamense* successfully in cultures (McLaughlin and Zahl 1961; Oshima et al. 1985), mainly as a source of selenium (Usup 1995), supports the importance of rain as a source of land-derived materials promoting the formation of blooms of this dinoflagellate. Therefore, increases in the frequency and intensity of rainfall events under the climate change scenario may be beneficial for the growth of *P. bahamense*.

Figure 12. Bahía Fosforescente, La Parguera (up) and Puerto Mosquito, Vieques (down). As with most bioluminescent systems, both are small, shallow, and have narrow inlets to the sea. Source: Google Maps

However, the dynamics underlying the responses of phytoplankton organisms to rainfall events are complex, variable, and unpredictable. For example, different scenarios after rainfall events have been reported for bioluminescent systems including reductions in the abundance of *P. bahamense* (and in the observed bioluminescence) with concomitant increases of the dinoflagellate *Ceratium furca* (Glynn et al. 1964; Gold 1965; Seixas 1988), the replacement of *P. bahamense* and *C. furca* with blooms of the dinoflagellates *Prorocentrum micans* and *Akashiwo sanguinea* (Seliger et al. 1971), drastic decreases in *P. bahamense* populations (Soler-Figueroa 2006; Figure 14A), a bloom of *P. bahamense* and significant increases of *C. furca* (Soler-Figueroa and Otero 2015; Figure 14B), and decreases in *P. bahamense P. bahamense* and in the bioluminescence levels (Soler-Figueroa and Otero 2016). These contrasting results may be explained by the time, intensity and amount of rain which may differentially affect the hydrological (e.g., water residence times and water circulation patterns) and water quality conditions (e.g., salinity, light availability, nutrient regimes), ultimately influencing the phytoplankton composition, abundance, and distribution (Phlips et al. 2012; Winder and Sommer 2012; Thompson et al. 2015; Wells et al. 2015). Additionally, the length of drought periods before the rainfall events (Paerl et al. 2010; Wetz and Yoskowitz 2013), the presence of other species (Cloern and Jassby 2010), and the nutrient types, concentrations, and ratios (Anderson et al. 2002; Phlips et al. 2012; Tsuchiya et al. 2013; Wells et al. 2015), govern the responses of phytoplankton organisms in these coastal ecosystems.

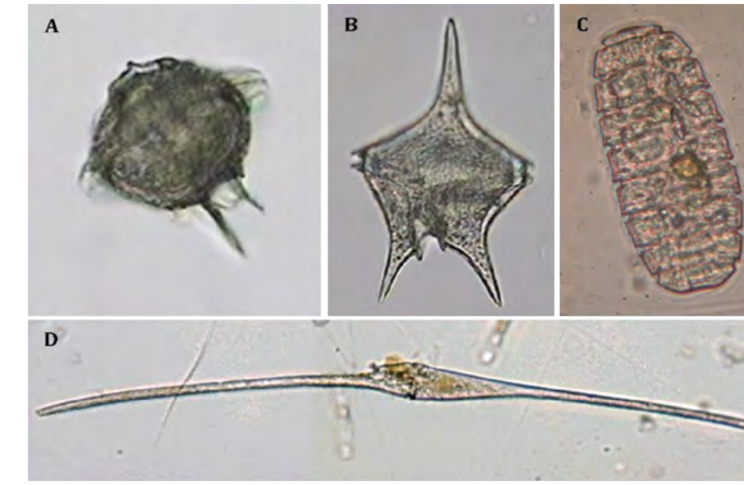


Figure 13. Bioluminescent dinoflagellates present in the bioluminescent systems of Puerto Rico. (A) Pyrodinium bahamense var. bahamense, (B) Protoperidinium sp., (C) Polykrikos sp., and (D) Ceratium fusus. (Magnification: A, B, C: 200×; D: 100, Photos: B.M. Soler-Figueroa)

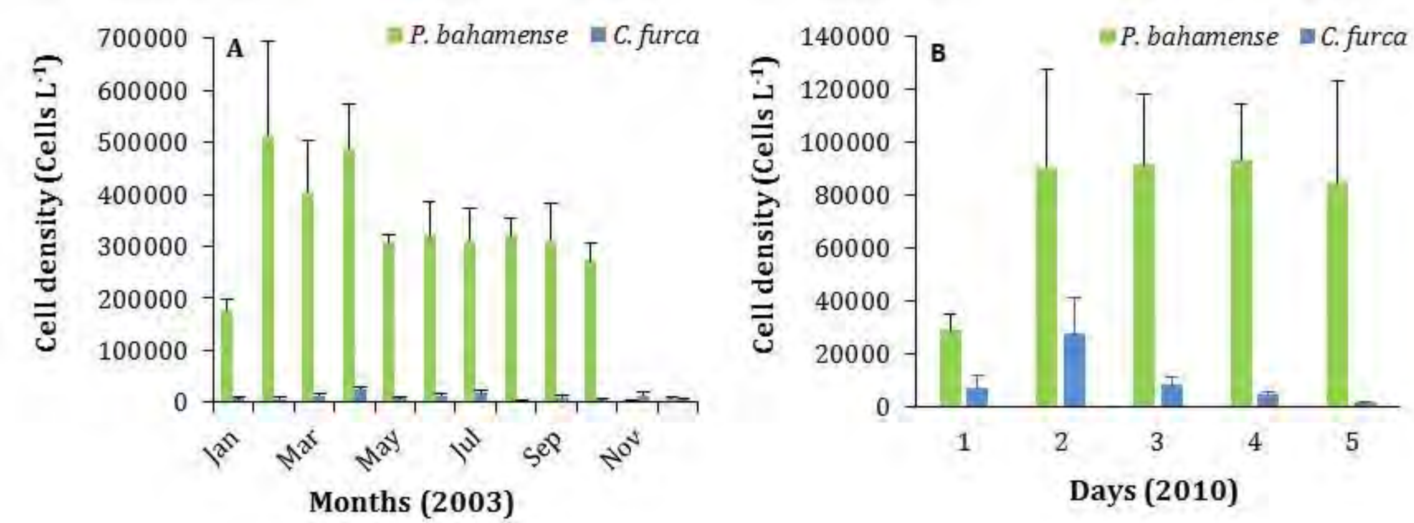


Figure 14. Contrasting responses in the populations of P. bahamense and C. furca after rainfall events. A) Drastic decreases in the cell densities of P. bahamense observed at Puerto Mosquito in November 2013 after ca. 400 mm of rain (Soler-Figueroa 2006). B) Blooms of P. bahamense and increases in C. furca populations observed at Bahía Fosforescente, La Parguera in November 2010 after ca. 97 mm of rain (from Soler-Figueroa and Otero 2015). Bars represent the standard errors.

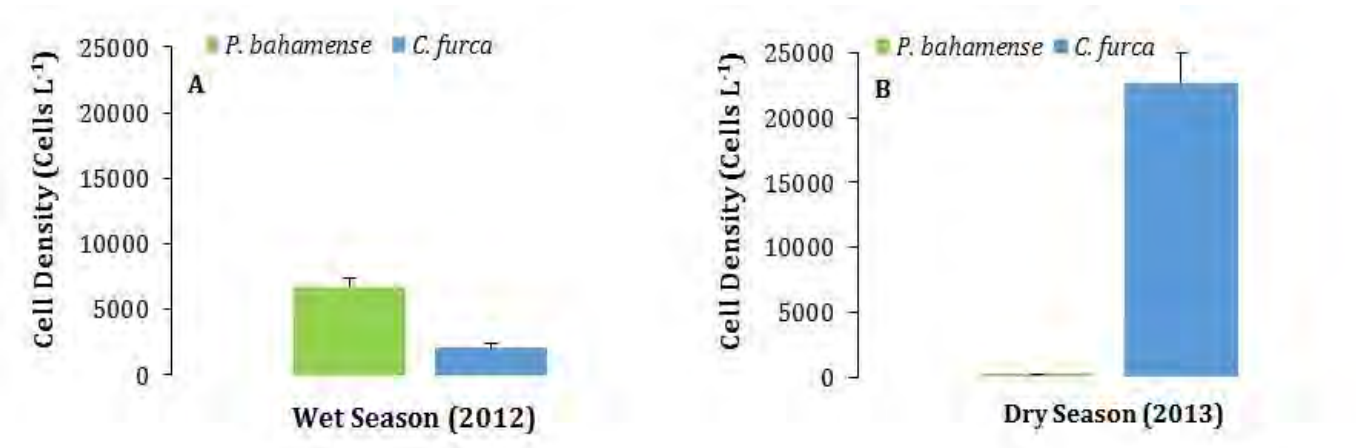


Figure 15. Comparisons of P. bahamense and C. furca populations between the A) wet and B) dry seasons (Soler-Figueroa 2015).

Increases in extreme events, such as storms and hurricanes, coupled with changes in wind stress and substantial inputs of land runoff will alter the water column stability, light penetration, and salinity regimes of bioluminescent systems. The impacts of salinity shifts may be less severe for *P. bahamense* populations due to the wide salinity ranges tolerated by this dinoflagellate (i.e., 10 – 45 practical salinity unit [psu]; Phlips et al. 2006; Sastre et al. 2013). For example, Soler-Figueroa and Otero (2015) observed cell densities of ca. 22,000 cells L-1 in Bahía Fosforescente after 38 mm of rain, which resulted in a salinity of 21 psu, demonstrating its low salinity tolerance. In contrast, increases in turbidity related to wind-driven resuspension of sediments and terrestrial runoff could severely impact the abundance of *P. bahamense* due to reductions in light penetration. Although the light requirements of this dinoflagellate are unknown, the incidence of *P. bahamense* in shallow ecosystems suggests that light availability plays a key role in the success of this species (Phlip et al. 2006). Also, the high wind speeds associated with storms can induce turbulent mixing of the water column, which is usually accompanied by the redistribution of phytoplankton species and in shifts from dinoflagellate dominance to diatom dominance (Margalef 1978; Margalef et al. 1979; Hinder et al. 2012). A similar scenario was observed in Bahía Fosforescente when sustained high wind speeds resulted in drastic reductions of *P. bahamense* populations, decreases of *C. furca*, and a shift toward a high abundance of diatoms (Soler-Figueroa 2015).

Extended drought periods and their associated low nutrient concentrations could also have devastating impacts on bioluminescent systems. For example, drastic decreases in *P. bahamense* populations (Soler-Figueroa 2015; Soler-Figueroa and E. Otero. 2015; Figure 15A, B) with concomitant reductions in the bioluminescence levels (Soler-Figueroa and Otero 2016) have been observed during the dry season in Bahía Fosforescente. Decreases in rainfall were also accompanied by shifts in the dinoflagellate composition towards a high abundance of *C. furca* (Figure 15A, B). Blooms of this dinoflagellate during low nutrient loadings have been linked to their luxury consumption strategies (i.e., excessive cellular storage not related to growth rate; Baek et al. 2008) and mixotrophic capabilities (i.e., the ability to prey upon other planktonic species; Smalley and Coats 2002; Smalley et al. 2003). Therefore, the prolonged drought conditions expected due to climate change may result in abrupt changes in the phytoplankton community of bioluminescent systems towards mixotrophic, heterotrophic, and small-sized phytoplankton species (due to their higher surface to volume ratio), as has been observed in other ecosystems (e.g., Finkel et al. 2010; Caron and Hutchins 2012; Phlips et al. 2014). These changes will be extended through the trophic food webs (Caron and Hutchins 2012; Rice et al. 2015), with potentially adverse effects on the structure and function of bioluminescent systems.

Bioluminescent systems are under continuous pressure and experience alterations due to complex interactions between natural processes, human activities, and climate change. Given their small volumes, shallow depths, and long water residence times, these bays and lagoons are highly vulnerable to any perturbation to their environment. Recent studies have shown that local precipitation patterns influence the dinoflagellate composition and the bioluminescence levels in Bahía Fosforescente, La Parguera (Soler-Figueroa and Otero 2015 and 2016).

APPENDIX D
Puerto Rico Shorelines

DUNE MORPHOLOGY AND PROCESSES

Coastal dunes are depositional landforms occurring adjacent to the beach that form because of aeolian (wind-driven) sediment transport. For aeolian transport to occur, the beach has to be wide to provide enough sediment and space for dune formation, the sediment grain size has to be small for the wind to transport it, and landward wind energy has to be strong enough over prolonged periods. If wind-transported sediment encounters a barrier such as vegetation, wave-driven debris, or a fence or building, sediment will be deposited and may result in a dune. Maun (2009) summarizes dune formation based on three requirements: 1) dominant landward wind energy that transports sand, 2) continuous sand supply, and 3) obstacles that cause deposition.

The northeasterly trade winds are the main source of strong and constant wind energy in Puerto Rico and other Caribbean islands. These planetary winds greatly influence the northern coast of Puerto Rico contributing to the development of high-energy, wide beaches that provide the sediment source for dune formation as long as beaches have the appropriate orientation. Unlike continental beaches, Caribbean islands such as Puerto Rico have beach orientation that vary greatly because of the numerous pocket beaches.

Coastal dunes cannot exist without a wide beach. The subaerial (portion from the vegetation to the shoreline) beach which is mostly dry is the source of sediment and space for dune formation to occur. A spacious subaerial beach zone is essential for an active dune forming processes. Dunes are a reserve of sand for the beach, especially when waves erode the dunes and deposit their sediment on the beach.

Beaches and dunes interact through wave energy that creates currents capable of eroding or accreting the beach. Therefore, beaches and dunes may look different depending on the circumstances altering wave energy related to the weather. Waves and currents may also alter the morphology of the beach and the availability of sediments for dune formation by widening or narrowing the subaerial part of the beach during seasonal cycles or climatic events. Constant sand movement gives the beach an unstable character that allows for the continuity of geomorphic processes (Komar 1999).

Coastal vegetation is the most common obstacle causing deposition and forming dunes. Dune vegetation can tolerate extreme conditions including high wind speed, salt spray, and burial (Maun 2009). Dune-forming vegetation includes grasses and creepers such as *Sporobolus virginicus* or "matojo de burro" (seashore dropseed) and *Ipomea pes-caprae* or "batata de playa" (beach morning glory). Other dune-forming obstacles include debris and non-natural structures such as trashcans, seawalls, and buildings.

FAUNA OF SHORELINE HABITATS

Seabirds and Shorebirds

Seabirds and shorebirds found in Puerto Rico spend a large part of their life cycle on the rocky and sandy beaches of the island. Some species migrate from North America in the fall and winter. Migratory birds use the island's littoral zone as a winter stopover. Resident species feed and breed in this habitat throughout the year. Seabirds spend time feeding on fishes, mollusks, and crustaceans in shallow coastal and open ocean waters. Shorebirds, as the name implies, are frequently found in flocks walking along sandy and rocky shores. Shorebirds have long legs and probing bills useful for finding invertebrates in the sand, mud, and water. Although other bird families are found on shorelines, seabirds and shorebirds depend predominantly on this ecosystem for their survival. Currently, the destruction of coastal shoreline ecosystems due to development is a major threat to these birds. Further research on population trends is needed in order to understand the current and future vulnerability of seabirds and shorebirds. Some of the commonly observed species which rely on coastal environments are d escribed below.

Brown Pelican, *Pelecanus occidentalis*

The brown pelican (Figure 16) is a resident of the island. Juveniles are brown with white bellies, while adults have brown bodies with white heads. Pelicans are on average, 100 to 137 centimeters long and weigh 3,500 grams. Pelicans have a long bill with a large expandable pouch used for fishing and catching shrimp. The brown pelican is the only species from its family that plunges into the water to catch prey. This species breeds in colonies in wooden nests on rocky cays. The largest colony in Puerto Rico is found on Cayo Conejo (Rabbit Key), Vieques. Due to past use of the pesticide DDT, which greatly affected reproductive success

Figure 16. Brown pelican (Pelecanus occidentalis) flying over Torrecilla lagoon, Piñones (Photo: Z. M. Vazquez)

of this species, brown pelicans were listed under the Endangered Species Act (ESA) until 2009 when the United States Fish and Wildlife Service (USFWS) determined the species had recovered and delisted it.

Magnificent Frigatebird, *Fregata magnificens*

The magnificent frigatebird (Figure 17) is a large resident tropical seabird with an extended wingspan of 2.5m. Its aerial agility allows it to capture fish by gliding along the water surface, and it also feeds on other seabird chicks. Magnificent frigatebirds build and nest on wooden platforms in tree top and shrubs near the shore. Few large, active colonies have been observed on the island, coinciding with a regional decreasing population trend over the past years.

Figure 17. Female magnificent frigatebird (Fregata magnificens) in Piñones (Photo: L. L. Fidalgo, MSEM)

Laughing Gull, *Leucophaeus atricilla*

The laughing gull (Figure 18), as its name implies, makes a peculiar chuckling sound that is easy to recognize. This opportunistic species feeds on almost anything it can catch or steal, from fish to trash, visiting a wide range of marine, freshwater, and terrestrial habitats. Nevertheless, they are mainly seen on the coastline. Laughing gulls frequently breed in colonies on islets near the shore away from terrestrial predators.

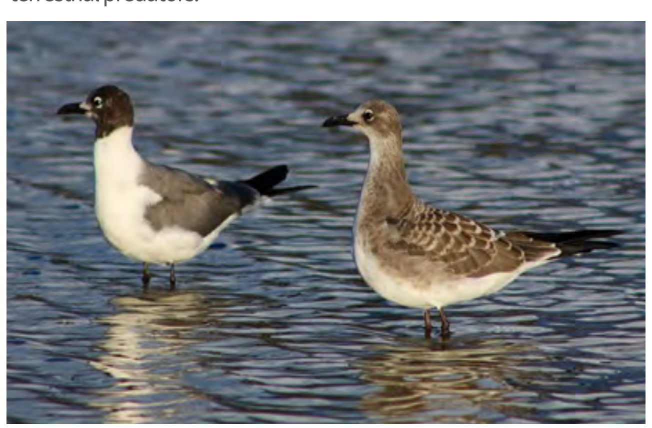


Figure 18. Adult (Left) and juvenile (Right) laughing gulls (Leucophaeus atricilla) during the nonbreeding period (Photo: Z. M. Vazquez).

Royal Tern, *Sterna maxima*

Another resident seabird in Puerto Rico is the royal tern (Figure 19). This is the largest species of the tern family, with an average size of 51 cm. This species depends on coastal marine habitats for feeding and breeding. The royal tern nests in colonies on small islets to avoid predators and to stay close to prey, such as fish and crustaceans. Coastal development and overfishing potentially threaten populations of this species.

Figure 19. Adult royal tern (Sterna maxima) in San Juan Bay during non-breeding period (Photo: L. L. Fidalgo, MSEM).

Spotted Sandpiper, *Actitis macularia*

The spotted sandpiper (Figure 20), and many other species under the family Scolopacidae, are migratory visitors to Puerto Rico. This species is present in Puerto Rico from September to March after flying from North America in search of food. Shorelines provide important habitat for this species for reproduction and foraging during the winter stopover. Spotted sandpipers are commonly seen along coastal riverbanks and rocky shores.

Figure 20. Adult spotted sandpiper (Actitis macularia) with winter plumage (Photo: L. L. Fidalgo, MSEM).

Figure 22. Sea turtle nesting areas in Puerto Rico. The red lines indicate the study site areas with main nesting activities.

Semipalmated Plover, *Charadrius semipalmatus*

One of the most frequently observed migratory shorebirds in Puerto Rico is the semipalmated plover (Figure 21). During the winter, this species is generally observed in flocks on the upper part of sandy beaches. Semipalmated plovers feed on insects found in coastal vegetation.

Figure 21. Adult semipalmated plover (Charadrius semipalmatus) resting on the sandy beach of Piñones (Photo: Z. M. Vazquez).

Sea Turtles

Nesting surveys were conducted from July 1, 2015 through June 30, 2016 on the west and northwest coast (which included beaches of the municipalities of Mayagüez Añasco, Rincón, Aguada, and Isabela), southeast (Yabucoa-Maunabo-Patillas), northeast (Fajardo-Luquillo), north (Arecibo, Barceloneta, Dorado), and the islands of Culebra, Vieques, Caja de Muertos, and Mona. Even though nesting activities were documented in other municipalities of Puerto Rico, only results from index beach sites are presented in this report (see Figure 22 for Index Beaches). Nesting season for leatherbacks peak during April to June and hawksbills from August to December (DNER 2016).

The majority of sea turtle nesting on the north coast of Puerto Rico is by leatherback sea turtles (Table 3) while hawksbills use index beaches on the west and east coasts, as well as offshore islands, with the most hawksbill nesting reported on Mona Island (Figure 23; Table 4).

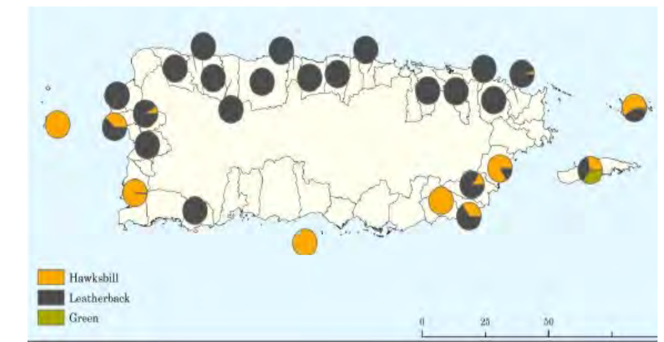


Figure 23. Pie charts depicting the proportion of nests by species in municipalities of main nesting beaches during 2016 season, Puerto Rico.

Table 3. Total number of nest numbers of leatherback index sites, nests laid at Puerto Rico (2016)

LOCALITIES	
DORADO	560
LUQUILLO-FAJARDO	315
MAUNABO	352
YABUCOA	140
VIEQUES	200
ARECIBO	115
AÑASCO	121
CULEBRA	44
ISABELA	50
MAYAGUEZ	48
BARCELONETA	11
SAN JUAN	20

Table 4. Total number of hawksbill nests laid at index sites in Puerto Rico (August- December 2015)

LOCALITIES	
MONA ISLAND	1328
CULEBRA	55
MAUNABO	97
PATILLAS	152
VIEQUES	101
HUMACAO	360
CAJA DE MUERTOS	45

Figure 24. Ipomea pes-caprae or beach morning glory found on the northern coast of Piñones, Puerto Rico Photo: L. L. Fidalgo, MSEM)

FLORA OF SHORELINE HABITATS

Beach and Dune Flora

Shoreline vegetation is characterized by species that can withstand harsh conditions including high wind speed, inundation, burial, salt spray, and low nutrient soil, among others (Maun 2009). These conditions are less intense with distance from the water, creating a landward vegetative species zonation. Pioneer species (species adapted to sand burial) are found closest to the waterline. This vegetation serves as a barrier that causes sediment deposition and initiates the formation of dunes. Their tolerance to burial allows them to withstand changes in the temperature and humidity of their microenvironment (Maun 2004). Once dune formation is initiated, the system of shallow roots possessed by pioneer species helps stabilize the dune system. The pioneer species of Puerto Rico include grasses and creepers such as *Sporobolus virginicus* commonly known as "matojo de burro" (seashore dropseed) and *Spartina patens* or "yerba de sal" (saltmeadow cordgrass); and *Ipomea pes-caprae* or "batata o bejuco de playa" (beach morning glory, Figure 24), and Canavalia (Figure 25). These species are most commonly found on the beach and at the toe of a dune's slope.'

Figure 25. Canavalia rosea or beach bean, La Pocita beach, Piñones (Photo: L. L. Fidalgo, MSEM)

Once the dune is initiated, its leeward slope and crest will be colonized by *Coccoloba uvifera* or "uva de playa" (seagrape, Figure 26). This tropical shrub has very strong branches and roots able to withstand inundation from high wave energy events, but it is not as tolerant to burial and salt spray as pioneer grasses and creepers. Therefore, in most dune environments, seagrape will be located farther landward in comparison to pioneer species. Though this species is essential for dune stabilization, it is not as efficient in initiating dune formation.

Figure 26. Coccoloba uvifera or seagrape found on stabilized dunes, Piñones (Photos: L. L. Fidalgo, MSEM)

Other shrubs commonly found on dunes are *Chamaesyce mesembrianthemifolia* or "Tártago de playa" (Coast spurge, Figure 27), *Argusia gnaphalodes* or "Té de playa" (Sea lavender), and *Suriana maritima* or "Temporana" (Bay cedar, Figure 28). These species are evergreen succulents that flower throughout the year, are drought tolerant, and propagate naturally on sandy beaches. The natural characteristics of these shrubs makes them ideal for erosion control and dune expansion.

Figure 27. Chamaesyce mesembrianthemifolia or coast spurge found on beach sand mats (Photo: L. L. Fidalgo, MSEM)

Figure 28. Suriana maritima or Bay cedar succulent shrub found in Piñones. (Photo: Laura L Fidalgo, MSEM)

Once dunes are stabilized, trees are the last type of vegetation to colonize the dunes. Mature dunes (Figure 29) have trees on the rear part furthest from the water, which creates a barrier for the backshore coastal zone, where human settlement may take place. Coconut palms (*Cocos nucifera L.)* and tropical almonds (*Terminalia catappa*) are familiar trees found on the sandy shores around Puerto Rico. Both species are adapted to shoreline dynamic environments. Thus, they have evolved to be fast-growing and hurricane resistant. The presence of shrubs and trees allows for dunes to sustain greater weather-related stress than some other habitats.

Figure 29. Mature dune on the coast of Piñones (Photo: L. L. Fidalgo, MSEM)

APPENDIX E
Marine Systems

SEAGRASS

CASE STUDY:
Long-term assessment of Caja de Muertos Island Seagrass Communities

By: Mariana C. León-Pérez

Caja de Muertos Island Nature Reserve (CMINR) is home to one of the largest expanses of seagrass beds in South Puerto Rico (Kendall et al. 2001). Spatial and temporal dynamics of seagrass cover where assessed in Caja de Muertos and Cayo Morillito from 1950 to 2014 using satellite and historic aerial photography (León-Pérez 2019 and León-Pérez et al. 2020).

In 2014, seagrass communities represented the second most abundant benthic category around Caja de Muertos Island, covering 1.5 km² of the study area (Figure 30). Most (56%) of the seagrass area mapped was dense seagrass habitats (70 – 100% cover) and mainly consisted of a combination of *Thalassia testudinum* and *Syringodium filiforme* species.

Thanks to the availability of historic aerial photography, León-Pérez et al. (2020) were able to reconstruct the historical distribution of seagrass beds in Caja de Muertos Island. An overall increase of 64% was reported from 1950 to 2014 (Figure 31), contrasting with worldwide seagrass declining trends (Orth et al. 2006). Armstrong (1981) and Hernández-Cruz (2006) found similar results, where seagrass cover increased 170% over a period of 43 years in Cayo Enrique, La Parguera, and 89% over a period of 64 years in Bahía Salina del Sur, Vieques, respectively. It is likely that the increase observed in Caja de Muertos Island was mainly a recovery response from tropical storm Baker that passed directly over CMNR in 1950. Although it is important to note that changes observed were not homogeneous in time and some differences were observed between years and between the studied zones (Figure 31).

It is predicted that more frequent and intense storms are going to impact our region due to climate changes. Hernandez-Delgado et al. (2018) and NOAA (2018) reported notorious declines in seagrass cover after the pass of Hurricane Maria in 2017. A preliminary examination of satellite data for Caja de Muertos Island after Hurricane Maria suggest a reduction in seagrass aerial extent and notorious declines in areas that used to have dense seagrass beds. Therefore, although this

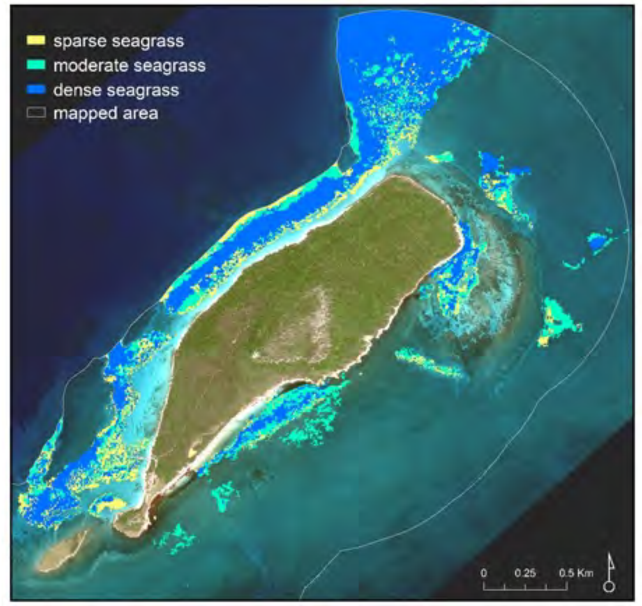


Figure 30. Seagrass categories mapped for 2014, projected on a high spatial resolution WorldView 2 image of Caja de Muertos Island.

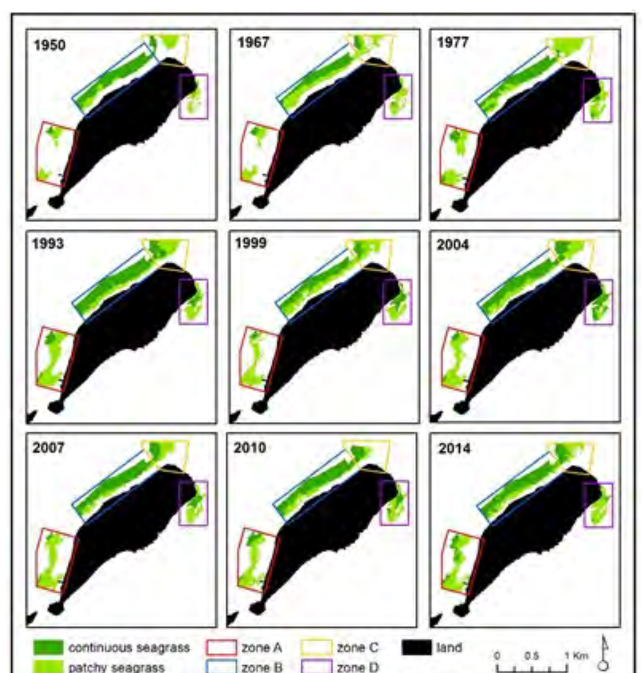


Figure 31. Seagrass cover from 1950 to 2014 within four zones studied at Caja de Muertos Island.

study highlights the capacity of seagrass beds in Caja de Muertos Island to recover from disturbances, more frequent and intense storms could jeopardize the capacity of these seagrass beds to bounce back after a disturbance. Even though some conditions caused by climate changes could benefit seagrass growth in Caja de Muertos Island, as for example, increase nutrient supply (van Tussenbroek et al. 2014) after rainfall events and increase CO_2 concentrations (Palacios and Zimmerman 2007), the effects of more intense and frequent storms could exceed the positive outcomes of these conditions. Therefore, long-term seagrass monitoring efforts are needed to understand the impacts of climate change related events and conditions, and to assess the need of implementing restoration measures.

CASE STUDY:
Invasive Seagrass, *Halophila stipulacea*

The invasive seagrass *Halophila stipulacea* (Figure 32), originally from the Indian Ocean, is a growing threat to native seagrass in the Caribbean. In 2002, H. stipulacea was first reported in Grenada, West Indies (Ruíz and Ballantine 2004). Since then, it has been observed around many other islands in the Caribbean (Willette et al. 2014). The rapid spread of this invasive seagrass has been aided by human intervention via fishing traps and anchors (Ruíz and Ballantine 2004; Willette et al. 2014). *Halophila stipulacea* can expand laterally at a high rate (up to 6 cm per day) and can displace manatee grass in as little as 10-12 weeks (Willette and Ambrose 2012). No seeds of *H. stipulacea* have been observed in the Caribbean (Willette et al. 2014) so spreading through fragmentation and boating activities is likely (see Weatherall et al. 2016 for a discussion of seagrass fragment dispersal and dispersal potential).

In 2016, *H. stipulacea* was reported at a number of sites around Culebra Island and Ceiba, Puerto Rico. The seagrass has been reported in the US Virgin Islands since at least 2008, where it is spreading rapidly in some areas, particularly those with frequent disturbance by recreational vessels. *Halophila stipulacea* was reported colonizing around coral reefs as deep as 24 m (Ruíz et al. 2017) and in high abundance in the Luis Peña Marine Reserve and Lobina Lagoon, Culebra. Given the ability of this species to tolerate a wide range of depths, substrates, and levels of light penetration, as well as observations in Puerto Rico and the Virgin Islands documenting its presence in areas with other seagrass species as well as corals, climate change may lead to conditions that favor the spread of this seagrass to the detriment of native seagrass and possibly corals.

Figure 32. Halophila stipulacea in Culebra Island, Puerto Rico.

FISHERY RESOURCES

Target Species

The highest percentages of total pounds landed for commercial fish and shellfish species in 2007-2011 and 2012 - 2017 are listed in Table 5. The DNER reported dolphinfish as the main recreational target for fishing tournaments, followed by blue marlin and wahoo from 2009 to 2013 (Table 5). Data from NOAA's Marine Recreational Information Program show that, for all recreational fishing modes, jacks and snappers were the highest-targeted species for 2017, followed by herrings and dolphinfish.

Fishermen sell their catch to fishing villas or associations, or directly to the public. A 2008 census showed that 80% of the fishers interviewed were full time fishers, generating an income of 50% or greater. The 2008 census report showed reef fish targeted 77% of the time by commercial fishers. The most targeted reef species was reported to be lobster ($6.00/lb) and conch ($4.00/lb) at 49% and 33% respectively. Deep water snappers were targeted 56% of the time and pelagics 42% of the time. Dive fishing was found to be responsible for almost all conch revenues and 60% of lobster revenues (Matos-Caraballo and Agar 2011; Agar and Shivlani 2017). Many reef species targeted by commercial fishers are vulnerable to overfishing because they are long-lived and grow slowly and, because they gather in spawning aggregations, large numbers of individuals can be easily captured.

Table 5. Percent landed of commercial species for 2007 - 2011 and 2012 - 2017 (Matos-Caraballo 2012; 2018)

SPECIES	% LANDED 2007-2011	% LANDED 2012-2017
QUEEN SNAPPER	10.71	5.8
SILK SNAPPER	7.3	8.2
YELLOWTAIL SNAPPER	6.3	7.7
LANE SNAPPER	5.75	5.3
TUNA, VARIOUS	6.1	2.2
WHITE GRUNT	2.7	0.3
DOLPHINFISH	4.3	5.9
KING MACKEREL	2.4	1.5
PARROTFISH, VARIOUS	2.3	1.3
TRUNK FISH, VARIOUS	2.5	0.0
RED HIND	1.4	2.1
CERO	1	1.2
SPINY LOBSTER	13.3	16.1
QUEEN CONCH	10.8	14.6

Table 6. Total weight in kilograms per year of species landed during recreational tournaments for 2009 to 2011. Table taken from Puerto Rico Marine Recreational Fisheries Statistics Program, 2009 – 2013 Final Report.

TOURNAMENT CATEGORY	2009 LANDINGS	2010 LANDINGS	2011 LANDINGS	2012 LANDINGS	2013 LANDINGS	TOTAL LANDINGS	AVERAGE LANDINGS
DOLPHINFISH (*Coryphaena hippurus*)	9,656.76	4,871.11	7,986.50	9,734.25	11,021.80	43,270.42	8,654.08
BLUE MARLIN (*Makaira nigricans*)	660	1,030.21	479.8	241.13	806.88	3,218.02	643.6
WAHOO (*Acanthocybium solandari*)	N/D*	248.9	307.72	1,112.22	908.5	2,577.34	644.33
WAHOO/DOLPHINFISH	218	265.9	273.16	NT	NT	757.06	252.35
WAHOO/SAILFISH	N/D*	145	60	205	182	592	148
SEVERAL SPECIES	0	18.08	158.3	0	0	176.38	88.19
SHORE	72	146.86	11.31	55.06	38.37	323.6	64.72
KAYAK	NT	NT	NT	71.32	77.59	57.81	67.7
TARPON/SNOOK**	0	0	0	0	0	0	0
TOTAL	10,606.76	6,726.06	9,276.79	11,418.98	13,035.14	50,972.63	10,562.97

*ND=No weight data, **=all released, NT=No tournament.

CORAL REEFS AND OTHER CORAL HABITATS

CASE STUDY:

Status of Back Reef/Lagoon Shallow Water Zones: NASA-Funded Coral Reef Research

The present condition of coral reefs in Puerto Rico is influenced by the coastline along which they are located. Those off the west coast have suffered from the impacts of sedimentation, runoff and eutrophication for the past decades with some reefs being almost at the brink of disappearing in terms of coral cover (Torres and Morelock 2002).

Over three years (2014-2017), the National Aeronautics and Space Administration (NASA) funded an interdisciplinary effort (Human Impacts to Coastal Ecosystems in Puerto Rico [HICE-PR]) to study the effects of land use and land cover changes in the Río Grande de Manatí (north coast; [RGM]) and the Río Loco (southwest coast; [RL]) watersheds on the condition of their associated coastal and marine ecosystems, including mangroves, seagrasses and coral reefs. In particular, the study concentrated on the analysis of the benthic coral reef components present in the back-reef and lagoons zones (Figure 33). The coral reefs of La Parguera in the southwest are some of the most studied shallow-water marine ecosystems in Puerto Rico due to the presence of the University of Puerto Rico's Department of Marine Sciences' facilities at Isla Magueyes. The RL watershed in adjacent Guánica was part of the study.

The RGM watershed has an approximate area of 608 km² and is characterized by a coastal plain with underlying karst topography. The watershed lies in the central part of the north coast with major urban growth along a coastline that has characteristically suffered severe erosion (Morelock et al. 1985). The RGM has one of the highest sediment discharges around the island averaging 10 m³ per second (Larsen and Webb, 2009). The watershed has a mostly humid climate (average rainfall of 1,875 mm per year). Land use in the area is agriculture bordered to the south by accelerated urban expansion. The coastline is characterized by beaches, rocky shorelines, nearshore coral reefs, and some seagrass meadows and salt marshes. A number of threatened coral species are common in some of the fringing reefs associated with this watershed. The ecosystems in the watershed have been impacted by coastal development, eutrophication, and debris disposal for decades. Results of the HICE-PR project showed a high cover of scleractinian corals (Average = 35%) with a predominance of elkhorn (*Acropora palmata*), brain (*Pseudodiploria strigosa* and *P. clivosa*) and lobed and mountainous star (*Orbicella annularis* and *O. faveolata*) corals in sites located approximately 1 km east of the Manatí river mouth (Playa Tómbolo). In contrast, the benthos of reef sites located closer to the river mouth (0.5 km east; Playa Machuca) show a predominance of macroalgal species such as *Dictyota* sp. and turf algae with less than 5% coral cover (dominated by the highly resistant *Siderastrea siderea* and *S. radians*; Torres-Pérez et al. unpublished).

Figure 33. Sites monitored through the NASA-funded HICE-PR project from 2014-17. A. North coast (Manatí); B. Southwest coast (La Parguera and Guánica).

The Río Loco watershed in southwest PR has an approximate area of 414 km². Some of the most ecologically and economically important shallow-water ecosystems (i.e., coral reefs, seagrass beds) along the southwest coast are associated with this watershed. The coast is dominated in large part by fringing mangroves that support local fisheries and are centers of recreational activities vital to the economic well-being of the area. The "geographic" boundary of the selected benthic ecosystems associated with the Guánica watershed are within the outlet of Guánica Bay and extend outside of the bay east and west along the coast. From 2000-2010, Guánica experienced an 18% increase in human population according to US Census data. Coral reefs in Guánica have been affected by an increased amount of fine clay sediments and nutrients for at least 50 years as a result of changes in the land use/land cover and irrigation practices associated with population growth. The input of terrigenous sediment to nearshore waters has caused a decrease in nearshore reef quality (Center for Watershed Protection 2008) and biodiversity. Reefs surrounding Guánica Bay have been classified as sites with "exceptional vulnerability" to river discharge, industry, sediment resuspension, agriculture, and dredging (Warne et al. 2005). Other pollutants within the watershed from human activities include high nitrogen concentrations (Ortiz-Zayas et al. 2001) and pesticides (Pait et al. 2008, 2009). The Guánica/Río Loco watershed was identified by the US Coral Reef Task Force Watershed Partnership Initiative (USCRTF-WPI) as a priority site, and the flagship study site for the implementation of activities aimed at reducing land-based sources of pollution for the protection of the watershed coastal and marine ecosystems, particularly the coral reef ecosystem (Carriger et al. 2013). Further, through the Corals and Climate Adaptation Planning (CCAP) project of the USCRTF Climate Change Working Group, this is one of the priority watersheds used to study the implementation of a climate smart management plan for reef resilience.

Similar to the Manatí reefs, a number of threatened coral species are common in some fringing reefs associated with the watershed. An analysis of the shallow-water back-reef and lagoon zones of some of the reefs in La Parguera and Guánica show a dominance of gorgonian plains, sandy areas, and zones dominated by branching corals (mostly staghorn [*Acropora cervicornis*], elkhorn [*Acropora palmata]* and finger [*Porites* sp.] coral). A direct relationship was found between the distance from the Río Loco mouth in the Guánica Bay and hard coral cover south and west of the bay entrance (Figure 34).

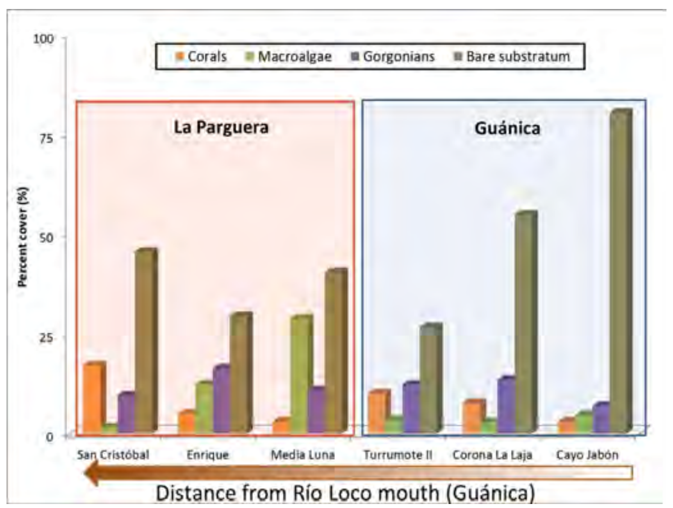


Figure 34. Differences in benthic composition as it relates to distance from the Río Loco mouth. The arrow indicates distance from the river mouth and usual flow direction.

CASE STUDY:

Status of Coral Reefs in Puerto Rico: Puerto Rico Coral Reef Monitoring Program

A total of 42 coral reef stations are included in the Puerto Rico Coral Reef Monitoring Program (PRCRMP), sponsored by NOAA and administered by the PR DNER. The location of the current coral reef monitoring sites is shown in Figure 35.

Baseline characterizations of the reef benthic and fish communities began in 1999 and have continued as new reef sites are added over the years. Annual surveys of 21 reefs on alternate years allow for monitoring of all 42 reefs over two years. Some of the parameters that are measured and monitored include the percent reef substrate cover by live corals and other sessile-benthic biota, as well as the taxonomic composition, density and size-frequency distributions of reef fishes and motile-megabenthic invertebrates. The methodological approach is based on a non-random, geographical, east-west, inshore-offshore, and depth stratified sampling design with sets of five permanent 10m-long transects established in areas of optimum coral growth at each reef. The percent reef substrate cover data are based on a continuous-intercept technique using a chain overlain on the line transects.

Reef stations include an array of geographical locations, depth zones (very shallow, shallow, intermediate, mesophotic), position on the insular shelf (coastal, intermediate, shelf-edge, oceanic), physiographic reef zones (reef crest, fore-reef, back reef, bank/shelf), geomorphological reef formations (fringing, patch, spur-and-groove, aggregate), and reef complexity based on measurements of rugosity (low, intermediate, high, very high).

Very shallow reefs (3 to 5 meter depth)
Very shallow reef stations within the 3 – 5 m depth range include reef-crest and back reef zones of fringing and bank reefs on the insular shelf. A total of 11 very shallow reef stations are included in the monitoring program with a percentage of live coral cover ranging from 5.0% at Maria Langa – Guayanilla to 56.1% at Bajo Gallardo – Cabo Rojo. A total of 21 scleractinian coral species and one hydrocoral (*Millepora* sp) have been identified along transects. Overall, the mean live coral cover at these very shallow reefs in 2017 was 27.5%. In terms of the percent live coral cover, three out of the four top-ranked reef stations within the 3 – 5m depth range are dominated by elkhorn coral, *Acropora palmata.* Five reef stations are dominated by lobed star coral, *Orbicella annularis* (complex); one reef station (Cibuco – Vega Baja) is dominated by finger coral, *Porites porites;* one station (Cayo Ratones – Salinas) dominated by greater starlet coral, *Siderastrea siderea*; and one station (Maria Langa – Guayanilla) dominated by mustard hill coral, *P. astreoides.* Bajo Rodriguez (Mayagüez) and El Negro (Cabo Rojo) are the reef stations with the highest number of hard coral species intercepted by transects with 12 and 11 species, respectively. Bajo Gallardo and Tres Palmas have the least number of coral species intercepted by transects with three and five, respectively. The two latter reef stations are essentially elkhorn coral biotopes.

The status of the very shallow reefs surveyed by the monitoring program are highly dynamic in nature because some (e.g., Tres Palmas 3, Bajo Gallardo 5, Cayo Aurora 3) are subjected to partial or total breakage due to variable wave action on different time scales, and thus are in a continuous and dynamic state of change.

Evidence of infection by what appears to be "patchy necrosis" has been noted in Tres Palmas and Bajo Gallardo. Although the disease prevalence is high and standing dead colonies apparently resulting from this or other infectious disease(s) are common, both reefs are thriving, and coral growth and recruitment appear to be occurring at faster rates than the deleterious effects of the disease(s) manifest.

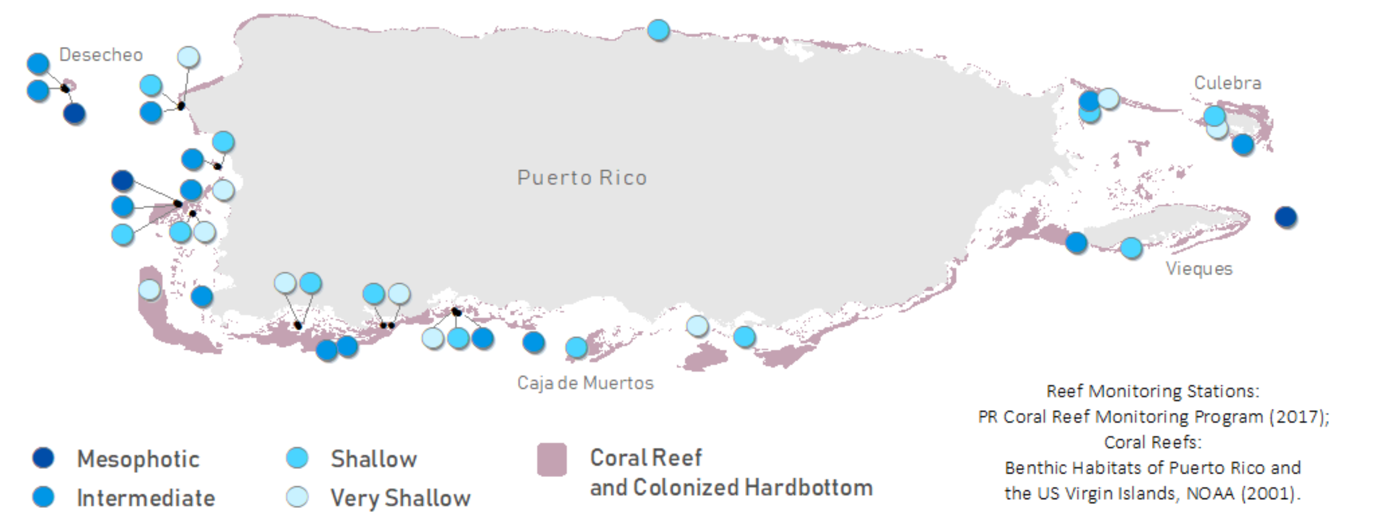


Figure 35. Location of reef stations included in the PRCRMP and their characteristics.

During baseline characterizations in 2016, east coast reefs Cayo Diablo (FAJ) and Luis Peña (CUL) exhibited extensive mortality of colonies that may be related to previous events of coral bleaching. These reefs are structurally constructed and taxonomically dominated, in terms of live coral cover, by *Orbicella annularis.* This coral was the most severely affected by the 2005 bleaching event in Puerto Rico, particularly in areas of low water turbidity. Low turbidity is prevalent on the east coast, particularly along the chain of offshore keys.

Large-scale mortality of *O. annularis* was observed during the baseline characterization of the Media Luna back reef in La Parguera. The relatively large size of dead standing colonies is indicative of favorable growth conditions until the reef was impacted by a major environmental stressor consistent with coral bleaching. West coast counterparts (Bajo Rodriguez, El Negro), although dominated by *O. annularis*, exhibited higher richness of coral species contributing to the reef substrate cover. This is relevant because these other coral species may have been more resilient to previous coral bleaching events than *O. annularis*. Also, the presence of large and healthy colonies of *O. annularis* suggests that a large-scale coral mortality event was not experienced by these reefs during the 2005 bleaching events.

Shallow reefs (8-15 m depth)
Shallow reefs in the 8 – 15 m depth are largely associated with patch, spur and groove, and fore reef formations within the insular shelf. From the 2015-2017 surveys, live coral cover varied between 12.7% at Cayo Esperanza in Vieques and 37.0% at Tourmaline in Mayagüez. The overall mean live coral cover of reefs included in the monitoring program within this depth range was 22.2%. A total of 25 scleractinian and one hydrocoral species were intercepted by transects, and the star coral complex, *O. annularis*, is the dominant coral group in terms of substrate cover in ten out of the 14 reefs surveyed.

The condition of reefs within the 8 – 15 m depth included in the 2015-17 PRCRMP reflects a high degree of resilience variability in response to environmental stressors, particularly the effects of previous coral bleaching events. For example, live coral cover at Tourmaline Reef declined by about 22.6% after the 2005 coral bleaching event, but after 12 years recuperated to the pre-bleaching coral cover with growth of branching corals (*M. auretenra* and *P. porites*) replacing previously occupied reef substrate by massive corals (*O. annularis* and *Colpophyllia natans*). In contrast, live coral cover at Puerto Botes Reef in Isla Desecheo declined by 58.5% after the 2005 coral bleaching event and had not recuperated by 2017. Puerto Botes now exhibits a taxonomic phase shift in its coral community structure in the sense that *P. astreoides* has displaced *O. annularis* as the dominant coral species in reef substrate cover.

Intermediate reefs (16-23 m depth)
Intermediate reefs in the 16 – 23 m depth range are typically spur-and-groove and bank reef formations associated with the shelf-edge and outer neritic shelf banks. The overall mean live coral cover of reefs included in the monitoring program within this depth range was 20.1% in 2017. Live coral cover varies between 14.9% at Canjilones Reef in Vieques and 36.6 % at Guanajibo Reef in Cabo Rojo. The lobed star coral complex, *O. annularis* is dominant in terms of substrate cover in ten out of the 12 reefs surveyed.

Puerto Canoas Reef in Isla Desecheo is another example of severe degradation of the coral community after the 2005 coral-bleaching event. Drastic declines in live coral cover, particularly *O. annularis,* have led to community structure phase shifts in which branching corals, *Porites porites*, have displaced massive corals as the dominant species in terms of reef substrate cover (García-Sais et al. 2017 and references therein). Likewise, the condition of Derrumbadero Reef in Ponce and Canjilones Reef in Vieques in 2017 was severely degraded with a marked decline in live coral cover, mostly *O. annularis*, after the 2005 coral bleaching event. Dead coral sections at Derrumbadero and Canjilones are now largely overgrown by turf and red encrusting algae (*Ramicrusta* sp).

The bank reef at Guanajibo in Cabo Rojo is an interesting case of a reef system markedly dominated by the *Orbicella* spp. complex that does not exhibit widespread coral mortality induced by recent environmental stressors, such as coral bleaching. This reef system is under the influence of the Guanajibo River plume and thereby characterized by semi-estuarine or intermittently estuarine conditions that tend to increase water turbidity. It has been proposed that water turbidity may act to protect corals during bleaching events in Puerto Rico (García-Sais et al. 2017). Also, the dominant coral species is *O. franksi,* which may be more tolerant to bleaching environmental precursors than the related *O. annularis.*

Mesophotic reefs (25 – 30 m depth)

Mesophotic reefs are associated with outer shelf deep terraces (El Seco) and the insular shelf edge (Tourmaline, Isla Desecheo). El Seco is a bank reef, Tourmaline is a spur-and-groove reef, and Puerto Canoas is a patch reef formation. A total of 21 coral species (mean: 10.1 spp/reef) have been intercepted by transects during monitoring surveys through 2017 in these mesophotic reefs. Live coral cover at these reef stations varies from 23.7% at Tourmaline Reef in Mayagüez to 41.1 % at El Seco in Vieques. The three reefs vary considerably with regard to their morphology, benthic community structure, ecological health, and resilience to environmental stressors.

Tourmaline reef is at the shelf edge off Mayagüez Bay. This reef is a coral buildup characterized by very large, massive coral colonies, particularly from the *Orbicella* spp. complex (mostly *O. faveolata*), that convey very high rugosity to the reef. Despite a slow but continuous recuperation trend since the baseline survey in 2004, this reef had extensive sections of dead coral colonized by benthic algae and other encrusting biota in 2017. Coral mortality and loss of substrate cover by live corals was not detected at this reef during and/or after the 2005 bleaching event. Thus, environmental stressors influencing the present reef condition occurred prior to the 2005 bleaching event and prior to our baseline survey in 2004.

Puerto Canoas Reef in Isla Desecheo is a patchy coral buildup largely constructed by Boulder Star Coral, *Orbicella spp.* (complex). Very large colonies with laminar formations of *O. annularis* (mostly *O. faveolata*) represent 56.5 % of the total cover by live corals (García-Sais et al. 2017 and references therein). With a mean live coral cover of 48.1 %, Puerto Canoas was one of the top reefs in the PRCRMP in terms of % reef substrate cover by live corals before the 2005 bleaching event. During 2006, live coral declined markedly and continued a declining trend until reaching a minimum cover of 24.7 % in 2010. Since then, live coral cover has been on a slow, but consistently increasing trend up to a mean of 27.8 % in 2017. A total of 12 coral species are intercepted by transects at Puerto Canoas.

El Seco Reef is a coral bank formation located near the edge of the southeastern Vieques shelf in depths of 30 – 40 m. The coral reef system is largely a biotope of boulder star coral, *Orbicella franksi,* growing as horizontal table-shaped colonies of up to one meter, supported by pedestals of unknown origin and variable heights. Even though its entire areal extension has not been mapped, the coral formation of El Seco represents the largest continuous coral reef system in Puerto Rico (García-Sais et al. 2017 and references therein). The mean coral cover at El Seco measured during the 2016 monitoring survey was 41.1 %, with *O. franksi* representing 92.0 % of the total live coral cover. There is no evidence of recent massive coral mortality at El Seco, indicating that the coral community at this mesophotic reef was resilient to the 2005 and perhaps other regional coral bleaching events.

Tourmaline reef. Source: Jorge Sabater

CASE STUDY:

Coral Disease and Bleaching

Coral Bleaching

One of the key characteristics of reef-building corals is their mutualistic symbiosis with populations of photosynthetic dinoflagellates commonly known as zooxanthellae. However, the beneficial mutualistic relationship between corals and zooxanthellae breaks down under stressful situations. Coral bleaching can occur during sudden reductions in salinity, or increases in chemical toxins, sea surface temperatures or solar irradiance, as the zooxanthellae are either expelled from the coral tissues (Hoegh-Guldberg 1999) or lose their photosynthetic pigments (Torres et al. 2007). Deprived of their energy source, corals become more susceptible to competitors, such as macroalgae (seaweeds), starvation, disease, and death (Harvell et al. 1999; Diaz-Pulido and McCook 2002; Diaz-Pulido et al. 2009).

Temperature

The most direct evidence of stress caused by climate change on coral reefs comes in the form of mass coral bleaching often due to stressful conditions resulting from prolonged sea surface warming. A small increase of 1.0°C, particularly during periods of 8 weeks or longer, can trigger a mass bleaching event (Buddemeier et al. 2004; Eakin et al. 2010). Bleaching events lasting 8-12 weeks or longer may trigger significant coral mortality (Eakin et al, 2010). Based on current trends, climate models have shown that coral bleaching has become an annual event since 2020 (Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2007; Hoegh-Guldberg and Bruno 2010).

Mass coral bleaching in the past two decades has been clearly linked to El Niño-Southern Oscillation (ENSO) events (Hoegh-Guldberg 1999; Glynn et al. 2001). These have increased in frequency, severity, and duration since the 1970s (Stahle et al. 1998; Mann et al. 2000). This combination (sea surface warming and intense ENSO events) has resulted in a dramatic increase in coral bleaching (Glynn 1994; Brown 1997; Wilkinson 2000). A rising baseline in warm-season sea surface temperature (SST) in coral reefs (Fitt et al. 2001; Lough 2000) suggests that physiological bleaching is at least partly to blame in the three most significant mass bleaching events in the Caribbean in 1987, 1998, and 2005. Each mass bleaching event over the last decades has caused major coral mortality in different localities. Although the data indicate that coral bleaching was much worse during the 1982- 83 El Niño than in 1997-98, temperature extremes during the two events were similar (Glynn et al. 2001; Podesta and Glynn 2001). The differences in response to these comparable events offers some support for the idea that corals or coral communities can adapt to higher temperatures over decades, either through adaptive bleaching (Baker 2003) or through evolutionary selection for more heat/irradiance-tolerant corals that survive bleaching events (Glynn et al. 2001). However, this is debatable as adaptation occurring over such a short time period seems unlikely and no evidence of an acclimatization response has been found to-date.

Sedimentation

The presence of suspended sediments affects the growth and cover of many reef-building coral species (Acevedo et al. 1989; Torres 2001; Torres and Morelock 2002). A study by Cardona-Maldonado (2008) found a significant inverse relationship between coral cover and the light attenuation coefficient (Kd; implicating turbidity from sediments and nutrients) in several reefs on the west and south coasts of Puerto Rico. Ryan et al. (2008) documented a significant (up to 2x) increase in sediment accumulation in the back-reef areas west of the Guánica Bay over the past 80 years, suggesting greater terrestrial sediment influx to the area. However, whether the presence of dissolved compounds in the water column benefits or affects shallow-water reef corals is still under debate. For instance, Ayoub et al. (2008) found that particularly colored dissolved organic matter (CDOM) absorbs radiation within the UV-B range (280-320 nm) and UV radiation attenuated more quickly on inshore reefs than in offshore oligotrophic waters such as those usually found at shelf edge reefs. This might explain some of our results that show a relatively high cover of sediment-sensitive species (such as *Acropora palmata* and *A. cervicornis)* in reefs located just outside the Guánica Bay. Examples from the Great Barrier Reef in Australia have shown that, while in the short-term (decades), excessive terrestrial sediment influxes degrade coral reefs, particular coral species can tolerate high sedimentation and turbidity providing for long-term (centuries to millennia) reef growth (Perry et al. 2012). More detailed studies are needed to clarify these contrasting results regarding the effects of suspended versus dissolved matter on reef biodiversity.

Major Bleaching Events

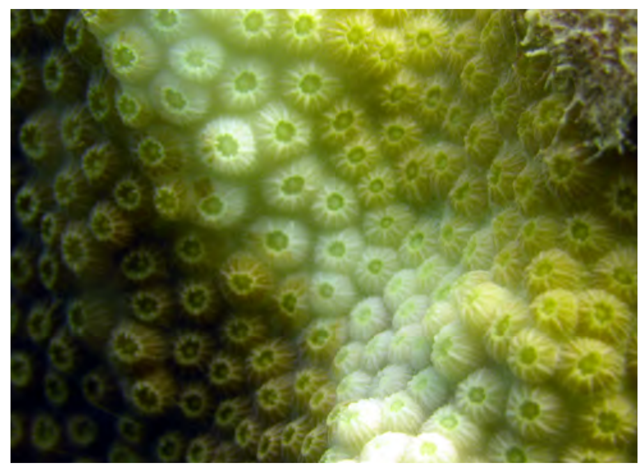
Notably, no incidents of mass coral bleaching were formally reported in the Caribbean before 1983 (Glynn 1983, 1996). According to 2012 data from Reefbase, from the early 1980s to 2012 more than 4,000 observations of bleaching had been reported. One of the earliest incidences was documented during the 1982-83 ENSO (Glynn 1983, 1988). Further, bleaching incidents were also recorded for 1987 and throughout 1998 (Williams et al. 1987; Williams and Bunkley-Williams 1988; Goenaga et al. 1989; Hernández-Pacheco et al. 2011), including Puerto Rico (Williams et al. 1987; Williams and Bunkley-Williams 1988; Goenaga et al. 1989; Williams and Bunkley-Williams 1990; Goenaga and Vicente 1990; Hernández-Delgado and Alicea-Rodríguez 1993; Hernández-Delgado 2000). In 2005, Caribbean reefs again experienced mass bleaching. Massive declines of corals across the entire Caribbean basin were reported with the average hard coral cover on reefs reduced from about 50% to 10%, in three decades mostly as a combined result of hurricane impacts and Caribbean-wide factors, likely associated with climate change (Gardner et al. 2003). The large- scale, white plague-like condition that occurred following the 2005 record-breaking SST across the northeastern Caribbean and subsequent bleaching event caused a 60% to 80% loss in coral cover (Miller et al. 2006; Miller et al. 2009; Weil et al. 2009), particularly impacting reef-building species such as the star coral species' (*Orbicella* spp.) complex (Hernández-Pacheco et al. 2011). During the 2005 event, combined white plague disease outbreaks, yellow band occurrences, and intensive bleaching caused an average 53% loss in live coral tissue in La Parguera (Cróquer and Weil 2009; Weil et al. 2009). Centennial colonies of *Orbicella faveolata* died within months as they were further infected by what appeared to be a cyanobacteria (Torres-Pérez, personal observations).

The 2005 Caribbean bleaching event resulted from increased SST up to 89.2°F at depths of 30 m and about 91.6°F on some reef crest zones off eastern Puerto Rico (Hernández- Delgado et al. 2006). In late 2005, the coral bleaching off the south and west coasts of Puerto Rico was devastating, and more evident on the reefs where the *Orbicella* species' complex was dominant in terms of substrate coverage (Hernández-Delgado, as quoted in García-Sais et al. 2008). This was followed by a massive outbreak of white plague, which caused mortality and a reduction of between 50% and 80% of live coral. This bleaching episode alerted many stakeholders to the susceptibility of Puerto Rico's coral reefs to the impacts of climate change, as increasing SST may result in more intense bleaching episodes. The impacts of bleaching on coral reefs depend on the frequency, severity, and spatial extent of the bleaching event. Depending on the coral species and depth at which it is located, there may be a change in growth rate of corals. Further, mass bleaching events have been shown to trigger significant declines in coral reef fish abundance and diversity (Pratchett et al. 2006; Pratchett et al. 2008). Climate-related factors, in combination with long-term fishing impacts, have been pointed out as a cause of long-term declining trends in reef fish abundance across the wider Caribbean region (Paddack et al. 2009).

Other Effects of Rising SST on Coral Reefs

Thermal expansion of the ocean from increasing SST and water from ice melt will result in an increase in the pressure gradient, which could cause changes in upwelling patterns (Bakun 1990). In the Caribbean, upwelling areas off the Guianas-Brazil Shelf, downstream of island passages, and off Venezuela are known to influence fishery production. Changes in upwelling or other circulation patterns could significantly affect large-scale reef connectivity, thereby affecting the dispersal and transport of larvae and nutrients, and potentially having long-term impacts on the distribution of corals and associated reef species across the wider Caribbean. Connectivity could also be compromised by increased fragmentation of reef habitat, due to coral bleaching and ocean acidification. Changes in the spatial and temporal scales of connectivity have implications for coral reef ecosystem management, especially the design and placement of no-take marine protected areas (MPAs; Munday et al. 2009). The size and spacing of MPAs may need to be strategically adjusted if reserve networks are to retain their efficacy in the future.

Increasing sea surface temperatures off the coast of Puerto Rico could cause corals physiological stress, and a subsequent increase in coral susceptibility to disease which increases the virulence of bacterial and fungal pathogens. The most profound and widespread changes in Caribbean coral reefs in the past 30 years have been attributed to disease; however, the reasons for the sudden emergence and rapid spread of diseases are not well known (Buddemeier et al. 2004). Twenty-three diseases and syndromes affecting corals have been identified in the Caribbean, and, in most cases, the pathogen causing the disease is unknown (Weil and Rogers 2011). Disease outbreaks and consequent mortality of corals and other reef organisms have been a major cause of the increase in coral reef degradation over the past decades (Epstein et al. 1998; Harvell et al. 1999; Rosenberg and Ben-Haim 2002). Although diseases and syndromes of corals and other reef organisms remain incompletely characterized (Richardson and Aronson 2002), they are known to be caused by both bacterial and fungal agents. Diseases can be lethal, but they exhibit a wide range of rates of progression. Most appear to affect some coral species more than others, but few, if any, are species-specific (Buddemeier et al. 2004).



Caribbean yellow-band disease. Source: Dr. Ernesto Weil

CASE STUDY:

Strengthening the Ecological Integrity of Coral Reefs by Reintroducing Herbivores

One of the most dramatic shifts in benthic community structure occurred after the massive die-off of *Diadema antillarum,* a keystone herbivore. The 1983-1984 mass mortality of *D. antillarum* occurred throughout the Caribbean basin and was the most extensive and severe die-off ever recorded for a marine invertebrate (Lessios 1995). Before 1983, the presence of this organism was common (13-18 ind m-2) on coral reefs in Puerto Rico (Bauer 1980; Vicente and Goenaga 1984). *D. antillarum* played an important role in structuring coral reef communities by controlling algal abundance (Carpenter 1981; Carpenter 1986; Carpenter 1990a, b; de Ruyter van Steveninck and Bak 1986; Odgen et al. 1973; Robertson 1987; Sammarco 1982), and algal productivity (Williams and Carpenter 1990). After the massive die-off, populations were drastically reduced, by 95-100%, in many Caribbean locations (Lessios 1995) and, at the same time, fleshy macroalgal cover increased between 100% and 250% (Phinney et al. 2001). The absence of *D. antillarum* not only influenced the benthic algal productivity of coral reef communities, but it also impinged on the settlement of coral recruits. Since then, parrotfish and surgeonfish have been the only herbivores primarily controlling algal abundance on Caribbean reefs (Mumby et al. 2007). However, overfishing and the use of certain gear types (fish traps) has caused steep reductions of parrotfish (Jackson et al. 2014), which has negatively affected coral reef habitat quality (Mumby 2016).

Most modern coral reefs in Puerto Rico are characterized by high algal abundance. The lack of herbivory and elevated inputs of nutrients into coral reefs are the main causes for the high algal abundance. Regulating fisheries and restocking herbivorous individuals are two ways to increase herbivory on corals reefs (Williams 2017). Dr. Stacey Williams, a scientist at the Institute for Socio-Ecological Research and Coastal Survey Solutions, LLC, has successfully collected *D. antillarum* settlers (Figure 36), reared the settlers to early adults (3-4 cm) in a laboratory environment, and reintroduced these individuals to coral reefs in La Parguera. This is a novel approach to *D. antillarum* recovery because the process bypasses the need to culture larvae until they metamorphose and then settle. Another benefits of this approach is that a new population of *D. antillarum* is introduced and, because the individuals are larger in size, "natural" predation of recruits is avoided (Williams et al. 2011).

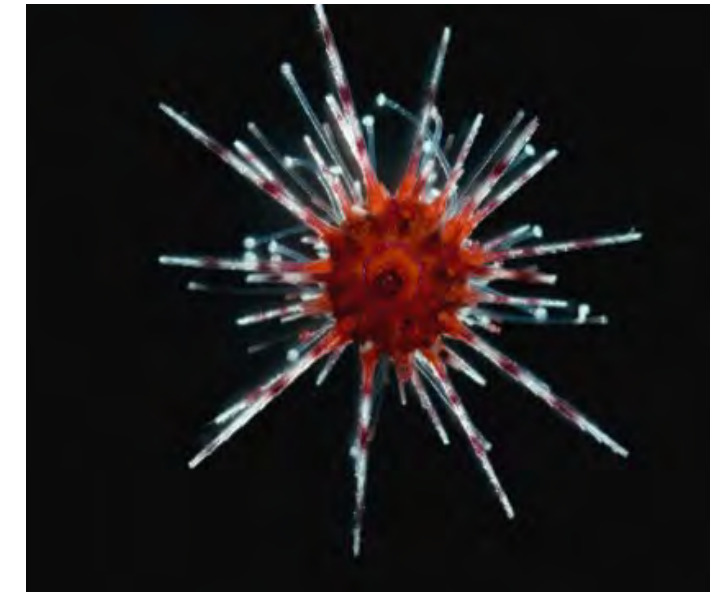


Figure 36. Diadema antillarum settler. Photo: Stacey Williams, ISER Caribe.

In 2016, 343 lab-reared *D. antillarum* were transferred and placed in corrals at a backreef of Media Luna, a mid-shelf emerged reef in La Parguera, Puerto Rico. The dominant benthic substrate at this reef was a mixture of turf algae and macroalgae, specifically *Dictyota* spp. and *Halimeda* spp. Seventy-nine (79) percent of young adults were recorded four months after the reintroduction and 75% after five months. Changes in benthic composition were evident in corrals one week after the reintroduction. *D. antillarum* in the corrals were efficient in grazing the benthos of algae, especially turf and *Dictyota* spp. in the corral. Ninety-five (95) percent of the

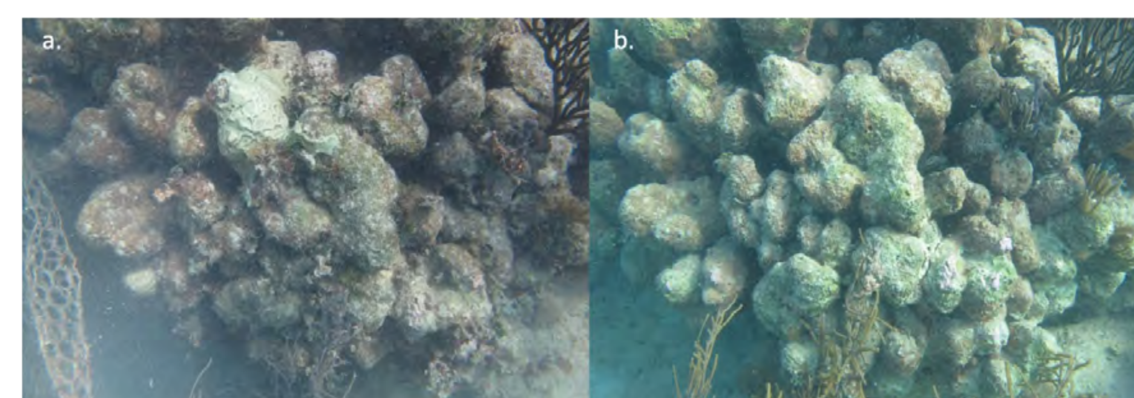


Figure 37. Photograph of the same enclosure before Diadema restoration (a.) and two months after the restocking (b.). The photograph on the right highlights the substrate free of benthic algae and encrusting tunicate, Trididemnum solidum.

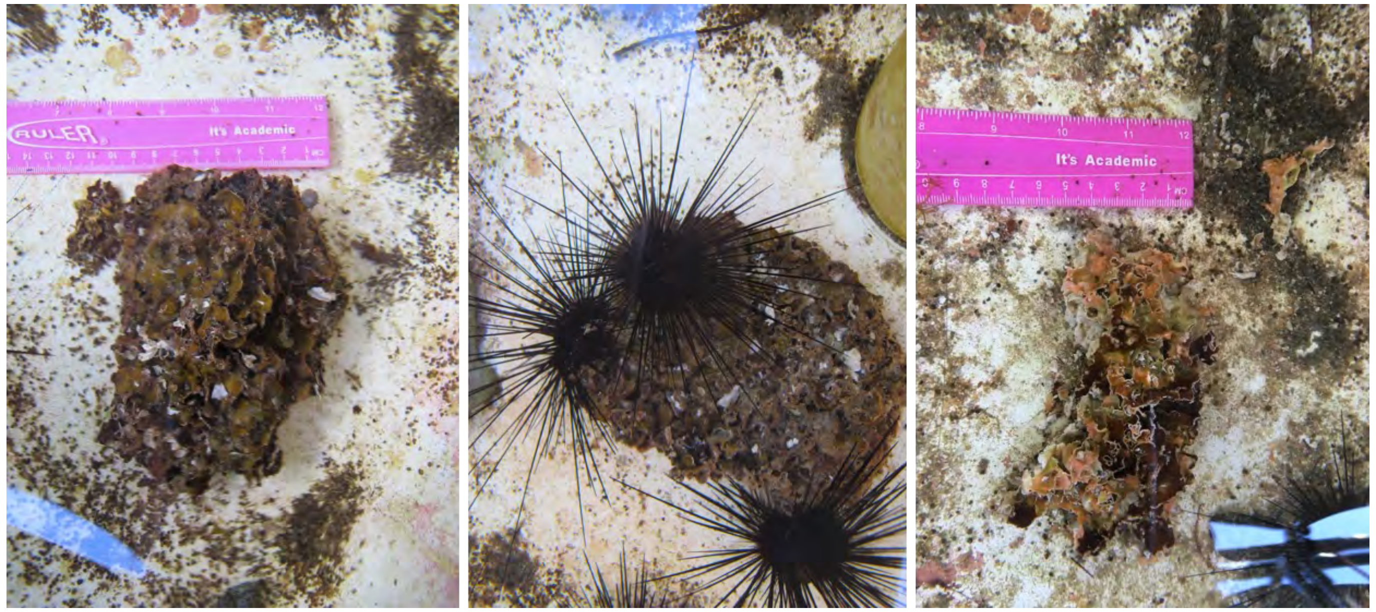


Figure 38. A piece of Ramicrusta spp. collected from Cayo Diablo reef in Fajardo that was placed in the wet tables with Diadema antillarum juveniles. The photograph to the far right is of the same piece, 12 days after being placed in the wet table. The Diadema antillarum juveniles were actively eating the Ramicrusta spp. piece.

reef substrate was effectively grazed after two months of the reintroduction. The summary of these findings can be found in Williams (2017). This method of *D. antillarum* restoration has proven to be successful in reducing algal abundance on a coral reef.

In September 2016, Dr. Williams collected samples of *Ramicrusta* sp. at Cayo Diablo in Fajardo. *Ramicrusta* samples were placed in the wet tables with lab-reared *D. antillarum. D. antillarum* actively fed on *Ramicrusta* sp. until the sample was fully eaten, which took 12 days (Figure 37, Figure 38). Given that *D. antillarum* will eat *Ramicrusta* spp., these sea urchins can be reintroduced to coral reefs with a high cover of *Ramicrusta* spp. Restoring *D. antillarum* could help manage algal abundance, specifically *Ramicrusta* spp., and hopefully enhance recovery of scleractinian corals on the coral reefs in Puerto Rico.

CASE STUDY:

Ramicrusta spp. – A New Threat on Coral Reefs

Before the 1970's, scleractinian corals were the dominant component of most coral reefs in the Caribbean. However, after decades of disturbances, both natural and anthropogenic in nature (hurricanes, bleaching events, overfishing, *Diadema* die-off, etc.), coral reefs in the Caribbean exhibit drastic changes in community structure. Coral reefs once dominated by scleractinian corals have lost their resiliency and have shifted to an alternative state. The most commonly-referenced phase-shift in scientific literature is the coral to fleshy macroalgal shift (Hughes 1994; Shulman and Robertson 1996; McClanahan and Muthiga 1998; Rogers and Miller 2006). Reefs characterized by permanent states of algal dominance usually signify a loss of resiliency (Hughes et al. 2007) because macroalgal assemblages limit coral settlement, affect sediment deposition, and alter chemical properties close to the benthos (Birrell et al. 2008).

In Puerto Rico, a more recent and potential threat to the coral reefs is the increasing abundance of a red encrusting algae, *Ramicrusta* spp. (Ballantine et al. 2016). *Ramicrusta (textilis)* was first reported in Jamaica in 2009 (Pueschel and Saunders 2009) and later in Bonaire as *R. bonairensis* (Eckrich et al. 2011). In Puerto Rico, the first reports of *Ramicrusta* occurred in 2011 (Ballantine et al. 2011), and so far there have been three species of *Ramicrusta* identified in Puerto Rico, *R. textilis*, *R. bonairensis*, and *R. monensis* (Ballantine et al. 2016). Even though their taxonomic and genetic characteristics are well studied, there is still little known about *Ramicrusta* spp. abundance, distribution, regrowth capabilities, reproduction strategies, and their effects on the ecological function of coral reefs in Puerto Rico.

Ramicrusta spp. are known to overgrow and eventually kill living sessile-benthic organisms, including corals and octocorals (Ballantine et al. 2011; Eckrich et al. 2011; Eckrich and Engel 2013; Ruíz 2015). Ruíz (2015) observed *R. textilis* overgrowing half of the corals surveyed in Caja de Muertos, Puerto Rico. The aerial cover of *R. textilis* at this patch reef was extensive, with approximations close to 18,000 m^2 (Ballantine and Ruíz 2013). During the same study, Ruíz (2015) also reported *R. textilis* overgrowing 11 coral species, including *Acropora cervicornis* (Figure 39) and *Orbicella faveolata*, both designated as threatened under the Endangered Species Act (ESA) (Ballantine and Ruíz 2013). Since 2015, *Ramicrusta* spp. were reported on coral reefs at Mona, Caja de Muertos, Vieques, and Culebra Islands.

Ramicrusta spp. was identified north of Vieques in 2014 where it dominated 67% of the benthic cover. The Puerto Rico Coral Reef Monitoring Program (PRCRMP-DNER/NOAA) has been conducting annual monitoring of permanent transects since 1999 in more than 42 reefs around Puerto Rico. The first sightings of *Ramicrusta* spp. during monitoring under this program were during the 2016 surveys. In the 2016 surveys, *Ramicrusta* spp. was identified at all seven sites in Fajardo, Culebra Island, and Vieques Island. At these sites, *Ramicrusta* spp. was the dominant substrate with cover ranging from 41-75%. The same Vieques reefs were surveyed in 2013, and there were no reports of *Ramicrusta* spp. However, as of 2016, *Ramicrusta* spp. was the dominant algae with an average cover between 34.5% at 20m and 58.7% at 10m in depth. As of 2017, scientists in the monitoring program recorded *Ramicrusta* spp. at west coast reefs such as Tourmaline, Gallardo, and Tres Palmas and south coast reefs like La Parguera and Guánica.

The reason for the recent emergence of *Ramicrusta* spp. is unknown. The declining coral reef heath in the Caribbean (Jackson et al. 2014) may be contributing to the establishment of this crustose alga (perhaps altering the competitive dynamics between *Ramicrusta* and corals; Ballantine et al. 2016). *Ramicrusta* spp. was not known in the Caribbean prior to 2009. The potential impact of *Ramicrusta* spp. is more expansive, due to the recent observations of this species on coral reefs around Puerto Rico. *Ramicrusta* spp. could be a threat to the ecological function of coral reefs given its ability to overgrow corals and grow more quickly. Preliminary evidence from multiple coral reef ecosystems around Culebra Island and the southwestern Puerto Rican shelf (Hernandez-Delgado, unpub. data) suggests that no coral recruitment occurs on *Ramicrusta* spp.-dominated benthic habitats. Herbivory is one way to maintain and control the abundance of *Ramicrusta* spp. *Ramicrusta* spp. has been absent in areas when there is a presence of *Diadema antillarum* (Williams pers comm to H. Ruíz, 2015). Restoring herbivore populations may be a mechanism for maintaining a low abundance of *Ramicrusta* spp.

Figure 39. Acropora cervicornis colonies overgrown by Ramicrusta textilis.

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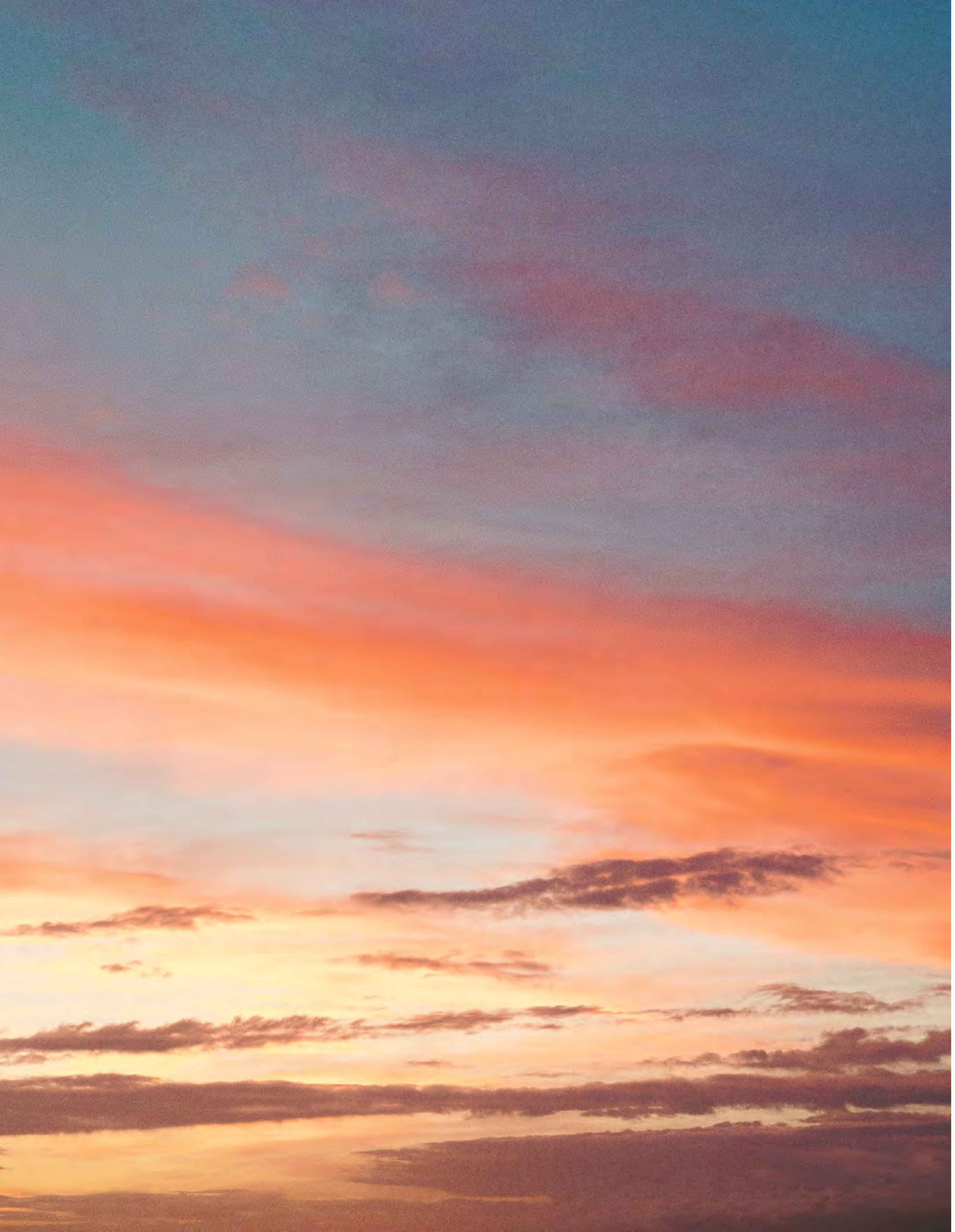
WORKING GROUP 3

Society and Economy

APPENDICES



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APPENDIX A
Cultural Heritage

CLIMATE STRESSORS ON CULTURAL HERITAGE

Mid-Century and End of Century
In Puerto Rico, coastal archeological sizes are threatened at differing degrees of increasing sea level (Figure 1). With an increase of 0.6 meters in sea level (conservative projections for mid-century) 56 sites will be inundated at the highest high tide in Puerto Rico, Vieques, and Culebra. An additional 69 sites lay within one meter above the high tide line. The number of inundated sites increases to 140 for a 1.8-meter projection in sea level rise (estimate for the end of century). An additional 148 sites lay within one meter above the high tide line. Note that there are two regions with important heritage sites for which there is no sea level rise data and therefore they were not included in this assessment: Isla de Mona, containing 21 of these sites (four historic and 17 indigenous), and Isla Caja de Muertos, containing one historic site.

Figure 2 and Figure 3 highlight specific regions in Loiza and Vieques that have numerous sites at risk of sea level rise. A total of 33 sites are projected to be affected on the island of Vieques, most of them along the southern coast. The northeast region of Puerto Rico, from San Juan to Fajardo, are projected to have a total of 49 impacted sites.

In addition to the threat of erosion, rising seas will lead to the formation of new intertidal zones, exposing formerly dry regions to periodic wetting and drying, thus increasing the rate of degradation of materials buried in that zone.

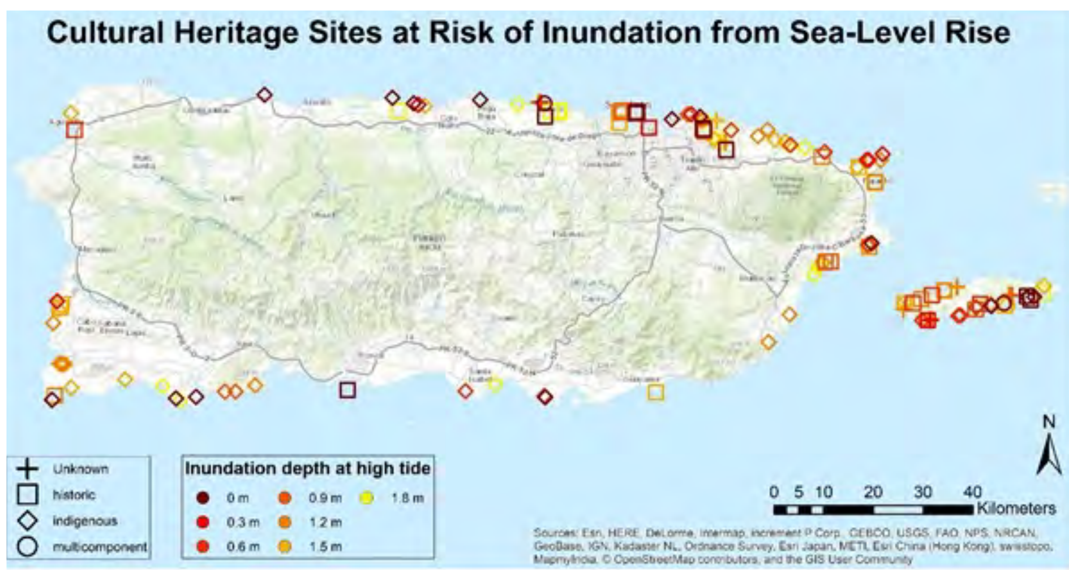


Figure 1: Sites at risk of inundation from 0 meters (present day) to 1.8 meters (projection for 2100). Sites are broken down into era (historic, indigenous, multicomponent, or unknown). Data sources: Archaeological data source obtained from the Instituto de Cultura Puertorriqueña; sea level rise data obtained from NOAA's online sea level rise data download.

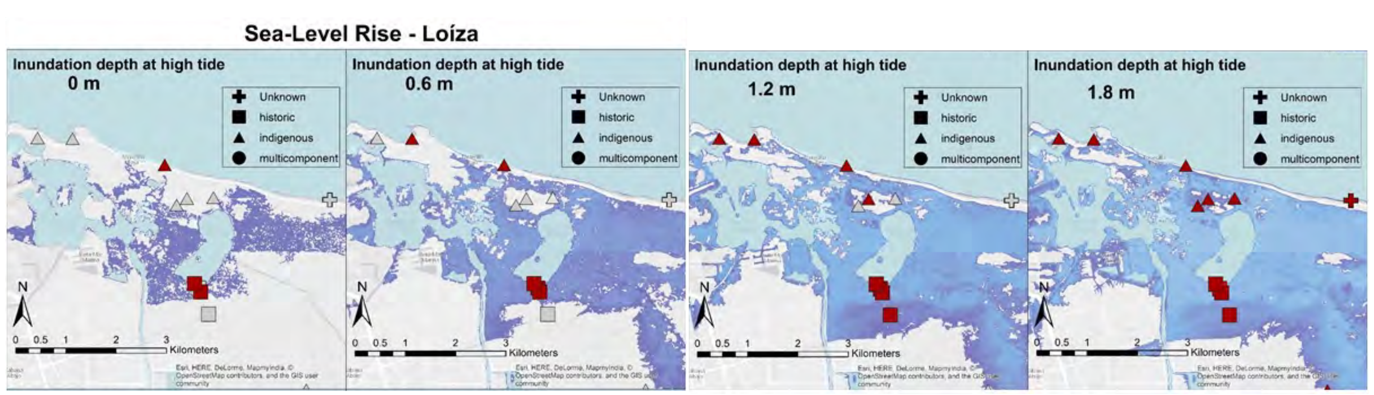


Figure 2: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in Loíza, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea-level rise projection for each quadrant. Data sources: Archaeological data source obtained from the ICP; sea level rise data obtained from NOAA's sea level rise data download.

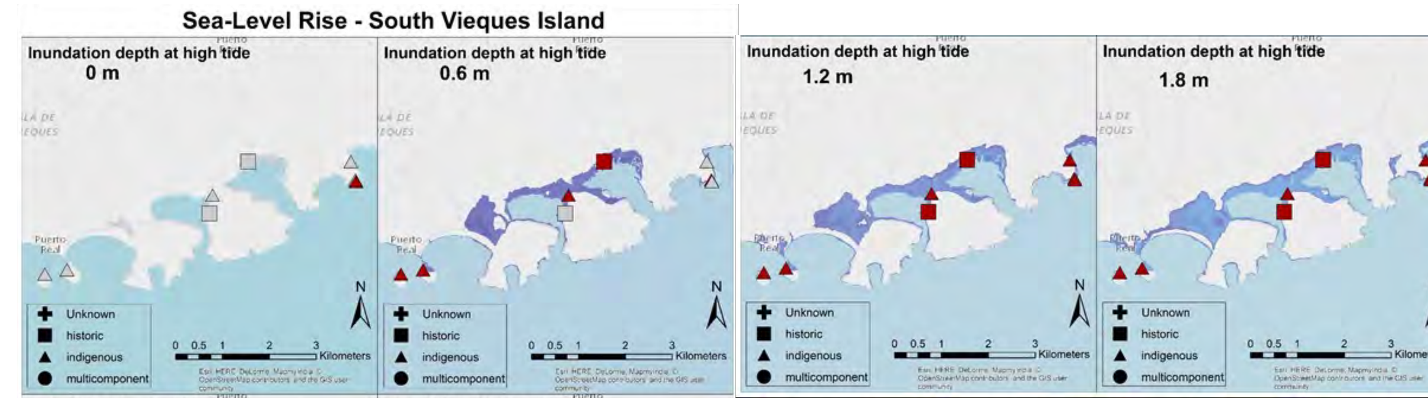


Figure 3: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in the southern portion of Vieques, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea level rise projection for each quadrant. Data sources: Archaeological data source obtained from the ICP; sea level rise data obtained from NOAA's sea level rise data download.

In addition, some coastal sites may become permanently flooded or submerged. This will limit access to sites and could lead to complete destruction or loss of a site. Further, saltwater intrusion will lead to the deterioration of material due to changes in the chemistry of surrounding soil and water (Colette et al., 2007). This deterioration can include corrosion, salt deposits, and rusting. Ocean water encroachment along the coastline will also increase the height of the water table, potentially damaging stratigraphy and buried artifacts, and increasing rot of organic materials. Finally, intrusion of salt water will alter the chemistry of the soils surrounding a site, increasing deterioration of artifacts from corrosion and rusting.

CLIMATE CHANGE ADAPTATION STRATEGIES

Providing adequate adaptive management to this large number of sites is a challenging task. In order to begin addressing how to incorporate climate impacts into adaptation management of cultural heritage in Puerto Rico, this section discusses three existing strategies. The first is a UNESCO report designed for State Parties to implement appropriate management of World Heritage Sites in response to climate change. This strategy was included in UNESCO's 2007 report Climate Change and World Heritage (Colette et al., 2007). The second, is proposed by the National Park Service's (NPS) 2016 report, Cultural Resources Climate Change Strategy and lists recommended directions for actions to best preserve and learn from cultural resources in the context of climate change (Rockman et al, 2016). Lastly, we also present the strategy proposed by the Scottish Coastal Archaeology and the Problem of Erosion (SCAPE) Trust (Dawson, 2013), which includes a model for prioritizing site intervention based on vulnerability.

UNESCO Climate Change and World Heritage Report
Even though it was originally written for World Heritage Sites, the 2007 UNESCO Report provides useful information for the design of local management plans that account for climate change and is therefore relevant for any cultural heritage site. This report introduces key topics that should be considered in the drafting and implementation of management plans that address climate change impacts. Adaptive management plans must be constantly re-evaluated. Management priorities identified in the plan should accompany refined climate projections. Once implemented, management actions should be monitored and continuously improved.

The UNESCO report identifies two types of site monitoring: community and professional. Professional monitoring includes the use of instruments, remote sensing products, and bio-sensing tools. Community monitoring is carried out by local members of the public, ideally after receiving education about the significance of heritage and the importance of observing and reporting changes to heritage site managers. Communities should also be included in management planning and implementation to ensure that they reflect local knowledge systems and the way they understand and adapt to changes in climate. Along these same lines, communication and awareness programs are important parts of building political and public support for the preservation of cultural sites.

The UNESCO Report also emphasizes the importance of sharing knowledge on both local and regional scales. To preserve cultural heritage from climate change threats, communities need increased interaction between members of different generations. By learning of past climate events, present generations can learn from past knowledge about a given place and apply lessons about its adaptive capacity for future generations. On a more regional level, organizations should share management plans and strategies. By coordinating information on training courses, risk assessments, monitoring, and adaptation, these institutions will strengthen capacity building.

NPS Cultural Resources Climate Change Strategy
The 2016 NPS report identifies directions for action under four overarching goals: connect impacts and information, understand scope, integrate practice, and learn and share. The report provides an eight-part concept framework that displays the four pillars of climate change response (science, adaptation, mitigation, and communication) in the context of climate change impacts on cultural resources. Each pillar is divided between impacts (e.g. how a changing climate may affect the preservation and maintenance of a cultural resource) and information (e.g. how cultural resources can provide information about past human interactions with environmental change).

The NPS report highlights that management decisions should prioritize cultural heritage based on its vulnerability and significance while engaging stakeholders. Areas found to be most at risk should then be prioritized for inventory. The report also recognizes the potential for total loss of sites, and the importance of monitoring and record keeping. Like the UNESCO Report, this NPS Strategy emphasizes local, national, and international collaboration to learn from and share transferable tools and techniques about climate change and cultural heritage.

NPS's framework and directions for actions are applicable to Puerto Rico's adaptive management of its cultural heritage. For example, by combining current technology with engineering from the 18th Century, the San Juan National Historic Site restored seven historical water cisterns in two fortifications. These cisterns have a combined total capacity of 932,000 gallons for rainwater storage and are currently used to supply non-potable water for park utilities. This intervention reduces the Park's vulnerability to drought by reducing its dependency to the island-wide water service.

SCAPE Trust Nine-Step Model for Site Prioritization
Based on their experience with Scottish coastal heritage, the SCAPE Trust developed a nine-step model to identify site vulnerability and to develop a prioritization for intervention plan. The model collects physical data on specific threat parameters, such as erosion, and combines that data with geographic data of cultural heritage site location to assess which sites are most vulnerable (Dawson, 2013). The model then categorizes the sites based on their type (e.g. historical, indigenous, etc.) and archaeological importance (e.g. culture, time-period, etc.). The vulnerability level together with the group classification set priority levels for site intervention. This way, cultural heritage managers can begin to sort through their many at-risk sites and address them in a specific order.

The model also suggests actions for specific sites. The first action is to visit the site to assess its current state. This is important, especially when considering erosion, as many changes may have taken place after the site's original survey and new priority levels may be more appropriate. Subsequent actions may depend on the results of the first action and include options such as desk assessment, survey, monitoring, excavation, or management plan. There is often more than one necessary action. The assessment of sea level rise impacts to Puerto Rico's cultural heritage sites -which included creating a database and standardizing records - constitutes the first two steps of the nine-step model as applied to sea level rise impacts on the island's cultural heritage sites.

As in the UNESCO and the NPS strategies, SCAPE also emphasizes the importance of community involvement. Through the Scottish Coastal Heritage at Risk (SCHARP) project, SCAPE developed a mobile application for community monitoring of at-risk sites. Through this citizen science program, local community members can visit and monitor sites and help update site records while providing their feedback on their importance. This activity has been successful at instilling a sense of ownership and stewardship in local communities. This hands-on, peer-to-peer collaboration with communities has also led to the modification of SCAPE's model to incorporate community needs and priorities in overall site intervention priority. The ShoreDig project works to consider the value and meaning of at-risk cultural heritage to local communities and has been successful in altering preservation options to incorporate community input and concerns.

Puerto Rico can utilize these existing tools to incorporate multiple voices into the discussion of priorities. Notably, SCHARP has already been adapted for new programs in other parts of Europe (Rockman et al., 2016). Site databases should include not only priorities for researchers and governments, but also for communities. This way the final priority level determination reflects a multitude of inputs.

Research Needs
Cultural heritage management in Puerto Rico is in a dire situation. There are three interlocking venues that intervene with Puerto Rican heritage: government, academia, and the public. Governmental agencies in charge of heritage in Puerto Rico are the Institute of Puerto Rican Culture (ICP), which oversees national-scale heritage laws including remains on land, underwater, or in caves and the State Historic Preservation Office (SHPO), which works with federal regulations and section 106 of the National Historic Preservation Act. Section 106 includes impact assessments to cultural heritage on federal lands or on all projects with federal funding. SHPO also oversees the National Register of Historic Sites, of which the ICP has a similar version of sites reported to them. In practice, these agencies have focused mostly on the regulatory part of construction development, but they have also conducted and supported research of a more academic vein. Both agencies, but particularly the ICP, lack proper funding, personnel, and administrative support. In addition to ICP and SHPO, the National Parks Service manages the San Juan Historic District, its structures, artefacts, and documents.

In academia, there are two institutions with a specialty in archaeology: the University of Puerto Rico Rio Piedras Campus (UPRRP) and the Centro de Estudios Avanzados de Puerto Rico y el Caribe (CEAPRC). Other institutions also offer research opportunities and single courses in archaeology. The Department of Sociology and Anthropology at the UPRRP offers a bachelor's degree in Anthropology with emphasis in Archaeology. The CEAPRC offers a master's degree in Archaeology. Both institutions are working against all odds to train the next generations of archaeologists for the island, but academic research programs are weak. Both academic and governmental institutions maintain museums and collections of tangible cultural heritage, including the UPR's Museo de Historia, Antropología y Arte, the Museum of the Universidad del Turabo, and the many collections housed at the ICP, the UPR, and other governmental and non-governmental institutions, such as Para la Naturaleza. There is also an unknown number of private collections of cultural heritage under different preservation and curatorial conditions.

The database analyzed in this study contained only sites in ICP's register under 20m of elevation. There are hundreds of archaeological and historical sites registered at the ICP above the 20m mark that were not included in this assessment. In addition, while there are 1,185 known sites in the assessed database, there are certainly many more that either have not been identified or have not been included in the register, both along the coast and across Puerto Rico's islands. Adaptive management strategies are incomplete without a comprehensive list of known sites. Therefore, a primary research need for Puerto Rico is to survey and update the register of archaeological sites, prioritizing regions with higher risk of adverse impacts such as the coasts. A comprehensive and systematic survey will assist in identifying additional sites and improve the capability of any adaptive strategy utilized. This is certainly a daunting task for a country where cultural heritage management is in crisis. It is recommended to enroll community involvement as proposed by SCAPE, SCHARP, NPS, and UNESCO. A project along these lines is being developed by Rivera-Collazo through the Scripps Center for Maritime Archaeology of University of California San Diego, with collaboration from the AleRT project (Archéologie, Littoral et Réchauffement Terrestre) of the University of Rennes in France and the Qualcomm Institute of UC San Diego.

Puerto Rico depends heavily on tourism, but the breakdown of earnings between tourism sectors is unclear. An economic assessment into what proportion of tourism earnings stems from cultural resources would allow for the measurement of costs to the island from damaged or destroyed sites. This in turn could then help support intervention, prioritization, and cultural resource management. It could also help identify new economic venues for cultural tourism.

This assessment only focused on the potential impact of sea level rise on coastal cultural heritage. It did not model for coastal erosion following inundation, nor did it assess the potential impact of all the other climate change impacts over Puerto Rico's tangible and intangible heritage. There are still many uncertainties as to how climate parameters may alter, damage, or degrade material heritage in general (Curran et al., 2016) and more specifically in Puerto Rico. There is also a need for research into new methodologies for the preservation of sites by record, in anticipation of total loss of certain sites (Murphy et al., 2011).

Summary
Climate change is already affecting and will continue to affect Puerto Rican cultural heritage. Impacts include changes in precipitation, with heavier and more intense rainfall occurring in many regions; increased air and sea surface temperature; increased acidification of the ocean; increased rates of erosion from wind and wave action; increased frequency of extreme weather events such as extreme heat, extreme precipitation, cyclones, and hurricanes; and rising sea levels. These climatic impacts will affect tangible heritage in many ways. Exposed artifacts will experience higher rates of deterioration. Some organic materials will decay faster. Wooden structures will become more susceptible to swelling, warping, or cracking. Ground around structures may erode, reducing the stability of sites. Buried materials exposed to increased wetting and drying will experience faster rates of decay. Extreme weather events will cause sudden damage, including failing pipes of historic buildings; collapse of walls from flooding; large rates of erosion in short periods of time; and flooding of museums, archives, and deposits of archaeological and historical objects. Heritage in marine environments will be at risk of wave erosion, decomposition of organic material, corrosion, rust, and structural damage.

Climate change impacts pose a threat to material cultural heritage. Historic and indigenous cultural sites throughout Puerto Rico, with over one-thousand sites located in low elevation coastal regions, constitute the physical record of the islands' heritage and history. Even if future climate change mitigation takes place, many of the projected impacts are already in motion and adaptive response is already necessary in many sectors. Puerto Rico's management of cultural heritage should incorporate adaptive strategies to ensure best practices, increased management resilience, and preparedness for potential loss of sites.

To address these climate impacts, adaptation strategies must be implemented in a site-specific manner, taking into consideration the unique management needs of each individual context. Management plans should be revised periodically to incorporate new information either about specific climate impacts or success of specific adaptation strategies. Plans should also recognize the potential for total loss and incorporate necessary record keeping of sites. Lastly, communities, regional organizations, and international groups should all collaborate to learn from and share management tools to increase the resilience of management plans. Existing models of assessment and prioritization will simplify the task of implementing site-specific adaptation strategies.

Climate change and cultural heritage have an intrinsic connection to one another. This nexus is one reason why the preservation of heritage is important, as highlighted by both the UNESCO and NPS strategies. Cultural heritage is not just at risk from climate change, it also plays an important role for the mitigation of climate change. Environmental archaeologists' study past societies that provide useful information about how they adapted to and altered a changing natural environment. Knowledge of what has taken place in the past improves present-day decisions about development and adaptation. Also, heritage strengthens individuals' identities at a specific place, and that attachment means they will care more and work harder to preserve that place. This is a major reason why engaging communities in public archaeology is a crucial step towards climate adaptation.

APPENDIX B
Agriculture and Food Production

CLIMATE CHANGE EFFECTS ON AGRICULTURE AND FOOD SECURITY

Increased climate variability, droughts, heavy rains, floods, saline intrusion into aquifers, and other climate related stressors have direct and immediate impacts on the agricultural sector, rural communities, and Puerto Rico's economic sustainability. Climate change effects on tropical cyclones directly impact import routes for main food sources since Puerto Rico imports over 80% of its food. Puerto Rico's climate is expected to become warmer and drier over the next century (Bowden et al., 2021), with increasingly intense storm events (Emanuel, 2020) which may lead to both increased drought and increased susceptibility to flooding. Effective adaptation and mitigation strategies to increase our resilience in the agricultural sector will require a detailed understanding of crop responses to climatic changes and the social ramifications of farm losses and changes in food availability.

The Food and Agriculture Organization of the United Nations (FAO) has warned of climate change effects on the productivity of forests and arable land due to altered rainfall patterns, water availability, salt intrusion, and the distribution of pests and diseases (FAO, 2016). Extreme weather events will impact food availability and access by causing poor harvests and loss of livestock. According to global projections, food security will decrease in developing countries located at low latitudes, particularly in tropical countries (IPCC, 2014). In tropical areas, a reduction in water availability and arable land is expected along with an increase in the amount of dry land. Increased temperatures may cause temporal mismatches in pollination and flowering (Shivanna, 2019; Kjøhl et al., 2011), while excessively high temperatures can lead to fruit drop in citrus (Rosenzweig et al., 1996) and increases in O_3 concentrations have been linked to a decrease in the distance bees can identify flowering plants (McNulty et al. 2015). Warmer temperatures will potentially increase diseases and pathogens that affect fish populations, impacting communities that are dependent on fisheries for food. The United Nations Intergovernmental Panel on Climate Change (IPCC) has deemed climate change a serious threat to agriculture and food security worldwide (IPCC, 2014), and over the next 25 years, the impacts to agriculture and forestry in the United States are expected to amplify current biotic stressors. The consequences of these effects will depend largely on the adaptive actions taken by land managers and producers, but also on the whole food system that includes trade, stocks as well as nutrition and social policies (Wheeler and von Braun, 2013).

CLIMATE CHANGE TRENDS IN THE CARIBBEAN & PUERTO RICO

Global climate models project an increase in average temperatures for the U.S. Caribbean by 2050 (Gould et al., 2018), and numerous climate studies have indicated that the Caribbean region will receive less precipitation in the future (e.g., Meehl et al., 2007; Biasutti et al., 2012; Campbell et al., 2011; Cashman et al., 2010; Harmsen et al., 2009; Bowden et al., 2021). In Puerto Rico, downscaled global climate models have revealed rates of anticipated warming and drying beyond that of projected regional averages (Khalyani, et al., 2016).

CASE STUDY:

Climate Change Effects on Coffee Farming in Puerto Rico

Historically, climate conditions in Puerto Rico have been very favorable to growing high quality coffee, but the island is experiencing changes in temperature and precipitation that present new challenges to coffee growers. Climate projections indicate Puerto Rico will become warmer and drier over the next few decades, and thus coffee may experience less favorable growing conditions. *Coffea arabica* (Arabica) accounts for most of the production in Puerto Rico and the world, but it is more sensitive to high temperatures and potentially more vulnerable than *Coffea canephora* (Robusta) to the effects from climate change. High temperatures and low precipitation levels can result in diminished coffee quality and yields as well as increased exposure and sensitivity to insects and diseases. Changes in precipitation patterns can also cause coffee to ripen at different times and may exacerbate labor issues in the industry as harvest seasons become less well-defined. *C. arabica* grows well in annual mean temperatures between 64°F-72°F (18°-22°C), while *C. canephora* is more tolerant to heat and can grow in temperatures up to ~80°F (~27°C). Annual rainfall of 1000 millimeters (~40 inches) is considered a minimum for *C. arabica* cultivation, but the desirable range of rainfall in Puerto Rico is between 1905-2540mm (75-100 inches) (Muñiz et al., 1999). Studies (Fain et al., 2017) project losses in suitable habitat for *C. arabica* within the next 20 years for Puerto Rico if the median annual temperature increases above the optimal range for coffee production (18°-22°C). Results suggest that top producing municipalities may find that 80% of areas highly suitable for growing coffee will become less suitable by 2070 if global greenhouse gas emissions remain high and temperatures increase as projected. Furthermore, results show that for 2011-2040, the entire island is projected to exceed mean annual temperature parameters for growth of *C. arabica* under the high greenhouse gas (GHG) emission scenario (A2) and the mid-low (A1B) scenario. Warming and drying trends may accelerate after 2040 and could result in top producing municipalities losing 60-84% of suitable growing conditions within their territories (Fain et al, 2017).

Coffee farmers and researchers around the world are joining efforts to find solutions to climate change challenges. Selective breeding has allowed the development of hybrid *C. arabica/C.*

canephora varieties more resistant to coffee rust and higher temperatures. Growers are experimenting with techniques for conserving soil moisture, like increasing tree and shade cover, terracing steep farmlands, and employing drip irrigation. The USDA Caribbean Climate Hub provides farmers with information on sustainable management practices that help reduce climate related risks.

Research Needs

The College of Agricultural Sciences at the University of Puerto Rico prepares and updates a yearly list of the most pressing research and education needs of the island's principal agricultural commodities. This information is gathered in meetings held during the year, and, increasingly, this list includes concerns related to the proliferation of diseases, pests, and weeds associated with increasing temperatures and changing rainfall and drought patterns. These concerns highlight the need to promote and continue collaborative research and surveillance efforts of our current crop and farming systems.

Research priorities include: devising alternative pest and disease control practices, responsive management practices tailored to pollination, developing disease-tolerant cultivars, and selecting biocontrol agents for major pests and diseases (UPR-Agricultural Experiment Station, 2014). Further research needs on water management and agriculture needs have also been identified (Harmsen & Howard Harmsen, n.d). Other pressing research issues include the conservation of plant germplasm and increasing accessibility of adequate seeds to farmers. In the case of livestock industries, priorities include the development of research to identify more breeds that are tolerant of heat stress and education on better husbandry practices. Documentation of alternative and innovative farming practices is scarce, therefore more in-depth systematic research on sustainable agricultural practices and practitioners is necessary to expand the body of knowledge for potential climate change adaptation strategies.

APPENDIX C
Risk Assessment for Critical Infrastructure in Puerto Rico – Overview

Puerto Rico is already experiencing an increase in average temperatures, altered rainfall patterns, and more frequent and intense extreme events such as heatwaves, droughts, and tropical cyclones. Consequently, these threats are causing communities to address how we plan, design for, and operate critical infrastructure in a changing climate. Confronting the more acute challenges and climate risks that influence the strategic and operational management of such infrastructure is becoming ever more challenging. Infrastructure evaluated by the Puerto Rico Professional College of Engineers and Surveyors ("CIAPR" for its initials in Spanish) is critical to our island's economic performance, social behavior, and other aspects of our livelihoods.

SCIENTIFIC APPROACH TO THE RISK ASSESSMENT FRAMEWORK

The scientific approach followed for this analysis is the framework for risk management described in the International Organization for Standardization's document ISO 31000 Risk management – Principles and guidelines (International Organization for Standardization, 2018).

All the evaluations, risk treatment, and adaptation measures herein described for infrastructure are all results of an assessment of multiple variables using an adapted analysis matrix. This document addresses high level or strategic issues and opportunities for the types of infrastructure evaluated.

The PRCCC established six minimum risk sources to be evaluated as potential positive or negative impacts to the various infrastructure types (Figure 4). The common assets established for all analyzed infrastructure were management, regulatory, legal, physical, supply chain, response, financial, product/service, and reputation. Figure 5 shows the steps and details of the risk assessment process, the basis for this analysis work, beginning with content establishment to risk treatment.

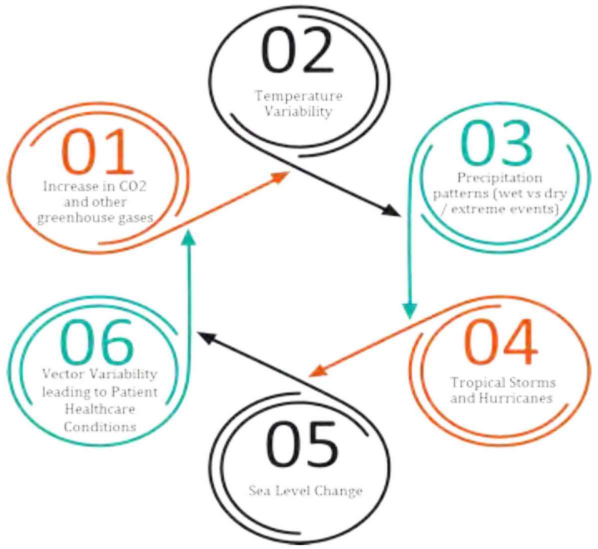


Figure 4. Six minimum risk sources under evaluation as potential impacts to infrastructure. Source: PRCCC.

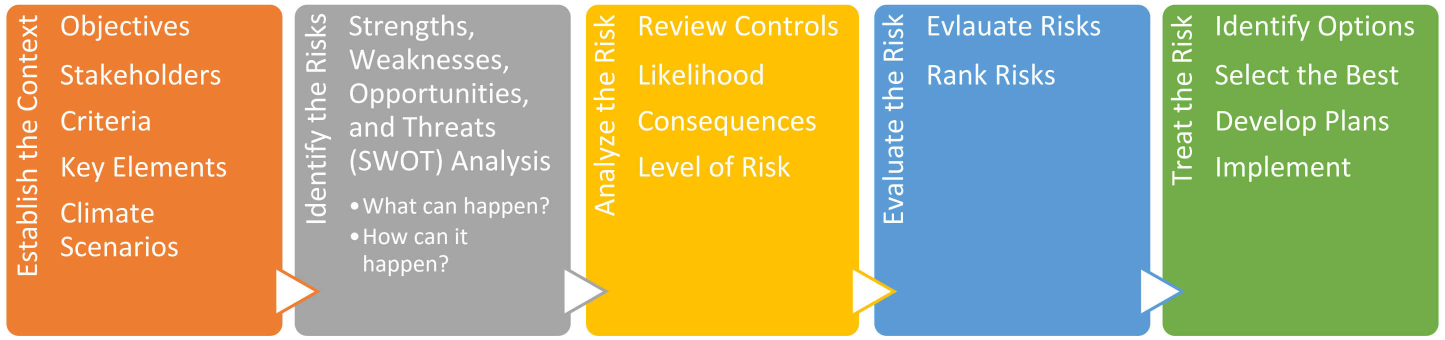


Figure 5. The process of risk assessment.

OVERALL SUMMARY

Based on the risk assessments developed for the different types of infrastructure, some common items were identified or resulted from the analyses:

1. *Need of baseline criteria. For most of the infrastructure evaluated, there was found to be a lack of information. Baseline criteria, information, and statistics must be generated to begin to prioritize areas for immediate action and long-term strategies. Data on specific factors for Puerto Rico should be enhanced, including analyses on local transportation conditions and context, infrastructure age, and impacts from past weather events and their effect on infrastructure.*

2. *Commitment from leaders in building adaptive measures to ensure resilience in the future. There is a need of improved governance regarding climate change. Part of this would mean reducing greenhouse gas emissions and integrating sustainable development into management objectives and organizational responsibilities.*

3. *Proper risk management to recognize, monitor, anticipate, communicate, and prepare for changing climate-related health risks. Operations should be adapted to changing risk conditions, including the prevention, response, management, and coping with uncertainty, adversity, and sources of risks.*

4. *Improved quality standards regarding climate change. Part of assuring a reliable quality of service/product is addressing the impacts of climate change on infrastructure now. This should be incorporated in the quality management program of the organization managing the infrastructure.*

Need to:

5. *Adopt a strategy of adaptation to minimize the consequences and maximize the opportunities of addressing climate change impacts.*

6. *Promote green building designs and integrate them into the organization's management system.*

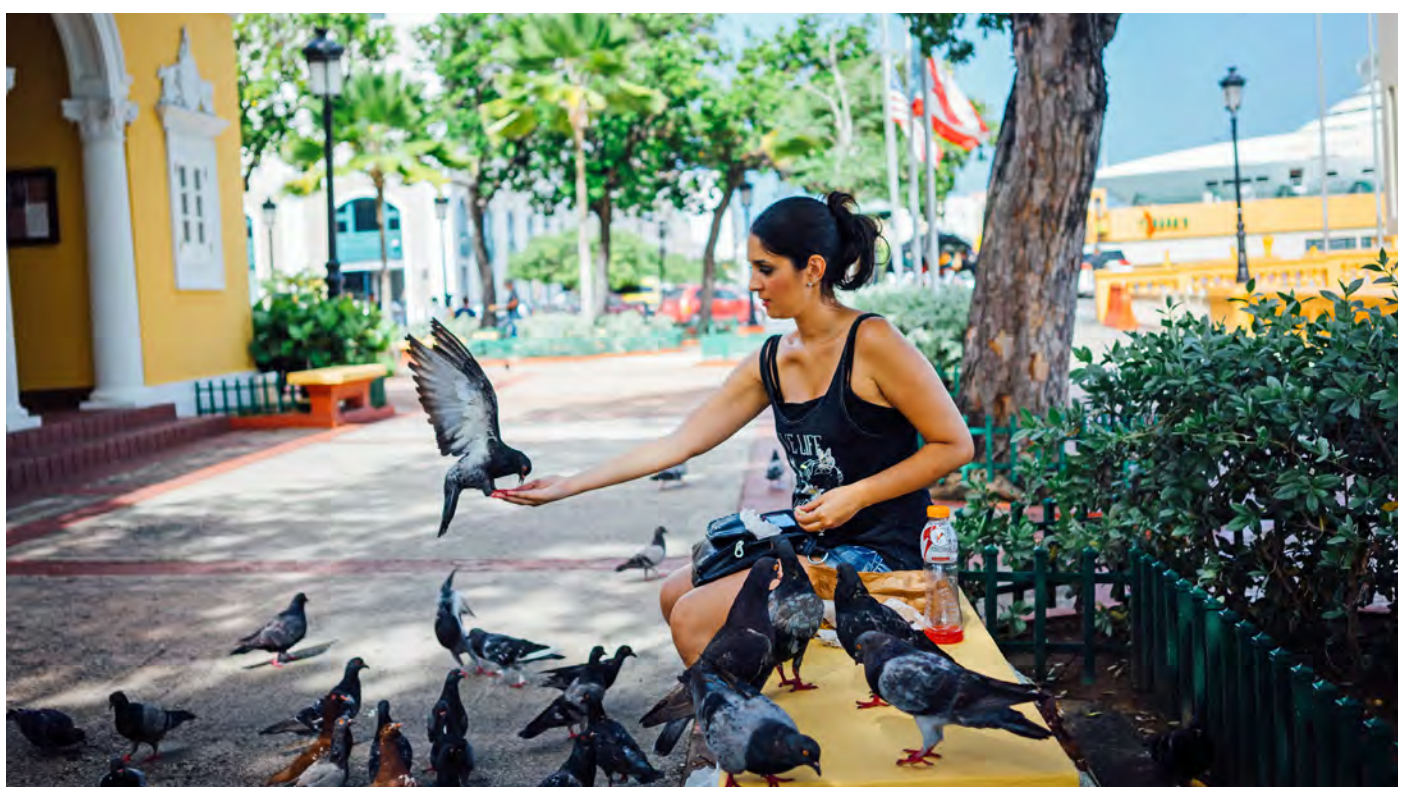
7. *Develop tools to analyze climate related risks and include these in the organization's risk profile.*

8. Implement responsible urban planning.

9. *Educate management and staff on climate related risks and how it impacts their ability to deliver their service/product.*

10. *Ensure government policies must support efforts related to climate change research, improve the resilience of critical public infrastructure to weather extremes, and regulate and approve resilience planning in sectors such as water, electricity, waste management, and healthcare.*

It is important to use these evaluations as a foundation on which to work toward continuous improvement. Our capacity for resilience and adaptation progresses with improved and more complete data and information, properly executed risk assessments, and the commitment of organizational leadership to incorporate these ideas into planning and policies.



APPENDIX D
Risk Assessment: Waste Management Infrastructure

The climate change impact on Puerto Rico's waste management systems infrastructure herein evaluated encompasses municipal solid waste (MSW), commercial, industrial, construction and demolition (C&D) waste, agricultural, and vegetative waste. Hazardous waste and wastewater management are not addressed within the scope of this section.

No recent characterization data was referred or analyzed as metrics and such data is limited in Puerto Rico. The latest island-wide characterization plan was created in 2003, representative of waste received at 31 active landfills (Wehran Puerto Rico Inc., 2003). This characterization documented that the average composition of solid waste discards were yard waste (20%), paper and cardboard (19%), and construction and demolition waste (17%).

Technological advances, life quality styles and high rates of resource consumption patterns have an inadvertent and negative impact on the environment, reflected upon the generation of waste far beyond the handling capacities of governments and agencies. Puerto Rico is grappling with the problems of high volumes of waste, the management costs involved, disposal technologies and methodologies, and the impact of waste management on the local and global environment. To support these significant changes, including population fluctuations, adequate data and metrics must be developed and maintained up-to-date, particularly reliable waste characterization. Based on the previous, both the government and the private sector need reliable metrics, planning, and analyses of different alternatives as part of a responsible decision-making process.

The Puerto Rico Solid Waste Management Authority (ADS for its Spanish acronym) reports an estimated per capita generation of 2.52 kilograms per person per day in 2014, with population data from the U.S. Census Bureau from 2010 (Wehran Puerto Rico Inc., 2003)[1]. ADS reported that up to seventy percent (70%) of this waste was disposed in landfills. From 2005 to 2013, the diversion rate in Puerto Rico has not exceeded nineteen (19%). Similarly, the recycling rate from 2010 to 2013 has fluctuated between 7.14% to 11.30% (Rivera and Ríos, 2017). Diversion rates are defined by the US Environmental Protection Agency (EPA) as the amount of material diverted from MSW disposal facilities, while recycling rates measure the amount of the diverted material that was destined to recycle. Only 9.66% of all waste diverted from local landfills in 2013 were intended for recycling purposes (ADS, 2017; Rivera and Ríos, 2017).

The Solid Waste Management Association of North America (SWANA) defines integrated solid waste management as an environmentally and economically sound, systematic approach to solid waste handling to conserve and recover resources and dispose of solid waste while considering human health and the natural environment. The proper integration of diverse alternatives into Puerto Rico's waste management plan requires understanding of the service and value chains involved. The value chains are dictated in Puerto Rico's regulations overseen by the ADS. The agency, in compliance with Law 70 of September 18th, 1992 (Reduction and Recycling of Solid Waste in Puerto Rico Act of 1992), as amended, is charged with maintaining waste recycling metrics, goal set at 35% by 2006, amongst other technical and educational tasks. Analogous to this charge, the primary goal of the ADS is implementing the hierarchy of integrated solid waste management, from most preferred to least preferred: reduction, reuse, recycling and composting, energy recovery, and disposal.

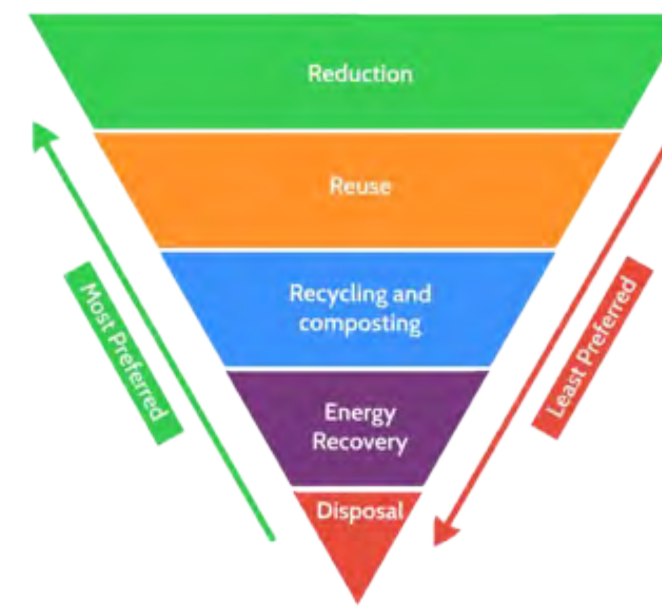


Figure 6: Solid Waste Management Hierarchy (Reduction and Recycling of Solid Waste in Puerto Rico Act of 1992)

1 With the approval of Law 171-2018, all the programs administered by the ADS were transferred to the Puerto Rico Department of Natural and Environmental Resources

Waste in Puerto Rico is generated within Local Government Units (LGU), known locally as municipalities, from residences, commercial, and industrial establishments. Potentially recyclable materials are diverted by way of drop-off locations and Materials Recycling Facilities (MRFs). Waste is disposed in landfills mostly and at times needs to be transported by way of Transfer Stations (Loon Chan et al., 2006).

As climate change progresses, potential impacts on the waste management industry in Puerto Rico must be considered (see Table 1). For instance, extreme weather events such as hurricanes, floods, and earthquakes, among others, can generate enormous amounts of waste materials in a short period of time, creating additional waste management challenges (Brown et al., 2011). Waste management during disasters is a localized issue that must be considered in Integrated Solid Waste Management (ISWM) System planning efforts. Solid waste management infrastructure is critical to maintain sanitary conditions, hence the importance of planning, designing, and maintaining systems and infrastructure resilient to climate change.

Potential impacts taken into consideration while performing these risk assessment evaluations for all four infrastructure components, or service chain elements, described in continuing sections, were considered based on stakeholders´ perspective. Further, the critical single or ongoing/cumulative events or scenarios evaluated consider diverse assumptions and perspectives specific to this industry.

Table 1 provides an overview of the perceptions considered during evaluations involving climate change risk exposure to critical waste management infrastructure of non-hazardous municipal solid waste (MSW) in Puerto Rico. The main goal was to generate a preliminary assessment on how climate change is affecting the solid waste management industry, its operations, and infrastructure, among other assets.

ASSESSMENT METHODOLOGY

For this assessment, the context was established by defining critical infrastructures within the waste management industry. The related waste management industry infrastructure components, or service chain elements, evaluated in 2017 by the team of writers were collection, transfer and transport systems, segregation and materials recovery, treatment and energy recovery, and disposal. Risk exposure to critical waste management infrastructure of non-hazardous MSW was evaluated taking into consideration ISWM system strategies and policies. Scenario analyses were used to evaluate how critical single or ongoing/cumulative events will potentially affect the existing waste management systems and to determine how to respond or best protect the infrastructure in such situations. This preliminary risk assessment, not intended to be a quantitative or an exhaustive research on the impacts of climate change of the waste management infrastructure above mentioned, provides an overview of crucial issues that may be encountered in the industry and are to be considered in the future.

Table 1: Potential climate change impacts in waste management systems

CLIMATE VARIABLE	POTENTIAL IMPACTS
HIGHER TEMPERATURES	– *Increased risks of combustion (landfill fires).* – *Altered waste decomposition rate.* – *Occupational Health and Safety issues such as greater exposure of workers and the public to vectors and infectious diseases.* – *Increased odor, vermin, dust and litter requiring more frequent waste collection.* – *Overheating of equipment and vehicles.*
SEA LEVEL RISE	– *Aquifer chemistry alteration due to saltwater intrusion; additional consideration for leachate impacted aquifers.* – *Water intrusion and erosion at facilities located in coastal areas, in particular any closed landfills or unmonitored old dumps.* – *Coastal erosion and land subsidence may compromise facility siting in an island with such diverse microclimates and natural resources to protect.*
INCREASED RAINFALL AND STORM SURGE	– *Increased risk of flooding could lead to weaken landfill foundations, allowing leachate to escape to both surface and ground waters.* – *Need for reliable Disaster Waste Management Planning and Implementation.* – *Need for reliable emergency response training as an Occupational Health and Safety issue when disaster response is needed to be performed by facility or collection personnel.* – *Saturated soil may compromise slope and/or liner stability at landfill facilities.* – *Increased leachate generation.*

Table 2: Scenarios and times evaluated for the waste management infrastructure risk assessment.

SIGNIFICANT SINGLE EVENTS	OCCURRENCE	ONGOING CUMULATIVE EVENTS	LIKELY TO BECOME CRITICAL OR BENEFICIAL
0.5-METER SEA LEVEL RISE	10 TO 20 YRS	INCREASE IN GREENHOUSE GAS EMISSIONS	10 YRS
1 METER SEA LEVEL RISE	20 TO 50 YRS	TEMPERATURE VARIABILITY	10 TO 20 YRS
STORM SURGE SCENARIO BASED ON CATEGORY 1 THROUGH 5 HURRICANE FLOODS	10 YRS	PRECIPITATION PATTERNS	10 YRS

Significant or critical single scenarios and likelihood of occurrence used in this evaluation include those discussed by the PR Climate Change Council (PRCCC, 2016), while ongoing or cumulative events and their potential of becoming critical or beneficial were identified based on PRCCC's guidance. Up to four matrices for risk analysis of the waste management industry components were developed, each portrayed different likelihoods of the provided scenarios. As a baseline, the scenarios and timeframes listed in Table 2 were adopted.

Threats posed by such scenarios were assessed for the following assets: Management, Physical, Financial, Regulatory, Supply Chain, Product/Service Technology, Legal, Reputation, and Response. A range of stakeholders were engaged throughout the evaluation process, including but not limited to: contribution of public and private operators of the systems or management alternatives, front-line workers, communities, central government, residential, commercial, and industrial owners or facility operators. The risk analyses involved reviewing controls, management regimes, and responses known to be in place to deal with each scenario and the adaptation or impact upon each listed asset. Progression of the assessments included the consequences of each risk against the infrastructure´s purpose by way of forming a judgement about the likelihood of each identified risk leading to probable consequences.

Legal assets considered included laws approved by the U.S. Congress or the Puerto Rico Legislative Assembly and legal orders on behalf of the primary environmental agencies involved. Whereas the regulatory assets considered were standards and rules adopted primarily by local environmental agencies; regulations represent how laws are to be enforced. Regulatory considerations also included general knowledge of facility permit conditions.

Impact (Event)	Likelihood					Consequences	Rating	Risk Treatment or Adaptation Measures (existing or potential)
	VL	L	M	H	VH			
On-going / Cumulative Occurence - Temperature Variability	0		x	0	0	21	63	Train emergency response personnel in site-specific risks or vulnerabilities; improve operator-response agency communication. Evaluate and adapt current routes to accommodate emergency planning procedures for when these events occur.
Significant Single Event - Storm surge scenario based on Cat.1-5 hurricane flood	0	0	0	X	0	24	96	Train personnel in heat stress prevention. Enforce proper maintenance and frequent revision of tires and potentially affected vehicle parts such as wipers and plastic/rubber joints by heat and increasing sun radiance.
On-going / Cumulative Occurrence - GHG emissions increase	0	0	0	X	0	17	68	Implement environmentally sound policies to reduce vehicles emissions. Promote Best Available Control Technology (BACT).
On-going / Cumulative Occurrence - Precipitation Patterns	0	0	0	X	0	17	68	Enforce proper maintenance and frequent revision of tires and potentially affected vehicle parts Re-route inaccesible roads and implement safety policy to prevent potential risks while conducting waste collection tasks.

Table 3: Waste management infrastructure risk register with a focus on collection and transfer systems (Likelihood: VL = Very Low; L = Low; M = Moderate; H = High; VH = Very High).

RISK EVALUATION

Collection, transfer, and transport systems

Collection, Transfer, and Transport Systems (CTTS) is a critical service for maintaining sanitary conditions to protect public health. Collection is typically the responsibility of local government and, in Puerto Rico waste collection system, most of the residential sector is provided by or subcontracted by each of the seventy-eight (78) municipalities. Multi-family residential properties, as well as industrial and commercial collection services, are often provided by private operators.

The most common service employed in Puerto Rico is the curbside collection, providing collection services for most highly transited or visible commercial as well as tourist areas daily, while recycling routes in residential developments are typically collected every other week. Collection locations, routes and other specifications depend principally on the existing roadways and the collection vehicle's ability to access properties and waste dumpster containers. Hence, waste collection and transportation are large cost elements in MSW management and are considered an integral part of integrated solid waste management.

As noted earlier and summarized in Table 3, climate change and potential scenarios may pose significant risk to the waste management industry therefore compromising environmental and community health and safety. Critical scenarios such as increased precipitation patterns and flooding manifested in communities near to the coastal line and/or located on flooding zones, may altered access roads thus interrupting waste collection routes. Furthermore, uncollected solid waste may block drains, and cause flooding and subsequent spread of waterborne diseases.

Segregation and materials recovery

The traditional waste management practice used in Puerto Rico is the disposal of waste in sanitary landfills, which is the least preferred alternative in the waste management hierarchy. The problem worsens due to limitations of space available on island for waste management. In addition, remaining operable landfills are reaching their lifespan or are overcoming serious management or legal problems. These limitations urge society to find solutions involving the community, public, and private sectors while implementing innovative technologies, with the goal of motivating behavioral changes regarding consumerism and increasing environmental awareness.

According to the PRSWA, in 2014 there were 115 recyclable materials collection centers and four Materials Recovery Facilities, commonly known as MRFs, operating in Puerto Rico. Apart from the MRFs, most of the collection centers located on the island are operated by municipalities, providing services to rural areas and those with limited accessibility.

Actions such as recycling mandates in municipalities have positively impacted the island's low diversion and recycling rates noted earlier but they must be continuously enforced. Local regulations implemented or proposed, such as the ordinance to regulate the provision of single-used plastic bags, plastic straws, and any future improvement to the used tires management rules, provide opportunities to reduce or minimize materials that eventually would end up at a disposal facility.

Impact (Event)	Likelihood					Consequences	Rating	Risk Treatment or Adaptation Measures (existing or potential)
	VL	L	M	H	VH			
Significant Single Event - 1 meter sea level rise	0	X	0	0	0	12	24	Improvement of existing infrastructure in order to cope with potential changes in waste composition. Research and development opportunities in the island's solid waste industry.
Significant Single Event - Storm surge scenario based on Cat.1-5 hurricane flood	0	0	0	X	0	24	96	Improvement of existing infrastructure in order to better manage increase volume of materials. Research and development opportunities in the island's solid waste industry. Train emergency response personnel in site-specific risks or vulnerabilities; improve operator-response agency communication. Implement Best Available Control Technology and BMPs when designing, constructing, and operating
On-going / Cumulative Occurrence - GHG emissions increase	X	0	0	0	0	11	11	Research and development opportunities in the island's solid waste industry.
On-going / Cumulative Occurrence - Precipitation Patterns	0	0	0	X	0	25	100	Research and development opportunities in the island's solid waste industry. Improve stormwater management infrastructure (to prevent onsite recyclable materials contamination)

Table 4: Waste management infrastructure risk register – Segregation and materials recovery focus (Likelihood: VL = Very Low; L = Low; M = Moderate; H = High; VH = Very High).

Impact (Event)	Likelihood					Consequences	Rating	Risk Treatment or Adaptation Measures (existing or potential)
	VL	L	M	H	VH			
Significant Single Event - Storm surge scenario based on Cat.1-5 hurricane flood	0	0	0	X	0	18	72	Facility siting regulations and best practices.
On-going / Cumulative Occurrence - GHG emissions increase	0	0	0	X	0	20	80	Promote Best Available Control Technology (BACT) and Best Management Practices (BMPs) when designing, constructing, and operating Landfill Gas (LFG) systems. Research and development opportunities
On-going / Cumulative Occurrence - Precipitation Patterns	0	0	0	0	X	80	85	Facility siting regulations and best practices. Improve weather prediction technology and communications.

Table 5: Waste management infrastructure risk register – treatment & energy recovery focus (Likelihood: VL = Very Low; L = Low; M = Moderate; H = High; VH = Very High).

Some other positive measures used include curbside pickups of recyclable materials, materials recovery facilities, textile recycling, scrap metal recycling, automobile, or vehicle recycling, composting, and, most recently, anaerobic digestion.

Diverse locations of collection centers and MRF facilities increase the possibility that potential climate change scenarios would impact their management and operations. Like CTTS, those facilities located on the coastal line would be most affected by an increase in sea level, while others may be affected by high precipitation and storm surges compromising proper waste handling. Waste managed at MRFs may also be affected during these scenarios as waste would need to be accumulated potentially exceeding facilities' capacity. In addition, recyclable materials exposed to stormwater and/or precipitation, thus increasing its moisture content, could be contaminated and its value in the market will decrease, creating additional management challenges in handling the materials. These and other operational details were evaluated for the different events including risk adaptation measures listed in Table 4.

Despite all these diversion alternatives currently implemented, there is a lack of information or outdated data available from local agencies related to materials and/or waste handled in these facilities. This situation must be addressed, and operators must comply with existing metrics and reporting requirements to understand and assess the segregation and materials recovery process in the island. "The EPA has taken steps to encourage and cultivate higher recycling rates in the municipalities" (USEPA, 2016). These efforts even more necessary as the state of disposal facilities continues worsening.

A short-term focus is recommended by local experts as being the diversion of high-volume materials such as debris or construction and demolition (C&D) waste as well as used tires. Four critical elements to achieve this must be considered upon reassessment of the recycling industry on the island, these are: legislation, collection system, infrastructure and markets for recycled products (Iglesias Vélez, n.d.).

Treatment and energy recovery

The corresponding alternative prior to disposal, per Puerto Rico's adopted hierarchy, is energy recovery.

Technologies or processes, some of which have been implemented on a small scale on the island, include the production, recovery, or reuse of liquid fuels like biodiesel, ethanol, and oil. As there is limited infrastructure related to this alternative currently available on island, the risk analysis performed considered the projection that in the future these facilities would be available. Refer to corresponding summary of analysis, identified as part of the Risk Register in Table 5.

As with any thorough ISWM Plan, any perceived competition between alternatives can be clarified via public policy already in place. In other words, adequate planning and permitting for the implementation of these facilities may require decision makers and operators to ensure any material with market value be recycled or, as an example, an aerobic composting process may follow anaerobic digestion. More recent integration of residential composting programs and anaerobic digestion facility on the island would need to be further evaluated for effectiveness within an island-wide diversion effort.

Disposal
According to the USEPA, the waste sector itself contributes approximately 5% to the GHG emissions in Puerto Rico, slightly higher than the 2.1% national average.For a specific site, the quantity of methane emissions will depend on waste composition, landfill operation, landfill gas management, cover materials, and climate.

An evaluation of disposal facilities in this exercise was performed with limitations. Only 29 currently active landfills, except for two closed in past years, were considered in the matrix analyses. No closed landfills, some referred to old dumps were analyzed as no georeferenced information or updated status of these facilities was available. Further, available GHG data from the EPA is only available for those landfills required to report. Per 40 CFR §98, municipal solid waste landfills required to report GHG emissions are those that generate CH_4 in amounts equivalent to 25,000 metric tons CO_2 or more per year (EPA, 2016).

Conversely to regulations, the primary management preference currently available in Puerto Rico is disposal in sanitary landfills. Like diversion rates, Puerto Rico lacks inventory, metrics, or reliable control of illegal dump sites as well as "old closed dumps." With measures evaluated by municipalities on Pay-As-You-Throw measures, it is imminent the island maintains some control and metrics over illegal dump sites to ensure alternatives as implemented do not impact consumer behavior or the environment adversely. Influential public education will be a key factor in the success of this and any other proposed alternative.

Of all the infrastructure components or service chain elements evaluated, disposal is one with the most significant contribution and one that will be most affected by GHG increase. In order of most to least affected or susceptible based on this scenario, the assets were ranked as follows: management, financial, physical, legal, reputation, regulatory, supply chain, product/service, and response. This assumption is based on the premise that landfills could expect to face legal recourse which will affect the way these facilities are managed, and the financial responsibility will certainly increase.

Even though a somewhat reliable set of data was extracted from the EPA's FLIGHT Tool and portrayed in Figure 7, inconsistent reporting from a few landfill facilities is perceived; some landfills have data gaps while others show unreliable data. Per data extracted, landfills in Puerto Rico over the course of years 2010 through 2019 have accounted for an average of 4.6% of GHG emissions in 2019 compared to the rest of the reported facilities (USEPA, 2020), still higher than the previously cited 2.1% national averag.

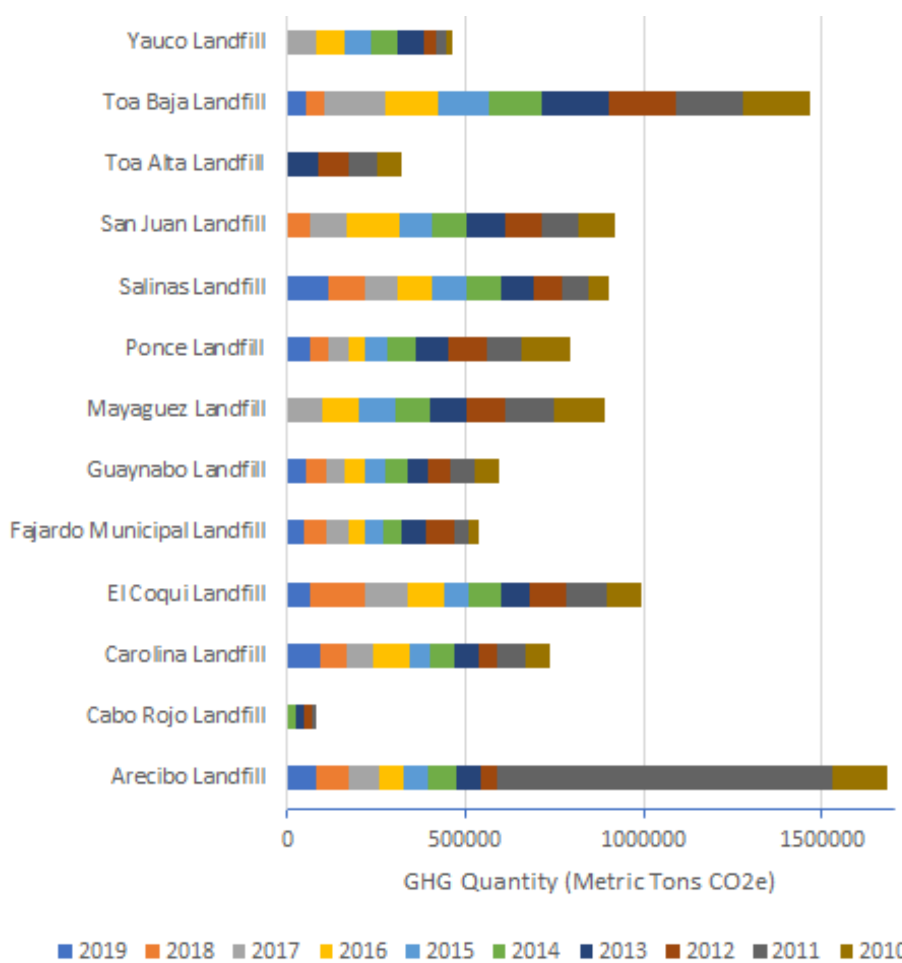


Figure 7. GHG Data Extracted from EPA's FLIGHT Tool for the Landfills in Puerto Rico (USEPA, 2020).

Impact (Event)	Likelihood					Consequences	Rating	Risk Treatment or Adaptation Measures (existing or potential)
	VL	L	M	H	VH			
Significant Single Event - 1 meter sea level rise	0	X	0	0	0	10	20	Ensure no landfill expansions towards potentially affected areas are approved or built.
Significant Single Event - Storm surge scenario based on Cat.1-5 hurricane flood	0	0	0	X	0	20	80	Ensure no landfill expansions towards potentially affected areas are approved or built.
On-going / Cumulative Occurrence - GHG emissions increase	0	0	0	X	0	27	108	Promote waste diversion by implementing Integrated Solid Waste Management (ISWM) alternatives. Research and development opportunities in the island's solid waste industry. Improve monitoring technology to improve statistics and projections. Promote Best Available Control Technology (BACT) and Best Management Practices (BMPs) when designing, constructing, and operating Landfill Gas (LFG) systems.
On-going / Cumulative Occurrence - Precipitation Patterns	0	0	0	X	0	32	128	Train emergency response personnel in site-specific risks or vulnerabilities; improve operator-response agency communication. Improve weather prediction technology and communications.

Table 6: Waste management infrastructure risk register with a focus on disposal (Likelihood: VL = Very Low; L = Low; M = Moderate; H = High; VH = Very High).

As GHG increase is progressively understood to impact climate change, reputation of facilities contributing to this rise will be affected. Society's resistance to landfills will affect the rest of the assets evaluated and that make up the entire disposal element. As these are only a portion of the 28 landfills considered, GHG emissions increase resulted as not being the scenario with the highest Risk Exposure Rating.
Regarding other impacts evaluated, location was a principal consideration when evaluating the 28 landfills throughout this risk analysis process. Weaknesses of these facilities such as the vulnerability of landfill operations to applicable regulations and assumed scenarios were a key part of the assessment. Landfill facilities may be vulnerable to climate change effects that would compromise the slope stability, affect active area operations, as well as increase or decrease the supply chain (incoming waste). On a macroscale, the likelihood and consequences of these and other effects were assessed for single or cumulative scenarios for all 28 landfills. Table 6 shows a summary of the evaluations performed for these facilities, including likelihood, consequences, risk rating, as well as risk adaptation measures prioritized per event or scenario.

Since such deep analysis, Puerto Rico and its Solid Waste Industry have faced notable challenges, including the 2017 Hurricane Season, earthquakes in 2020, and an ongoing COVID-19 Pandemic. All landfills are exposed to hurricanes, many of which may cover the entire Island upon landfall (Iglesias Vélez, n.d.). These factors have posed additional strain upon these highly relied upon disposal facilities, causing a ripple effect upon the industry by increasing operational costs and creating an even higher need for alternative management and treatment options.

Among the USEPA's landfill siting restrictions we find that most of the landfills in Puerto Rico suffer from conflicts with these requirements, among them (Guerrero, 2021):

- *Five (5) landfills are located in the Karst region*
- *Four (4) of them in floodplain valleys*
- *Ten (10) impact wetlands*
- *Nine (9) have the potential to impact drinking water sources*
- *Four (4) have the potential to impact nature reserves*
- *Seven (7) are located adjacent to residential areas*

According to EPA, the remaining capacity of the landfills on the Island was declared to be from 2.5 to 3.5 years (Guerrero, 2021). There are doubts as to whether this number was achieved considering debris due to atmospheric phenomena -and other climatic and non-climatic disaster events- stated earlier. Regardless, the need for diversion alternatives has been a real need on the island for years.

Adaptations and Opportunities
Technological advances in waste management, if adopted properly, will allow existing WM infrastructure to better mitigate the effect from critical scenarios due to climate change. Furthermore, adverse impacts on the environment and society from the waste management industry may be best addressed by establishing integrated programs where all waste management processes are considered as collective and interrelated. Even though financing is a concern, a short-term goal should be to develop an ISWM System and build the technical, financial, and administrative capacity to manage and sustain it.

Table 7 summarizes generalized alternatives and opportunities identified as most relevant to potential climate change impacts on the existing waste management infrastructure, while the risk register results from the completed evaluation detailing consequences and rating rankings for each infrastructure component were included earlier in this section.

Table 7: Actions and opportunities for adaptations of waste management infrastructure

ACTIONS	OPPORTUNITIES
– Ensure that the regulatory framework is adequate to optimize waste prevention (or reduction). *– Promote waste diversion by implementing Integrated Solid Waste Management (ISWM) alternatives.* *– Improve weather prediction technology and communications.* *– Promote Best Available Control Technology (BACT) and Best Management Practices (BMPs) when designing, constructing, and operating Landfill Gas (LFG) systems.* *– Train emergency response personnel in site-specific risks or vulnerabilities; improve operator-response agency communication.* *– Improve existing facilities by implementing adequate storm water management designs that would allow for more efficient drainage and avoid storm water contact with potentially contaminant materials or waste.* *– Design sorting, recycling and composting facilities to reduce waste storage needs.* *– Update equipment to increase efficiency and reduce maintenance costs in changing climate.* *– Prevent erosion on landfill slopes, covers and roads.* *– Continue and adequately enforce leachate, groundwater and Landfill Gas (LFG) monitoring in active and closed landfills.* *– Increase financial and technical resources for frequent maintenance and repairs.* *– Reassess recycling strategies considering critical elements: legislation, collection system, infrastructure and markets for recycled products with particular focus on high-volume materials.*	*– Use of non-hazardous solid waste as a resource.* *– Integration of anaerobic digesters and other alternatives.* *– Waste companies should consider to further perform risk assessments of the impacts of climate change on their routine waste operations.* *– Research and development opportunities in the island's solid waste management industry.*

APPENDIX E
Risk Assessment: Healthcare Infrastructure

INTRODUCTION
Globally and locally, extensive work is being conducted on the effects of climate change to health, including development of mitigation strategies. A realistic appraisal of healthcare infrastructure and its vulnerability to severe weather should acknowledge that weather extremes have been observed in Puerto Rico and will continue to occur, such as heat waves, floods, temperature extremes, and tropical cyclones.

Climate change also has the capacity to produce severe consequences for human health and social wellbeing. Health scientists from the Graduate School of Public Health of the University of Puerto Rico, have conducted studies on how trends in climate change relate to increased asthma, more virulent allergens, medical emergencies from heat stress, and vector-borne illnesses (Méndez-Lázaro et al., 2016).

This puts a burden on the healthcare system, both in terms of increasing numbers of hospital admissions as well as in terms of the consequences arising from potential health facility infrastructure failures.

It is critically important that more studies be conducted regarding the management and safeguarding of the healthcare physical infrastructure and adaptive operational strategies to respond to the evolving risks presented by climate change. This risk assessment is a first step towards the goal of exploring and understanding the impacts of present and future extreme weather risks to the healthcare infrastructure.

STEP 1:
Understanding the Context

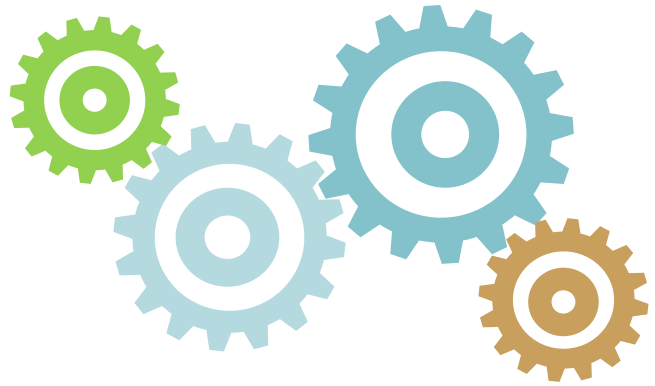
OVERVIEW
A realistic appraisal of the health care infrastructure and its vulnerability to severe weather should acknowledge that weather extremes are and will continue. Given the forecasts and severe events, it would be expected that the healthcare sector would be prepared for the events. Unfortunately, history has shown that this has not been so.

For example, when Hurricane Katrina hit New Orleans, the hospitals were flooded, and because they all had their electrical equipment as well as their back-up generators in the basement, they lost all power. Since the hospital windows were not operable, hospital staff had to break all the windows to get air into the facility.

Hospitals are dependent on complex, intricate, continuous, and substantial amounts of ongoing maintenance, and may be entirely incapacitated by the failure of a single point of vulnerability. Extreme weather events are likely to increase health care delivery systems' exposure to hazards and risk, while climate change effects will cause the efforts to build resilience into the healthcare infrastructure even more challenging.

It is equally important to understand that the resilience of the healthcare infrastructure is more than having capable and protected physical assets. What good is a hospital that withstands a 500-year storm if the staff cannot get to work? If patients cannot reach it? If stocks of food, water, medical supplies or fuel are exhausted after several days?

A comprehensive and integrated Healthcare Infrastructure Risk Management Program will not only consider physical assets, but also others such as personnel, supply chain, access, response capacity, etc.



CLIMATE CHANGE RISKS
Heat waves are typically defined as events exceeding specified temperature thresholds, often accompanied by high or low humidity extremes. They can vary from short-term climate variability (such as heat waves and storms that can trigger health emergencies over timescales from days to weeks) to long-term climate change (onset of seasons and average number of hot days and nights over decades). Large urban areas, which tend to have more asphalt and concrete surfaces that store heat for longer and slowly release it at night, may cause populations in these areas to be at a greater risk of heat related injuries (NOAA, n.d.). In addition, elderly people and young children, sick people, and economically disadvantaged people, who are less likely to have air conditioning, are at greater risk for overexposure to heat (NOAA, n.d.).

Temperature extremes are associated with increased risks of death and hospitalization from heat stress and aggravation of underlying diseases, especially of the heart, kidney, and lungs. In addition, high temperatures and sunlight speed the reactions that lead to the formation of the air pollutant ozone, which in turn, irritates the lungs and causes worsening of conditions like asthma and chronic obstructive pulmonary disease (Méndez-Lázaro et al., 2016). As a result, during heat waves, patient volume surges in emergency departments, urgent care centers, and physician practices. At the same time, the urban energy infrastructure is over-stressed, and the electrical grid is challenged to provide sufficient energy to meet residential and commercial cooling demands.

More intense hurricanes and storms could affect this infrastructure, also with the increasing in sea level some coast areas can be flooded more frequently. Hospitals and healthcare clinics near the coast can be affected.

One of the most devastating storms in recorded history in the United States was Hurricane Maria in 2017, which gave visibility to infrastructure vulnerabilities and inequality of access to services. Those who were economically disadvantaged, had chronic health conditions, and the elderly population were particularly vulnerable to the subsequent health impacts from the hurricane (Niles and Contreras, 2019).

SWOT ANALYSIS

A SWOT analysis considers the Strengths, Weaknesses Opportunities, and Threats. In this case, the focus is the health care industry in Puerto Rico. For this risk assessment, stakeholders considered the following health industry infrastructure:

- *Safety/Emergency Management*
- *Transport*
- *Critical clinical department personnel (including Labs and Pharmacy, Respiratory Therapy), Support Services (Laundry, Environmental Services, Food Service)*
- *Infection Control*
- *Engineering/Physical Plant*
- *Human Resources*
- *Administration*
- *Communities*
- *Hospital/health care associations*
- *Local and Federal Government*
- *Public Health Agency*
- *Fire Department*
- *Puerto Rico Building Code Official*
- *Architects, engineers, and designers*

The SWOT analysis with stakeholders resulted in the following:

STRENGTHS

- *Infrastructure with significant, dedicated, infrastructure maintenance*

WEAKNESSES

- *Lack of understanding regarding climate change*
- *Lack of commitment regarding climate change*
- *Significant user of water systems*
- *Significant generator of waste*
- *Significant generator of greenhouse gases*

OPPORTUNITIES

- *Hospitals and healthcare institutions could become examples of low carbon development, deploying onsite renewable energy technologies such as wind and solar, super-efficient building design, minimized waste generation, water recycling and more.*

THREATS

- *Temperature variability*
- *Precipitation patterns (wet vs dry / extreme events)*
- *Tropical storms and hurricanes*
- *Sea level change*
- *Vector variability leading to patient healthcare conditions*

Table 8: Risk raking criteria for health infrastructure.

RISK EXPOSURE	NUMBER SCALE	DESCRIPTION	COLOR CODE
VERY HIGH	20-25	*Extreme Risk: Immediate controls required*	RED
HIGH (H)	10-16	*High Risk: High priority control measures required*	ORANGE
MODERATE (M)	5-9	*Some controls required to reduce risks to lower levels*	YELLOW
LOW (L)	3-4	*Low Risk: Controls likely not required*	BLUE
VERY LOW	1-2	*Negligible Risk: Risk events do not require further consideration*	GREEN

STEP 2:

Risk Identification

Risks were identified by:

- *Incident scenarios with their consequences related to the assets were identified*
- *Describing and listing how climate changes impact on the key assets of the critical infrastructure.*
- *What can happen?*
- *How can it happen?*
- *Scenarios were classified as Significant Single Event or On-Going/Cumulative Occurrence*

The risk rating criteria are defined in Table 8.

LIKELIHOOD CRITERIA:

The likelihood description is generic however the consequence description depends upon the context of the analysis. The likelihood criteria used for this analysis are described in Figure 8.

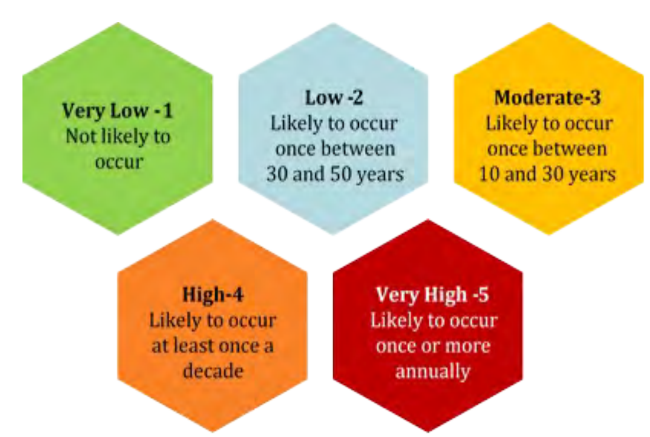


Figure 8: Likelyhood criteria for health infrastructure.

STEP 3:

Risk Analysis

A risk analysis for health infrastructure consists of determining the likelihood and consequences for the identified risk scenarios. The consequences and their likelihood are then combined to determine the level of risk. Through this analysis, the scenarios with the highest risk rankings were:

- *Management adoption of alternative energy sources in order to minimize impact of CO_2 and greenhouse gas emissions.*
- *Organizational and business continuity management activation in order to respond to extremeevents.*
- *Organizing and addressing emergency plans and supply storage in order to address the vulnerability of the event and the need for longer-term inventory.*
- *Increased number of patients with serious or perceived conditions visiting hospitals for which management has to adapt in order to provide proper care.*
- *On a short -term basis, increase in financial investment to adopt alternative energy sources.*
- *Increase in energy expenses*
- *Service interruption and financial cost of replacing/repairing critical infrastructure under 100-year flood elevation.*
- *Increase in financial expenses to (1) prepare infrastructure for an increase in patient demand (2) supplies and (3) salaries of additional health workers needed to respond to the increase in number of patients.*
- *Increase in regulatory requirements to reduce footprint.*
- *Need to comply with regulatory requirements regarding placing of critical infrastructure above 500 yr. flood.*
- *For advance-notice events, facilities that intend to shelter in place must secure sufficient food and supply inventories to operate for extended (and difficult to predict) durations. Organizing and storing these supplies in accessible location(s) out of harm's way can present space challenges.*

Table 9 below summarizes the scenarios with the highest risk rankings of health infrastructure in Puerto Rico.

Table 9: Risk ranking of health infrastructure in Puerto Rico by scenario.

SCENARIO (EVENT)
Management adoption of alternative energy sources in order to minimize impact of CO_2 and greenhouse gas emissions.
Organizational and business continuity management activation in order to respond to extreme events.
Organizing and addressing emergency plans and supply storage in order to address the vulnerability of the event and the need for longer-term inventory.
Increased number of patients with serious or perceived conditions visiting hospitals for which management has to adapt in order to provide proper care.
On a short -term basis, increase in financial investment to adopt alternative energy sources .
Increase in energy expenses.
Service interruption and financial cost of replacing/repairing critical infrastructure under 100-year flood elevation. Increase in insurance premium.
Increase in financial expenses to (1) prepare infrastructure for an increase in patient demand (2) supplies and (3) salaries of additional health workers needed to respond to the increase in number of patients.
Increase in regulatory requirements to reduce footprint Need to comply with regulatory requirements regarding placing of critical infrastructure above 500 yr. flood.
For advance-notice events, facilities that intend to shelter in place must secure sufficient food and supply inventories to operate for extended (and difficult to predict) durations. Organizing and storing these supplies in accessible location(s) out of harm's way can present space challenges.
Storm surge and coastal flooding affecting critical building systems, including generators and information technology (IT)/communication systems.
Regulatory requirements regarding protection and facilities controls to tend to patients that present vector symptoms.
Damage to the infrastructure combined with an increase of patients seeking care leads to an interruption and/or disruption of patient care.
Positive or negative impact to reputation based on the hospital capacity to provide quality healthcare during and after the event.
Positive or negative impact to reputation based on the hospital's capacity to provide quality healthcare to patients showing symptoms related to the vectors while still tending to the standard patient care needs.
Extreme weather events create surges of demand for health care while simultaneously threatening the continuity management of that care.
Increased use of fans and air-conditioners may cause overheating and put stress on electrical equipment, posing a risk of fire.
Financial losses, increased financial expenditures to ensure quality of service electrical power outages impacting essential equipment in lower floors, manual medical recording may be needed .
Hospitals must also prepare and stockpile supplies to remain operational through extended transportation and supply chain disruption.
Increase in demand of healthcare workers, supplies, equipment, energy consumption, and beds to proper healthcare series.
Lack of access of front-line healthcare workers of both clinical care staff—doctors and nurses—as well as aides and diagnostic technicians, food service and environmental services personnel, administrators and engineers required to ensure that safe, resulting in interrupted quality patient care.
The increased likelihood of higher events associated with climate change may cause a greater number of people within the community to suffer from heat stress and its associated effects impacting the capacity of response.
Water shortages may lead water supply failures and/or to compromised water quality.
Critical infrastructure, including generators, IT, fuel storage tanks, fuel vents, and fuel pumps become exposed because they are below flood elevations.
Financial burden to retroactively relocate or protect critical clinical service. Increase in insurance premium.
Increase in regulatory code compliance required to protect healthcare critical infrastructure.
Extreme events interruption of quality of the service.
Negative reputational impact due to poor controls and actions to mitigate CO_2 and greenhouse gas emissions.
Extreme events may create an access problems for physicians and other staff travelling to and from the hospital.
Disruption in patient care if sufficient supplies are not secured to treat incoming flow of patients.
Increased number of emergency visits due to heat stress causes an increase in hospital demands of personnel and patient treatment rooms.

STEP 4:

Risk Treatment

As this is a risk assessment of the Healthcare Infrastructure as a general category, Table 11 shows the criteria established for the risk treatment evaluation.

With this in mind, the risk treatment will be addressed by asset (Table 12).

SOURCE OF RISK	RISK RATING
Increase in CO_2 and other greenhouse gases	11
Tropical storms and hurricanes	10
Sea level change	9
Temperature variability	8
Vector variability in patient conditions	8
Precipitation patterns (wet vs dry / extreme events)	7

Table 10: Risk ranking by source of risk for health infrastructure in Puerto Rico.

TIME FRAME	COST	EFFECTIVENESS	ACCEPTABILITY
SHORT can be implemented within 10 years	$ can be completed within existing or planned budget allocation	LOW will have minor effect on risk event	LOW significant public/corporate/stakeholder resistance
MEDIUM can be implemented within 10-20 years	$ $ will require additional funding	MODERATE will have moderate effect on risk event	MODERATE moderate public/corporate/stakeholder resistance
LONG can be implemented within 20 – 50 years	$ $ $ will require major additional funding/major capital program	HIGH will virtually overcome risk event	HIGH little or no public/corporate/stakeholder resistance

Table 11: Risk treatment criteria for health infrastructure.

Table 12: Risk treatment addressed by asset.

ASSET	RISK RATING BY ASSET	ADAPTATION MEASURE OR RISK TREATMENT	TIMEFRAME	COST	EFFECTIVENESS	ACCEPTABILITY	COMMENT / EVALUATION
MANAGEMENT	11	*1.* Risk Management: Recognize, monitor, anticipate, communicate and prepare for changing climate-related health risks. *2.* Adapt operations to changing risk conditions: prevent, respond to, manage, and cope with uncertainty, adversity and stress. *3.* Business Continuity: Recover from crisis and disruptions with minimal outside support; and continually improve for the future.	SHORT can be implemented within 10 years	$ can be completed within existing or planned budget allocation	MODERATE will have moderate effect on risk event	MODERATE moderate public, corporate and/or stakeholder resistance	
FINANCIAL	10	Education and risk assessment will deliver the administration with proper information about climatic and environmental conditions, health conditions, and an understanding of the healthcare institution's current and future response capacity needs. Said information and data will allow for informed decisions regarding financial expenditures of capital required to address climate change consequences and develop new models to finance preventive approaches.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	MODERATE moderate public, corporate and/or stakeholder resistance	Should be analyzed as opportunities.
REGULATORY	10	Comply with the International Building Code (IBC), which references ASCE 7 (Minimum Design Loads and Associated Criteria for Buildings and Other Structures) and ASCE 24 (Flood Resistant Design and Construction) Standards. It sets the minimum requirement and criteria for the design and construction of buildings and structures in flood hazard areas. In addition, the FEMA Flood Insurance Rate Maps (FIRMs) are used when conducting coastal flood hazard assessment and zoning regulations.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	MODERATE moderate public, corporate and/or stakeholder resistance	
REPUTATION	8	Assessment of reputational risk, including whether there are any potential issues with: – Commitment and actions regarding climate change – Stakeholder communication – Involvement with the community – Environmental regulatory compliance – Environmental and/or social considerations Identify opportunities: – Proactive controls regarding climate change that will protect infrastructure and lead to organizational resilience – Public education regarding the impact of climate change in health – To present and protect the environment in public policy	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	HIGH little or no public, corporate and/or stakeholder resistance	
PRODUCT & SERVICE	8	Increasingly take steps to understand how climate change will affect service delivery due to the impact on their community, staff, and patients. Evaluate the effectiveness of their actions and systems under diverse climatic conditions and enhance their institutional capacity accordingly. Some strategies to consider: – Integration of climate change considerations into the existing business continuity programs for control of the facilities and infrastructure. – Improved management of the environmental determinants of health, such as waste management, water and sanitation, and air quality. – Include disaster risk reduction, emergency preparedness and management, as pertains to the health infrastructure consequences or extreme climate change events, such as heat waves, floods and droughts, storms and hurricanes, and sea level rise.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	HIGH little or no public, corporate and/or stakeholder resistance	
PHYSICAL	7	Assess any physical risks associated with extreme weather and climate change, and their potential impacts on the healthcare infrastructure (operations, facilities, supply chain, staff, patients, communities). Potential risks should be included. Climate change treatment considerations should be integrated into the institutions' infrastructure risk management program and the preparedness planning for extreme event. Considering how climate change may enhance the sources of risk evaluated in this study is an important first step in assessing infrastructure's risk treatment options.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	MODERATE will have moderate effect on risk event	Should be analyzed as opportunities. Cost vary depending on each institution current controls.
SUPPLY CHAIN	7	– Conduct a risk analysis of the transportation infrastructure for critical healthcare delivery in order to understand the underlying vulnerabilities of tunnels, bridges, access roadways, and, where applicable, public transit services. • Enhance data on Puerto Rico specific factors: understand local transportation conditions and context, infrastructure age, and impacts from past weather events and how these can impact the institution. • Assess access roads and building evacuation routes for extreme vulnerabilities, and consider whether downed trees, floods, or blocked channels will affect road use and site access. Then address the proper authorities responsible for taking action about the assessed vulnerabilities. Monitor. • Develop or maintain access redundancies. – Analyze restrictions and obstacles that may hinder staff access to the facilities. Plan for said events. • Develop carpool and vanpool systems that can be activated following events to respond to staff access needs. – Analyze supply demands requirements during disruptions. Prepare and stockpile supplies to remain operational through extended disruptions. – Develop extreme weather impact scenarios based on recent events, forecasts, and local conditions to identify vulnerabilities and cascading effects. – Understand evacuation routes and procedures when locating helipads, ambulance drop-off zones, and other vital points of access.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	HIGH little or no public, corporate and/or stakeholder resistance	
RESPONSE	6	Risk assessments for current and projected future exposure to extreme events and emerging climate change risks may include: – Health sector contingency plans for extreme weather events developed, including risk reduction, preparedness and response. – Emergency response plans customized for the individual healthcare facility defined and implemented in case of need. – Routine training of healthcare staff in the emergency response plans and roles. – Simulation event exercises.	SHORT can be implemented within 10 years	$$ will require additional funding	MODERATE will have moderate effect on risk event	HIGH little or no public, corporate and/or stakeholder resistance	

RESILIENCE, ADAPTATION, AND SUSTAINABILITY

Health care systems and facilities, generally operate on public funds or thin economic margins. Areas of resiliency focus should include:

- Infrastructure (institution level infrastructure: physical buildings and campus infrastructure as well as mobile technologies); and
- Critical services and personnel, supply chain, sustainability/ energy and water efficiency, and enhancing ecosystem services.

When selecting the options for risk treatment, the values and perceptions of stakeholders should be considered, including the most appropriate ways to communicate with them. Each individual healthcare organization should clearly identify the order in which the risk treatments will be implemented, document the reasoning for the decision making, and document the implementation plans. Monitoring of climate-sensitive environmental risks against actual evidence is an essential part of the risk treatment plan to ensure that the measures remain effective against the constantly changing variables of climate change. The ability to respond to the results ensured from the monitoring process, will allow for organizational adaptation.

Section 5.5.2 of the ISO 31000 International Standard states: "Selecting the most appropriate risk treatment involves balancing the costs and efforts of implementation against the benefits derived, with regard to legal, regulatory, and other requirements such as social responsibility and the protection of the natural environment" (International Organization for Standardization, 2009).

Challenges to the functionality of healthcare delivery of services include the following:

- Supply disruptions, such as the loss or reduction of infrastructure and or the staff/resources needed to function and deliver care; and
- Demand disruptions, such as an increase in patients, actual or anticipated, above the existing capacity.

Storms, hurricanes, extreme precipitation, drought, sea level rise, are not avoidable, but their consequences—the loss of human life, property, and essential services—can be avoided or reduced when a facility, and the organization that manages it, is resilient through proper risk management. The most resilient operations can mitigate and minimize damage, provide continued support and emergency services, and take advantage of the post-disaster circumstances to improve or facilitate positive change through adaptation.

Risk management strategies that are employed to treat risk result in improved resilience, thus allowing for continuance of services. To achieve this, it is critical to integrate available meteorological and scientific knowledge, emergency management, public policy, and engineering solutions on a timely basis to protect critical infrastructure, especially hospitals, from known risks.

Important components of a climate resilient health infrastructure and services include:

- Ensuring that the location of health facilities and the building codes that are applied account for current and projected future climate risks, such as the potential for increased frequency and intensity of heat waves, cyclones or storm surges.
- Considering the provision of essential environmental services to health facilities, such as water and sanitation services which may be compromised by flood or drought, mechanical services such a ventilation, and electricity supply that may be cut off during extreme weather events.
- Understanding the present and future climate risks they may face for the planning and activities of the risk treatment options to be effective. Relying only on municipal codes and regulations places the healthcare critical facilities at risk. Continual monitoring and review of risk assessments are essential to informed decision-making, prioritization of projects, and longer-range planning. Considering how their facilities interacts with its community, as well as how resources and capacity might shift if extreme weather affects some or all system's regional assets.

Thus, for the healthcare infrastructure to be resilient in the face of climate change, risk management adaptation measures are required. Examples of these measures are:

- Increasing engineering design thresholds to recognize more severe weather intensities (design thresholds include design temperatures, mean flood elevations, etc.).
- Using predictive climate models to set design values, such as maximum outdoor air temperatures for load sizing, maximum rainfall events for storm water systems, projected sea level rise for minimum elevations, and maximum wind speeds for enclosures of critical spaces.
- Managing supply chain needs, and adopting changes that contemplate more severe weather durations (increasing the minimum amounts of on-site food, water, and fuel storage).
- Increasing the capabilities of "island operations" in healthcare, recognizing that on-site infrastructure, staff, and supplies may be required for extended periods of time following extreme events because of damaged community infrastructure (regional electrical grid, municipal potable water supplies, impacted roads and transportation, loss of communication systems), and that facilities may need to operate for more than 96 hours without external supplies.

Nevertheless, despite the urgency of addressing both sustainability and resiliency, awareness of the available improvement measures is low among the healthcare sectors. Being able to make a convincing case for investing in sustainability and resiliency measures is critical to gaining the support of corporate managers, boards, and policy makers. Strategies and tools to achieving this should include risk assessments (including risk reduction strategies and assessment of risks to infrastructure), risk management (including procurement, monitoring, clinical risk management, infrastructure systems, and energy supply and use), education on climate change, and decision making on adapting building capacity based on reliable data and knowledge (sustainable health care and climate change mitigation). Some broad obstacles that deter accomplishment are:

1. *A general lack of awareness of environmental vulnerabilities on the part of local decision makers and hospital management.*
2. *An absence of coordination and communication across federal and local agencies.*
3. *A minimal appointment of financial resources or incentives to encourage needed structural mitigation or adaptation for current and projected climate risks, in part due to the aforementioned obstacles.*
4. *Not involving the community and essential stakeholders in the process.*

IMPORTANCE OF INTEGRATING CLIMATE CHANGE INTO THE INSTITUTION'S RISK MANAGEMENT PROGRAM

Hospitals must consider a broad range of risks, from bioterrorism, to pandemics, to safety and security, to information security. Since healthcare facilities are exposed to multiple hazards, it is essential that multi-hazard assessments be addressed, as they can reveal potentially conflicting effects of mitigation measures. Thus, the results of a climate risk assessment should be mainstreamed and included in the institution's Risk Management Program. The importance of this has become increasingly evident following the catastrophic failures that have occurred.

For example, while elevating critical infrastructure allows the hospital to keep function during extreme events, new risks may arise that must be addressed, such as access and load requirement, fire exposure, chemical and spill controls. These would require code compliance and maintenance considerations.

INCORPORATING THE RISK TREATMENTS INTO A RISK MANAGEMENT PROGRAM

Important components of climate resilient health infrastructure and services include:

- Ensuring that the location of the health facilities and the building codes that are applied account for current and projected future climate risks, such as the potential for increased frequency and intensity of heat waves, cyclones or storm surges.
- Giving important consideration to the provision of essential environmental services to health facilities, such as water and sanitation services which may be compromised by flood or drought, mechanical services such a ventilation, and electricity supply that may be cut off during extreme weather events.
- Understanding the present and future climate risks they may face in order for the planning and activities of the risk treatment options to be effective. Relying only on municipal codes and regulations places the healthcare critical facilities at risk. Continual monitoring and review of risk assessments are essential to informed decision-making, prioritization of projects, and long-range planning. Considering how their facilities interact with its community, as well as how resources and capacity might shift if extreme weather affects some or all of a system's regional assets.
- Understanding that Healthcare organizations play a key role in community resilience. Health care workers are first responders; hospitals are critical facilities. For hospitals to remain operational, both to deliver essential medical care and serve as a safe haven, physical infrastructure (including utilities), key personnel (both medical and support), and supply chain resilience must all be in place.

RISK TREATMENT FOCUSED ON ASSETS

Management

Infrastructure protection and resilience is a key element of healthcare facility operation through extreme events. Managing a Healthcare Infrastructure Risk Management Program and leading it towards resilience to climate change is a cumulative process. It requires an adaptive management with the capacity to develop planning strategies that address the complex and long-term nature of climate change risks. This begins by making resilience a goal and incorporating a risk management framework into the organization and its culture, in addition to other governance responsibilities, such as the goals of improving healthcare, being responsive and efficient, and social and financial objectives.

This involves the capacity to: recognize, monitor, anticipate, communicate and prepare for changing climate-related health risks; prevent, respond to, manage, and cope with uncertainty, adversity and stress; adapt operations to changing risk conditions; recover from crisis and disruptions with minimal outside support; and continually improve for the future.

Particularly, it calls for a leadership capable of driving collaboration to develop a shared vision among diverse stakeholders, and coordinated, integrated planning to ensure that policies are comprehensive and health promoting.

An adaptive management is essential to address climate change. By integrating a comprehensive, all-inclusive, risk management framework within an organization, adaptive management involves a structured and iterative process of decision-making and implementation that is especially useful in the context of uncertainty. Adaptive management processes and approaches use active learning methods and a risk management program to help ensue multiple perspectives of information that can reduce uncertainty over time and adjust the system according to changes.

Organizational Considerations
Most health care organizations have disaster mitigation or emergency operation plans, but not all of them provide organizational business continuity management.

The disruption of administrative services by natural events can impair hospital functions as much as physical damage. The critical nature and interdependence of processes and its vulnerabilities need careful attention. Furthermore, any prolonged disruption on accesses to the healthcare facility can interrupt supply replenishment, for which the organization must prepare.

All staff, from clinical care staff to food service personnel to environmental services workers, keep health care facilities functioning. Health care workers are first responders, engaging in lifesaving measures that may expose them to dangerous conditions or injury. Therefore, the organizational risk management program must include an assessment of the potential workplace hazards that may arise in emergencies, many in fact related to the disasters, and planning should address measures to mitigate those hazards.

Likewise, interruption of potable water services, food supplies, and/or other community necessities may bring people to the hospital seeking assistance. Hence, it is critical to understand the broader operational expectations during and after disruptive events.

Financial
Education and risk assessments will deliver the administration with proper information about climatic and environmental conditions, health conditions, and an understanding of the healthcare institution's current and future response capacity needs. It is the basis for establishing early warning systems to identify and forecast potential financial impacts on the ability to deliver health services, as well as the financial impact of not taking actions regarding climate change, including the potential increase in infrastructure maintenance and climate-sensitive diseases costs.

Said information and data will allow for informed decisions regarding financial expenditures of capital required to address climate change consequences and develop new models to finance preventive approaches.

Physical Infrastructure
Physical risks are those related to damage inflicted on infrastructure and other assets. Climate change considerations should be integrated into the institutions' infrastructure risk management program and the preparedness planning for extreme events. Consideration of how climate change may enhance the sources of risk considered in this study is an important first step in assessing infrastructure's risk treatment options.

FEATURES OF ADAPTIVE MANAGEMENT

- Risk-informed
- Iterative processes
- Flexible
- Information seeking for learning
- Out of the box
- Uses models and scenarios to understand future context
- Embraces risk and uncertainty as a way to increase learning

SOME FACTORS THAT MAY INFLUENCE IN THE INABILITY OF HOSPITALS TO FUNCTION THROUGH EXTREME EVENTS ARE:

- **Dependence on external infrastructure**
  - Reliance upon, and compliance with, the minimum flood elevations designated by local zoning and FEMA maps (extreme weather events have exceeded thresholds with catastrophic results)
  - Reliance on aging municipal flood protection infrastructure
  - Reliance on the Puerto Rico energy infrastructure
- **Regulatory Conflicts**
  - Contradictory regulations, codes and utility practices, which require diesel fuel storage and locate major utility infrastructure such as electrical switchgear at grades vulnerable to flooding
- **Building envelope failures**
  - *Building façade and enclosure failures, along with improperly anchored equipment subject to high winds, resulting in equipment blowing off roofs, which in turn compromises roofing systems and waterproofing*
  - *Envelope failures related to the age or condition of building enclosures that were designed prior to contemporary extreme weather considerations or building code regulations adopted in Puerto Rico*
- **Building infrastructure systems failures**
  - Aged and complex critical infrastructure. Some even, in multi-building campuses, making hospitals highly vulnerable to single points of failure
  - The aging infrastructure maintenance requirements are aggravated by the dynamic conditions of shifting extreme weather patterns
- **Reliance on on-site diesel emergency generator plants,** which have grown larger and more complex, require ongoing maintenance and testing, and are prone to failure under full load conditions (required fuel storage may be too short to allow for safe refueling in a weather emergency, when fuel shortages are acute and roads may be impassable)

HEALTHCARE INFRASTRUCTURE PLANNING, BUILDING DESIGN, AND REGULATION

Healthcare buildings should be designed to survive loss of essential services such as electricity, water, and waste management after a natural disaster, utility outage, or major event. In other words, hospitals must be capable of "island" operation—that is, being able to maintain operational capability even when losing municipal electricity, water and waste utility systems for extended periods of time.

Examples of strategies that extend the ability to inhabit buildings in the event of major ongoing utility disruptions are onsite renewable energy, daylight, potable water storage tanks and passive ventilation.

Land use decision-making affects the resilience of the institution's campus or building. In Puerto Rico, several generations of weak land use planning decisions have severely disrupted a range of ecosystem services and natural resilience to extreme weather events.

Recent extreme events suggest that relying only on historical data will not ensure future building performance, especially for critical buildings such as hospitals. Considering extreme weather hazards in combination with building type, age, and risk assessment of current and emerging risks will help healthcare institutions improve their climate resilience.

It is therefore imperative to understand the broader context of land use within which a campus or building is located or being planned, and to consider the ways that land use decision making can treat or intensify severe weather impacts.

Orientation of the building can affect the thermal and wind performance of the envelope. Orienting buildings to minimize thermal loads, particularly heat loads, will reduce the probability of overheating if a building's air conditioning systems fail. In tropical climates such as in Puerto Rico, exterior solar shading options and landscaping can reduce extremes of solar impact.

Currently, hospitals are not required to retroactively relocate or protect critical clinical service programs (for example, emergency departments, lab or imaging equipment, kitchens, and laundries). Nevertheless, depending on their layout and unique risks, protection for these critical functional program areas should be encouraged as a best practice, as they are essential for proper functioning of operation.

Power, emergency power, and water are all necessary to support a shelter-in-place situation, and investments in infrastructure resilience are needed to minimize future climate change risk. Based on this, some healthcare providers have already assessed their potential vulnerabilities and are addressing them.

BUILDING REGULATIONS

For existing healthcare facilities, it is important to understand the codes that were in place when buildings were constructed, while for new facilities, it is imperative to compare future climate risk projections against current local codes.

In Puerto Rico, hospitals are licensed by the Department of Health. In addition, building, mechanical, electrical, and fire protection International Code Council codes must be complied with. These codes, define the "minimum" standards of construction, installation, and maintenance. The Joint Commission (TJC) accredits hospitals but does not set resilience criteria. To qualify for benefits, the Centers for Medicare and Medicaid Services (CMS) also require specific compliance with NFPA or NEC standards in order to qualify to serve Medicare and Medicaid populations. The Veterans Administration has its own set of design criteria.

Another design tool is the Minimum Standards for the Design and Construction of Hospitals and Health Care Facilities (Facility Guidelines Institute, 2014). It designates minimum fuel supplies, and define mechanical, electrical and communication systems that must be supplied by on-site emergency power systems. The Facility Guidelines Institute's (FGI), is an independent, not-for-profit organization dedicated to developing guidance for the planning, design, and construction of hospitals, outpatient facilities, and residential health, care, and support facilities

Structural

Foundations, bearing walls, columns and beams, staircases, floors and roof decks are types of structural components that help support a building. Structural risk analysis considers potential damage to structural components of the institution's structures. The structural aspects of design and construction of healthcare infrastructure are regulated by the International Building Code and other regulations. In addition, depending on the site planning, structural components may include roads and/or bridges.

Nevertheless, because many other factors affect healthcare functions, it is important to understand that building regulations alone, cannot guarantee control of risk sources associated to uninterrupted operation of a healthcare facilities.

Non-structural

The effects of damage to non-structural building components and equipment, as well as the effects of breakdowns in public utility services, communication and IT infrastructure, transportation, or other elements, can be as disruptive and dangerous to patients as any structural damage. Non-structural components include architectural components, such as exterior walls, window and roofing, as well as interior components of buildings, such as suspended ceilings.

Energy and Utility Infrastructure

In Puerto Rico, due to the high wind and flood hazard zones, particular care must be exercised with energy and utility infrastructure. Utilities include all systems, equipment, and fixtures, including mechanical, electrical, plumbing, heating, ventilating, and air conditioning.

Utility systems and equipment are best protected when elevated above the Design Flood Elevation (DFE). Equipment that is required for emergency functioning during or immediately after an event, such as emergency generators and fuel tanks, should be installed as shown in Table 13.

Plumbing conduits, water supply lines, gas lines, and electric cables that must extend below the DFE should be located, anchored, and protected to resist the effects of flooding.

Table 13: Elevation requirements for the instalation of energy and utility infrastructure.

MINIMUM ELEVATION OF UTILITIES AND EQUIPMENT ASCE 24 (TABLE 7-1) FOR CATEGORY IV STRUCTURE CLASSIFICATION

All A Zones not identified as Coastal A Zones	BFE +2 ft or DFE, whichever is higher
All V Zones and Coastal A Zones: where the lowest horizontal structural member is parallel to direction of wave approach	BFE +2 ft or DFE, whichever is higher
All V Zones and Coastal A Zones: where the lowest horizontal structural member is perpendicular to direction of wave approach	BFE +3 ft or DFE, whichever is higher

Electrical

The emergency power supply system is probably the most critical element of a health care system. Together with fuel supply and storage facilities, this system enables all the other hospital installations and equipment that have not sustained direct physical damage to function during a disruption or event.

About Power Reliability and Emergency Power

Healthcare institutions in Puerto Rico rely on public utility grids for electrical service, with private onsite boiler and chiller plants providing energy needs to the buildings. The International Electric Code (IEC) and the National Electric Code (NEC-NFPA 70) present the regulatory requirements.

Emergency power systems are generally encompassed of on-site electrical generators powered by reserves of diesel fuel, that are sized to cover critical medical equipment and building system loads, including, at a minimum, building ventilation (typically not conditioning), vertical transportation, and key support service requirements. Emergency power generation must activate within 10 seconds of loss of grid power. It is an industry practice to ensure sufficient fuel for 96 hours of operation. Diesel generator systems are required to be tested monthly, and once every three years under full load conditions for 4 hours.

Because on-site generators may fail when used at full loads for extended periods of time, another good practice is to have an electrical pre-connection for external mobile generators. The ability to switch quickly from the electrical system to a mobile generator can allow the facility to size on-site generators for code-required life safety, critical patient care equipment (systems that must be able to be operational within 10 seconds of power loss), and critical medical support services. Additional mobile generators can be used to handle air conditioning and other systems that can tolerate longer disruption. Prior to a major weather event, external generators can be safely mobilized nearby, and safely deployed once the event has passed.

Hospitals must ensure that emergency power systems—generators and fuel pumps—are accessible to building staff at all times, so that emergency power can be maintained continuously, even during flood conditions.

Energy Efficiency

Reducing healthcare facility dependence on fossil fuel energy through conservation efforts improves resilience. The less energy required to operate a health care facility, the longer that facility can remain operational on a given capacity of reserve fossil fuel.
Moreover, the healthcare should be an industry motivated to model the transition to a post-fossil fuel economy.

Alternative sources of power independent from the electrical grid also helps in emergencies; while all hospitals have diesel generators, much of this infrastructure has proven to be vulnerable and inadequate for prolonged grid outages.

Renewable Energy

Renewable energy systems provide enhanced resilience, both for long term climate change action and continuation of service during extreme weather. Healthcare institutions may consider wind or solar energy photovoltaic systems for both thermal energy (domestic hot water heating) and electric power generation.

History data shows that performance of renewable energy systems in areas where there have been extreme weather events has been good, with limited damage to such systems from high winds or flooding.

Licensed engineering professionals with such matter expertise can help calculate the most cost-efficient alternative that not only will allow for continued operations during an event, it will reduce energy cost.

Elevators

In case of patient evacuation, elevator service is essential. Elevator service is vulnerable not only to power outage, but also to direct damage to elevator installations. For example, wind and windborne debris can damage elevator penthouses, opening a path for water penetration that can disable elevator motors and controls, as has happened during hurricanes.

Ventilation systems

Ventilation systems are extremely vulnerable to disruption as a result of indirect building damage. Extreme winds often overturn improperly attached roof-mounted ventilation and air conditioning equipment, causing the ductwork to collapse once the building enclosure is penetrated. Airborne debris from windstorms can quickly clog the air filtration systems, rendering them impaired or inoperable. Proper anchorage is essential to control these.

Flooding due to Extreme Rain

Puerto Rico requires compliance with the International Building Code (IBC), which references ASCE 7 (Minimum Design Loads and Associated Criteria for Buildings and Other Structures) and ASCE 24 (Flood Resistant Design and Construction) standards. It sets the minimum requirement and criteria for the design and construction of buildings and structures in flood hazard areas. In addition, the FEMA Flood Insurance Rate Maps (FIRMs) are used when conducting coastal flood hazard assessments and zoning regulations.

Puerto Rico enacted regulations requiring new hospitals to place infrastructure and essential services as per IBC, ASCE 7, and ASCE 24 according to the classification of structures for flood resistant design and construction. ASCE 7 specifies the flood loads and other loads. Hospitals and other healthcare buildings with surgery or emergency treatment facilities are classified as a Category 4.

Existing hospital buildings on coastal floodplains and flood hazard area sites should assess current and projected storm surge data as they undertake infrastructure upgrades (as per Code Regulation) to ensure that storm surge and coastal flooding do not affect critical building systems, including generators and information technology (IT)/communication systems.

Water Use and Supply
Consistent access to a reliable potable water supply is another key element of resilience. Without water for toilets, laundry service, food service, and medical services, hospitals operations would be paralyzed.

Regarding regulations and standards:

- *The Center for Medicare and Medicaid Services (CMS) Conditions for Participation/Conditions for Coverage (42 CFR 482.41) requires that health care facilities make provisions in their preparedness plans for situations in which water supply interruptions may occur. But, they do not have a standard for the quantity of reserve or back-up water that is required.*

- *The Joint Commission also requires hospitals to address the provision of water as part of their Emergency Operations Plan (EOP), but does not require a specific reserve capacity.*

Water supply interruptions can result from water main breaks or flooding or high wind damage to municipal water infrastructure. In addition, water pump failures (due to flooding or lack of power) can compromise water availability in upper floors of healthcare buildings.

Moreover, an increase in water supply demand should be expected during events. A unique challenge is adequately estimating said demand.

Long-term water supply resilience is improved through a range of measures: water conservation, on-site water capture, and reclaimed water reuse systems.

Stormwater
Stormwater is the general term for water harvested from precipitation or runoff. As climate change is expected to impact rainfall, it becomes significant to view rainwater as a resource: harvesting it and holding back stormwater discharge.

Nevertheless, in floods, proper stormwater management is critical as roof drainage systems, retention basins and flow systems may overflow and cause localized flooding and water damage. Furthermore, sewers are apt to overflow, back up, or break down. Patient care is immediately affected when the toilets back up, or sterilizers, dishwashers, and other automated cleaning equipment cannot be discharged. The use of retention ponds or holding tanks, coupled with backflow and diversion valves, can be employed to solve this problem. In addition, landscape and advanced stormwater management techniques can improve groundwater infiltration and reduce surface runoff and flooding. Some strategies may include:

- *At the healthcare site, protect and restore existing hydrologic functions through planting native or appropriate non-native vegetation, re-grading soils where necessary, and restoring the functions of floodplains, and vegetated buffer strips*

- *Managing stormwater on site by reducing impervious surfaces, harvesting rainwater, and directing remaining stormwater runoff to soil and vegetation-based water treatment methods.*

- *Using stormwater for beneficial purposes (for example, collecting it for irrigation and other non-potable uses)*

Reclaimed Water Reuse and Rainwater Capture
Globally, hospitals and healthcare facilities are beginning to look into employing rainwater catchment systems to provide water for irrigation, cooling towers, and other process loads. Reclaimed water is water that's already been used by the facility but is re-purified to potable standards again and used in potable and non-potable applications. It's different than gray water in that it is purified before reuse.

Sewage/Wastewater
Wastewater system components may become sources of contamination during floods. In flood situations, all plumbing fixtures connected to the potable water system may become points of failure in the system if they allow floodwaters to contaminate the system. The rising floodwaters may force untreated sewage to back up through toilets or floor drains.

Fixtures below the DFE should be isolated from those above DFE. Specially designed devices that prevent backflow can be installed, or restrooms below the DFE can be provided with overhead piping that may require specially designed pumps to operate properly. An added measure of resilience would be to have on-site wastewater treatment facilities.

RESOURCES:

- **The Centers for Disease Control and Prevention (CDC) and American Water Works Association (AWWA) have published an Emergency Operations Plans (EOP) guide titled "Emergency Water Supply Planning Guide for Hospitals and Healthcare Facilities" to assist health care facilities in meeting requirements of EOPs established by CMS and Joint Commission, estimating water demands, and preparing options for meeting demands during extended supply interruptions.**

- **The CDC, NOAA and EPA have a resource for public health professionals preparing for drought: "When Every Drop Counts: Protecting Public Health During Drought Conditions".**

Source: Wanda I. Crespo

Medical Gases
Medical gases are essential in healthcare operations in addition to water, steam, and fire sprinkler systems. These installations must be properly secured and braced, in order to prevent them from being dislodged or broken, causing dangerous leakage and potential additional damage to the structure, the people, and the environment.

Supply Chain
Extreme weather events, like many types of emergencies, cause transportation disruptions and can result in significant restrictions on travel, ranging from high-occupancy restrictions on roads to fuel rationing.

Sea level rise and increased precipitation intensity, present greater challenges to the transportation system infrastructure when combined with subsidence of the land and vulnerable coastal geology of Puerto Rico, as well as storm surge and wave impacts associated with coastal storms.

For example, in Puerto Rico, severe precipitation that causes flooding of roadways, bridges, and evacuation routes can reduce the life of highway infrastructure. It can also increase road washout, landslides, and mudslides that damage roadways and overloaded drainage systems, causing traffic backups and street flooding.

On the other hand, storm surge can damage and destroy coastal roadways, bridges and airports, and sea level rise could exacerbate such effects.

As part of the risk analysis, the transportation infrastructure for critical health care delivery should be reviewed, as it is important to understand the underlying vulnerabilities of tunnels, bridges, access roadways, and, where applicable, public transit services.

Healthcare institutions must prepare and stockpile supplies to remain operational through extended transportation and supply chain disruptions.

In extreme cases, such as floods, restrictions extend to "essential personnel" only. Unfortunately, emergency preparedness plans have often neglected to include non-clinical personnel in this category, which aggravates staffing shortages.

Some strategies may include:

- Enhance data on Puerto Rico specific factors: understand local transportation conditions and context, infrastructure age, and impacts from past weather events and how these can impact the institution.

- Assess access roads and building evacuation routes for extreme vulnerabilities, and consider whether downed trees floods, or blocked channels will affect road use and site access. Then address the proper authorities responsible for taking action about the assessed vulnerabilities. Monitor.

- Develop extreme weather impact scenarios based on recent events, forecasts, and local conditions to identify vulnerabilities and cascading effects.

- Develop or maintain access redundancies.

- Understand evacuation routes and procedures when locating helipads, ambulance drop-off zones, and other vital points of access.

- Develop carpool and vanpool systems that can be activated following events to respond to staff access needs.

Product/Service
During events, healthcare institutions are responsible not only for sheltering the patients in place but to deliver medical services to an increased flow of patients that usually follows. This entails that hospital and healthcare institutions must maintain (1) the operational infrastructure services and (2) the vital medical care delivery services.

Experience from recent historic extreme weather events demonstrates that ground floor emergency departments in flood-prone areas made it extremely difficult, and in some occasions impossible, to provide reliable care. Likewise, expensive and necessary diagnostic equipment (often located on ground floors due to weight and need for proximity to the Emergency Dpt.) may also be destroyed or rendered unusable.

As part of the Risk Management Framework, the Healthcare Institutions should establish processes to continuously monitor and take gradually increasing steps to understand how climate change will affect their population and service delivery, evaluate the effectiveness of their programs and systems under diverse climatic conditions, and enhance their institutional capacity accordingly.

Some strategies may include:

- *Integration of climate change considerations, into the existing business continuity programs for control of the facilities and infrastructure.*
- *Improved management of the environmental determinants of health, such as waste management, water and sanitation, and air quality.*
- *Include disaster risk reduction, emergency preparedness and security management, as pertains to the health infrastructure consequences of extreme climate change events, such as heat waves, floods and droughts, storms and hurricanes, and sea level rise.*

Personnel

Just as critical, hospitals require all healthcare staff to deliver both direct patient care and necessary support services. This includes doctors and nurses, medical aides and diagnostic technicians, food service and environmental services personnel, administrators and engineers in order to ensure that safe, quality patient care continues uninterrupted. In addition to full or part-time employees, there could be additional contracted consultants.

For shelter-in-place, critical staff may be required to remain on-site during and after events. This can create an extremely stressful situation if immediate family members are left to fend for themselves at home. Therefore, for extreme weather events, as part of their contingency plan, hospitals sometimes include housing of the families of critical staff, in order to continue proper provision of service.

It is important that facilities coordination be in place for such events. Plans should include estimations of the number of personnel required and roles to be undertaken, as it is probable they would be required to take on essential roles that are beyond their general job description.

Response

Storms, floods, extreme heat, and sea level rise can damage the healthcare infrastructure and compromise its ability to provide patient safety and deliver key medical services. Hospitals not only have to care for people with acute injuries and illness caused by an event, but also those with health conditions that may be exacerbated by the event.

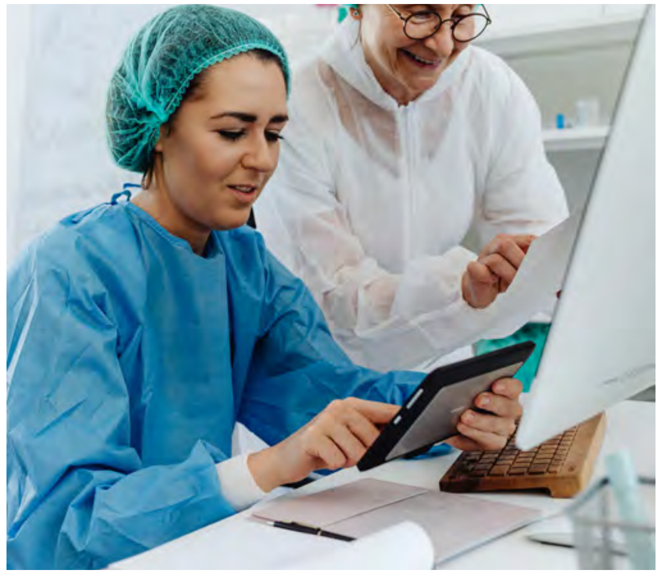
Because of the compromised health of inpatients and the complexity of evacuation and transport, hospitals are designed and constructed to “shelter in place” during and after extreme events. Extreme events can quickly escalate if health service infrastructure is not properly equipped to respond during and after an event.

During extreme events, critical elements of sheltering in place that impact extended response are power outages, and loss of mechanical ventilation, air conditioning and humidification or dehumidification functions.

Unless very large, generators are rarely able to provide air conditioning or general lighting. Increasing attention is on enhancing building envelope design to reduce solar gain or heat loss so as to extend habitable temperatures for longer periods of time.

Strategies to extend passive survivability include implementation of building façade design measures ranging from roof overhangs or fixed solar shading devices, to the use of operable windows, which permit enhanced thermal comfort. Operable windows are not generally used in hospitals, but they may be considered to mitigate overheating in hospital buildings in the event a building remains occupied following total system failure.

It is important to point out, however, that passive survivability measures should be carefully considered in conjunction with a multiple-hazard assessment: some measures may be inappropriate for chemical or bio-terrorism events.



The staff should participate in the development of health care risk assessments and emergency plans, in risk assessment and emergency plan reviews and updates, including exercises and lessons learned after specific events.

Communication systems may be disrupted, so communication changes and equipment alternatives, such as the possibility of manual documentation, should also be considered in advance and included in the response planning activities.

Regarding the community, some response strategies may include:

- *Warning procedures for the community especially those at highest risk.*
- *Availability of safe and environmentally controlled gathering spaces for the community to seek relief, and to avoid unnecessary burdens being placed on healthcare response areas by those not in need of healthcare interventions.*

Knowledge exchange and cooperation in policy and planning among the public health, emergency management and the communities should be strengthened. Innovative efforts are needed to work across these areas of responsibility and engage other sectors in response activities.

Risk assessments for current and projected future exposure to extreme events and emerging climate change risks may include:

- *Develop comprehensive health sector contingency plans for extreme weather events, including risk reduction, preparedness and response*
- *Emergency response plans customized for the individual healthcare facility defined and implemented in case of need*
- *Routine training of healthcare staff in the emergency response plans and roles*
- *Simulation event exercises*

Training and Education

Health care staff require training and education opportunities to effectively adopt resiliency actions and responses during events. Even with a comprehensive adaptation plan at a healthcare facility, significant challenges arise if workers are not trained on protocols and procedures for reducing health risks, impacts on infrastructures, and response.

Healthcare workers are viewing resilience and sustainability programs as complimentary and mutually reinforcing. It is important that health care workers, health care asset management personnel, and medical staff in Puerto Rico receive sustainability and environmental management training that includes considerations of emergency preparedness and resilience measures.

From services staff trained in the use of less-toxic chemicals (which reduces inventories of hazardous chemicals that can be exposed to floodwaters) to security staff briefed on resilience, to medical staff trained in care of climate related illnesses, worker training is increasingly building on the experience of workers to improve the safety, sustainability, and resilience of the health care workplace, leading to optimized response capabilities.

Reputation

In the context of climate-change, risk to the hospital’s reputation can be understood as the probability of profitability loss of gain following the healthcare institution’s activities or positions that the public judges as harmful or positive respectively. Climate-related risk is increasingly likely to add a cost to the balance sheet with the issue now as relevant to investors, local communities, and society.

Impacts to the reputation can be either direct, stemming from healthcare-specific actions, such as the generation of greenhouse gases and high levels of water consumption, or indirect, in the form of public perception of the overall healthcare industry. A poor reputation on climate can hurt the hospital’s bottom line and profitability. It could also impact the regulatory environment and investor relationships.

On the other hand, healthcare institutions that make an informed effort to reduce emissions now—after careful risk assessment of their individual context—could find themselves in a better position to meet regulations that may eventually be put in place and have their reputations enhanced by making such efforts and strategy public.

The involvement of the healthcare institutions in their communities is key. It is important for the healthcare institution to become a reputable educator and advocate of climate change policy. Health care professionals, especially doctors and nurses, undertake a role as positive messengers for health in society. Considering the enormous healthcare and social costs of climate change, healthcare professionals are in a position to educate their patients and the community about the public health impacts of climate change and help prepare them for these impacts.

Communities face unique extreme weather risks and have varying levels of resilience needs to those risks. Social factors affect the capacity of communities to prepare for and recover from climate change events. Because access to health care services is a key element of disaster survival and recovery, health care organizations cannot undertake infrastructure resilience without understanding their particular role in their community and wellbeing of its residents, and the social and environmental justice issues that define their communities.

In fact, it is an essential step in risk management: The ISO 31000 standard, in section 5.3.2 states that “Understanding the external context is important in order to ensure that the objectives and concerns of external stakeholders are considered when developing risk criteria."

Healthcare institutions that adopt a synergistic approach that includes constant communication with their communities, understanding of the community's social and cultural needs, valuing their perception, and collaboration on response plans, enjoy a positive reputation in return.

The more educated a community is, the more capable of climate change adaptation they will be, leading to more prepared individuals in case of events. A reputable healthcare organization, that leads by example, will be more capable of facing events when they have the support of their equally educated community and peers. A prepared, active and well organized community can reduce risks, save lives and contribute to minimizing the impact of extreme events.

CONCLUSION

Health care systems and facilities around the world generally operate on public funds or thin economic margins. Puerto Rico is no exception. Areas of resiliency focus include:

- *Infrastructure (institution level infrastructure: physical buildings and campus infrastructure as well as mobile technologies) ; and*
- *Critical services and personnel, supply chain, sustainability/ energy and water efficiency, and enhancing ecosystem services.*

Nevertheless, despite the urgency of addressing both sustainability and resiliency, awareness of the available improvement measures is low among the healthcare sector. Being able to make a convincing business case for investing in sustainability and resiliency measures is critical to gaining the support of corporate managers, boards, and policy makers. Strategies and tools to achieving this include:

- *Risk assessment (including risk reduction strategies and assessment of risks to infrastructure);*
- *Risk management (including procurement, monitoring, clinical risk management, infrastructure systems, and energy supply and use);*
- *Education on climate change;*
- *Decision making on adapting building capacity based on reliable data and knowledge (sustainable health care and climate change mitigation).*

The economic and quality of life benefits of sustainability are important and significant. Examples include reductions in costs to facilities, increased energy and water conservation, reductions in greenhouse gas emissions, improved air quality, healthier patients, staff, and communities, and positive reputation.

Therefore, conservation of the healthcare infrastructure offers numerous opportunities for positive outcomes, ultimately lowering the cost of the resiliency and sustainability improvements that allow facilities to continue providing services to the community during adverse events.

Climate change threatens to exacerbate the multiple challenges facing healthcare infrastructure systems and facilities in our island. By combining synergistic measures that produce more sustainable healthcare operations with infrastructure initiatives that create more resilient facilities, systems, and communities, the healthcare sector could simultaneously reduce costs and ensure continuity of operations during extreme events.

In many ways, building resilience is about using the best information available about potential risks and doing what healthcare institutions have practiced for many years. That is, strategic planning, risk assessment, investing in infrastructure, diversifying the supply chain, safeguarding staff and patients, and educating about health.

Leading health institutions will gain competitive advantages from more effectively managing climate change risks, specifically by expanding their risk management practices to include the constantly emerging, very real, extremely serious risks that accompany climate change.

"HOSPITALS ARE ENERGY AND RESOURCE-INTENSIVE ENTERPRISES THAT, AS THEY OPERATE TODAY, CONTRIBUTE SUBSTANTIALLY TO CLIMATE CHANGE WHILE INADVERTENTLY CONTRIBUTING TO RESPIRATORY AND OTHER ILLNESSES. PROCUREMENT, RESOURCE USE, TRANSPORTATION AND OTHER POLICIES AND PRACTICES CONTRIBUTE TO THE HEALTH SECTOR'S SIGNIFICANT CLIMATE FOOTPRINT. IT IS CLEAR THAT THE HEALTH SECTOR CAN ALSO PLAY A LEADERSHIP ROLE IN MITIGATING CLIMATE CHANGE - THAT IS, REDUCING ITS MAGNITUDE AND CONSEQUENCES – BY GETTING OUR OWN HOUSE IN ORDER."

—

Maria Neira
Director, Department of Public Health and Environment
World Health Organization

RECOMMENDATIONS FOR FUTURE HEALTHCARE INFRASTRUCTURE EVALUATION

1. Include Residential Health Care Settings

Over the last years, the expansion of residential care facilities has been significant, with concentrations of long-term care and assisted living facilities in more vulnerable coastal areas. Included in this category are nursing homes, which offer skilled nursing for the elderly and very frail in need of ongoing medical attention, and adult care facilities, which primarily support residents who require help with basic daily tasks such as meals or bathing. Other types of residential facilities include those that offer treatment, care, and supportive housing for individuals with substance abuse problems, developmental disabilities, or other behavioral or mental health challenges; and those that offer housing for children and child protective services.

These facilities have intricate ownership, governance, and financial structures, ranging from licensed long-term care facilities owned and managed by non-profit integrated health networks to small, individual, private for-profit endeavors that operate "below the radar" of license and regulatory requirements. Physically, they range from large, institutional buildings to adapted single-family homes. Regardless of the size of the facility, all of these providers must look after the health, safety, and are liable and responsible for the well-being of these vulnerable individuals.

2. Consider asset value in the risk assessment

3. Identification of level of maturity of the infrastructure

4. Add other risk analysis techniques

APPENDIX F
Adopting ISO Standards

BACKGROUND

INDCs and NDC

In anticipation of the U.N. Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015, countries publicly outlined what post-2020 climate actions they intended to take under the new international agreement, known as their Intended Nationally Determined Contributions (INDCs). The INDCs are the way by which governments communicate at an international level the steps they will take to address climate change in their own countries.

These communicated climate actions largely help determine whether the world achieves the long-term goals of the Paris Agreement: to hold the increase in global average temperature to well below 2°C, to pursue efforts to limit the increase to 1.5°C, and to achieve net zero emissions in the second half of the 21st century.

When a country formally joins the Paris Agreement, the “intended” is dropped and an INDC is converted into a Nationally Determined Contribution (NDC). Under the Paris Agreement, countries pursue domestic mitigation measures and are expected to submit an updated NDC every five years.

U.N. Sustainable Development Goals

Sustainable development can be defined as a form of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The U.N. Sustainable Development Goals are a call for action from all countries – regardless of if they are poor, rich or middle-income – to promote prosperity while protecting the planet. There are a total of 17 goals; these are based on the recognition that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental with: protection (www.un.org/sustainabledevelopment).

Achieving future sustainability must be a collective effort, it requires a balance between the needs of the environmental, social and economic systems, reason why 193 countries have pledged their support towards the 17 United Nations Sustainable Development Goals (UN SDGs) and their 169 targets.

ISO

The International Organization for Standardization (ISO) is an independent nonprofit, non-governmental international organization consisting of a member network of the national standards institutes of 165 countries with one member per country regardless of its size. The Central Secretariat in Geneva, Switzerland, coordinates all activities.

For a standard to be accepted for development, there must be global relevance of the proposed item. This means that it indeed responds to an international need and will eventually be suitable for worldwide implementation on as broad a basis as possible.

Through its member bodies, technical committees and subcommittees are created that bring together experts from all around the world to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote. Due to the global nature of their development, ISO standards are equally applicable to all types and sizes of organizations.

As of 2021: ISO encompassed 797 technical committees and subcommittees, and 23,949 standards.

ISO standards relate to each other

Achieving organizational goals is very difficult if standards do not relate to each other and are implemented on silos. For example, an environmental system cannot be properly implemented if the risks are not properly addressed through risk management.

Thus, ISO standards are developed under a common framework that support design, implementation, evaluation, and continuous improvement. This common framework allows them to relate to each other in a way that facilitates a comprehensive and integrated implementation of diverse standards within an organization.

Moreover, although they share a common framework, they must allow for choice and flexibility depending on the industry, organization, and country.

Sustainability and environmental related standards

There are thousands of ISO standards that address sustainability, of these, over 600 are environment-related standards. Moreover, they are aligned with the UN Sustainable Development Goals.

The use of standards with common framework facilitates measurement of progress and communication amongst Nations.

Since ISO standards are developed under a consensus process by global experts, these are leading climate action in a variety of ways by:

- *Facilitating transparent and comparable reporting*
- *Providing a foundation of best practices upon which to build climate change programs, actions and/or protocols*
- *Facilitating comprehensive, integrated implementation of climate change efforts on diverse subject matters and issues related to the operations of an organization*
- *Providing opportunities for improved consistency, increased flexibility and decreased effort associated with climate change actions*
- *Offering a consistent technical approach that simplifies verification of climate change actions and facilitates GHG emissions trading*
- *Facilitate achieving Nationally Determined Contribution (NDC) and UN Sustainable Development goals*
- *Building greater confidence in GHG inventory and improving stakeholder credibility*

OFFICIAL ISO DESCRIPTIONS

The following ISO descriptions are some examples of Standards that may be applicable for Puerto Rico.

Risk Management

ISO 31000

Proper Risk Management is part of responsible governance and accountability.

Risk Management Programs enable organizations, regardless of their nature or size, to understand the organization’s risk exposures and identify the associated consequences which could affect its success in meeting its strategic goals. Risk Management Programs encompass all areas in which an organization is exposed to risk, identify how risks interact comprehensively throughout an organization, and relates the interaction of actions taken to address them with the purpose not only in the preservation of value, but future innovation. It allows leadership to recognize the risks associated with the organization’s core responsibilities and take informed decisions regarding these.

The technical committee (ISO/TC 262) responsible for the ISO 31000 Risk Management Standard, and its Chair, Mr Kevin Knight have indicated that ISO 31000 has been adopted as a national standard by more than 50 national standards bodies covering over 70% of the global population. It has also been adopted by a number of UN agencies and national governments as a basis for developing their own risk-related standards and policies, especially in the areas of disaster risk reduction and the management of disaster risk.

Mitigation and Adaptation
ISO 14080
Greenhouse gas management and related activities
ISO partnered with key international stakeholders, such as the (UNFCCC) and the World Bank, in developing strategic roadmaps for a system of standards on climate change mitigation and adaptation.

This standard sets out a framework and principles to make adaptation and mitigation schemes more compatible and elaborate on their different approaches. It addresses methodologies on climate actions, and will help governments and businesses around the world to directly support the Paris Agreement to limit global warming to below 2 °C and achieve the U.N. Sustainable Development Goals.

The scope of the standard is to provide guidelines by means of a framework and principles for establishing approaches and processes to:
- *Identify, assess and revise methodologies*
- *Develop methodologies*
- *Manage methodologies*

The standard is applicable to climate actions to address climate change, including adaptation to its impacts and GHG mitigation in support of sustainability. Such actions can be used by or for projects, organizations, jurisdictions, economic sectors, technologies and products, policies, programs and non-government activities.

Events
ISO 20121:2012
Event sustainability management systems — Requirements with guidance for use
Specifies requirements for an event sustainability management system for any type of event or event-related activity and provides guidance on conforming to those requirements. In fact, the UN Climate Change Conference COP21 – CMP11 PARIS 2015 event was organized following ISO 20201 (Event sustainability management systems).

Tourism
ISO 21401
Tourism, and related services — Sustainability management system for accommodation establishments — Requirements
Helps accommodation providers reduce their impact on the environment, promoting social exchange and making positive contributions to their local economies.

ISO 21416
Recreational diving services - Requirements and guidance on environmentally sustainable practices in recreational diving

It features international best practice such as deterring divers from feeding or removing aquatic life, or how to operate boats in an environmentally friendly manner.

Source: Juan L. Torres Pérez, PhD

ISO 21417
Recreational diving services — Requirements for training on environmental awareness for recreational divers
Aims to educate divers on the environmental impact of their sport so that they are in a better position to reduce the risks of harming our waters.

Communities
ISO 22370
Security and resilience — Urban resilience — Framework and principles
Describes a framework and principles that are coherent with the 2030 Agenda for Sustainable Development, including the New Urban Agenda, Paris Agreement and Sendai Framework, that can be applied to enhance urban resilience.

This standard was developed in response to demand arising from urban areas in all parts of the world for support to make them safer and more resilient to all manner of hazards, risks, weaknesses and vulnerabilities. It was developed to provide local governments and relevant stakeholders with analytical tools to measure urban resilience and develop relevant actions. By engaging all stakeholders in resilience efforts, urban areas have the ability to harness transformational change and improve the lives of their inhabitants.

ISO 26000
Guidance on social responsibility This standard was developed with the consensus of more than 450 experts from 99 countries and 42 international liaison organizations. It is the benchmark of good practice and expertise from industry, government, labor organizations, non-governmental organizations and consumers.

ISO 26000 provides guidance on how businesses and organizations can operate in an ethical and transparent way that contributes to sustainable development while considering the expectations of stakeholders, applicable laws and internationalorganizations.

With a holistic approach, ISO 26000 offers practical guidance to any organization, anywhere in the world, wishing to contribute to sustainable development. It helps them:

- *Understand how they currently impact society and contribute to sustainable development*
- *Identify, engage and respect their relevant stakeholder expectations*
- *Define which issues are relevant and significant, and ensure they are prioritized for action*
- *Be in compliance with applicable laws and consistent with international norms of behavior*
- *Integrate responsible behavior throughout their organization and relationships*

Other standards include:
- ISO 14090, *Adaptation to climate change – Principles, requirements and guidelines*
- ISO 14091, *Adaptation to climate change – Vulnerability, impacts and risk assessment*
- ISO 14092, *Adaptation to climate change — Requirements and guidance on adaptation planning for local governments and communities*

Environmental Management
The ISO 14000 family of standards for environmental management are recognized as the global benchmark for promoting good practice in environmental management and design. The ISO 14000 family also includes supporting tools for environmental management and the design of environmentally friendly products and services.

ISO 14001
Environmental management systems – Requirements with guidance for use
This standard helps organizations achieve their objectives in an environmentally sustainable manner.

Other standards in the family include:
- *ISO 14004, Environmental management systems – General guidelines on implementation*
- *ISO 14006, Environmental management systems – Guidelines for incorporating ecodesign*
- ISO 14040, *Environmental management – Life cycle assessment – Principles and framework*
- ISO 14044, *Environmental management – Life cycle assessment – Requirements and guidelines*

Quantifying GHG Emissions
ISO standards are designed to be policy-neutral, giving them the flexibility to be applied to many different GHG programs around the world. The growing use of ISO GHG standards for both regulatory and voluntary purposes is a testament to their versatility and their contribution to linking GHG markets around the world. They provide an internationally agreed framework for measuring GHG emissions, verifying claims and accrediting the bodies that carry out such activities to ensure accuracy and completeness.

Standards in the family include:

- ISO 14064, *Greenhouse gases*
- ISO 14065, *Greenhouse gases – Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition*

Resilience and Security
ISO 22301
Security and resilience — Business continuity management systems — Requirements
This standard specifies the requirements to implement, maintain and improve a management system to protect against, reduce the likelihood of the occurrence of, prepare for, respond to and recover from disruptions when they arise.

ISO 22320
Societal security — Emergency management — Requirements for incident response

This standard gives guidelines for incident management, including:

- *Principles that communicate the value and explain the purpose of incident management*
- *Basic components of incident management including process and structure, which focus on roles and responsibilities, tasks and management of resources*
- *Working together through joint direction and cooperation*

This document is applicable to any organization involved in responding to incidents of any type and scale.

Related standards
ISO has already developed many other standards that have an impact on climate change in areas such as nuclear energy, solar energy, hydrogen technologies, intelligent transport systems, building environment design, and sustainability in building construction.

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List of Acronyms

AR	Assessment Reports
ASCE	American Society of Civil Engineers
ASD	Agricultural Statistics Districts
AWWA	American Water Works Association
BC	Black Carbon
BMWP	Biological Monitoring Working Party
°C	degrees Celsius
C&D	construction and demolition
CACL	Spanish acronym for Light Pollution Advisory Committee (CACL, for its acronym in Spanish)
CARICOOS	Caribbean Coastal Ocean Observing System
CATEC	Center for Applied Tropical Ecology and Conservation
CATS	Caribbean Time Series Station
CCAP	Coastal Change Analysis Program
CCAP	Corals and Climate Adaptation Planning
CCMP	Comprehensive Conservation and Management Plan
CDC	Centers for Disease Control and Prevention
CDOM	Colored Dissolved Organic Matter
CEAPRC	Centro de Estudios Avanzados de Puerto Rico y el Caribe
CENECCA	Center for the Education on Environmental Climate Change
CERC	Catastrophic Crisis and Emergency Risk Communication
CH_4	Methane
CIAPR	Spanish acronym for Spanish acronym for Colegio de Ingenieros y Agrimensores de Puerto Rico/ Professional College of Engineers and Land Surveyors of Puerto Rico (sic)
CMINR	Caja de Muertos Island Nature Reserve
CMIP	Climate Model Intercomparison Project
CMS	Centers for Medicare and Medicaid Services
CO_2	Carbon dioxide
CO_3^{2-}	carbonate ion
Code	National Electric Code
COOP	Cooperative Observer Program
COP21	Conference of the Parties
CRE	Climate Ready Estuaries program
CRS	Community Rating System
CSJNR	Cabezas de San Juan Nature Reserve
CTD	Conductivity, Temperature, and Depth
CTTS	Collection, Transfer, and Transport Systems
CYBD	Caribbean yellow band disease
DFE	Design Flood Elevation
ENSO	El Niño Southern-Oscillation
EOP	Emergency Operations Plan
EQB	Environmental Quality Board
ESA	Endangered Species Act
°F	degrees Farenheit (sic)
EYNF	El Yunque National Forest
FAO	Food and Agriculture Organization of the United Nations
FBI	Family Biotic Index
FFG	feeding functional groups
FGI	Facility Guidelines Institute
FIRMs	Flood Insurance Rate Maps
FWS	Fish and Wildlife Service
g/l	gallon per liter
GNP	Gross National Product
H+	Positively charged Hydrogen ion
H_2CO_3	carbonic acid
ha	hectares
HCO^{3-}	bicarbonate
HICE-PR	Human Impacts to Coastal Ecosystems in Puerto Rico
HIM	Harvey, Irma and Maria
IBC	International Building Code
ICOMOS	International Council on Monuments and Sites
ICP	Instituto de Cultura Puertorriqueña Institute of Puerto Rican Culture
IEC	International Electric Code

List of Acronyms

IEPR Spanish acronym for Instituto de Estadísticas de Puerto Rico/Puerto Rico Institute of Statistics

IITF International Institute of Tropical Forestry

INDCs Intended Nationally Determined Contributions

IPCC Intergovernmental Panel on Climate Change

ISO International Organization for Standardization

ISWMP Integrated Solid Waste Management Plan

IT Information Technology

JPPR Spanish acronym for Junta de Planificación de Puerto Rico/Puerto Rico Planning Board

LP La Parguera

LTER Long Term Ecological Research

m meters

m^2 square meters

MDGs Millennium Development Goals

MERRA-2 Modern-Era Retrospective Analysis for Research and Applications

mg/L milligram per milliliter

MGD million gallons per day

MII Macroinvertebrate Integrity Index

mm millimeters

mm/yr millimeters per year

MPA marine protected areas

mph miles per hour

MRFs Materials Recovery Facilities

MSW Municipal Solid Waste

$MtCO_2e$ metric tons of gross CO_2 equivalent

N_2O Nitrous oxide

NAAQS National Ambient Air Quality Standards

NAO North Atlantic Oscillation

NASA National Aeronautics and Space Administration

NDC Nationally Determined Contribution

NEC net ecosystem calcification

NECNR Northeast Ecological Corridor Natural Reserve

nm nanometer

NOAA National Oceanic and Atmospheric Administration

NOS/CO-OPS National Ocean Service-Center for Operational Oceanographic Products and Services

NPS National Park Service

NRHP National Register of Historic Places

NWI National Wetlands Inventory

NWS National Weather Service

OA Ocean Acidification

OAPS Ocean Acidification Product Suit

OC Organic Carbon

OGPe Spanish acronym for Office of Permit Management

OI Optimum Interpolation

PM Particulate Matter

ppm parts per million

ppt parts per thousand

PRASA Puerto Rico Aqueduct and Sewer Authority

PRCRMP Puerto Rico Coral Reef Monitoring Program

PRCZMP Puerto Rico Coastal Zone Management Program

PRDSR Puerto Rico Department of Sports and Recreation

PRSGCP Puerto Rico Sea Grant College Program

PRTC Puerto Rico Tourism Company

psu practical salinity unit

RCC River Continuum Concept

RCP Representative Concentration Pathway

RGM Río Grande de Manatí

RL Rio Loco

RPRAC Resilient Puerto Rico Advisory Commission

SAM Sociedad Ambiente Marino

SCAPE Scottish Coastal Archaeology and the Problem of Erosion

SCHARP Scottish Coastal Heritage at Risk

SCORP State Comprehensive Outdoor Recreation Plan

SCTLD stony coral tissue loss disease

SDGs Sustainable Development Goals

SHPO Historic Preservation Office

SIDS Small Island Developing States

SJBE San Juan Bay Estuary

SLR Sea Level Rise

SQM Sky Quality Meter

SSPs Shared Socioeconomic Pathways

SST Sea Surface Temperatures

SWANA Solid Waste Management Association of North America

SWM Solid Waste Management

TJC The Joint Commission

UN United Nations

UNESCO United Nations Educational, Scientific and Cultural Organization

UNFCCC United Nations Framework Convention on Climate Change

UPRRP University of Puerto Rico Rio Piedras Campus

USCRTF-WPI US Coral Reef Task Force Watershed Partnership Initiative

USEPA United States Environmental Protection Agency

USFWS U.S. Fish and Wildlife Service

USGCRP United States Global Climate Research Program

UV ultraviolet

VIDAS Vegabajeños Impulsando Desarrollo Ambiental Sustentables

WBD white band disease

WG Working Group

WMP Waste Management Plan

WPD white plague disease

WTTC World Travel and Tourism Council

µg/mµ micrograms per cubic meter

Ω Saturation state

Ωarag aragonite

CLIMATE CHANGE COUNCIL

PUERTO RICO

Puerto Rico's STATE OF THE CLIMATE 2014-2021

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