2020 NEW JERSEY

SCIENTIFIC REPORT ON CLIMATE CHANGE

June 30, 2020

THE GREAT SEAL OF THE STATE OF NEW JERSEY

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STATE OF NEW JERSEY
DEPARTMENT OF ENVIRONMENTAL PROTECTION

COVER PHOTO: HIGH POINT STATE PARK, NEW JERSEY

June 30, 2020

Dear New Jerseyans,

The New Jersey Department of Environmental Protection (DEP) is pleased to present the *New Jersey Scientific Report on Climate Change*, in accordance with Governor Philip D. Murphy's Executive Order No. 89 (October 29, 2019). There is no serious disagreement among scientists that global atmospheric warming, caused largely by human activities, is leading to significant changes in climate patterns around the world. This report is the first comprehensive effort to assemble the latest and most reliable scientific information on the current and predicted future impacts of climate change that are specific to New Jersey's natural and built environments.

Many of the impacts of climate change are already familiar to New Jersey's residents, including increasing temperatures, rising sea levels, and more frequent and intense storms. New Jersey has seen the evidence of climate change in our increasingly mild winters, more frequent heavy rains, flooding along inland streams and rivers, and more "sunny day" tidal flooding along areas of the coast. These events can threaten public health and safety, destroy property, undermine critical infrastructure, and damage New Jersey's economy, including the vibrant tourism industry supported by our beloved shore and lake communities. As we well know, climate threats can wreak long-lasting economic damage. Indeed, parts of New Jersey are still struggling to recover from Superstorm Sandy over 8 years later.

As our climate continues to change, it is urgent that New Jerseyans understand what future impacts are likely to occur, and when. Together, we can plan for and adapt to those changes, helping one another to keep our communities safe and our economy strong. This first *Scientific Report on Climate Change* provides information that will help New Jersey proactively plan and prepare for climate realities.

While there is always some degree of uncertainty in predicting future conditions, we are fortunate that some of the best scientists and scientific institutions in the world call New Jersey home, and they have provided us reliable information and projections that are specific to our state and critical to informing our path forward. DEP is particularly grateful to our Science Advisory Board for lending its expertise to review the Scientific Report on Climate Change. We also acknowledge and deeply appreciate and the contributions of the many distinguished scientists and institutions whose work is relied upon and cited throughout the report, including the groundbreaking contribution of Rutgers University in *New Jersey's Rising Seas and Changing Coastal Storms: Report of the 2019 Science and Technical Advisory Panel*.

Recognizing that the science of climate change will continue to evolve, the DEP remains committed to monitoring new developments and will update this report at least every two years.

Together, informed by science, we will make the wise choices that build a more resilient New Jersey.

Sincerely,

Catherine R. McCabe, Commissioner
New Jersey Department of Environmental Protection

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ACKNOWLEDGMENTS

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Development of this report would not have been possible without the contributions of many people within the DEP. Thank you to all the contributing authors for the content they developed and thank you to everyone within the DEP who provided guidance and support through the many phases of the report's development.

The Scientific Report includes a vast amount of knowledge on an extensive list of topics; however, it does not include all of the available data, literature, and research and does not represent an inclusive list of all the areas that will be impacted by climate change. For example, climate change may also pose significant complications to public health but the science around these issues continues to evolve. Additional information is needed before conclusive statements can be made. Any errors found within the report are the responsibility of the editors.

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EXECUTIVE SUMMARY

MOUNT TAMMANY, WARREN COUNTY, NEW JERSEY

The New Jersey Department of Environmental Protection's first scientific report on climate change summarizes the current state of knowledge regarding the effects of climate change on New Jersey's environment. This report collects the best available science and existing data regarding the current and anticipated environmental effects of climate change globally, nationally, regionally, and locally to present state-specific information to inform State and local decision-makers as they understand and respond to its impacts. These impacts are significant and wide-ranging, requiring a comprehensive and forward-thinking response by all levels of government, economic sectors, communities, and populations.

"Climate change is the defining challenge of our age."

- Ban Ki-Moon, former Secretary-General of the United Nations General Assembly

As atmospheric levels of carbon dioxide and other greenhouse gases increase, New Jersey will experience significant direct and secondary changes in its environment. These include increases in temperature, variability in precipitation, frequency and intensity of storms, sea-level rise, ocean acidification, and the associated impacts to ecological systems, natural resources, human health, and the economy. Climate change is driven by increases in atmospheric levels of greenhouse gas concentrations and as these levels increase, additional heat is absorbed by Earth's atmosphere. Human activities, particularly the emissions of heat trapping greenhouse gases from the burning of fossil fuels and land use changes like deforestation, have increased atmospheric carbon dioxide concentrations by more than one third since the early 1900s (Bereiter et al. 2015) and are now the primary driver of climate change (Global Change 2020). At the start of the Industrial Revolution, carbon dioxide levels were about 280 parts per million. The average annual carbon dioxide level initially exceeded 400 parts per million in 2016 and continues to rise (Tans and Keeling 2020). Given the role of carbon dioxide as a greenhouse gas, an increase of this magnitude is expected to result in an unprecedented increase in global temperature. The magnitude of this increase will primarily depend on global emissions of greenhouse gases and how Earth's climate system responds to this human-induced warming. This report references three greenhouse gas emission scenarios.

- Low emissions scenario – Global emissions of greenhouse gases are dramatically reduced (resulting in 3.6˚F [2˚C] by 2100); not likely to be met under current mitigation policies (IPCC 2018a).
- Moderate emissions scenario – Represents current emission and temperature trajectories (corresponds with 5.4˚F [3.0˚C] by 2100) (IPCC 2018a) and is most likely to occur; in some studies this scenario also represents the midpoint between the low and high scenario (Kopp et al. 2019).
- High emissions scenario – Global greenhouse gas emissions are not reduced from current levels (resulting in 9˚F [5˚C] by 2100); accounts for high population growth and little greenhouse gas mitigation; most unlikely outcome but should not be discounted as it offers insight to possible conditions if mitigation measures do not continue (IPCC 2018a).

In 2007, New Jersey enacted the Global Warming Response Act to address this issue of increased greenhouse gas concentrations. While the mitigation of greenhouse gases is a vital step to addressing climate change, the focus of this report will be the effects of climate change on New Jersey.

Due to the increase in greenhouse gas concentrations since the end of the 1890s, New Jersey has experienced a 3.5˚F (1.9˚C) increase in the State's average temperature (Office of the New Jersey State Climatologist 2020), which is faster than the rest of the Northeast region (2˚F [1.1˚C]) (Melillo et al. 2014) and the world (1.5˚F [0.8˚C]) (IPCC 2014). This warming trend is expected to continue. By 2050, temperatures in New Jersey are expected to increase by 4.1 to 5.7˚F (2.3˚C to 3.2˚C) (Horton et al. 2015). Thus, New Jersey can expect to experience an average annual temperature that is warmer than any to date (low emissions scenario) and future temperatures could be as much as 10˚F (5.6˚C) warmer (high emissions scenario) (Runkle et al. 2017). New Jersey can also expect that by the middle of the 21st century, 70% of summers will be hotter than the warmest summer experienced to date (Runkle et al. 2017). The increase in temperatures is expected to be felt more during the winter months (December, January, and February), resulting in less intense cold waves, fewer sub-freezing days, and less snow accumulation.

TEMPERATURE

KEY FINDINGS:

- *New Jersey is warming faster than the rest of the Northeast region and the world.*
- *Since 1895, New Jersey's annual temperature has increased by 3.5˚F.*
- *Historically unprecedented warming is projected for the 21st century with average annual temperatures in New Jersey increasing by 4.1˚F to 5.7˚F by 2050.*
- *Heatwaves are expected to impact larger areas, with more frequency and longer duration by 2050.*
- *Climate change could result in a 55% increase in summer heat-related mortalities.*

Temperature increases are felt more strongly in New Jersey because of the high urbanization of the state which results in large expanses of asphalt and concrete instead of forests, fields, and other open spaces that can provide cooling effects. These conditions make heat waves especially pronounced and lead to increased impacts in densely populated urban areas. This heat island effect (Carnahan and Larson 1990) will be a growing concern as summer temperatures increase. Heat waves are expected

JERSEY CITY, NEW JRESEY

to impact larger areas, with more frequency and longer durations (Lyon et al. 2019) resulting in reduced agricultural yields and power plant efficiency, increased energy use, air pollution, water use, and negative health effects (Mazdiyasni and AghaKouchak 2015). Urban populations are particularly vulnerable as climate models predict an increase in the number of days per year with temperatures affecting human health due to heat stress. In this decade (2020s), climate change could result in a 55% increase in summer heat-related mortality (high emissions scenario; compared to the 1990s) and more than a doubling in mortality by the 2050s (Kinney et al. 2004).

PRECIPITATION

Key Findings:

- *Annual precipitation in New Jersey is expected to increase by 4% to 11% by 2050.*
- *The intensity and frequency of precipitation events is anticipated to increase due to climate change.*
- *Droughts may occur more frequently due to the expected changes in precipitation patterns.*
- *The size and frequency of floods will increase as annual precipitation increases.*
- *Tropical storms have the potential to increase in intensity due to the warmer atmosphere and warmer oceans that will occur with climate change.*

As temperatures increase, Earth's atmosphere can hold more water vapor which leads to a greater potential for precipitation. Currently, New Jersey receives an average of 46 inches of precipitation each year (Office of the New Jersey State Climatologist 2020). Since the end of the twentieth century, New Jersey has experienced slight increases in the amount of precipitation it receives each year, and over the last 10 years there has been a 7.9% increase. By 2050, annual precipitation in New Jersey could increase by 4% to 11% (Horton et al. 2015). By the end of this century, heavy precipitation events are projected to occur two to five times more often (Walsh et al. 2014) and with more intensity (Huang et al. 2017) than in the last century. New Jersey will experience more intense rain events, less snow, and more rainfalls (Fan et al. 2014, Demaria et al. 2016, Runkle et al. 2017). Also, small decreases in the amount of precipitation may occur in the summer months, resulting in greater potential for more frequent and prolonged droughts (Trenberth 2011). New Jersey could also experience an increase in the number of flood events (Broccoli et al. 2020).

A warmer atmosphere means storms have the potential to be more intense (Guilbert et al. 2015) and occur more often (Coumou and Rahmstorf 2012, Marquardt Collow et al. 2016, Broccoli et al. 2020). In New Jersey, extreme storms typically include coastal nor'easters, snowstorms, spring and summer thunderstorms, tropical storms, and on rare occasions hurricanes. Most of these events occur in the warmer months between April and October,

SEASIDE PARK, NEW JRESEY

with nor'easters occurring between September and April. Over the last 50 years, in New Jersey, storms that resulted in extreme rain increased by 71% (Walsh et al. 2014) which is a faster rate than anywhere else in the United States (Huang et al. 2017). As temperatures increase so will the energy in a storm system, increasing the potential for more intense tropical storms (Huang et al. 2017), especially those of Category 4 and 5 (Melillo et al. 2014).

SEA-LEVEL RISE

KEY FINDINGS:

- *Sea-levels are increasing at a greater rate in New Jersey than other parts of the world.*
- *By 2050, there is a 50% chance that sea-level rise will meet or exceed 1.4 feet and a 17% chance it will exceed 2.1 feet. Those levels increase to 3.3 and 5.1 feet by the end of the century (under a moderate emission scenario).*
- *"Sunny day flooding" will occur more often across the entire coastal area of New Jersey due to sea-level rise.*
- *It is extremely likely that Atlantic City will experience "sunny day flooding" 95 days a year, and a 50% chance it will experience 355 days a year, by 2100 (under a moderate emission scenario).*

Flooding caused from more intense rain events and storms will be exacerbated in the coastal area by increases in sea-level. In New Jersey, sea-levels are rising faster than they are globally due to changes in the Gulf Stream, localized land subsidence, and continued geologic influences as land slowly adjusts to the loss of the North American ice sheet at the end of the last ice age. In Atlantic City, Cape May, and Sandy Hook, sea-level has risen at a rate of approximately 0.2 to 0.5 inches per year since the beginning of the 20th century, and this rate will continue to increase (Kopp et al. 2019). The amount of greenhouse gases that are emitted is tied to rates of sea-level rise. By 2050, New Jersey will likely experience at least a 0.9 to 2.1-foot increase (above the levels in 2000; all emissions scenarios), 1.4 to 3.1-foot increase by 2070 (moderate emissions scenario), and potentially a 2.0 to 5.1-foot increase by 2100 (moderate emissions scenario).

Understanding how precipitation and sea-level rise will change in the future is vital to New Jersey's coastal zone because low-lying coastal areas are already experiencing tidal flooding, even on sunny days in the absence of precipitation events. An increase in sea-level will cause further issues as stormwater recharge is challenged as sea-levels submerge discharge points, resulting in increases in flooding. In Atlantic City, tidal flooding events have already increased from happening less than once per year in the 1950s to an average of eight times per year between 2007 and 2016. Under a moderate emissions scenario by 2100, it is extremely likely (greater than a 95% chance) that high-tide flooding will occur in Atlantic City at least 95 days a year with a 50% chance it will occur 355 days per year.

OCEAN ACIDIFICATION

KEY FINDINGS:

- *Since the industrial age, ocean pH levels have declined and the ocean is now 30% more acidic.*
- *If carbon dioxide emissions continue at current rates, ocean pH levels are expected to fall, creating an ocean that is more acidic than has been seen for the past 20 million years.*
- *Southern New Jersey counties rank second in the United States in economic dependence on shelled mollusks, which will suffer from increasing ocean acidity.*

New Jersey will not only be impacted by higher reaching tides, but also by the chemistry of the ocean as the carbon dioxide concentration increases. Carbon dioxide is not only detrimental as a greenhouse gas, but also for its role in ocean acidification. In the most basic terms, carbon dioxide dissolves in seawater, beginning a chain reaction leading to more acidic conditions. Since the Industrial Revolution, the ocean has become 30% more acidic and ocean pH levels will continue to decline along the coast of New Jersey. In response to this increase in acidity, shellfish and coral species will build weaker shells. Ocean acidification also affects the success of hatching, larval development, organ development, immune response, metabolic processes, and olfaction (smell) in marine species. New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled mollusks (NRDC 2015). While New Jersey is not predicted to see unfavorable acidification conditions for shellfish until 2100, given the State's dependence on shellfish resources, there will be high social and economic impacts (NRDC 2015, Ekstrom et al. 2015).

AIR QUALITY

KEY FINDINGS:

- *The effects of climate change are likely to contribute to an increase in air pollution, lead to increased respiratory and cardiovascular health problems, like asthma and hay fever, and a greater number of premature deaths.*
- *Environmental degradation from climate induced increases in air pollution will reduce visibility and cause damage to crops and forests.*

As temperature, precipitation, sea-level rise, and ocean acidification increase, so will the impacts to New Jersey's air, water, habitats, and wildlife. Despite on-going efforts to reduce ground-level ozone precursor emissions, New Jersey's air quality will be impacted due to changes in meteorological conditions, often referred to as the ozone-climate penalty which is "the deterioration of air quality due to a warming climate" (Fu and Tian 2019). These impacts will be particularly high for dense urban areas (NASA 2014). High ground-level ozone concentrations have a varying degree of impact on human health, ranging from eye irritation to severe respiratory distress and can lead to chronic illness or premature death (NJDEP 2016). Particulate matter has been associated with serious chronic and acute health effects including lung cancer, chronic obstructive pulmonary disease (COPD), cardiovascular disease, and asthma (Fann et al. 2016, Nolte et al. 2018). As concentrations of ground-level ozone and particulate matter increase, New Jersey is likely to experience an increase in the human health impacts attributed to both. Additionally, increased temperatures will result in longer frost-free periods which will result in longer allergy seasons, increased exposure to pollen allergens (Fann et al. 2016), and increased asthma and hay fever (Nolte et al. 2018).

WATER RESOURCES: SUPPLY AND QUALITY

KEY FINDINGS:

- *Water supplies will be stressed from the increase in the growing season and extreme temperatures expected due to climate change.*
- *Rising sea levels may lead to increased saltwater intrusion in New Jersey aquifers where wells are over pumped.*
- *Freshwater intakes and aquifer recharge areas may be threatened if sea-level rise pushes the salt front further upriver.*
- *Combined sewer overflow communities may be further challenged as sea-level rise and/or increased rain events submerge discharge points that are currently above the waterline.*
- *Surface and groundwater quality will be impaired as increased nutrients and contaminants enter waters due to runoff from more intense rain events.*

Climate change will alter the quantity and quality of New Jersey's ground and surface water resources (NJDEP 2017a). Currently, the amount of water needed in New Jersey has been relatively sustainable due to precipitation levels and appropriate management practices. New Jersey will put a greater demand on its water supplies as human populations, forests, wetlands, and wildlife require more water in warmer temperatures. Temperature increases will lead to longer growing seasons which will require more water for irrigation use (crops, nurseries, golf courses, outdoor residential). Increased temperatures will also result in New Jersey experiencing higher winter stream flows due to more winter rain and a reduction in snow accumulation. Reduced winter snow accumulation may ultimately lead to reduced snow melt and lower spring stream flows (Williamson et al. 2016).

New Jersey's water quality will be impaired as extreme precipitation events increase runoff, bringing excess sediment and contaminants to New Jersey's streams. This excess of nutrients, along with New Jersey's increased temperatures, will lead to eutrophic conditions (Sinha et al. 2017) and an increased potential to stimulate rapid and excessive growth of harmful algal blooms (Sinha et al. 2017, Ho et al. 2019). Saltwater intrusion could also impair the water quality of groundwater aquifers in coastal areas that are stressed from over-pumping (McAuley et al. 2001, Lacombe and Carlton 2002). Sea-level rise may also threaten the quality of surface water systems as the salt front moves upstream and impacts freshwater intakes, aquifer recharge areas, and aquatic ecology. A sea-level rise of 2.4 feet will result in the salt front on the Delaware River moving 6.8 miles upstream (Najjar et al. 2000). Existing treatment infrastructure in New Jersey is not designed to treat elevated salt levels and drinking water standards do not exist for the primary components of saltwater.

Stormwater management systems will also need to be modified to accommodate more intense precipitation events and increased occurrence of nuisance flooding (Wright et al. 2019). Combined sewer overflow communities are of particular concern as sea-level rise and increased precipitation events submerge discharge points that are currently above the waterline. As these systems are overwhelmed from inundation, contaminants are free to move into waterways and the surrounding environment. New Jersey's industrial sites located near coastal areas will also be at greater risk of direct discharge of unintended or contaminated materials.

AGRICULTURE

KEY FINDINGS:

- *The productivity of crops and livestock are expected to change due to the climate-induced changes in temperature and precipitation patterns.*
- *New Jersey may become unsuitable for specialty crops like blueberries and cranberries in the future as higher temperatures reduce necessary winter-chills.*

All of these changes may limit the use of water supplies for some industrial, agricultural, or recreational uses. This is of particular concern to New Jersey's agriculture sector which may be impacted by a longer growing season (NJ Climate Adaptation Alliance 2014, Frumhoff et al. 2007), wetter conditions in the early season, delayed spring plantings, warmer and drier conditions mid-season (NJ Climate Adaptation Alliance 2014), and increased need for irrigation to sustain the health of crops (Sweet et al. 2017a), pastureland, and livestock (NJ Climate Adaptation Alliance 2014). New Jersey crops and livestock may see a decrease in growth and productivity due to increased dry spells, heat waves, and sustained


CRANBERRY BOGS, NEW JERSEY PINE BARRENS

droughts (NJ Climate Adaptation Alliance 2014). The productivity of New Jersey dairy cows is predicted to reduce resulting in loss to the industry (USGCRP 2016). By mid-century, New Jersey may become unsuitable for blueberries and cranberries (Frumhoff et al. 2007). New Jersey farmers will increase use of pesticides as agricultural pests and weeds will move northward, resulting in additional environmental concerns (NJ Climate Adaptation Alliance 2014).

FORESTS

Key Findings:

- *The persistence of Southern pine beetle in New Jersey represents an early example of the destruction of invasive pests that can occur due to climate change impacts.*
- *Wildfire seasons could be lengthened, and the frequency of large fires increased due to the hot, dry periods that will result from increased temperatures.*

Climate change is expected to bring changes to New Jersey's forests, wetlands, terrestrial, freshwater, and marine systems. Forests are likely to be stressed by instances of drought and the expanded range of pests. This stress is expected to be amplified by the non-climate stressors that forests already face from human decisions. The moisture tolerant species, like maples, in New Jersey forests will be stressed by rising temperatures, whereas the drought tolerant species, like oaks and pines, will be better suited for the impacts of climate change (Swanston et al. 2018). Pest species are expected to take advantage of warmer temperatures and disperse into forests that have not before experienced the pressure of these pests (Olatinwo et al. 2014). New Jersey pine forests will specifically be impacted by the invasive southern pine beetle. This beetle has the potential to kill tens of thousands of acres as thermal controls move north (Trần et al. 2007). Other pests are likely to experience range shifts, increased vigor, and increased impact to New Jersey forests due to climate change.

New Jersey forests could also experience impacts from a longer wildfire season and increased occurrence of large fires (Nolte et al. 2018). Of particular concern is the Pinelands area of southern New Jersey which is the most susceptible to forest fire and has a tremendous propensity towards burning (Forman and Boerner 1981, Buchholz and Zampella 1987).

WETLANDS

Key Findings:

- *Some freshwater wetlands may be lost due to inundation with saltwater.*
- *Some New Jersey tidal wetlands may not gain elevation at a rate that equals the rate of sea-level rise and thus some are expected to be lost to increased rates of sea-level rise.*
- *Increased flooding and salinity are projected to lead to a loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100.*
- *Atlantic white cedar, a globally rare species, is expected to lose habitat in New Jersey because of rising sea levels.*

New Jersey's freshwater and coastal wetlands are vulnerable to the effects of climate change which will impact the functions and ecosystem services they provide. Freshwater wetland ecosystems are expected to experience increases in salinity from increased sea-levels and flooding during storms. As a result, some freshwater wetlands may be lost due to inundation with saltwater. This saltwater inundation has already caused New Jersey to experience "ghost forests," or stands of dead trees, surrounded by transitional marshes. Atlantic white cedar, a globally rare species, grows in low-lying coastal areas but is completely intolerant of saltwater making it extremely susceptible to rising seas (Little Jr. 1950) and is expected to continue to lose habitat in New Jersey. Tidal wetlands are already being negatively impacted by current rates

CLAM ISLAND, LONG BEACH TOWNSHIP, NEW JERSEY

of sea-level rise (Hartig et al. 2002, Langley et al. 2009), and some salt marshes are not gaining elevation at a rate that equals local relative sea-level rise (Cahoon 2015, US EPA 2019). The result is that high salt marsh is shifting to middle and low marsh as habitats are regularly flooded and giving way to species that are more resilient to sea-level rise (Payne et al. 2019). The result is the expected loss of habitat for species like ribbed mussels and crabs, and the eventual conversion of marsh habitat to mud flats and open water.

While it is possible for marshes to migrate inland as sea-levels rise, 29% of potential migration areas in New Jersey are blocked by roads and other development (Lathrop and Love 2007). Increased flooding, salinity, and sea-level rise may lead to the loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100 (Lathrop and Love 2007).

TERRESTRIAL CARBON SEQUESTRATION

KEY FINDINGS:

- *The loss of coastal wetland and forest habitats to climate change will result in carbon losses and increase New Jersey's net greenhouse gas emissions.*

Coastal wetland and forest habitats are carbon sinks (Lathrop 2014) that serve as an important component of New Jersey's mitigation of greenhouse gas emissions. The sequestration ability of New Jersey forests and wetlands is threatened by sea-level rise and other climate change factors such as the southern pine beetle. Forests killed by beetles will regrow and over time will adapt in response to this disturbance, but this regrowth and adaptation is a long process and the carbon losses from such an event will cause forests to become a net carbon emitter.

TERRESTRIAL SYSTEMS

KEY FINDINGS:

- *Climate change is likely to facilitate expansion of invasive plant species.*
- *29% of New Jersey's bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey.*
- *Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 due to habitat loss from sea-level rise.*

Changes to New Jersey habitats will impact plant, bird, fish, amphibian, reptile, and mammal species. New Jersey is home to 2,100 native plant species, several globally rare communities such as sea-level fens and Atlantic white cedar, a little over 800 rare or endangered species, and several plant species such as Hammond's yellow spring beauty and bog asphodel which are found nowhere else in the world (Breden et al. 2006). Warmer temperatures will push plants to flower earlier, will not provide needed periods of cold weather, and will likely result in declines in reproductive success of plant and pollinator species (Memmott et al. 2007, Lipton et al. 2018). Unique habitats like the maritime forests found on New Jersey's barrier islands and endangered species like the Nantucket serviceberry are the most vulnerable to sea-level rise, flooding, and erosion caused by climate change (Anderson et al. 2013, New Jersey Natural Heritage Program 2019).

Bird species are good indicators of ecological change and are early responders to climate change threats. According to the Audubon Society, 29% of New Jersey's 248 bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey (Audubon 2019). Shorebirds like Common Terns, Red Knots, and Saltmarsh Sparrows are more highly vulnerable to climate change than other bird species because they migrate, breed, or winter in areas that will be severely affected by climate change such as the low-lying, coastal areas of New Jersey (Smith et al. 2011, Palestis and Hines 2015). Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 due to habitat loss from sea-level rise (Roberts et al. 2019).

RED KNOTS

FRESHWATER SYSTEMS

KEY FINDINGS:

- *Freshwater fish, like brook trout, that need cold-water habitats are expected to lose habitat as water temperatures increase due to climate change.*
- *Reptiles with temperature-dependent sex determination could experience changes in sex ratios as New Jersey temperatures increase.*

Freshwater fish will also be impacted by climate change. Fish, like the brook trout, that require cold water habitats are expected to lose habitat as water temperatures increase and will be replaced by warmer-water tolerant fish (Jones et al. 2013). Accounts of New Jersey trout streams are already showing this cold-to-warm-water tolerant species shift and most current cold-water fisheries are projected to be warm-water fisheries by 2100 regardless of greenhouse gas emissions scenario (Zimmerman and Vondracek 2006). In addition, droughts will likely promote crowding, increased competition, physiological stress, and mortality for freshwater fish populations.

Reptile and amphibian populations in New Jersey may experience shifts in distribution, range, reproductive ecology, and habitat availability. Increased temperatures could lead to changes in mating, nesting, reproductive, and foraging behaviors of species, including a change in the sex ratios in reptiles with temperature-dependent sex determination (Schlesinger et al. 2011, Butler 2019). Increased storms and extreme temperatures could contribute to unusual mass mortality and cold stunning events in diamondback terrapins (Egger 2016). An increase in droughts throughout New Jersey will decrease the availability of freshwater habitats such as vernal ponds for amphibians, and sea-level rise may further decrease the amount of available habitat.

MARINE SYSTEMS

KEY FINDINGS:

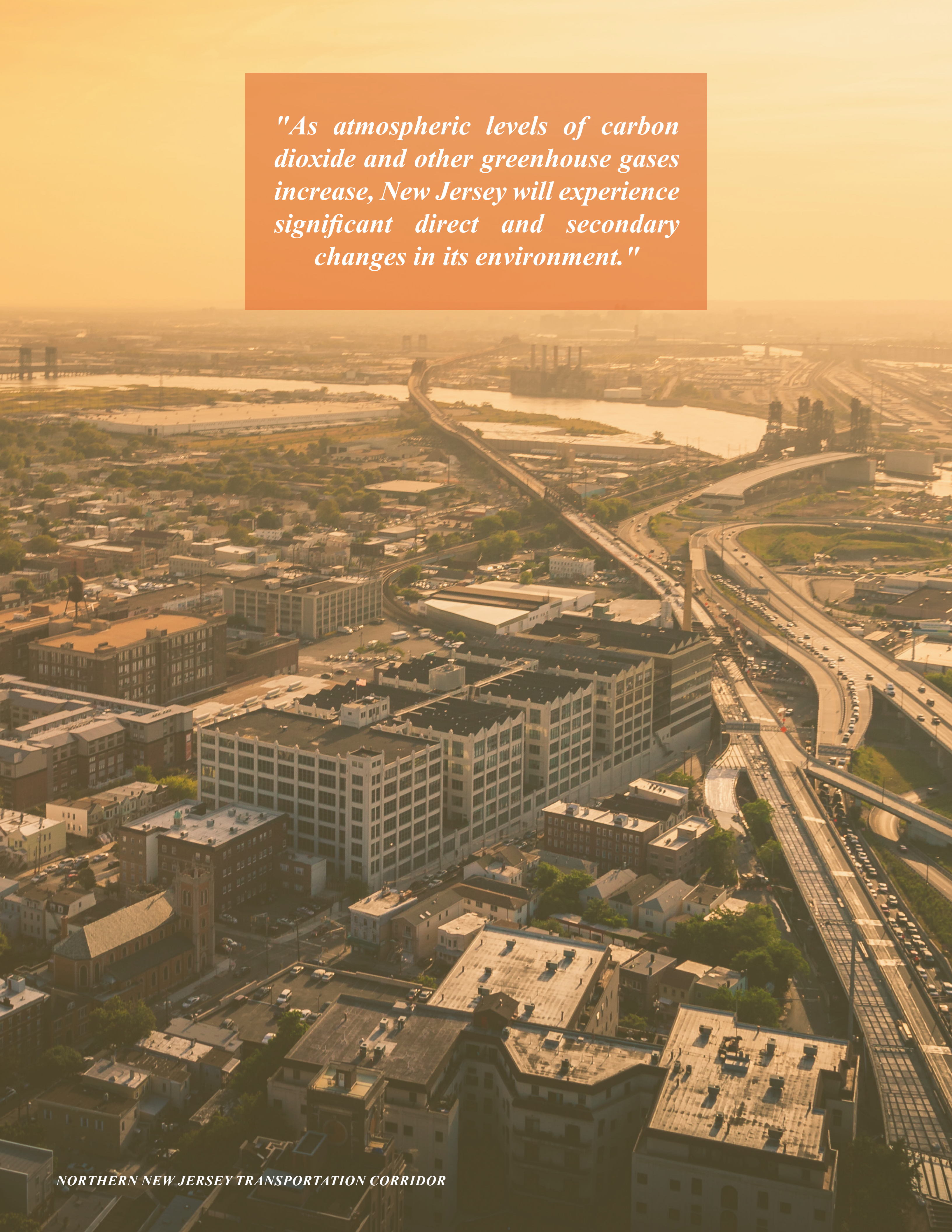
- *Current climate changes could result in more "dead zones" from hypoxic events, which are of particular concern for summer flounder which is New Jersey's largest recreational fish species.*
- *Many commercially important shellfish species including hard clam, scallops, and oysters will develop thinner and frailer shells due to ocean acidification.*
- *As temperatures increase, environmental conditions in New Jersey estuaries may improve for invasive species like the clinging jellyfish.*

New Jersey's marine mammal populations will be impacted by the shift in distribution of prey sources due to the ocean warming. Finfish will be impacted through shifts in species spatial distribution, altered food availability, decreased survival due to changes in acidity and dissolved oxygen levels, and loss of habitat. Profitable fisheries, like summer flounder which is the largest recreational fished species in New Jersey, could experience declines as water quality changes occur in bays and estuaries. Summer flounder and black seabass may be impacted as the potential for hypoxic events increase in New Jersey (Kennish 2007, Brady and Targett 2010). New Jersey's shellfish industry will be impacted as shellfish species including hard clam, scallops, and oysters develop thinner and frailer shells due to ocean acidification and are stressed from increased precipitation leading to reduced salinity and harmful bacteria (Levinton et al. 2011).


LAKE MARGUERITE, HELMETTA, NEW JERSEY

New Jersey is likely to experience the spread of non-native and invasive plant and animal species if new climates and habitats allow them to outcompete native species and rapidly reproduce and adapt (Rustad et al. 2012). Clinging jellyfish serve as an example where climate change improved environmental conditions for an invasive species. Similarly, fisherman are now reporting fish species like sheepshead, cobia, and triggerfish earlier in the year and with increasing regularity (Kleisner et al. 2017, Morley et al. 2018). These species were once late summer visitors to New Jersey waters.

As described above, New Jersey is experiencing many challenges as the climate shifts and will continue to experience more. Consistent with the information summarized in this scientific report, the Statewide Climate Change Resilience Strategy will be developed to promote immediate and long-term adaptation and resilience strategies to protect New Jersey's natural resources, communities, infrastructure, and economy. With reduction in emissions, to which New Jersey is already committed through the Global Warming Response Act, and plans for adaptation through the Statewide Climate Change Resilience Strategy, New Jersey cannot prevent the anticipated impacts of climate change, but is in a place to be a leader and model for how to address climate change in the rest of the United States and the world. Considering the fluid nature of the best available science regarding the effects of climate change on New Jersey's resources, this science report will be updated regularly to incorporate newly evolving scientific knowledge as it becomes available.



"As atmospheric levels of carbon dioxide and other greenhouse gases increase, New Jersey will experience significant direct and secondary changes in its environment."

NORTHERN NEW JERSEY TRANSPORTATION CORRIDOR

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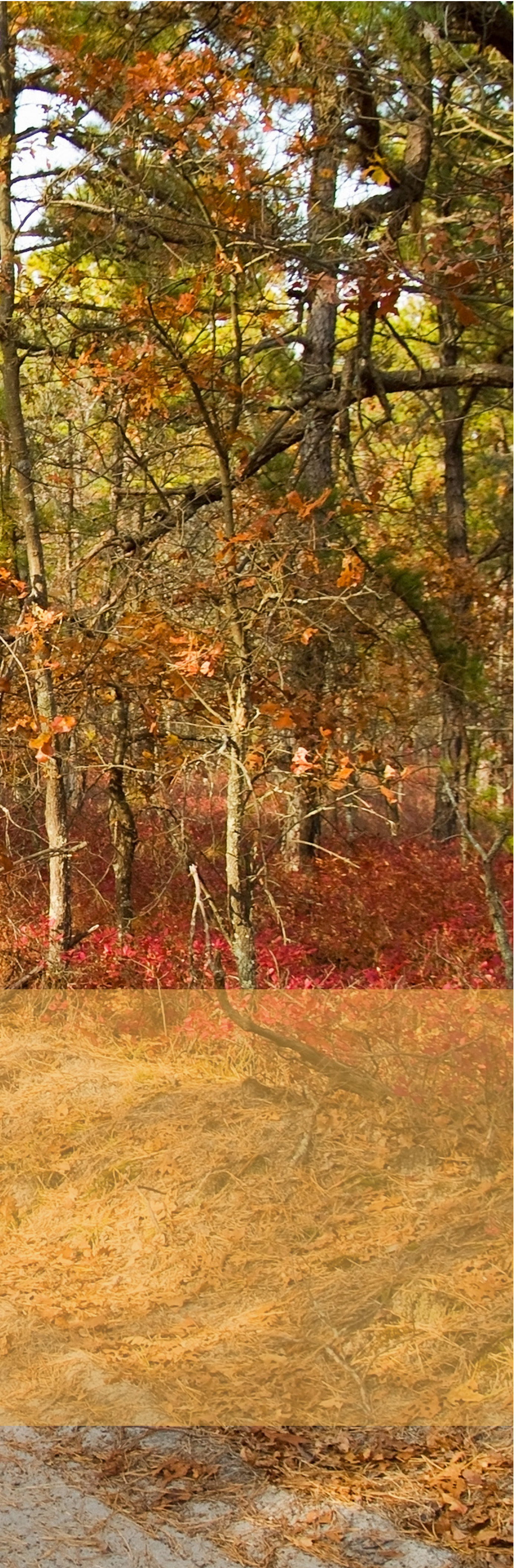
CHAPTER 1

INTRODUCTION

PINE BARRENS, SOUTHERN NEW JERSEY



In the past 10 to 15 years, there have been important advancements in the scientific understanding of climate change and its anticipated impacts on the environment. Reports from the New Jersey Climate Alliance, The National Oceanic and Atmospheric Administration (NOAA), and many other federal and non-governmental organizations detail some of the anticipated impacts of climate change in New Jersey. However, this is the first State-led assessment detailing the effects climate change will likely have on the natural resources within the state.

On October 29, 2019, New Jersey Governor Philip D. Murphy signed Executive Order (EO) No. 89 into effect. Among other things, this EO establishes, for the first time, the position of a Chief Resilience Officer as well as the Climate and Flood Resilience Program within the Department of Environmental Protection (DEP). EO 89 also calls for the DEP to develop a Scientific Report on Climate Change for the State of New Jersey (Scientific Report) within six months of its issuance.

The Climate and Flood Resilience Program's Bureau of Climate Resilience and the Division of Science and Research led the DEP's effort to develop the Scientific Report. To inform the content of the Scientific Report, experts from within the DEP's programs were consulted. This Scientific Report is based on the best available science and existing data regarding the current and anticipated environmental effects of climate change in New Jersey. In order to accomplish this goal, the DEP identified the existing science that would help further New Jersey's understanding of how climate change will likely affect the environment within the State and summarized it into this report. Additionally, the DEP Science Advisory Board provided an independent peer review of the Scientific Report.

This Scientific Report is divided into five chapters in an effort to properly cover issues relevant to New Jersey. Chapter 2 introduces a broad discussion of the issues as reported in numerous global, national, and regional-scale climate change reports. Subsequent chapters provide a more focused discussion of specific impacts of climate change as identified in current research. Chapter 3 provides a discussion of the primary driver of climate change, greenhouse gases. Chapter 4 details the major impacts and effects of climate change on New Jersey including temperature, precipitation, sea-level rise, and ocean acidification. Chapter 5 discusses climate change impacts to New Jersey's many resources: air, water, agriculture, and ecological systems. Chapter 6 identifies research and data gaps. Finally, Chapter 7 concludes the report.

1.1 Purpose

The purpose of this report is to further New Jersey's understanding of how climate change will likely affect the environment within the State by fulfilling articles 2a and 2b of EO 89. This language directs the Chief Resilience Officer and the Climate and Flood Resilience Program to:

"Develop a Scientific Report on Climate Change based on existing data and the best available science regarding the current and anticipated environmental effects of climate change in New Jersey, including but not limited to increased temperatures, sea level rise, increased frequency or severity of rainfall, storms and flooding, increased forest fires, and increased frequency and severity of droughts, anticipated by scientists at least through 2050."

and to:

"Deliver the Scientific Report on Climate Change to the Governor within 180 days of the effective date of this Order and update and supplement the report as necessary, but at least every two (2) years to reflect the latest available climate change science."

Climate change is anticipated to have far-reaching impacts, affecting every area of the State in different ways. Foremost, this report will leverage existing studies to inform decision-makers at all levels on how environment and natural resources may be affected by future climate conditions and associated hazards. This report will also inform State policies, plans, and programs, and give guidance ensuring New Jersey is taking the appropriate actions to the anticipated impacts of climate change. This report will also link existing scientific research with an anecdotal understanding in order to highlight where there are research gaps and additional studies are warranted.

1.2 Background, Climate Change Science

Earth's climate is changing faster now than it has at any other point in the history of modern civilization (Global Change 2020). The issue of climate change can be seen as a defining moment for our time (United Nations 2020). Its impacts are global in scope as well as unprecedented in scale. While the World Economic Forum (World Economic Forum 2020) identifies environmental impacts including extreme weather, natural disasters, and biodiversity losses as the most likely type of global risks to occur (Figure 1.1), a failure to take sufficient climate action to mitigate these risks is considered to be even more likely to occur with an even larger global impact. Climate change can perhaps most simply be described as the human fingerprint on greenhouse gases (United Nations 2020).

Researchers around the world have conducted thousands of studies that have documented increases in the temperature at the Earth's surface, in the atmosphere, and in the oceans (Dupigny-Giroux et al. 2018, Global Change 2020). This current warming trend is of particular significance because of the greater than 95% probability it is the result of human activity since the mid-20th century and it is proceeding at an unprecedented rate (IPCC 2013, NASA 2020). Human activities, particularly the emissions of heat trapping greenhouse gases from fossil fuel combustion, deforestation, and other land use changes, are now the primary driver of climate change observed since the industrial era (Global Change 2020). Greenhouse gases occur naturally in the atmosphere and are in fact essential to the survival of life on Earth, by retaining some of the Sun's warmth within the atmosphere (United

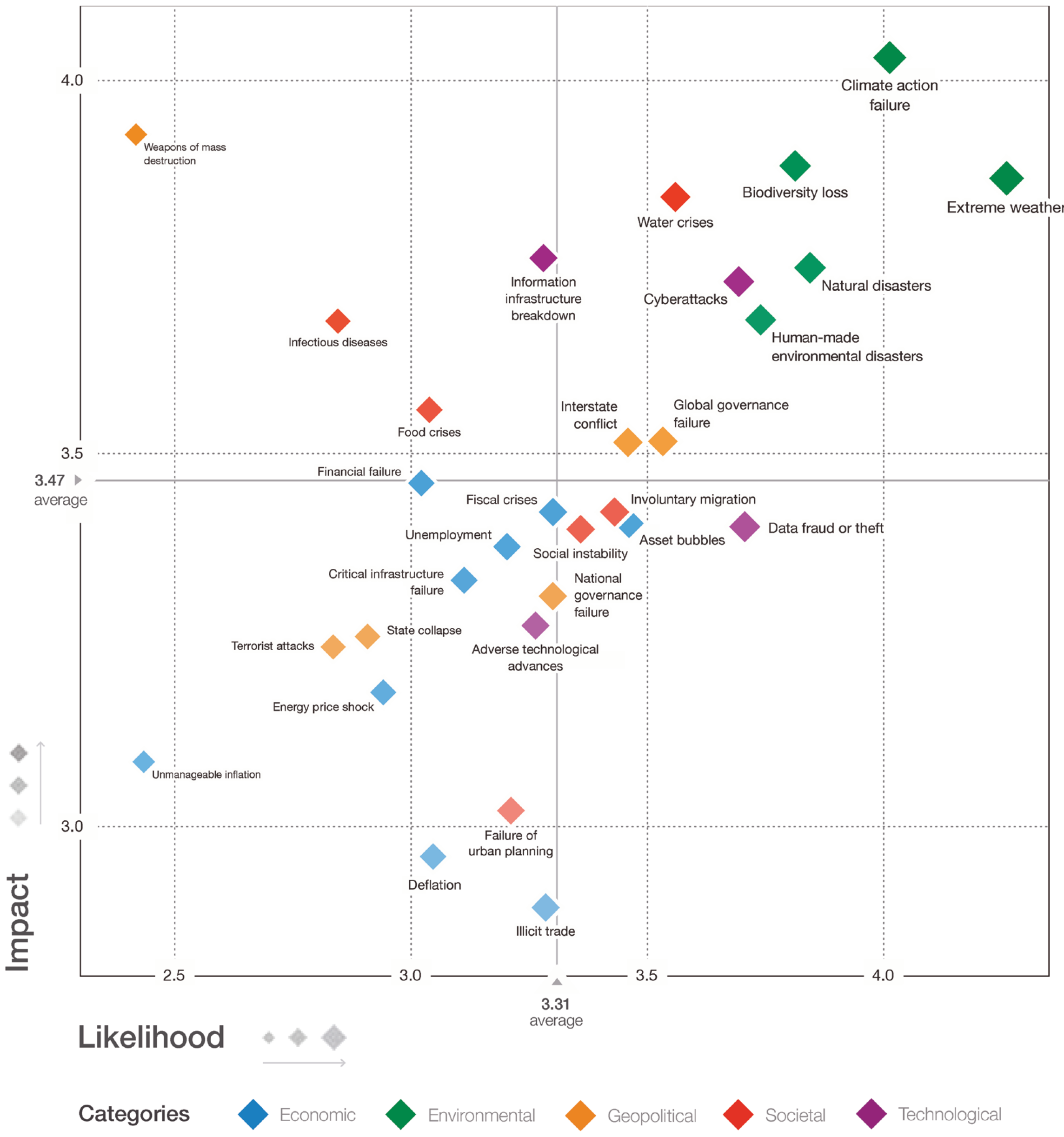


Figure 1.1 The Global Risk Landscape 2020. This represents the perceived threat of risk based on degree of impact, from low (bottom of the grid) to high (top of the grid) and likelihood of occurring from low (left of the grid) to high (right of the grid) (World Economic Forum 2020).

INTRODUCTION

Nations 2020). Without greenhouse gases, Earth would be significantly colder and uninhabitable.

There have been seven cycles of glacial advance and retreat in the last 650,000 years (NASA 2020). The last interglacial period ended about 11,700 years ago, marking the beginning of the modern climate era with human civilization emerging around 6,000 years ago. These climate shifts through geologic time are attributed to very small variations in Earth's orbit which change the amount of solar energy absorbed at its surface and are recorded in ice cores drawn from ice sheets in Greenland and Antarctica, as well as from mountain glaciers. These ice cores record a paleoclimatic record of Earth's atmosphere in response to changing climates. This same evidence can be found in tree rings, ocean and lake sediments, coral reefs, and the layering of sedimentary rocks. These records demonstrate that current warming is occurring roughly ten times faster than the average rate since the end of the last interglacial period (NASA 2020).

Industrialization, deforestation, and large-scale agriculture have contributed to greenhouse gas levels in the atmosphere not seen in three million years (United Nations 2020). The cumulative level of greenhouse gases continues to rise with growing populations, economies, and standards of living. A few well-established scientific links have been presented in a global body of research. First, greenhouse gas concentrations in Earth's atmosphere are directly linked to average global temperature. Second, greenhouse gas concentrations have been rising steadily, in concert with average global temperature, since the Industrial Revolution. Lastly, one of the most abundant greenhouse gases, CO_2, has been added to the atmosphere through the combustion of fossil fuels at unprecedented rates. Carbon dioxide is a minor component of the atmosphere but plays an extremely important role in regulating the greenhouse effect. Carbon dioxide is released into the atmosphere naturally through processes such as respiration in plants and animals and in volcanic eruptions. It is also introduced through human activities like the burning of fossil fuels and land use changes including deforestation (NASA 2020). Human activities have increased atmospheric CO_2 concentrations by more than a third since the early 1900s (Bereiter et al. 2015). Carbon dioxide is the most important "forcing" factor of climate change as it contributes to the greatest change in atmospheric energy fluctuations (IPCC 2018a). Other greenhouse gases include water vapor, methane, nitrous oxide, and chlorofluorocarbons (CFCs). Unlike other

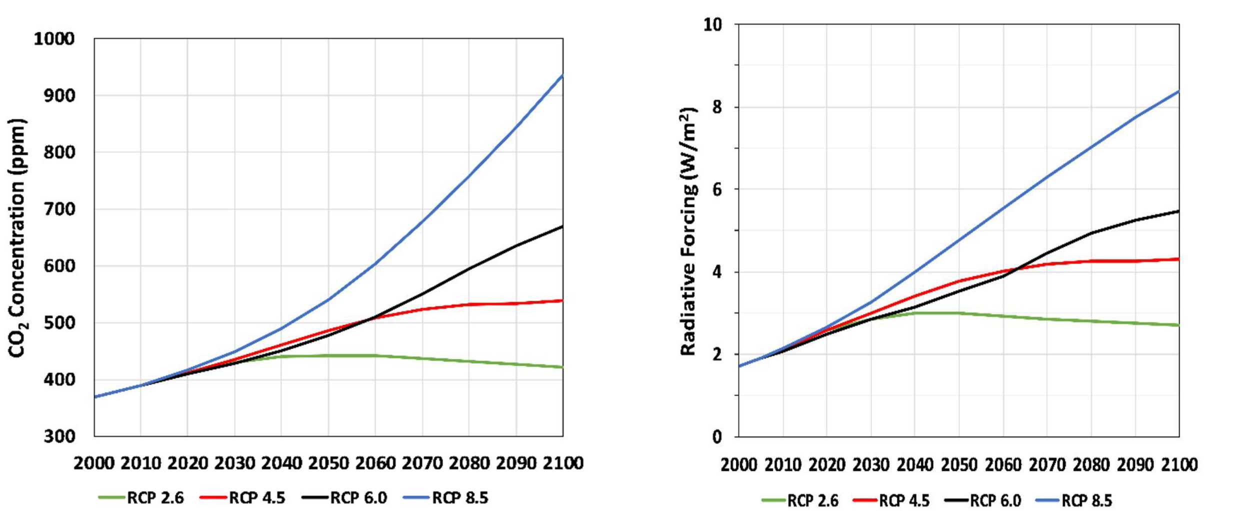


Figure 1.2. Projections of atmospheric CO_2 concentration and total radiative forcing through 2100 based on each RCP scenario. Data are available from the RCP Database (Version 2.0). Scenarios and projections follow (van Vuuren et al. 2011).

greenhouse gases, water vapor is controlled by the atmosphere itself, so is considered a function of climate instead of "forcing" climate change.

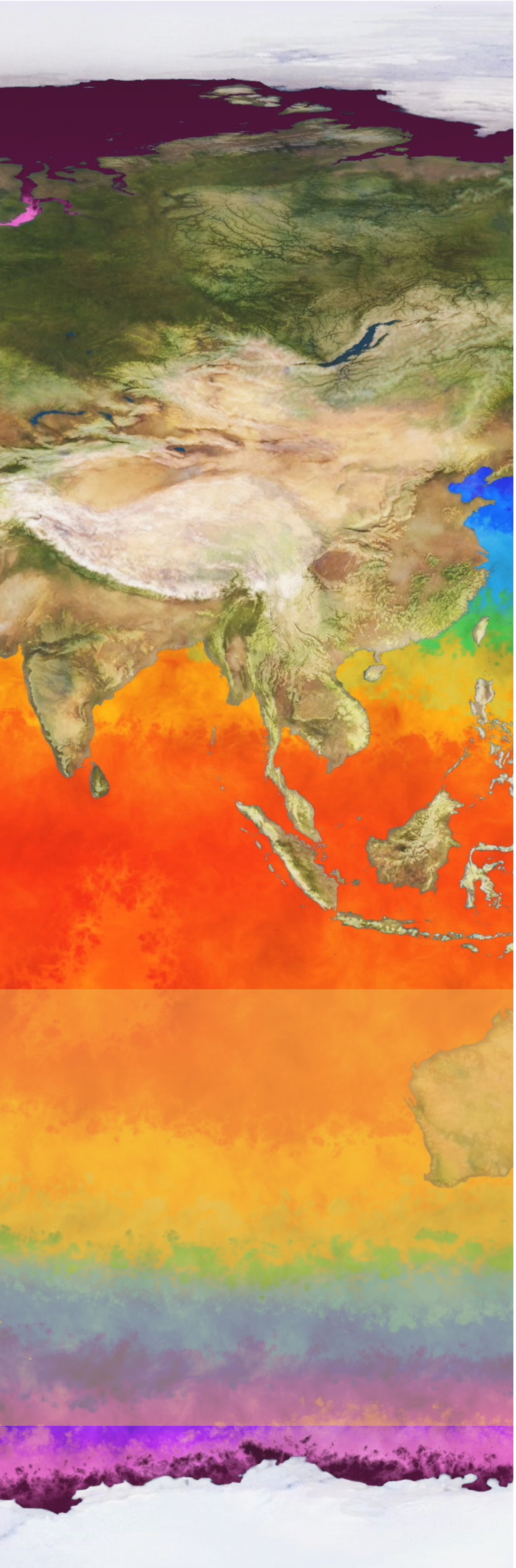
When projecting climate change conditions, scientists consider multiple future climate scenarios that include, among many other factors, potential atmospheric warming related to greenhouse gas emissions. The most widely used model scenarios are those developed by the scientific community and reviewed by van Vuuren et al. (van Vuuren et al. 2011). These scenarios, termed Representative Concentration Pathways (RCPs) project changes in radiative forcing, or changes to the atmospheric energy (heat) balance associated with climate change, out to the year 2300. Each pathway is measured against a baseline of relative atmospheric stability assumed in the year 1750 (IPCC 2018a). The RCPs range from a low emission scenario with a high greenhouse gas mitigation future (RCP 2.6) to a high emission scenario (RCP 8.5) that accounts for high population growth and little greenhouse gas mitigation. The low emission scenario was developed to emphasize a significant reduction of future emissions. Such low emissions are not likely to be met even with current mitigation policies. Therefore, any climatic projections based on this low emission scenario will most likely underestimate the conditions we are likely to experience. The high emission scenario, RCP 8.5, represents the 90th percentile of all baseline scenarios and the most unlikely outcomes (Figure 1.2). The RCPs also contain two central estimates of warming potential, RCP 4.5 and RCP 6.0. Both will require reductions in greenhouse gas emissions from current levels (van Vuuren et al. 2011). Each RCP corresponds to future average temperature increases (Table 1.1). Moderate level scenarios are most likely to better represent the emission and temperature trajectories (5.4˚F; 3.0˚C by 2100) many scientists believe we are heading toward and offer flexibility if some global policies are reversed or not met (Hausfather and Peters 2020). This does not mean that higher emission scenarios and associated projections should be discounted as they offer insight to possible conditions if mitigation measures do not continue.

Table 1.1. Global Mean Temperature Increases (°F) by 2100 Associated With Each Representative Concentration Pathway (RCP) Model Scenario (IPCC 2013). Temperature increases are relative to 1986-2005 reference period.

Scenario	Likely Range – Low	Average Temperature Increase	Likely Range – High
RCP 2.6	*0.5*	*1.8*	*3.1*
RCP 4.5	*2.0*	*3.2*	*4.7*
RCP 6.0	*2.5*	*4.0*	*5.6*
RCP 8.5	*4.7*	*6.7*	*8.6*

CHAPTER 2

OVERVIEW OF GLOBAL AND REGIONAL CLIMATE CHANGE



2.1 Global

Global climate is changing rapidly when compared to the pace historically set by natural variations in climate (Hayhoe et al. 2018). According to the International Panel on Climate Change (IPCC 2014) the average global temperature has risen by about 1.5˚F (0.8˚C) from 1901 to 2016. Evidence consistently points to human activities, particularly greenhouse gas emissions, as the dominant cause for this increase, without any credible evidence to support natural explanations for the warming. Earth's climate can be expected to continue changing through this century and beyond. How much change will primarily depend on global emissions of greenhouse gases and the natural response of Earth's climate system to this human-induced warming. A very high warming scenario without significant emissions reductions from current levels could see annual average global temperatures increase by 9˚F (5˚C) or more by the end of the century, compared to preindustrial temperatures. Global temperature increase could be limited to 3.6˚F (2˚C) or less if significant reductions in emissions are put into place (Dupigny-Giroux et al. 2018) but temperatures are currently trending towards 4.5˚F (2.5˚C) to 5.4°F (3˚C) under current mitigation policies (Hausfather and Peters 2020).

Given the mounting evidence that human activities were altering atmospheric composition, the countries of the world set up the *Intergovernmental Panel on Climate Change* (IPCC) in 1988 to synthesize and evaluate the state of scientific understanding about climate change, resultant impacts, and the potential for limiting further change. Since its creation, the Intergovernmental Panel on Climate Change has completed five comprehensive assessments (IPCC 1990, 1995, 2001, 2007, 2013), produced a number of additional reports, and stimulated substantial growth in research on climate change. In its 2007 report the Intergovernmental Panel on Climate Change concluded that "global warming is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

OVERVIEW OF GLOBAL AND REGIONAL CLIMATE CHANGE

The Global Carbon Project was established to collaborate with the international science community to create an agreed-upon knowledge base to support policy action to decrease the emissions of greenhouse gases in the atmosphere. The Global Carbon Project reported that total annual carbon dioxide (CO_2) emissions from fossil fuels and industry rose by 1.6% in 2017 over the prior year to 36.2 billion metric tons CO_2 (Jackson et al. 2018). In 2018, CO_2 emissions from fossil fuel sources increased by 2.7%. These findings are supported by the International Energy Agency World Energy Outlook 2018 and are far from a trajectory consistent with international climate goals. The Global Carbon Project expected even further increases to have occurred in 2019 given the persistent growth in oil and natural gas production and projected economic growth this year (World Resources Institute 2018).

The increase in greenhouse gases in Earth's atmosphere causes other changes in addition to rising temperatures. The world's oceans have absorbed greater than 90% of the excess heat and a quarter of the CO_2 produced annually from human activities (Hayhoe et al. 2018). These changes are causing the oceans to warm and become more acidic, respectively, resulting in rising sea surface temperatures and sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation. Due to the size of the ocean and the capacity to store heat, climate change from human-caused emissions of CO_2 and other greenhouse gases will continue to persist for decades to millennia. Furthermore, feedback loops within Earth's climate system have the potential to accelerate anthropogenic (human-caused) change (Hayhoe et al. 2018).

As global temperature increases into the future, the frequency and intensity of extreme high temperature events are virtually certain to increase as well (USGCRP 2017). Extreme precipitation events will also be very likely to continue to increase in their frequency and intensity throughout most of the world. However, the observed and projected trends for some other types of extreme events, such as floods, droughts, and severe storms for example, are more variable regionally.

2.2 National

From 1980 to 2019, the United States has sustained 258 weather and climate related disasters (National Centers for Environmental Information 2019) where the overall costs of damages per event reached or exceeded $1 billion (including Consumer Price Index adjustment to 2020). During 2019, the United States experienced an active year of billion-dollar

LONG BEACH ISLAND, NEW JERSEY

disaster events, including 14 weather and climate disaster events that each sustained losses exceeding $1 billion (National Centers for Environmental Information 2019). These disasters included three inland flooding events, eight severe storms, two tropical cyclones (Dorian and Imelda) and one wildfire event.

To understand how the frequency and intensity of disasters are changing, it is useful to consider how the climate is changing. Based on a Climate Science Special Report by the United States Global Change Research Program in 2018, it can be said with very high confidence that the average annual temperature throughout the United States has increased by 1.2˚F (0.7˚C) for the period of 1986–2016 relative to 1901–1960 and by 1.8˚F (1.0˚C) for the period of 1901–2016 (USGCRP 2017). Synthesis of paleo-temperature evidence indicates that the recent decades are the warmest in the past 1,500 years. Paleo-temperature records can be reconstructed by analyzing ancient sediments for lipids produced by cold-adapted and warm-adapted organisms. The average annual temperature in the contiguous United States is projected to rise and extreme temperatures are projected to increase even more than average temperatures (USGCRP 2017). These projections are particularly important to be aware of because the urban heat island effect will strengthen in the future as the structure, spatial extent, and population density of urban areas changes and grows (Rosenzweig et al. 2005).

In addition to temperature, the instance of heavy precipitation events in most parts of the United States have increased in intensity and in frequency since 1901 (USGCRP 2017). There are, however, significant regional differences in trends across the country. The largest increases in precipitation events occur in the northeastern United States. Collectively, these changes to temperature and precipitation will make the current environment feel much like that of other regions of the country, mostly those more southern and western (Fitzpatrick and Dunn 2019).

Not only will climate change affect the way it feels to live in the regions around the United States, but it will also make survival riskier. Climate Central in 2018 produced the first nationwide analysis of new homes in areas vulnerable to coastal flooding in all 24 coastal states and Washington DC (Climate Central 2019). This report showed on-average, how many homes will become exposed to annual ocean flooding in the coming decades, depending on the choices the world makes today regarding greenhouse gases. If only moderate cuts are made to current day greenhouse gas emissions, around 17,800 existing homes built after 2009 will face at least on average a 10% flood threat each year by 2050. These moderate cuts would be roughly in line with those of the Paris agreement on climate, whose targets the international community is at present not on track to meet. The figures are more than two times higher for 2100 and three times higher if emissions continue unchecked.

2.3 Regional

Regional assessments predict that the Northeastern United States will be especially vulnerable to impacts of climate change and the potential ecological, economic, and public health impacts could be devastating (Frumhoff et al. 2007). The United States National Climate Assessment presents observed and projected changes for the northeast region of the United States, reporting that average annual temperatures in the region increased by less than 1˚F (0.6˚C) in West Virginia to about 3˚F (1.7˚C) or more in the New England states since 1901 (Dupigny-Giroux et al. 2018). Temperatures off the coast and open ocean along the Northeast Continental Shelf have warmed by 0.06˚F (0.03˚C) per year over the period 1982–2016, which is three times faster than the 1982–2013 global average rate of 0.018˚F (0.01˚C) per year (Dupigny-Giroux et al. 2018). It is anticipated that the southern portion of the region (including Maryland, Delaware, southwestern West Virginia, and New Jersey) will experience an increase in the number of days per year with temperatures above 90˚F (32.2˚C) compared to the end of the last century (Melillo et al. 2014).

OVERVIEW OF GLOBAL AND REGIONAL CLIMATE CHANGE

The United States National Climate Assessment also reported that precipitation increased by over 10% or five inches (roughly 0.4 inches per decade) between 1895 and 2011 (Melillo et al. 2014). More than any other region in the United States, the Northeast has seen a greater recent increase in extreme precipitation (Melillo et al. 2014). From 1958 to 2010, the Northeast received more than a 70% increase in the amount of precipitation falling during events that are considered very heavy events (by definition, the heaviest 1% of all daily events).

Despite a trend toward more precipitation occurring since 1970, the Northeastern United States is seeing longer periods without rainfall during longer growing seasons (Frumhoff et al. 2007). The result is a drier growing season, especially during the summer months, when temperatures and evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) are highest. Additionally, drier conditions are exacerbated by reduced recharge from spring snowmelt as observations indicate that precipitation is transitioning to more rain and less snow in the Northeastern United States since 1970 (Frumhoff et al. 2007).

Higher temperatures allow for additional moisture in the atmospheric which contributes to more overall precipitation in some areas, especially in much of the Northeast (Frumhoff et al. 2007). Precipitation (as rain, rather than snow) and runoff are likely to increase in the Northeastern United States in both winter and spring. Such areas, where total precipitation is expected to increase the most, would also experience the largest increase in heavy precipitation events. Projections also indicate that spring snow melts may begin up to 14 days earlier under high emissions scenarios. Reduced stream flows late in the season due to earlier runoff, higher water temperatures, and reduced soil moisture in the summer and fall will stress human and environmental systems.

Sea-level rise is documented throughout the world, and it is an indicator of Earth's heat balance (Blunden et al. 2019). Sea level rose approximately 12 inches (30 cm) since 1900, exceeding the global average of about 8 inches (20 cm) (IPCC 2014, Melillo et al. 2014). Although there are local and regional influences on sea level that are not related to anthropogenic climate change (such as geological subsidence that exists in New Jersey), sea-level rise occurs due to two main reasons: ice melting on land (leading to increased water volume) and thermal expansion (the expansion of the ocean as it warms) (Blunden et al. 2019). Consistent with the observed trend, sea-level rise will lead to more frequent and extensive coastal flooding. By the end of the 21st century, several northeastern states will have notable portions of their projected populations at risk of adverse effects from sea-level rise (Hauer et al. 2016).

The Mid-Atlantic region of the ocean includes the area from Cape Hatteras in North Carolina to Cape Cod in Massachusetts (Dupigny-Giroux et al. 2018). The extent that climate change may possibly impact this region has been studied extensively over the past decade (Colgan et al. 2018). Climate-related changes that are likely to occur have been identified with ever increasing confidence. These changes include sea-level rise and also changes to marine and coastal ecosystems, with the breadth and depth of information varying across the region. The increased potential for more intense tropical storms (Huang et al. 2017) along with increased likelihood for severe thunderstorms and other weather hazards such as lightning, heavy rain, hail, and tornadoes (Diffenbaugh et al. 2013) make it clear that threats from climate change are clear and present in the Mid-Atlantic.

"Regional assessments predict that the Northeastern United States will be especially vulnerable to impacts of climate change and the potential ecological, economic, and public health impacts could be devastating."

SATELLITE IMAGE OF NEW YORK-NEW JERSEY AREA

- **In 2018, New Jersey's net greenhouse gas emissions were estimated to reach a low if 97.0 million metric tons of carbon dioxide equivalent.**
- **The transportation sector is the largest source of greenhouse gas emissions in the State.**

CHAPTER 3

GREENHOUSE GASES: THE PRIMARY DRIVER OF CLIMATE CHANGE

NEWARK, NEW JERSEY

Naturally occurring greenhouse gases are needed to sustain life on Earth, and are in fact, one of the reasons life on Earth is even possible. However, the greenhouse gas concentrations from human emissions in the last two centuries are so far above the natural baseline that these are now the primary driver of accelerated climate changes. These changes are altering the way humans and all life on Earth will interact and exist on the planet. For this reason, it is important to better understand greenhouse gases, their sources, and the impacts they have on the climate.

3.1 Greenhouse Gas Global Cause-Effect Chain: Basic Background

The fundamental physics of the greenhouse effect has been understood for more than a century. The greenhouse effect can be summarized as follows: the Sun emits intense amounts of solar radiation, or sunlight, that is either absorbed by Earth's surface and atmosphere or is reflected back into space (Wolff et al. 2020). The atmosphere and Earth's surface (land, ocean, and ice) reflect back into space thirty percent (30%) of this solar energy (Pielou 2001). Some of the absorbed solar energy is further absorbed by greenhouse gases and warms Earth's atmosphere, while some escapes back into space (Wolff et al. 2020). These naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases prevent some of the heat from escaping back into space, and thus serve as a kind of blanket which helps maintain Earth (as much as 60°F (33.3°C) warmer than it would otherwise be (Pielou 2001). This warming effect creates conditions that are essential for human life.

Scientists have been able to reconstruct a record of atmospheric CO_2 concentrations reaching back 800,000 years using ice cores drilled approximately 3 km (1.86 miles) deep in Antarctica (Lüthi et al. 2008). Figure 3.1 shows this record, with the peaks in CO_2 concentration occurring during warm

GREENHOUSE GASES:
THE PRIMARY DRIVER OF CLIMATE CHANGE

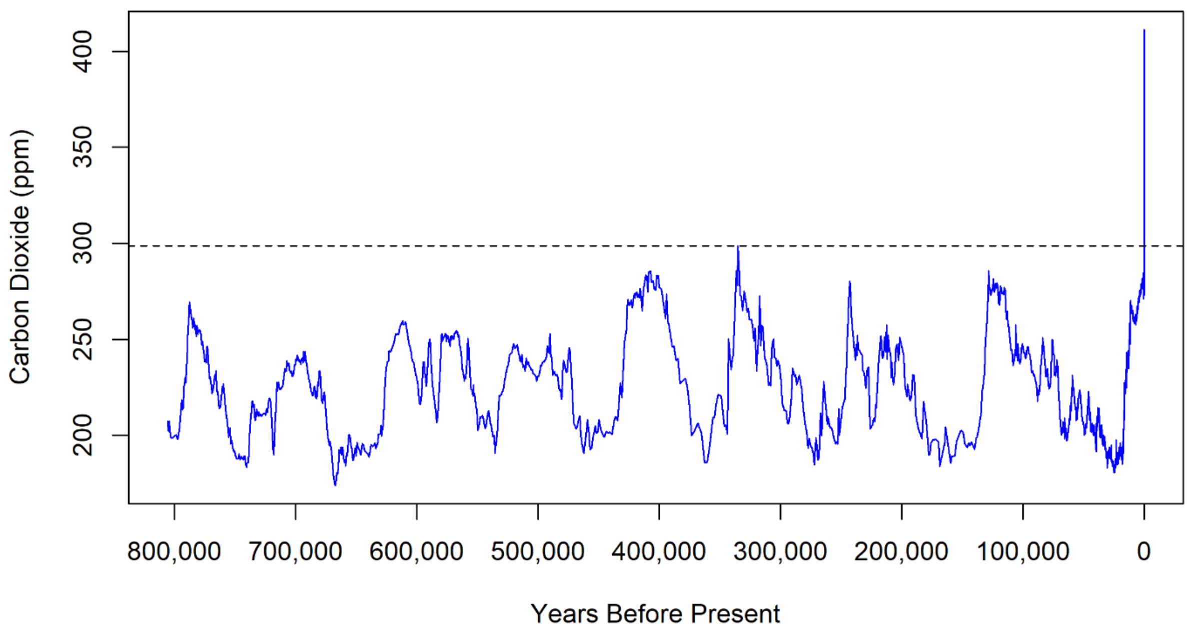


Figure 3.1. Atmospheric CO_2 Concentrations in Parts Per Million (ppm) for the Previous 800,000 Years. The figure shows fluctuating atmospheric CO_2 concentrations over the past 800,000 years. The high points represent warm interglacial periods and the valleys represent colder glacial periods. The timepoint 0 is 1950. The maximum annual concentration of 411 ppm occurred in 2019. The dashed line at 296 ppm represents the historic maximum. The historic CO_2 concentrations are reconstructed from composite air gas trapped in Antarctic ice cores while recent CO_2 concentrations are atmospheric levels reported from the Mauna Loa, Hawaii observation station. The ice core data is available at https://www.ncdc.noaa.gov/paleo/study/17975 (Bereiter et al. 2015) and the Mauna Loa data are available at https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html (Tans and Keeling 2020).

interglacial periods and the dips occurring during cold glacial periods (Lindsey 2019). Over the past 800,000 years the concentration of CO_2 did not exceed 300 parts per million (ppm), until recently.

The level of atmospheric gases has been changing since the start of the Industrial Revolution more than two centuries ago. At that point, CO_2 levels were about 280 ppm (IPCC 2001). Since then, billions of tons of excess greenhouse gases have been emitted into the atmosphere, resulting in more and more heat being trapped. The primary greenhouse gas emitted as a result of human activities is CO_2 and concentrations of this gas are increasing, as seen in Figures 3.1 and 3.2. Average annual CO_2 levels exceeded 400 ppm for the first time in 2016 and continued to rise through 2019 when levels reached 411 ppm as reported at the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory (Tans and Keeling 2020). Given the role of CO_2 as a greenhouse gas, an increase of this magnitude is expected to result in an unprecedented increase in global temperature.

> ***"Given the role of CO_2 as a greenhouse gas, an increase of this magnitude is expected to result in an unprecedented increase in global temperature."***

The increasing concentration of CO_2 was first observed more than 60 years ago (Le Treut et al. 2007). Since then other human-sourced greenhouse gases have been recognized as contributing to

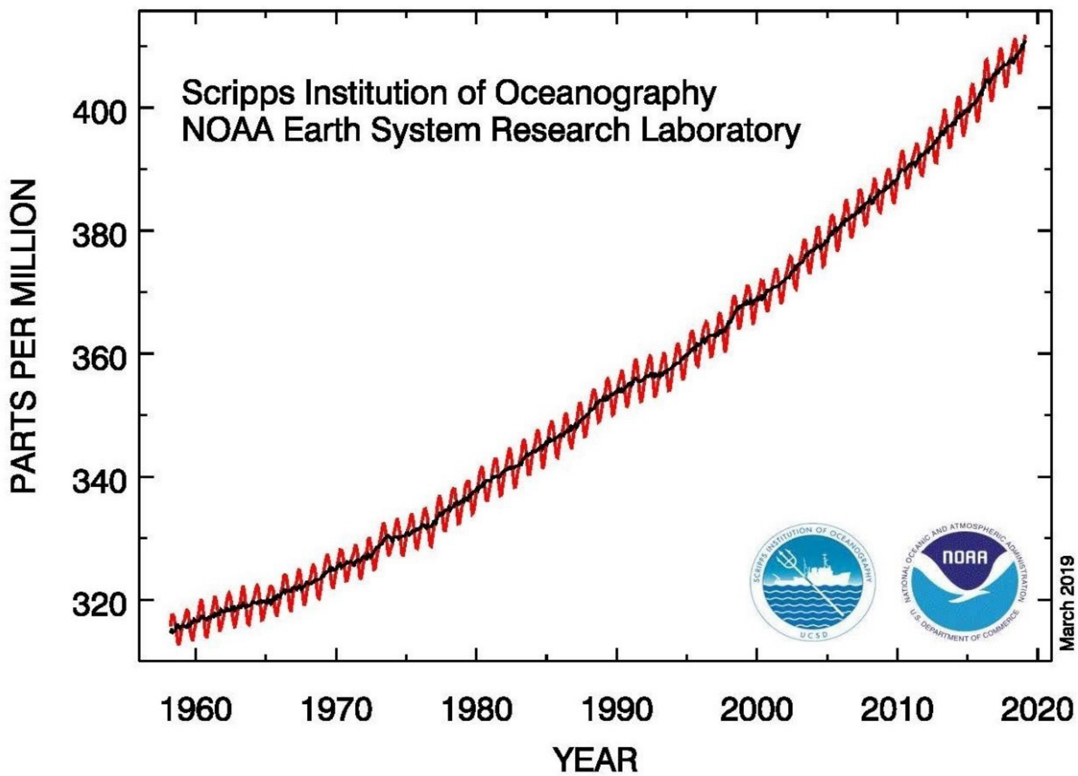


Figure 3.2. Keeling Curve - Carbon Dioxide Concentration. The figure shows the average monthly carbon dioxide concentration (in red), with a moving average of seven adjacent seasonal cycles (in black) that removes the season cycle. Figure and data available from the NOAA Earth System Research Laboratories; https://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html (Tans and Keeling 2020).

climate change, such as methane (CH_4), nitrous oxide (N_2O), ozone (O_3), many halogenated gases (especially chlorofluorocarbons [CFC-11 and CFC-12]), among others.

3.2 Greenhouse Gas and Biogeochemical Cycles

The biogeochemical cycles in land and oceans are key components of Earth's climate system. The cycles involve fluxes of chemical elements across various parts of Earth: from non-life to life, from soils to plants, and from the atmosphere to land to sea. The surface fluxes of the precursors, or building blocks, of many greenhouse gases are decisively influenced by biogeochemical and physical processes and are sensitive to changes in climate and atmospheric composition. Of critical importance, biogeochemical processes help control atmospheric concentrations of the main greenhouse gases - CO_2, CH_4, and N_2O. Vegetation, soils, and permafrost on the land together contain at least five times as much carbon as the atmosphere, and the oceans contain about fifty times more carbon than the atmosphere (see Figure 3.3 for a schematic of the carbon cycle) (Le Quéré et al. 2018). Thus, future climate change will be determined not only by anthropogenic (human-caused) emissions but also by the strength of the feedbacks between all aspects of Earth's climate system. This includes how much carbon, such as CO_2 and CH_4, is sequestered through natural ecosystems as part of the global carbon cycle, as well as the nitrogen cycle which determines how N_2O is dispersed throughout Earth's systems. While human-caused emissions are the dominant influence on the present-day carbon cycle, climate projections now take some of these feedbacks into account (USGCRP 2018).

GREENHOUSE GASES:
THE PRIMARY DRIVER OF CLIMATE CHANGE

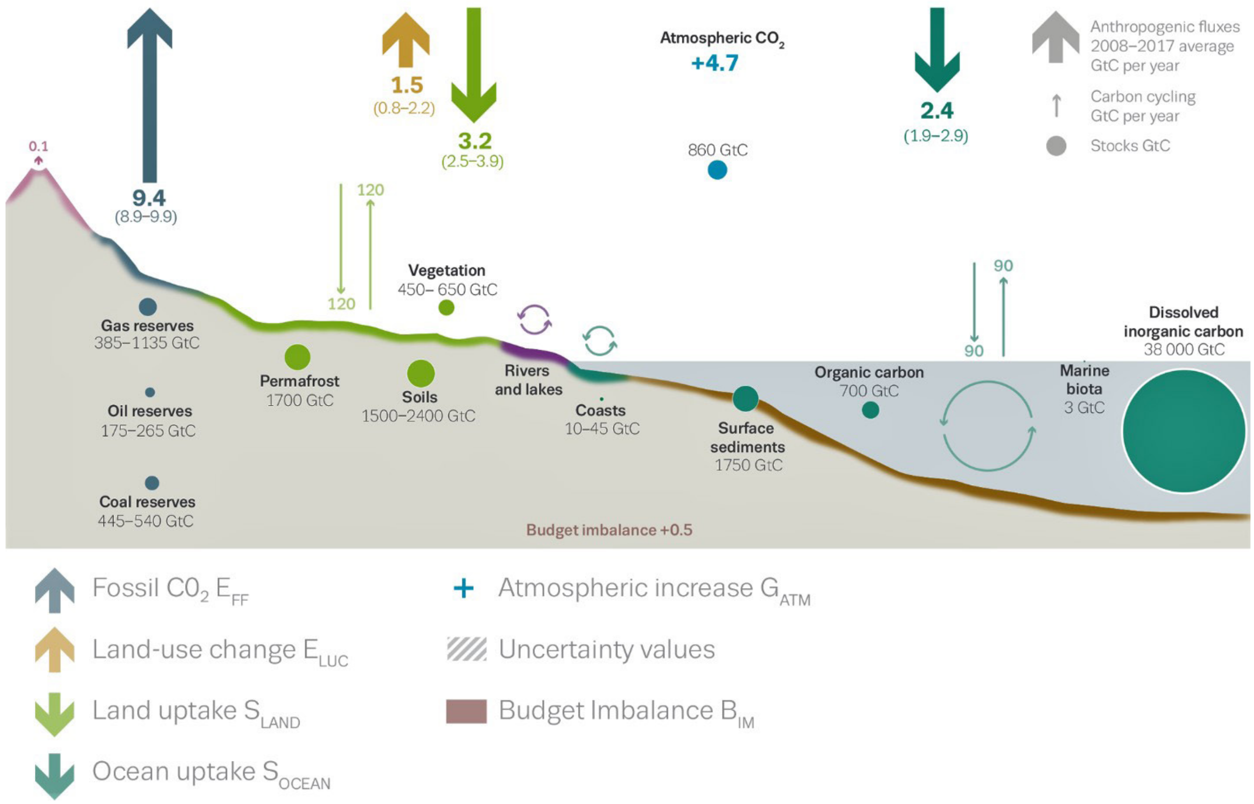


Figure 3.3. The Global Carbon Cycle. The schematic represents the overall influence on the global carbon cycle from anthropogenic (human-caused) activities, averaged globally for the decade 2008-2017. The natural background cycles are represented by the thin arrows, and the thick arrows, representing anthropogenic disruptions, are factored into natural cycles to calculate total fluxes. This schematic includes carbon stocks at the coasts, coastal marine sediments GtC (gigatons of carbon), EFF (fossil CO_2 emissions), ELUC (land-use change emissions), SOCEAN and SLAND (ocean and land CO_2 sinks), GATM (growth rate in atmospheric CO_2 concentration), and BIM (budget imbalance). Source: Earth System Science Data (Le Quéré et al. 2018).

Large-scale modifications of biogeochemical cycles are occurring due to human activities both in the United States and elsewhere, with impacts and implications now and into the future. Global CO_2 emissions constitute the primary driver of human-caused climate change (Galloway et al. 2014). However, accelerated alterations to other element cycles, especially nitrogen, phosphorus, and sulfur, also influence climate. These can directly affect climate or serve as indirect factors that affect the carbon cycle, magnifying or reducing the impacts of climate change. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight. For example, small particles known as aerosols that are created naturally and anthropogenically can reflect sunlight.

According to the Third National Climate Assessment, human activities cause carbon, nitrogen, and phosphorus to enter the environment from Earth's crust and atmosphere. This transfer is now occurring 36, 9, and 13 times, respectively, faster than what occurred from geological sources during pre-industrial times (Galloway et al. 2014). These increases come mostly from the burning of fossil fuels, changes to land-cover, production of cement, fertilizer extraction, and production for agriculture. While CO_2 is the most abundant heat-trapping greenhouse gas and increases in CO_2 concentration is the main cause of changes to the atmospheric energy (heat) balance associated with global climate change (atmospheric forcing), it is not the only cause. Methane (CH_4) and N_2O are also increasing in the atmosphere and have a

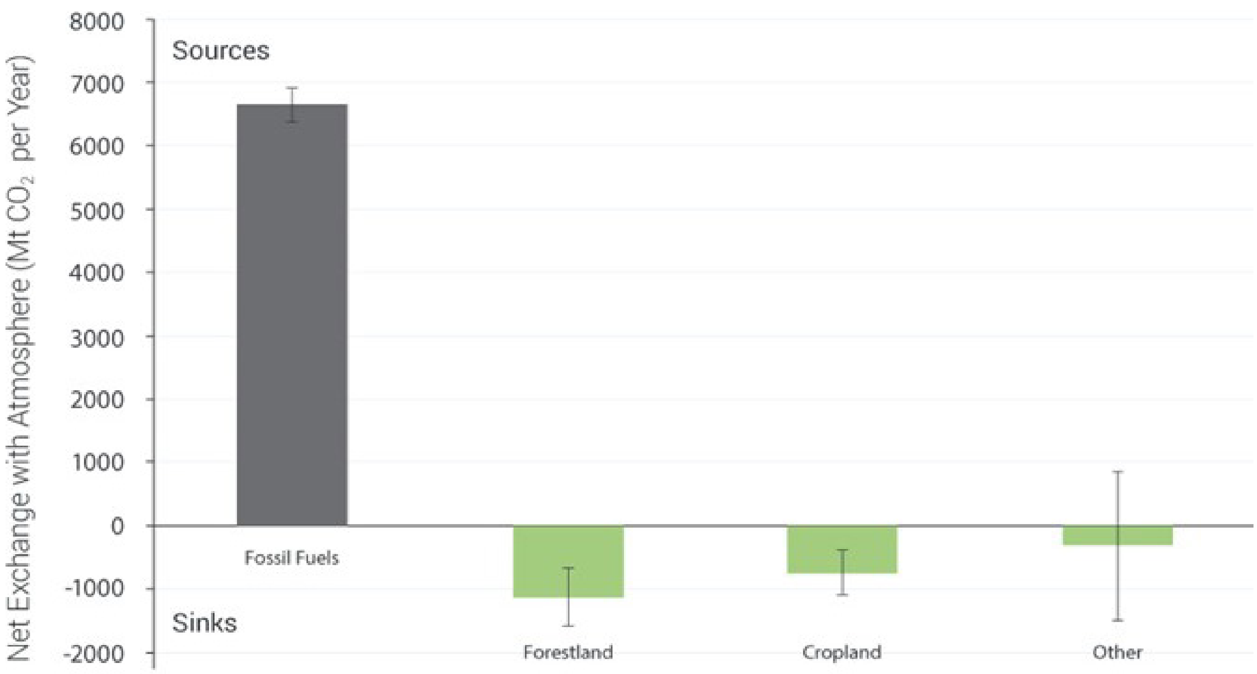


Figure 3.4. North American Carbon Dioxide (CO_2) Sources and Sinks: Magnitude, Attribution, and Uncertainty. The figure shows the amount of atmospheric CO_2 in metric tons of CO_2 (y-axis) that is released (a source) or sequestered (a sink) in North America from 2010. Source: (King et al. 2012).

higher global-warming potential than CO_2. Global warming potential is a measure of the energy that a gas absorbs over a particular period of time (usually 100 years), compared to CO_2 (NJDEP 2020a). Sulfur emissions, which produce aerosol particles that cool Earth by reflecting sunlight, also can impact climate change. In the United States and Europe, sulfur emissions have declined over the past three decades, especially since the mid-1990s with increased efforts to reduce air pollution.

From 1950 to 2007, the United States was the world's largest producer of anthropogenic CO_2 emissions, accounting for about 85% of CO_2 emissions in North America and 18% globally (Galloway et al. 2014). Carbon is not only released into the atmosphere in the form of CO_2 but can also be taken out of the atmosphere and stored in carbon sinks. Carbon sinks can store carbon for short or long periods of time and are found in ecosystems. One example is forests, which in North America have been sequestering carbon from the atmosphere into their soils and biomass (Galloway et al. 2014). Carbon sequestration in forests has increased over the past two decades as a result of increased forest area, recovered forests that are no longer harvested, improved forest management, and increased tree growth. This increased tree growth is due to beneficial climatic changes, fertilization by CO_2 and nitrogen, and longer growing seasons. Fertilization from CO_2 can occur when the increased concentration of atmospheric CO_2 results in increased photosynthesis in plants and increased moisture retention due to shorter stomatal, the pores located on leaves and stems, opening periods. The southeastern, south central, and Pacific northwest regions of the United States have the largest rates of carbon being sequestered from the atmosphere and into biomass. However, North America still is a net source of CO_2 because CO_2 emission from human activities is still more than three times higher than the rate of sequestration that occurs in ecosystems, as seen in Figure 3.4. For more information on carbon sequestration in New Jersey forests and wetlands, see Chapter 5.6.

Energy-related CO_2 emissions account for 86% of all greenhouse gases in the United States and after three years of continuous decline, rose in 2018 (Rhodium Group 2018). It is estimated that the United States economy-wide emissions increased by 1.5% to 2.5% in 2018. Driving this trend are the emissions from the transportation and industrial sectors, which increased in 2017 and accelerated in 2018 due to strong economic growth. Another substantial change from 2017 to 2018 was in emissions from the buildings and electricity sectors. Emissions from the building sector increased due to a return to historical average winter weather in 2018 after an unusually warm 2017.

3.3 Greenhouse Gas Emissions in New Jersey

The New Jersey Global Warming Response Act, designed to address increased greenhouse gas concentrations in the atmosphere, establishes greenhouse gas mandates to reduce statewide greenhouse gas emissions to at or below 1990 levels by 2020 and to 80 percent of 2006 levels by 2050. It also requires the Department of Environmental Protection (DEP) to establish an inventory of statewide greenhouse gas emissions to track the State's progress toward meeting the 2050 mandated reductions. The Global Warming Response Act requires DEP to biennially update the Statewide Greenhouse Gas Emission Inventory. The DEP released inventory updates in November 2009 (presenting 2005 – 2007 data), May 2011 (presenting 2008 data), November 2012 (presenting 2009 data), September 2015 (presenting 2010, 2011 and 2012 data), and December 2017 (presenting 2013, 2014, and 2015 data). The latest update provides estimated inventory data for the years 2016, 2017, and 2018 (inventories are subject to availability of information from the United States Energy Information Administration, which has a lag time of 2 years for collection and publication of data).

New Jersey's total gross greenhouse gas emissions in 2018 reached 105.1 million metric tons (MMT) of carbon dioxide equivalent, or CO_2e, which is a term used to compare the emissions from various greenhouse gases based on their Global Warming Potential to the reference gas of CO_2, which has a Global Warming Potential of 1 (NJDEP 2019a). However, it is also estimated that the State's land sector (forests and associated land cover) sequestered the equivalent of 8.1 $MMTCO_2e$ resulting in net greenhouse gas emissions of 97.0 $MMTCO_2e$ for 2018. The bulk of the 2018 greenhouse gas emissions were energy related, coming from transportation, electric generation, commercial and residential heating and industrial sources. The energy sector emissions represented 86% of the total gross emissions. The remaining emissions (14%) are attributed to non-energy sectors like waste management, agriculture, natural gas transmission and distribution, and refrigeration and air conditioning. These non-energy sector emissions consisted of mostly non-CO_2 greenhouse gases: CH_4, N_2O, and the highly warming halogenated/fluorinated gases.

The transportation sector remains the largest source of greenhouse gas emissions in the State with 40.6 $MMTCO_2e$ in 2018. The electricity generation sector now accounts for 18.1 $MMTCO_2e$, still a substantial portion of the inventory. Close behind are the combined commercial and industrial sectors with 16.6 $MMTCO_2e$ and the residential sector with 15.2 $MMTCO_2e$. Figure 3.5 shows the sectoral distribution of the greenhouse emissions in 2018.

According to the DEP 2018 Statewide Greenhouse Gas Emissions Inventory, the combined non- CO_2 greenhouse gas emissions from sectors using or producing halogenated gases, the electric transmission and distribution system (using sulfur hexafluoride as an insulator), the natural gas transmission and distribution system, and agriculture (enteric fermentation, manure, and soil management) increased to 8.0 $MMTCO_2e$ (NJDEP 2019a). The waste management sector comprised of solid waste landfills and wastewater treatment facilities account for 5.3 $MMTCO_2e$. Land clearing contributed 1.0 $MMTCO_2e$ as a result of lost carbon in biomass and soil removed or disturbed.

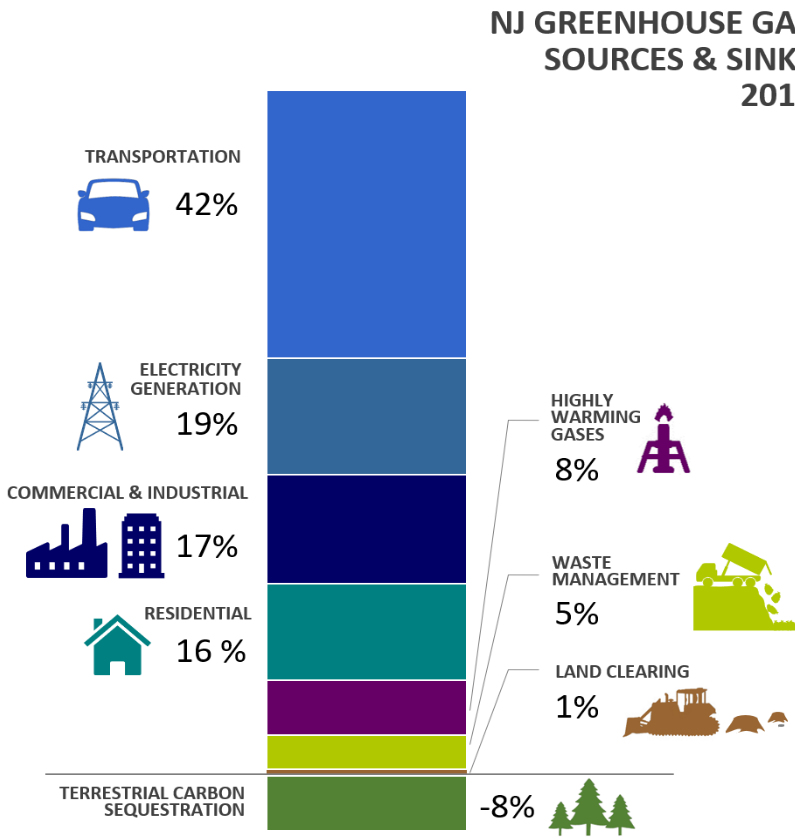


Figure 3.5. New Jersey Greenhouse Gas Sources and Sinks by Sector. This figure shows the distribution of Greenhouse Gas emission sources and sinks by sectoral distribution in 2018 (NJDEP 2019a).

Estimated greenhouse gas emissions for major sector activities over time are shown in Figure 3.6. The category with greatest contribution to greenhouse gas emissions in New Jersey since 1990 has been in the transportation sector, mainly on-road transportation. As a result of its continued dependence on gas- and diesel-powered vehicles and increased vehicle miles traveled, New Jersey has seen an increase in greenhouse gas emissions from transportation despite a modest increase in fuel efficiency of the overall United States motor vehicle fleet.

The electricity generation sector's energy use has varied over the years (see Figure 3.7) (NJDEP 2019a). New Jersey-based nuclear power continues to meet approximately 30-35% of New Jersey's current electric demand. As a result of low natural gas prices, natural gas electric generation displaced all but a small amount of New Jersey-based coal electric generation. Considering natural gas emits about half the CO_2 for the same amount of electric generation as coal, New Jersey has been able to produce considerably more power at a lower emission rate. This transition from coal to natural gas has allowed New Jersey to rely less on imported power generation from other states.

The transition from coal to lower CO_2 emitting natural gas has provided near term greenhouse gas reductions, but New Jersey will have to continue its commitment to the growth in use of renewable energy sources to meet its 2050 mandated reduction. The State's greenhouse gas emissions

GREENHOUSE GASES:
THE PRIMARY DRIVER OF CLIMATE CHANGE

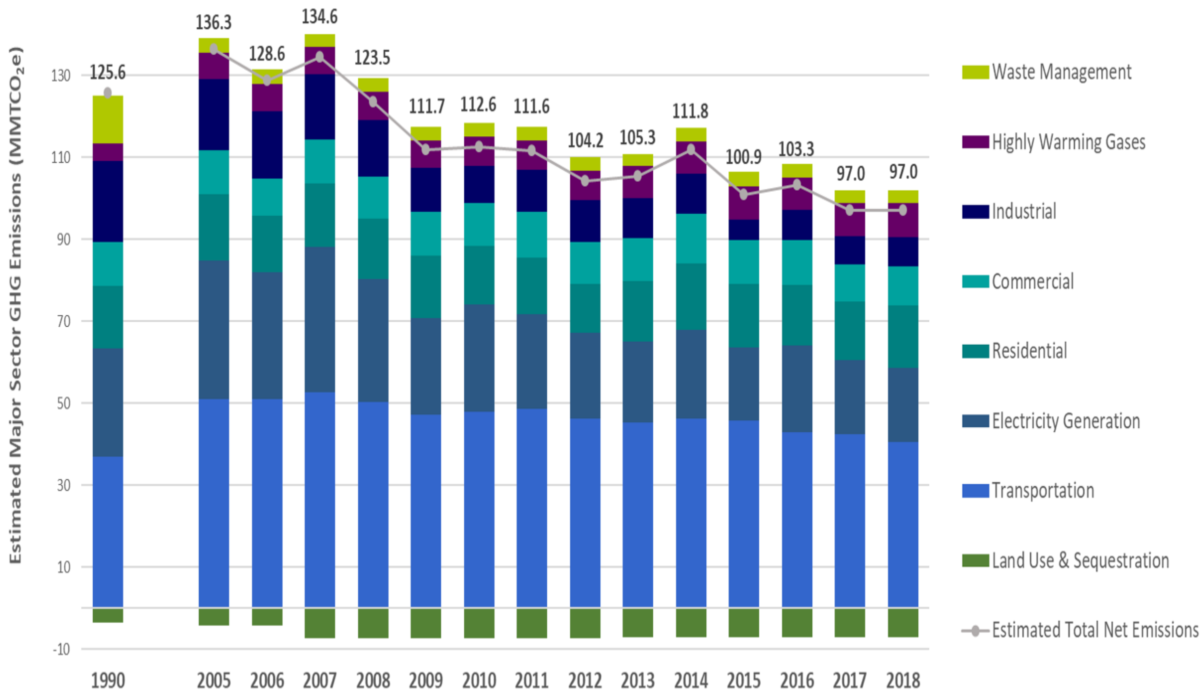


Figure 3.6. New Jersey Greenhouse Gas Emission Trends by Sector. This figure shows the estimated greenhouse gas emissions in million metric tons (MTT) for major sector activities from 2005 to 2018 compared to 1990. (NJD EP 2018a).

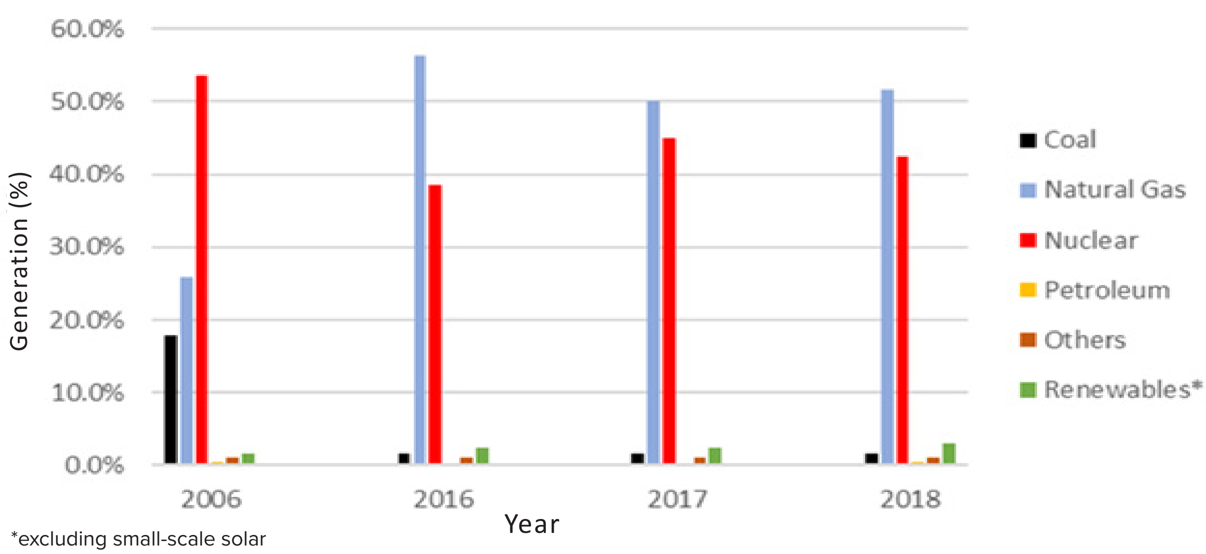


Figure 3.7. New Jersey Electricity Generation Fuel Mix. This figure shows the percentage of the electricity generation sector use by fuel source in 2006, 2016, 2017, and 2018. Source of Base Data: (US Energy Information Administration 2019).

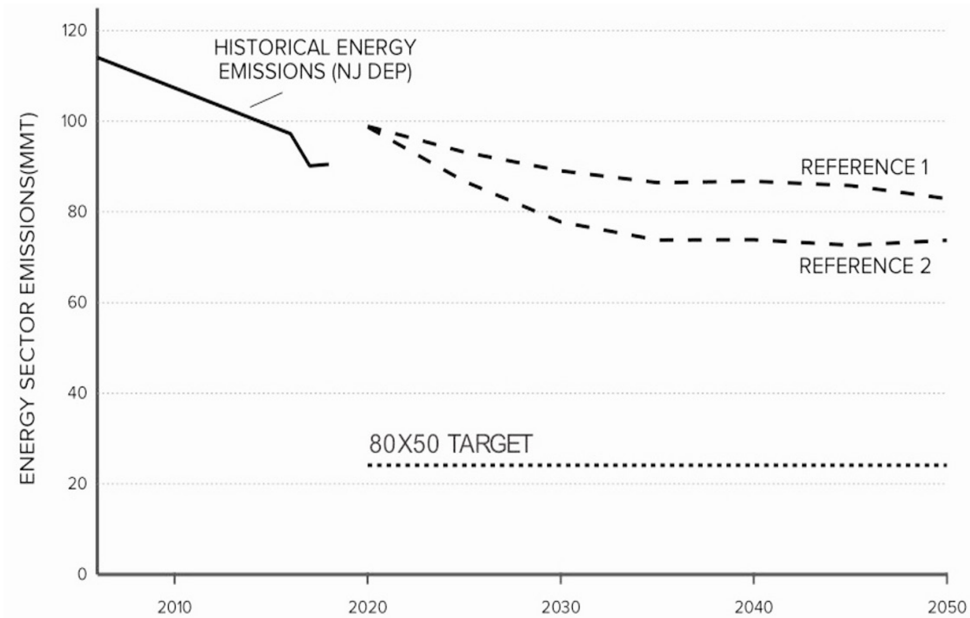


Figure 3.8. New Jersey Measured and Projected Greenhouse Gas Emissions. This figure shows the trajectory of the New Jersey historical energy sector emissions and emissions projected by the Integrated Energy Plan Reference scenarios as compared to the Global Warming Response Act (GWRA) "80x50" target (NJBPU 2019). Reference 1 reflects "business as usual" prior to the energy commitments made by the Murphy administration. Reference 2 reflects a "business as usual" pathway assuming achievement of recent energy mandates, including the Clean Energy Act and the State Zero-Emission Vehicle Program Memorandum of Understanding. Note that 2020 emissions are higher than those in 2018 due to economic growth and the retirement of the Oyster Creek nuclear plant. Figure from New Jersey's Energy Master Plan (NJBPU 2019).

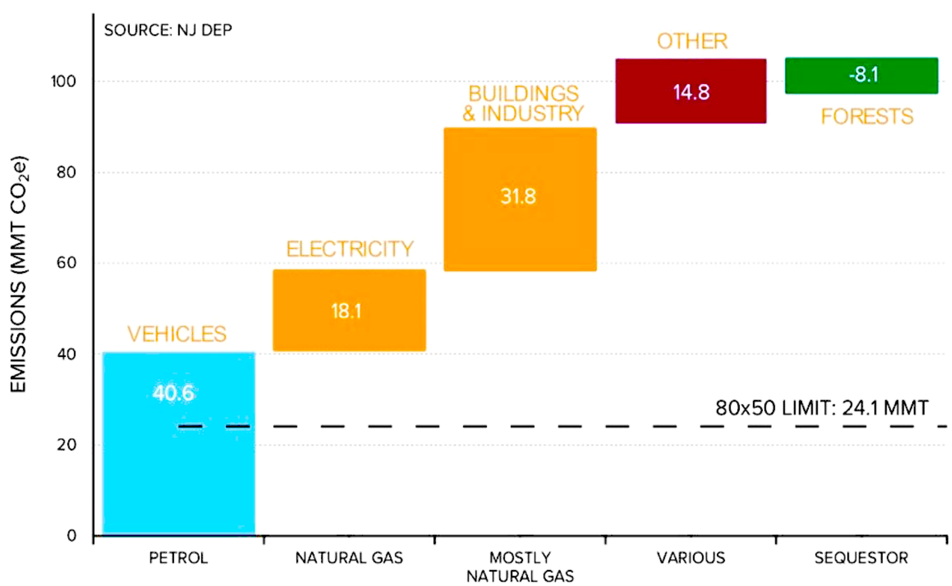


Figure 3.9. New Jersey Greenhouse Gas Emissions Today. New Jersey's energy system relies on the use of fossil fuels by vehicles, electricity, buildings & industry, and other entities (NJBPU 2019). The state currently emits approximately 97 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) each year when accounting for the 8.1 $MMTCO_2e$ sequestered by forests. The Global Warming Response Act (GWRA) target is 24.1 $MMTCO_2e$ by 2050. This figure is from New Jersey's Energy Master Plan (NJBPU 2019).

have decreased slightly in recent years, so emission levels continue to remain below the 2020 Global Warming Response Act limit (which is equivalent to the 1990 level). However, to achieve the 2050 Global Warming Response Act limit (of 80% below the 2006 value), New Jersey would need to reduce estimated greenhouse gas emissions by a substantial amount between 2018 and 2050. Figures 3.8 and 3.9 draw the trajectory toward the mandated greenhouse gas emissions reduction goal.

3.4 Air Quality and Greenhouse Gas Emissions in New Jersey

There are interactions between air quality and greenhouse gas concentrations driven by climate change. Recent research has identified and described the phenomenon of an ozone-climate penalty. The expected increase in global mean temperatures associated with climate change leads to higher tropospheric (the lowest layer of Earth's atmosphere which resides at the surface of Earth) ozone concentrations in already polluted regions, potentially eroding the benefits of expensive emission controls. Ozone-climate penalty is "the deterioration of air quality due to a warming climate, in the absence of anthropogenic (human-caused) polluting activities" (Fu and Tian 2019). This phenomenon is particularly relevant to New Jersey since ground-level ozone is the only National Ambient Air Quality Standard the State continues to be in non-attainment of, and a warming climate will increase ozone production. The National Ambient Air Quality Standards are set by the United States Environmental Protection Agency for six common air pollutants. Non-attainment means that air pollution levels are above the national ozone health-based National Ambient Air Quality Standard established by the Federal Clean Air Act and United State Environmental Protection Agency (NJDEP 2020b).

As discussed in more detail in Chapter 5.1-1.1, tropospheric ozone, or ground-level ozone, is created by chemical reactions of the pollutant gases (known as the precursor pollutants) nitrogen oxide (NOx) and volatile organic chemicals (VOCs) interacting with heat and sunlight. NOx and VOCs have been found to have a varying degree of negative impact on human health (NJDEP 2020c) and are therefore a concern to air quality. Volatile organic chemicals are emitted from natural and anthropogenic sources, while NOx is primarily the product of fossil fuel combustion. The initial 2008 Statewide Greenhouse Gas Emission Inventory research examined fossil-fueled electrical generating unit (EGU) (power plants) operations before and during Eastern Seaboard heat wave events, which also tend to produce violations of the 8-hour ozone standard. The 8-hour ozone standard is the United States Environmental Protection Agency (EPA) ozone standard of 75 ppb averaged over an 8-hour period. The investigation revealed substantial daily, as well as hourly, variations in NOx concentration. In general, baseload coal-fired electric generating units, many of which at the time of the research lacked adequate NOx control technology, were put into use as the load on the electric generating system increased due to a heat wave. As load increases, intermittently used residual oil-burning boilers are deployed. As electric supply must always equal demand, intraday hourly peaks are generally met by generation from high NOx-emitting quick starting combustion turbines, which are powered by fossil fuels. The State was among the first to document the connect between the surge in NOx concentrations that would occur on high ozone, high electric demand days in New Jersey and the surrounding region thereby highlighting the connection between air quality and greenhouse gas concentrations (McNevin 2008).

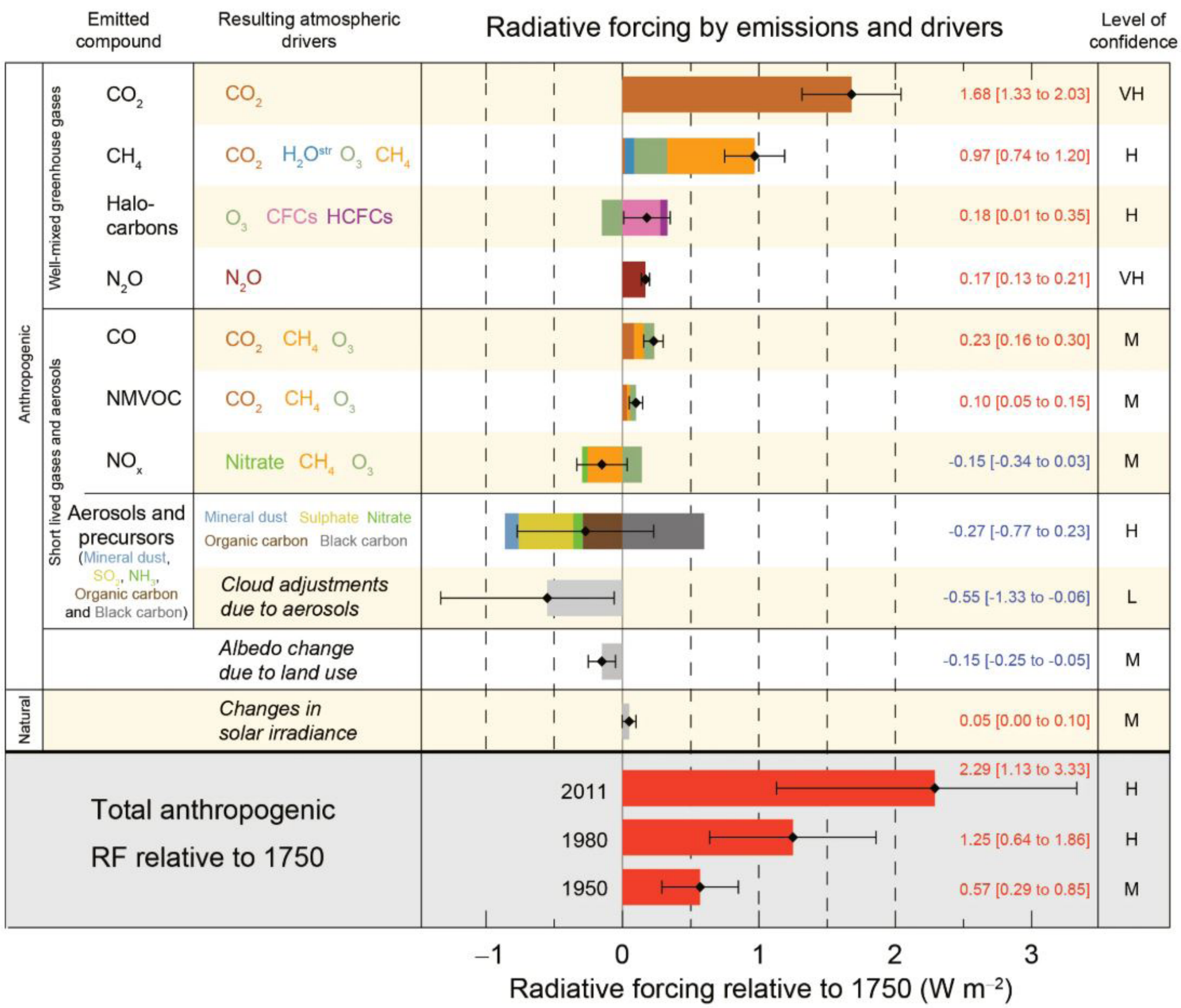


Figure 3.10. Radiative Forcing Estimates. Estimates from 2011 relative to 1750. Values are global average radiative forcing (RF); the black diamonds represent best estimates of the net radiative forcing with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – very high, H – high, M – medium, L – low, VL – very low). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcing due to contrails (0.05 W m-2, including contrail induced cirrus), and hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (total 0.03 W m-2) are not shown. Concentration-based RFs for gases can be obtained by summing the like-colored bars. Volcanic forcing is not included as its episodic nature makes it difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three years relative to 1750. For further technical details see (IPCC 2013).

3.5 New Challenges: Role of Short-Lived Climate Pollutants/Forcers

The existing metrics of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) focus on the effects of six main greenhouse gases – carbon dioxide (CO_2), methane (CH_4); nitrous oxide (N_2O); hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (United Nations 1997). However, a notable potion of total global atmospheric forcing (or changes to the atmospheric energy [heat] balance associated with global climate change) is caused by short-lived climate pollutants/forcers with atmospheric lifetimes of less than 20 years. These were excluded from the Kyoto metrics because their contributions were not well understood at that time. For instance, the Kyoto metrics do not account for black carbon (BC), which is now recognized as the second-most important pollutant contributing to climate warming globally after CO_2. The Intergovernmental Panel on Climate Change (IPCC), Fifth Assessment report makes clear that, in addition to CO_2 and CH_4, BC and HFCs have been the main contributors to global atmospheric forcing and ultimately global warming (Figure 3.10) (IPCC 2013).

Other highly warming gases trap heat in the atmosphere more effectively than CO_2. Climate scientists use the concept of global warming potential to compare the relative global warming effects of different gases. Global warming potential measures the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to CO_2. The greater the value of the global warming potential, the more that a given gas warms Earth per molecule compared to CO_2 over that time span. Carbon dioxide has a global warming potential of 1 because it is the point of reference established by the scientific community and the Intergovernmental Panel on Climate Change. The most recent Intergovernmental Panel on Climate Change assessment report (IPCC 2014) employs multiple methods to determine the global warming potential and account for different future global warming scenarios. Although these gases are only emitted in relatively small amounts compared to CO_2, they have a significant and measurable contribution to climate change due to their high global warming potential per molecule. Highly warming gases accounted for 8.0 $MMTCO_2e$, or 8% of New Jersey's total greenhouse gas emissions in 2018 (NJDEP 2019a) and include the following gases:

Methane (CH_4), which is a gas emitted during the formation, mining, and transport of coal, natural gas, and oil. Emissions also result from agricultural practices and decay of organic waste in landfills.

Nitrous oxide (N_2O), which is a gas emitted during agricultural and industrial activities, combustion of fossil fuels and solid waste. Lesser emissions result from use in medical products (e.g., as an aerosol propellant).

Halogenated gases, which are gases that have the highly reactive elements chlorine, fluorine, or bromine in their molecular structure and include hydrofluorocarbons (HFCs), per- and polyfluoroalkyl substances (PFAS), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF3). Fluorinated gases also include chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), both of which are scheduled for phase out of use under the 1987 Montreal Protocol (USEPA, accessed 2019). Sources of fluorinated gases (F-gases) include industrial and commercial operations including leaks from electronics and metals cleaning and refrigeration systems; heat pumps and air conditioning equipment; semiconductor, magnesium, and aluminum manufacturing; and insulation in electrical transmission and distribution equipment. In New Jersey, most of the emissions of halogenated gases are associated with their uses in, and releases from, air conditioning and refrigeration systems. Sulfur hexafluoride is also a halogenated gas but has been treated separately in New Jersey greenhouse gas emission inventories due to its specialized uses as an insulating fluid in high voltage electrical equipment. The global warming potential for these gases can be in the thousands or tens of thousands. The fastest rising sector of greenhouse gas emissions globally are from halogenated gases, which have high global warming potentials, and are now being used in place of the ozone depleting substances (ODS), that are banned from use (Gallagher et al. 2014).

Black carbon is the main light absorbing component of black soot. While globally, the largest sources of black carbon are cook stoves and wood burning, in New Jersey the primary source is incomplete combustion from older diesel engines and forest fires. It warms the atmosphere by absorbing solar radiation and influencing cloud formation. Furthermore, black carbon deposition increases surface melt of snow and ice, leading to reduced snowpack. Black carbon typically remains in the atmosphere for days to weeks, as opposed to CO_2, that stays in the atmosphere for decades. While in the atmosphere, black carbon has a global warming potential of over 3,000. Once it returns to Earth's surface through rain or air deposition, its climate impacts are mostly relevant to the cryosphere, or regions of frozen water.

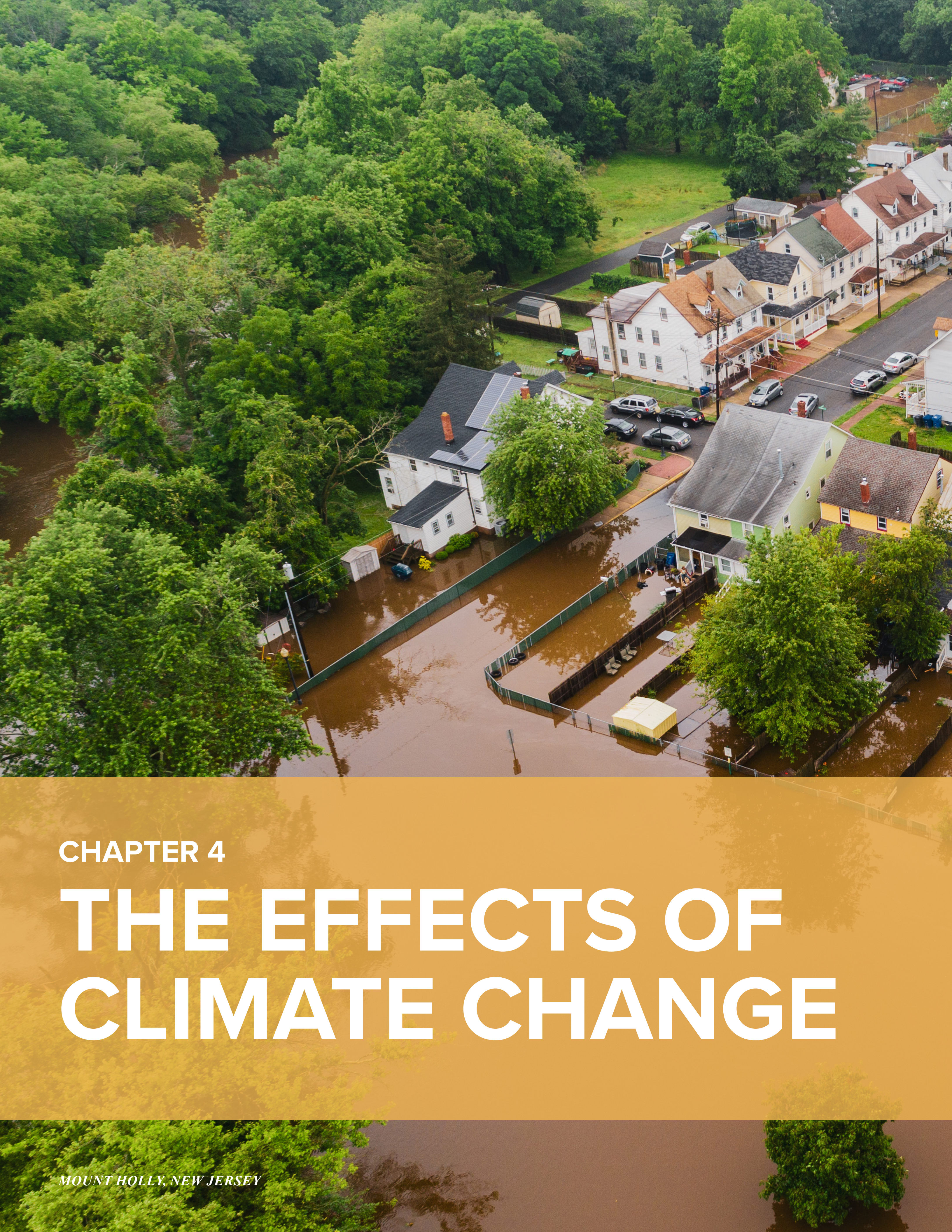
In order to help avoid the most dangerous consequences of climate change, there is an emerging view within the scientific community that efforts to address climate change should focus not only on substantially reducing CO_2 emissions, but also on reducing short-lived climate pollutants that remain in the atmosphere for much shorter periods of time. It is contended that global action on CO_2 and other long-lived greenhouse gases together with short-lived climate pollutant/forcers offers the only path to achieve the internationally agreed goals set forth in the Paris Agreement. The Paris Agreement was adopted by the parties to the UNFCCC with the goal of limiting warming to well below 3.6˚F (2˚C) above pre-industrial levels and to pursue efforts to limit the temperature increase to 2.7˚F (1.5˚C) (Xu et al. 2013).

Recent changes to New Jersey's Global Warming Response Act direct the State to consider short-lived climate pollutants, including black carbon, in the State's greenhouse gas inventories and recommendation reports. While understood to be globally significant, control measures in the United States and New Jersey make black carbon a less significant contributor to climate change in the Northeastern United States.

3.6 Impact of Changes in Greenhouse Gas Concentrations

As discussed throughout this chapter, greenhouse gas concentrations and their future trajectories will have a direct effect on how quickly Earth warms. This warming will lead to changes in our climate and result in extreme heat (as discussed in Chapter 4.1), precipitation changes (as discussed in Chapter 4.2), floods and drought (as discussed in Chapter 4.2.6 and 4.2-5), sea-level rise and melting in the cryosphere (the frozen water part of Earth system; as discussed in Chapter 4.3), and ocean acidification (as discussed in Chapter 4.4). These, in turn, lead to multiple impacts in air quality (Chapter 5.1), water resources like drinking water and water quality (Chapter 5.2), agriculture and aquaculture (Chapter 5.3), and ecological systems including forests (Chapter 5.4), wetlands (Chapter 5.5), and other ecosystems (Chapter 5.7-5.9).

Subsequent chapters of this report detail and elaborate on the impacts briefly discussed here in the context of New Jersey.



CHAPTER 4

THE EFFECTS OF CLIMATE CHANGE

MOUNT HOLLY, NEW JERSEY

The following chapter provides details about the direct effects of climate change, such as temperature, precipitation, sea-level rise, and ocean acidification being experienced globally, regionally, and in New Jersey. The chapter discusses each effect individually, describes what New Jersey is currently experiencing, provides insight into what can be expected into the future, and what current and future impacts will be for the State.

Chapter 4 is divided into the following sections:

- New Jersey is warming faster than the rest of the Northeast region and the world.
- Since 1895, New Jersey's annual temperature has increased by 3.5˚F.
- Historically unprecedented warming is projected for the 21st century with average annual temperatures in New Jersey increasing by 4.1˚F to 5.7˚F by 2050.
- Heatwaves are expected to impact larger areas, with more frequency and longer duration by 2050.
- Climate change could result in a 55% increase in summer heat-related mortalities.

CHAPTER 4.1

TEMPERATURE

NEW JERSEY TURNPIKE

4.1 Temperature

There is strong evidence that increasing concentration of atmospheric carbon dioxide (CO_2) and other greenhouse gases from the emissions of human activities, as well as natural climate variability have warmed Earth's surface by over 1.5˚F (0.8˚C) between 1901 and 2016 (USGCRP 2017). This temperature increase has contributed to an increase in precipitation, intensity of some weather events like heat waves and warm-weather storms, ecological changes, and a rise in global sea level. Continued greenhouse gas emissions at or above current rates are expected to cause further warming and alter the global climate system, likely inducing greater changes than those observed during the 20th century.

The urbanization of large portions of New Jersey results in large expanses of asphalt and concrete, and the loss of forests, fields, and other open spaces. These conditions make heat waves especially pronounced and lead to increased impacts in densely populated urban areas. This effect is called the heat island effect (Carnahan and Larson 1990). Urban heat islands result from a combination of dense construction, lack of green space, and the heat generated from traffic congestion. Additionally, many cities act as an artificial valley, trapping heat (and pollution) between high-rises, resulting in higher temperatures on the sidewalk than on a roof, in a city park, or outside the city. Urban heat islands are a growing concern as summer temperature increase.

Heat stress is of special concern for vulnerable urban populations. Climate models predict an increase in the number of days per year with temperatures that will affect human health due to heat stress. In this decade, under a high emissions scenario, climate change could result in a 55% increase in summer heat-related mortality as compared to the 1990s and more than a doubling in mortality by the 2050s (Kinney et al. 2004).

4.1-1 Global Temperatures

Earth's second warmest year on record since 1880 occurred in 2019; only 2016 was warmer (NOAA National Centers for Environmental Information 2020). Every year since 2000 has been warmer than the 1981-2010 global average. Specific parts of the world reported the following in 2018: fifth warmest year for the Bahamas, fourth warmest year for South Africa, third warmest year for Mexico and Australia, second warmest year for Alaska, Turkey, and Europe, warmest year for Jamaica, and South Korea recorded its highest temperature in August 2018 (Blunden et al. 2019).

Observed global temperature data indicate a warming climate. In order to predict future temperatures associated with climate change, past climate change patterns must first be understood. Scientists have been able to reconstruct temperature and CO_2 records going back 800,000 years by analyzing entrapped air inclusions in ice cores from Antarctica (Lüthi et al. 2008). Examining temperature and CO_2 together, it is evident that atmospheric CO_2 concentrations and temperature are strongly correlated.

As described in Chapter 3 Greenhouse Gases, in 2016 the concentration of CO_2 in the atmosphere exceeded 400 ppm for the first time (Tans and Keeling 2020). This substantial increase in CO_2 over the last 150 years is expected to come with a considerable increase in global temperature.

In addition to warming air temperatures, global sea surface temperatures are also rising. Regional sea surface temperatures are influenced by natural variability, human-induced emissions of heat-trapping gases, and particulate pollution (Ting et al. 2019). From 1901 through 2015, the average global sea surface temperature rose an average of 0.13˚F (0.07˚C) per decade, or 1.5˚F (0.8˚C) since the beginning of the last century (Figure 4.1) (US EPA 2016). In Figure 4.1, the global temperature anomaly evident in the early 1940s is due to extremely cold winters in Europe, while temperatures were exceptionally high in other parts of the world such as Alaska, Canada, and Central

THE EFFECTS OF CLIMATE CHANGE
TEMPERATURE

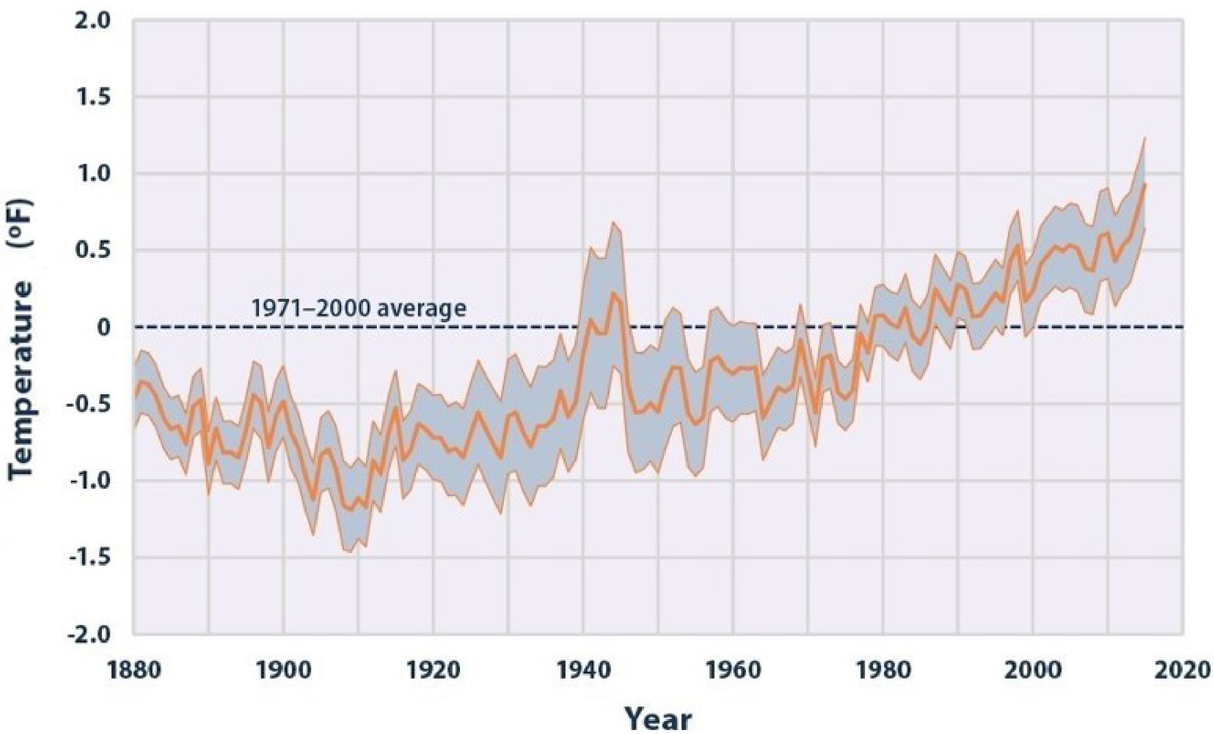


Figure 4.1. Average Global Sea Surface Temperature Anomaly, 1880-2015. The center orange line represents the difference between the annual average and the 1971-2000 average. The shaded region reflects the uncertainty in the data due to the number of measurements collected and the precision of the methods used (US EPA 2016).

Asia (Brönnimann 2005). After reconstructing and modeling the global troposphere-stratosphere system, this global temperature anomaly has been attributed to a strong and prolonged El Niño event. As global air temperatures continue to rise, global sea surface temperatures are also expected to continue rising.

4.1-2 Regional Temperatures

The United States National Climate Assessment presents observed and projected climate changes for the Northeast region of the United States, reporting that temperatures in the region increased by 1˚F (0.6˚C) in West Virginia to 3˚F (1.7˚C) in New England since 1901 (Dupigny-Giroux et al. 2018). By 2035, it is expected that the average temperature in the Northeast will be 3.6˚F (2˚C) warmer than pre-industrial times, regardless of future emissions. This will represent the largest regional increase in the contiguous United States. By about 2050 much of the southern portion of the region (including New Jersey, Delaware, Maryland and southwestern West Virginia) is expected to experience over 60 additional days per year with temperatures above 90˚F (32˚C) compared to the end of the last century (1970 to 2000) (Melillo et al. 2014). Similarly, the number of days below freezing and the amount of frozen precipitation will be reduced due to the rates of winter warming which exceeds those of other seasons (Broccoli et al. 2020). It should be noted that some of the expected additional days above such thresholds include days that currently average just below those levels.

4.1-3 New Jersey Temperatures

The Office of the State Climatologist at Rutgers University reports statewide temperature and precipitation records back to 1895. These data show a statistically significant increase in New Jersey's average annual temperature of 3.5˚F (1.9˚C) over the past century (Figure 4.2) (Office of the New Jersey State Climatologist 2020).

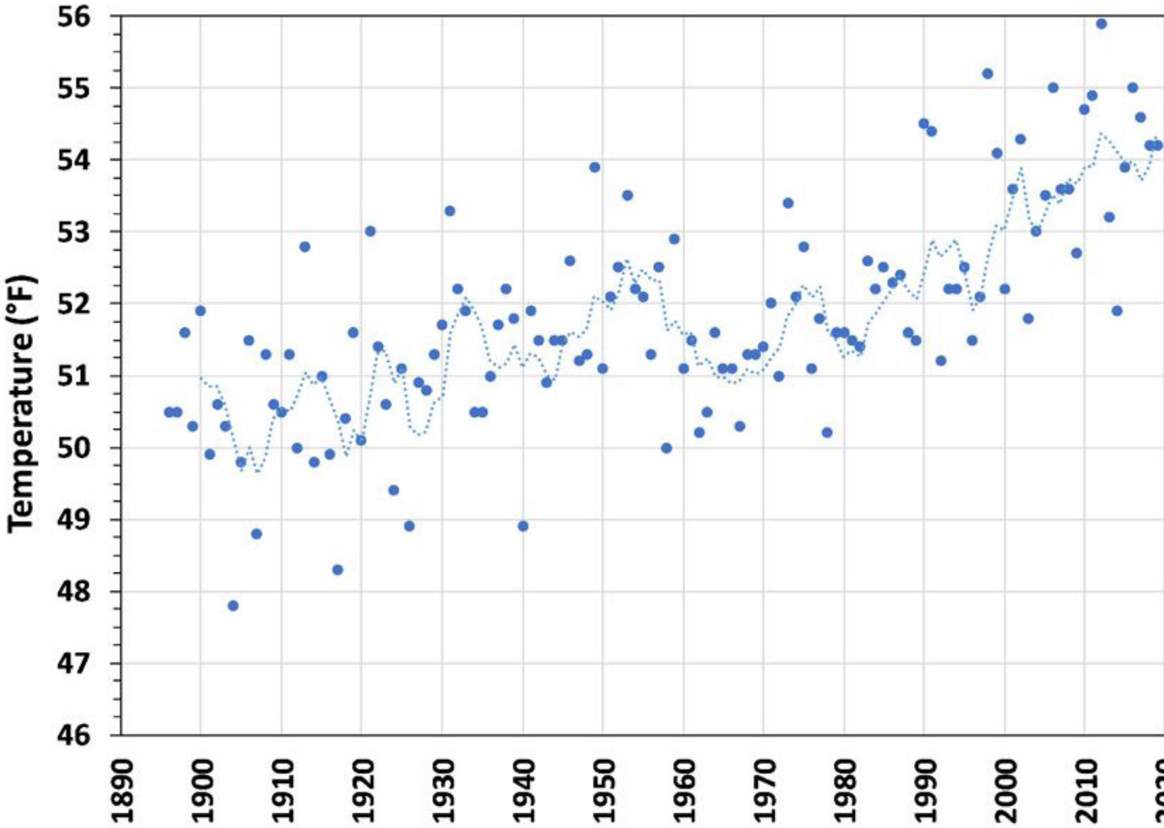


Figure 4.2. New Jersey 12-Month Average Air Temperature from 1895 to 2019. Points represent the average annual temperature and the dashed line represents a five-year average of those points. Data from the (Office of the New Jersey State Climatologist 2020).

New Jersey is warming faster than the rest of the Northeast region (2˚F [1.1˚C]) (Melillo et al. 2014) and the world (1.5˚F [0.8˚C]) (IPCC 2014) during the same time period. The rate of warming in New Jersey has increased since 1970. Utilizing data from the New Jersey State Climatologist through the end of 2019, several trends were observed: the ten warmest calendar years on record have occurred since 1990 while the ten coldest years all occurred before 1940; the warmest year on record occurred in 2012 when the average annual temperature was 4.1˚F (2.3˚C) above the long-term average (1895 – 2019) and 3.0˚F (1.7˚C) above the 30-year normal; the four warmest winters on record have occurred since 1998, and the eight warmest summers have occurred since 1999.

For the seasonal analyses, winter months included December, January, and February, while summer months included June, July, and August. Recently, many more unusually warm months have occurred in the State than unusually cold months. Over the period 1990-2019, months with a top-5 warmest average temperature have occurred 43 times while none of the months in that same period recorded a top-5 coldest average temperature. The last top-5 coldest temperature was December 1989 (Office of the New Jersey State Climatologist 2020).

"...the ten warmest calendar years on record have occured since 1990..."

THE EFFECTS OF CLIMATE CHANGE
TEMPERATURE

Table 4.1. Annual and Seasonal Increases in Air Temperatures Over the Period 1895 to 2019 (Office of the New Jersey State Climatologist 2020). The change in temperature was determined from the linear slope of the entire period of record.

	°C	°F				
	Annual	Annual	Winter	Spring	Summer	Fall
Statewide	1.9	3.5	4.8	3.0	3.1	3.0
Division 1 North	2.0	3.6	5.1	3.1	3.0	3.1
Division 2 South	1.9	3.4	4.6	2.9	3.1	2.8
Division 3 Coast	2.2	4.0	5.0	3.6	3.6	3.5

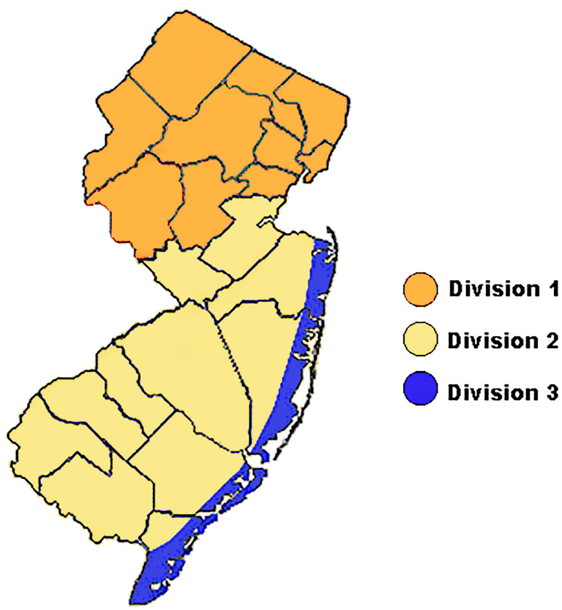


Figure 4.3. Regional Climate Divisions of New Jersey for Temperature Analysis (Office of the New Jersey State Climatologist 2020).

Monthly average temperature data from the New Jersey State Climatologist (Office of the New Jersey State Climatologist 2020) were analyzed for long-term trends and seasonal variation within each of three divisions of New Jersey (Figure 4.3). To determine the change in temperature over time, the linear slope was calculated over the 123-year period (1895 to 2018) for each division (Table 4.1).

Statewide, average annual temperature in New Jersey has increased by 3.5˚F (1.9˚C) over this period. Temperature increases vary geographically within the state. In the coastal region (Division 3), the average annual temperature has increased by 4.0˚F (2.2˚C) since 1895, with the northern region (Division 1) increasing by 3.6˚F (2˚C), and the southern region of the state (Division 2) increasing by 3.4˚F (1.9˚C). Seasonally, winter shows the greatest temperature increase (December, January, and February). In the northern region, the average winter temperature increased by 5.1˚F (2.8˚C) since 1895, followed by the coastal region at 5.0˚F (2.8˚C), and the southern region at 4.6˚F (2.6˚C).

4.1-4 Temperature Projections

A continued warming trend in New Jersey is very likely. Global climate models that factor in future greenhouse gas emissions are used to project the magnitude of future temperature increases. Projections published by Runkle *et al.* (2017) are based on two scenarios, one in which greenhouse gas emissions continue to increase at the current rate (higher emissions) and another in which greenhouse gas emissions increase at a slower rate (lower emissions) (Figure 4.4). Under both scenarios, historically unprecedented warming is projected in the 21st century. Even under a low emissions scenario, the lower end of the projection range suggests that annual temperatures will routinely be as warm as the warmest years in the historical record. Under a high emissions scenario, future annual temperatures could be as much as 10°F (5.6˚C) warmer than the historical record. The projections by Runkle et al. (2017) compare future temperatures to the 1901 to 1960 annual average and suggest that by 2050 average annual temperatures in New Jersey will be approximately 1˚F (0.6˚C) to 6°F (3.3˚C) warmer (Figure 4.4) (Runkle et al. 2017). By 2100 temperatures are projected to be 3˚F (1.7˚C) to 9˚F (5.0˚C) warmer under a lower emissions scenario (RCP 4.5) and 6˚F (3.3˚C) to 13˚F (7.2˚C) warmer under a higher emissions scenario (RCP 8.5) (Figure 4.4). Similar projections are also offered by the New York City Panel on Climate Change who suggests that localized annual average temperatures will increase from 4.1˚F to 5.7˚F (2.3˚C to 3.2˚C) by 2050 (Horton et al. 2015). The recent 10-year average annual temperature is currently about 3˚F (1.7˚C) above the 1901-1960 period average (data from the Office of the State Climatologist).

By the middle of the 21st century, around 70% of summers in the Northeast are anticipated to be hotter than the warmest summer to date. Such an increase in average annual temperatures will lead to more intense heat waves and less intense cold waves (Runkle et al. 2017) and an extended growing season (Frumhoff et al. 2007). As a result, the number of sub-freezing days and snow accumulation will be reduced. Heatwaves are also expected to substantially increase in spatial extent by the middle of the 21st century with an increased frequency and duration of heat waves in New Jersey (Lyon et al. 2019). Driven by periods of increased temperature, heatwaves result in many adverse impacts such as lower yields of agricultural products, increases in energy consumption, reduced power plant efficiency, air pollution, negative effects on human health, and increased water loss through evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) (Mazdiyasni and AghaKouchak 2015). Such long-term temperature changes will have far reaching impacts, as described throughout this report.

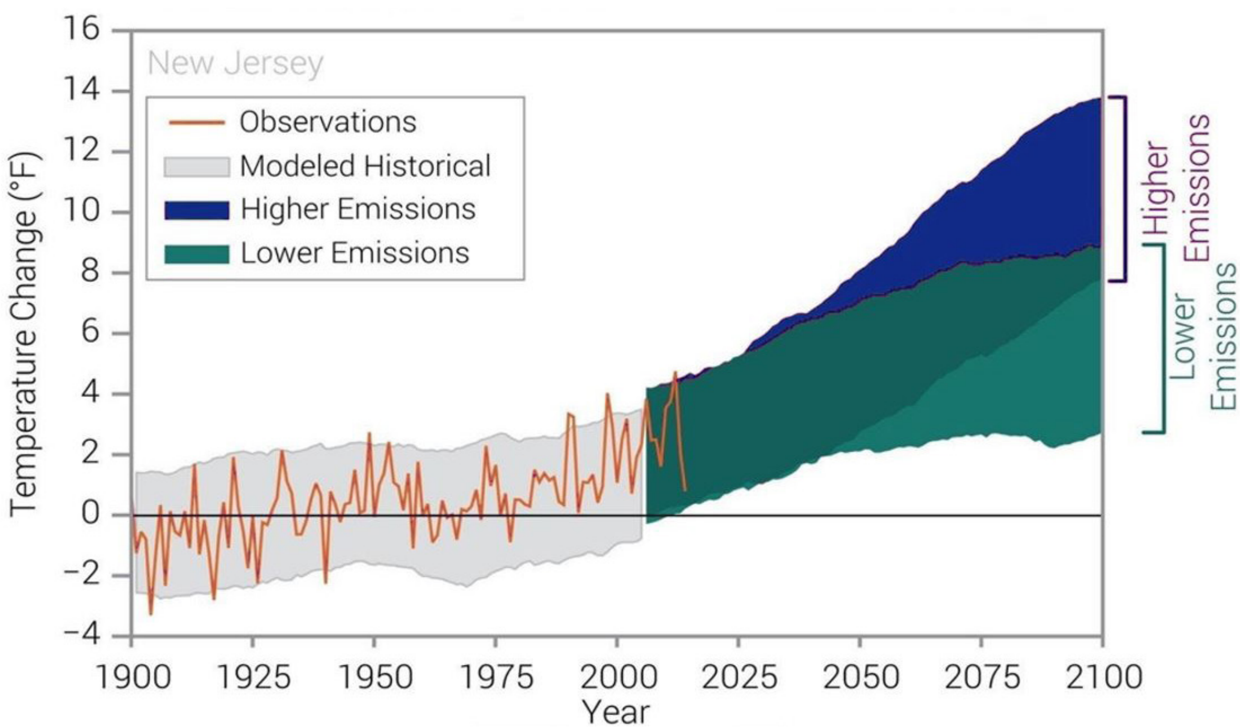
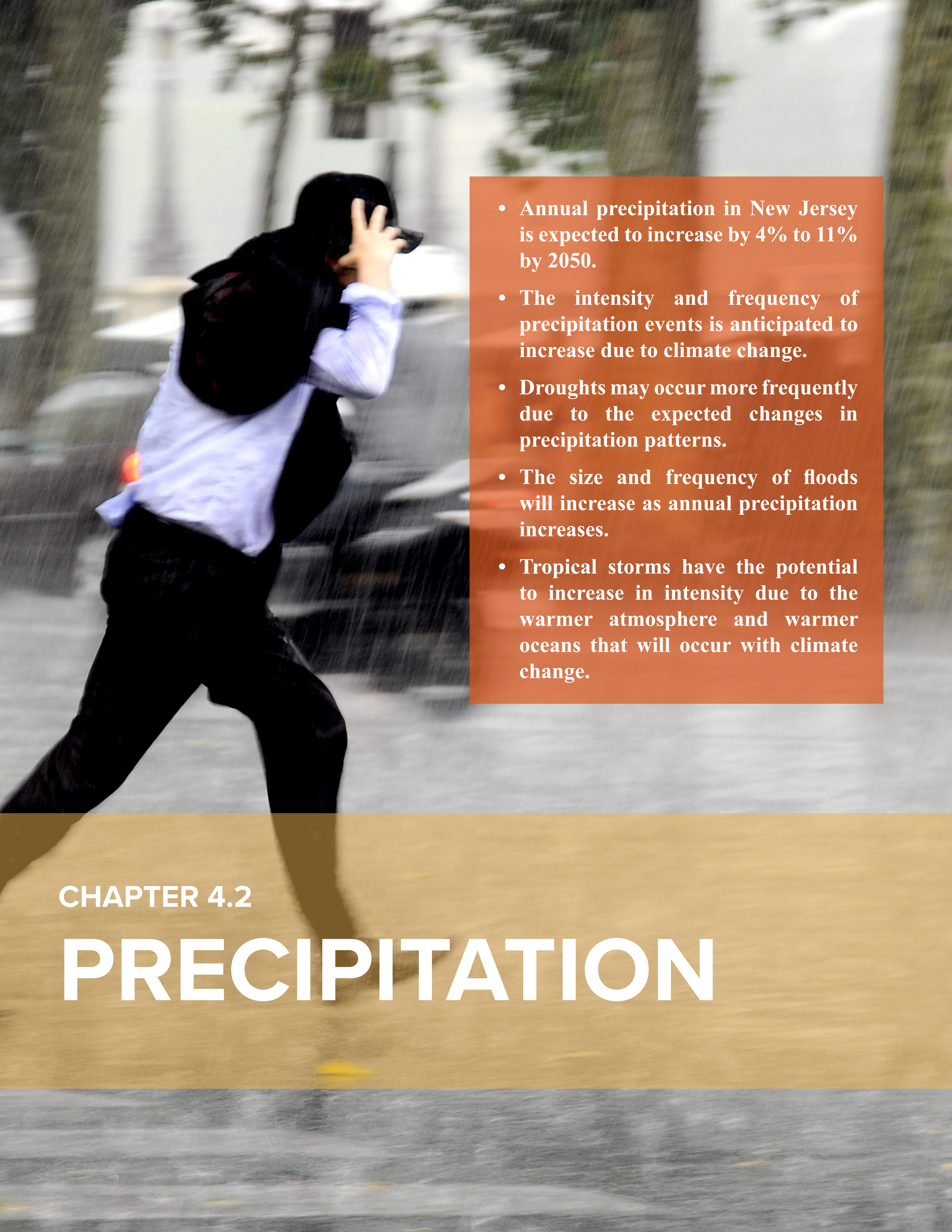


Figure 4.4. Observed and Projected Changes (Compared to the 1901-1960 Average) in Near-Surface Air Temperature for New Jersey. Observed data are for 1900-2014. Projected changes are for 2006-2100 (Runkle et al. 2017).



- Annual precipitation in New Jersey is expected to increase by 4% to 11% by 2050.
- The intensity and frequency of precipitation events is anticipated to increase due to climate change.
- Droughts may occur more frequently due to the expected changes in precipitation patterns.
- The size and frequency of floods will increase as annual precipitation increases.
- Tropical storms have the potential to increase in intensity due to the warmer atmosphere and warmer oceans that will occur with climate change.

CHAPTER 4.2

PRECIPITATION

4.2 Precipitation

The amount of water vapor in the atmosphere is influenced by the regional weather system, atmospheric temperature, and regional geography. The amount of precipitation that may fall is dependent on the amount of water vapor available in the atmosphere and other necessary weather conditions. Locally, precipitation is dictated by continental influences including inland mountains and coastal influences including offshore conditions (Marquardt Collow et al. 2016). Cooler temperatures and greater amounts of precipitation occur at higher elevations around the more mountainous areas of the region. In New Jersey, the amount and frequency of precipitation varies over short and long periods of time. While average annual precipitation totals show a slight increase, climate change is expected to exacerbate the intensity of rainfall events and extend the duration of drier periods. Such changes could have immediate impacts to public safety due to increased flooding, water supply availability, water quality, stormwater infrastructure, and ecological impacts.

4.2-1 Global and Regional Atmospheric Conditions

Radiation from the Sun evaporates water from Earth's ocean, freshwater, and land surfaces (Trenberth 2011). Water vapor circulates throughout the troposphere (the layer of the atmosphere closest to the land surface) by winds. As the water vapor moves higher into the troposphere it combines with particles, forming the droplets of clouds. The water then returns to Earth's surface as rain or snow. Precipitation falling on land that does not infiltrate to groundwater will remain as runoff on the surface, ultimately flowing back to the oceans via streams and rivers. Water is also returned to the atmosphere from plants through transpiration and from open water and soils by evaporation (evapotranspiration). Evapotranspiration rates are greatest during the growing season.

4.2-2 Changes in Global and Regional Atmospheric Conditions

As carbon dioxide (CO_2) levels increase, the temperature of Earth's atmosphere also increases (Guilbert et al. 2015). As air temperatures increase so will the saturation of water vapor in the atmosphere. For every 1.8˚F (1.0˚C) increase in air temperature, the atmosphere can hold up to approximately 7% more moisture (Trenberth 2011). More moisture in the atmosphere provides the means for storms to be more intense (Guilbert et al. 2015) and increases the chances of extreme rainfall events (Coumou and Rahmstorf 2012, Marquardt Collow et al. 2016).

A warmer atmosphere will also contribute to the warming of the oceans. Although the main source of ocean heat is solar radiation; clouds, water vapor, and greenhouse gases all additionally emit the heat they have absorbed and some of this heat is absorbed into the ocean (Dahlman and Lindsey 2020). Since tropical cyclones are fueled by the energy found in ocean waters, a warmer atmosphere and warmer oceans will provide the potential for tropical storms to increase in intensity (Coumou and Rahmstorf 2012). Tropical cyclones are typically responsible for heavy precipitation events in the summer and fall in the Northeast United States (Marquardt Collow et al. 2016). These factors are likely to affect the Northeastern United States and cause conditions that have the potential to be more intense than those seen during Hurricane Sandy in 2012 (Lau et al. 2016).

While changes in global circulation patterns will likely have significant impacts on local precipitation patterns, it remains difficult to estimate localized precipitation changes due to the spatial and temporal (time) variability of global atmospheric drivers (Guilbert et al. 2015). If the concentration of greenhouse gases from emissions continues to rise as expected, the eastern United States can expect to see an increase in the number of days where the atmospheric conditions would be supportive of severe thunderstorms and other hazards such as lightning, heavy rain, hail, and tornadoes (Diffenbaugh et al. 2013).

4.2-3 Frequency and Severity of Precipitation in New Jersey

Precipitation can be monitored in many ways, with two of the most common ways being the average annual precipitation occurring in a defined area and precipitation from extreme events. Extreme precipitation events are those events that result in very heavy rain or snowfall, usually within a short period of time and represent the heaviest 1% of all daily precipitation events (Melillo et al. 2014).

On average, New Jersey receives 46 inches (116.8 cm) of precipitation annually (Office of the New Jersey State Climatologist 2020) from all types of precipitation events including from rain showers to hail storms to extreme rain or snow events. This average varies across the state with a north to south gradient due to geographical differences in the inland and coastal areas (Agel et al. 2015, Runkle et al. 2017). The north to central portion of the state averages 49 inches (124.5 cm) of precipitation annually while the coastal and southern regions average 44 and 45 inches, (111.8 cm and 114.3 cm) respectively (Office of the New Jersey State Climatologist 2020). This variation in precipitation is due to the lifting of moist air by the topography in northern New Jersey, which cools the air, condensing the water vapor, and precipitation is enhanced. This occurs mainly because cooler air at higher elevations does not hold as much condensation as warmer air at lower elevations (Marquardt Collow et al. 2016). Meanwhile, coastal areas experience less precipitation due to the maritime atmosphere being stabilized by the adjacent waters of the Atlantic Ocean.

Statewide, instances of extreme annual precipitation of five inches (12.7 cm) or more above the current long-term average occur, but they have been historically infrequent (Broccoli et al. 2020). Between 1895 and 1999 such wet years occurred 20% of the time, but have become more frequent over the last twenty years, occurring 30% of the time (Office of the New Jersey State Climatologist 2020). To date, 2018 was the wettest year on record with a total of approximately 65 inches (165.1 cm) of precipitation, approximately 18 inches above the 1918-2010 normal (Office of the New Jersey State Climatologist 2020). Conversely, dry years, those with precipitation of five or more inches (12.7 cm) below the current long-term average, have decreased in frequency. Such dry years have occurred only twice in the last twenty years (10% frequency) where they accounted for almost 27% of annual totals between 1895 and 1999.

Assessing long-term precipitation trends in New Jersey is fundamental for projecting future precipitation levels. An analysis of statewide precipitation data from 1895 to 2019 shows a weakly significant increase in the total annual precipitation (Office of the New Jersey State Climatologist 2020). Although, when averaged over five- and ten-year periods, the averaged annual precipitation show stronger statistical increases over the same 125-year period (Figure 4.5). Evaluating these short-period averages accounts for common interannual variability associated with precipitation patterns. Annual precipitation totals for the last 10 years show a 7.9% increase over the long-term average. This recent increase is supported by Runkle et al. (2017) who note a similar 8% increase of their most recent 10-year average annual precipitation over the long-term average.

From a regional perspective, no changes in long-term daily precipitation were identified in the Northeast (Guilbert et al. 2015), but seasonal increases were identified (Hayhoe et al. 2007). Seasonal and interannual variability masks long-term changes making it more difficult to separate climate induced changes from natural fluctuations.

In the Northeastern United States, extreme precipitation days can occur in any month but the majority occur in the warm months between April and October (Agel et al. 2015). Events typically include coastal nor'easters, snow storms, spring and summer thunderstorms, tropical storms, and

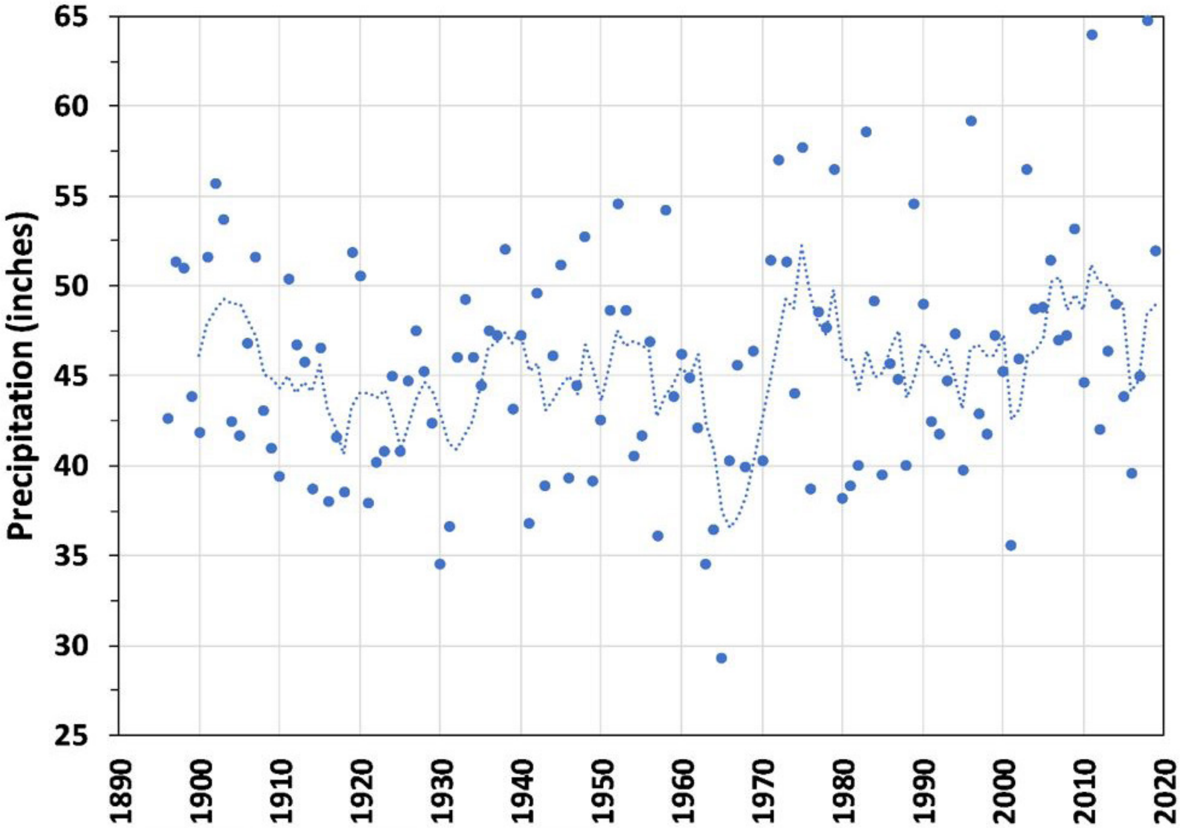


Figure 4.5. Statewide Annual Precipitation in Inches (1895 – 2019). Points represent the statewide annual precipitation and the dashed line represents a five-year average of the data based on year of interest and the previous four years. Data acquired from the (Office of the New Jersey State Climatologist 2020).

on rare occasions hurricanes (Runkle et al. 2017). Damaging nor'easters are most common between September and April and bring strong winds, heavy rain or snow, and often result in coastal flooding (NOAA 2020a). Most years, New Jersey experiences at least one significant coastal storm but has experienced five to ten storm events in some years. Precipitation events often occur in the Northeastern United States as persistent multiday events (two to five days); however, the most intense precipitation usually occurs within several hours within a single day (Agel et al. 2015).

Just as with annual precipitation, there is a large year to year variability in the frequency and intensity of extreme weather events like nor'easters and hurricanes. Variability also exists between inland and coastal areas, as well as among seasons. Coastal stations experience more extremes in the spring than inland stations, while inland stations experience more extremes in the summer than coastal stations. Overall, more extreme events were recorded in coastal areas than inland from 1901-2014 (Huang et al. 2017). In more recent times (1979-2008), on an annual basis, the Northeastern United States coastal areas are experiencing a greater intensity of extreme precipitation events than inland areas, but inland areas experience more extreme precipitation days (Table 4.2) (Agel et al. 2015).

The frequency of multi-day precipitation events has been increasing over time. Nationally, there has been a significant increase in the occurrence of two-day precipitation events from the period of 1901-1960, to the period of 1961-2017 (USGCRP

Table 4.2. Annual Extreme Precipitation Days Per Year and Storm Intensity in Inland and Coastal Areas of the Northeast U.S. (Agel et al. 2015). Data is from 1979-2008 for the Northeast U.S. region.

Northeast Region	Extreme Precipitation (days/year)	Intensity (in./day; mm/day)
Inland	*1.63*	*2.04 (51.8)*
Coastal	*1.33*	*3.11 (79.1)*

2017). The same study points to a 40% increase in the likelihood of three-day precipitation events since 1900.

Several studies have found increases in the frequency and amount of heavy precipitation in the Northeastern United States over the last century (Colle et al. 2015, Marquardt Collow et al. 2016). Extreme precipitation events have increased in the Northeastern United States by 71% over the last 50 years (Walsh et al. 2014), which is at a faster rate over the past three decades than anywhere else in the United States (Huang et al. 2017). While there is large variability when considering precipitation trends, analysis of data shows an increase in intensity and frequency of heavy precipitation events (Agel et al. 2015) and that even when using different data sources and periods of analysis, the historical record of daily precipitation in the United States supports the claim that there is a statistically significant upward trend in heavy precipitation that is occurring in the Northeastern United States (Agel et al. 2015, Hoerling et al. 2016). This type of heavy precipitation event is occurring more frequently, is projected to occur two to five times more often by the end of the century, as compared to the later part of the last century (Walsh et al. 2014), and is projected to increase in intensity (Huang et al. 2017).

4.2-4 Precipitation Projections

There are difficulties in predicting whether annual precipitation or the number of extreme precipitation events will increase because of the various meteorological interactions that drive precipitation patterns (Marquardt Collow et al. 2016). It is generally accepted that warmer sea-surface temperatures will increase the potential energy in a storm system, ultimately increasing the potential for more intense tropical storms (Huang et al. 2017).

From the time that the Intergovernmental Panel on Climate Change's (IPCC) First Assessment Report was published, there has been compelling evidence that more heavy precipitation events would occur as global water cycling intensified as a symptom of global warming (Hoerling et al. 2016). While uncertainties and variations still exist and climate models have improved, the Intergovernmental Panel on Climate Change Fifth Assessment Report (2014) reinforces early models' assertion that as greenhouse gas forcing increases, radiative forcing (or changes to the atmospheric energy [heat] balance associated with global climate change) will cause more heavy precipitation events to occur.

Climate projections predict that the total annual precipitation in the Northeast region of the United States will remain relatively consistent with the current conditions (Hayhoe et al. 2007). Data produced by AdaptWest to develop resources for climate adaptation planning show that annual precipitation in New Jersey may increase by 2.3 inches to 3.5 inches (5.8 cm to 8.9 cm) above the 1980-2010 average (46.7 inches [118.6 cm]) by the 2080s based on mid (RCP 4.5) and high (RCP 8.5) emission scenarios, respectively (Horton et al. 2015). Such increases reflect a 4.9% and 7.5% increase in annual precipitation by the end of the century. A recent study by the New York City Panel on Climate Change estimates that annual precipitation in the area could increase between 4% and 11% by 2050 (Horton et al. 2015).

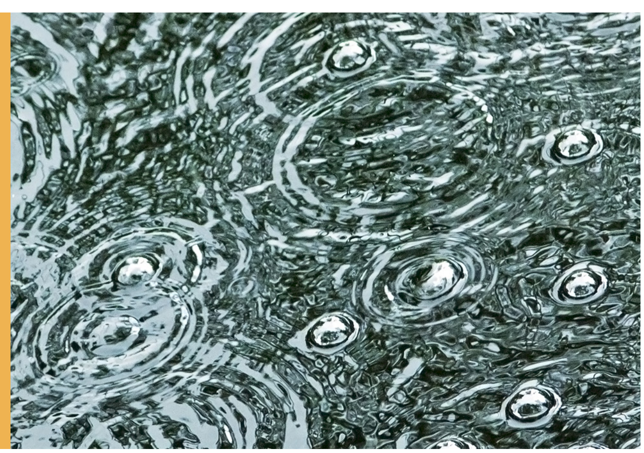
Seasonal variations are anticipated to occur with small decreases in the amount of precipitation occurring in summer months and small increases in winter months (Fan et al. 2014). Under a high emissions pathway, New Jersey may see seasonal increases in precipitation in winter and spring (Demaria et al. 2016, Runkle et al. 2017). Increased winter temperatures will result in more rain, and as a result, fewer snowfalls. Such changes have implications for seasonal runoff. Additionally, variability in the amount and timing of precipitation events is anticipated. For example, heavy precipitation events where more than 2-4 inches (5-10 cm) falls in a single day are projected to increase on a national scale (US EPA 2017). Furthermore, the expected changing climatic conditions are expected to lead to longer and more persistent wet and dry periods throughout the Northeast region (Hayhoe et al. 2007, Guilbert et al. 2015).

As Earth warms and additional water vapor moves to the atmosphere, changes in timing and intensity of heavy precipitation events will become more likely. Studies have observed increases in extreme daily precipitation over the Northern Hemisphere from 1950-2005, which could be a sign of human influences on precipitation trends. However, while models indicate that heavy precipitation events will increase in many areas in the near term (2016-2035) compared to the period from 1986-2005, the underlying cause of this trend is uncertain. The increase could also be caused by natural variability instead of a response to human influences alone (IPCC 2014). Much of the increase in extreme precipitation has occurred over the last several decades, and analysis has linked the change during 1979-2013 to the normal decadal ocean variability and less so to direct human-induced climate change (Hoerling et al. 2016).

Extreme precipitation events are observed to be increasing throughout the contiguous United States, with the largest increase occurring in the northeast region (Marquardt Collow et al. 2016). Wright et al. (2019) also present a significant increase of over 130% has occurred in the frequency of extreme rainfall events that exceed the 10-year 24-hour storm between 1950 and 2017 in the Northeast. Not only are increases anticipated in the intensity of precipitation events and the frequency at which extreme events will occur (Broccoli et al. 2020), precipitation events are also anticipated to show more variation in timing and spatial distribution due to climate change. This is important as the potential for increases in precipitation can lead to increased flooding events and even more droughts with potential to impact public safety and infrastructure (Broccoli et al. 2020).

The normal annual and long-term variability in climate and weather events make it difficult to attribute the occurrence of a particular extreme event, such as a severe hurricane or torrential downpour, to climate change rather than natural climate variability. However, there is data that indicates that the increased occurrence of such events may be attributed to changes in climate (Wuebbles et al. 2014). The number of Category

"While average annual precipitation totals show a slight increase, climate change is expected to exacerbate the intensity of rainfall events and extend the duration of drier periods."



3, 4, and 5 North Atlantic hurricanes has increased since 1951, most likely due to higher sea surface temperatures occurring in the region where Atlantic hurricanes form. Based on the fact that sea surface temperatures are expected to increase as a result of the concentration of greenhouse gases in the atmosphere, future projected scenarios show a potential for hurricanes to become more intense as they move towards the east coast of the United States. Projections to estimate how the number and severity of extratropical cyclones (nor'easters, for example) might change in the future also contain a large amount of due to how models predict storm tracks and how well weather patterns, such as El Nino – Southern Oscillation and other low-frequency variables, are simulated (Colle et al. 2015, Kopp et al. 2019). Given the high level of uncertainty, little scientific consensus has been reached regarding future conditions of such storms.

Besides increases in sea surface temperature, there are additional climate variations that could occur that would increase the potential for more intense hurricanes. One such change relates to vertical wind shear, which is the magnitude and directional difference between winds in the lowest region of Earth's atmosphere, the troposphere. Vertical wind shear along the east coast of the United States provides a natural protective barrier from hurricanes making land fall (Ting et al. 2019). Greenhouse gas forcing has the potential to reduce vertical wind shear and degrade that natural barrier, providing favorable conditions for more intense hurricanes.

4.2-5 Drought

Drought is a prolonged period of abnormally low precipitation with respect to local and regional averages, leading to a shortage of water. Increased evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) and reduced soil moisture amplified by warmer and drier conditions over an extended growing season (Wuebbles et al. 2014) has the potential to cause more frequent and prolonged droughts (Trenberth 2011).

Drought and heatwave conditions are occurring more frequently across the United States and are having significant impacts on ecosystems and society (Mazdiyasni and AghaKouchak 2015). Impacts include:

- reduced water supply capacity
- reductions in gross primary productivity, which leads to shortages in food production and prices
- economic losses from potential impacts to livestock, transportation by river, hydropower production, bioenergy, and energy consumption

Changing climatic norms, if occurring simultaneously, can cause significant impacts (Mazdiyasni and AghaKouchak 2015). For example, a heatwave in conjunction with extended periods of dry weather in the summer season can cause drought and significant societal and environmental impacts despite the insignificance of either event occurring alone.

The consumption of water for potable use, agriculture needs, and non-agricultural irrigation has been increasing in some regions in the state. Changes in precipitation patterns and particularly extended periods of low rainfall is likely to make droughts more frequent, adding stress to local water supplies (NJDEP 2017a).

There are three types of drought that effect the United States: meteorological drought (average precipitation in a region), hydrological drought (how decreased precipitation affects streamflow, soil moisture, and groundwater recharge), and agricultural drought (when water supply cannot meet crop demands). Drought conditions, even short lived, can bring permanent changes to the water supply. If a state has adequate water storage to get through a drought or dry season, there will not be negative changes, but changes in streamflow and discharge can alter a state's ability to have sufficient water storage (Strzepek et al. 2010).

In New Jersey, a water-supply drought is declared when the volume of water needed is greater

"An increase in more frequent and intense rain events will increase the potential for flooding."

than what is available. The most recent water supply drought was initiated in July 2016 for the northeastern, northwestern, and central drinking water supply regions in New Jersey. This was one of the warmest and driest summers on record throughout much of the Northeastern United States. Additionally, historically low winter snowfall preceding the summer of 2016 exacerbated drought conditions and led to record low streamflow in some regions (Sweet et al. 2017a).

It is anticipated that droughts lasting three to six months and longer may slightly increase in frequency in the Northeastern United States under a low emissions scenario and will significantly increase under a high emissions scenario (Frumhoff et al. 2007). Climate models support this claim by suggesting that short-term summer droughts could increase in frequency which would pose challenges to farmers and water resource managers in the Northeast region of the United States (Runkle et al. 2017, Sweet et al. 2017a).

4.2-6 Flooding

Extreme weather events often lead to flooding. Extreme weather events containing heavy precipitation often lead to flooding. Floods occur when waterways exceed their banks and the surrounding flood plain is inundated for a period of time. Floods may occur following heavy rainfalls, localized thunderstorms, or rapid melting of snow (Langbein and Iseri 1995). Major floods are characterized as events that have caused extensive inundation of structures and roads, significant evacuations of people and/or transfer of property to higher elevations. An increase in more frequent and intense rain events will increase the potential for flooding. This risk of flooding also increases during periods of drought when the soil is too dry to absorb large amounts of rain in a short period of time.

Flooding risk due to climate change will be different for the various regions of the United States, but it is expected that the Northeast will be susceptible to increased seasonal flooding. As annual precipitation has increased in the Northeast, so too has the size and frequency of floods (Wuebbles et al. 2014, Guilbert et al. 2015). Regional trends analyses indicate flooding events generally occur during the same seasons without much variation (Collins 2019). However, this study indicates that there are some watersheds within the Northeast where the number of flooding events from June to October increased between 1941-2013. These months historically have a low number of flood events suggesting that flood potential in warmer months is increasing. There is limited understanding of how flooding has and will change seasonally. Any change to the timing of floods will have implications for communities, flood plain infrastructure, and habitats, and may be indicative of climatic changes resulting in floods.

In the New England and Mid-Atlantic regions of the Northeastern United States, climate-induced increases in the magnitude and frequency of floods have been observed (Collins 2019). Several major floods have occurred in New Jersey since 2000, including in 2000, 2004, 2005, 2006, 2007, 2010, 2011, 2012, and 2016 (USGS 2019).

In addition to the flooding risk from increases in precipitation, coastal areas are particularly vulnerable to flooding from storm surge and increased intensity of coastal storms and will most likely be faced with worsening conditions as sea levels rise (Colle et al. 2015). For additional discussion on sea-level rise please refer to Chapter 4.3.

- Sea-levels are increasing at a greater rate in New Jersey than other parts of the world.
- By 2050, there is a 50% chance that sea-level rise will meet or exceed 1.4 feet and a 17% chance it will exceed 2.1 feet. Those levels increase to 3.3 and 5.1 feet by the end of the century (under a moderate emission scenario).
- "Sunny day flooding" will occur more often across the entire coastal area of New Jersey due to sea-level rise.
- It is extremely likely that Atlantic City will experience "sunny day flooding" 95 days a year, and a 50% chance it will experience 355 days a year, by 2100 (under a moderate emission scenario).

CHAPTER 4.3

SEA-LEVEL RISE

4.3 Sea-Level Rise

Sea-level rise is documented throughout the world and serves as an indicator of Earth's increasing temperature. Increased sea levels have the potential to affect many resources throughout the state. Such effects are documented throughout this report including public safety in the face of coastal inundation and increased flooding, reduced water supply and water quality, and ecological impacts, among others. Addressing risks imposed by rising seas is essential to protecting the public and our resources.

The 20th century global sea-level rise rate is estimated at between 0.04 to 0.07 in/yr (1.1 to 1.9 mm/yr) (Horton et al. 2018). However, sea-level rise is not consistent around the globe. The primary factors contributing to global sea-level rise include thermal expansion of the oceans due to increased water temperatures and melting terrestrial glaciers and polar ice sheets. Additional factors influencing regional and local sea-level rise include changes in ocean circulation, vertical land movement (subsidence due to natural sediment compaction and groundwater withdrawals), isostatic rebound (adjustment of land surface to the loss of ice sheets at the end of the last interglacial period), as well as local coastal morphology (Miller et al. 2009, Horton et al. 2018, Kopp et al. 2019). A combination of these factors will dictate local or regional rates of sea-level rise.

Temperature and sea-levels are increasing at a greater rate in New Jersey than other parts of the world. In New Jersey, the average annual temperature has increased by about 3.5˚F (1.9˚C) since the late 19th century and is predicted to increase by 1.0 to 6.0˚F (0.6 to 3.3˚C) by 2050 (Runkle et al. 2017). The rate of sea-level rise in the Northeastern United States has been higher than the global rate over the last several decades and is expected to continue to be amplified. In New Jersey, sea levels at Atlantic City, Cape May, and Sandy Hook have risen at a rate of approximately 0.16 in/yr (4 mm/yr) since the beginning of the 20th century (Kopp 2013, NOAA 2019). Pre-anthropogenic (human-caused) sea-level rise in New Jersey was approximately 0.08 in/yr (2 mm/yr) (Stanley et al. 2004, Miller et al. 2009). This suggests that anthropogenic factors have contributed to a doubling of the historic rate of rise. There is uncertainty surrounding exactly why the rates in the Northeastern United States and New Jersey are greater, but it may be in part due to changes in the Gulf Stream (Sweet et al. 2017b), localized subsidence and continued geologic influences as solid Earth slowly adjusts to the loss of the North American ice sheet at the end of the last ice age (Kopp et al. 2019).

4.3-1 Basis and Selection of Sea-Level Rise Projections

Local estimates of sea-level rise are available from the New Jersey Climate Change Alliance Science and Technical Advisory Panel (STAP) report prepared by Rutgers University (Kopp et al. 2019), the National Oceanic and Atmospheric Administration (NOAA) (Sweet et al. 2017b), and the US Army Corps of Engineers (USACE 2013). Projections outlined in the 4th National Climate Assessment (USGCRP 2017) and the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) were reviewed but not considered because they do not offer localized projections. Importantly, each report uses a slightly different approach and thus offers different sea-level rise projections. After careful deliberation, DEP determined to use the projections provided by the STAP because of its New Jersey-specific focus.

The 2019 STAP report provides probabilistic-based sea-level rise projections specific to New Jersey with decadal estimates under high, moderate, and low emissions scenarios to the year 2150 (Kopp et al. 2019). The projections include consideration of the most current science and understanding of Arctic and Antarctic ice-sheet conditions. The high climate scenario assumes continued growth of greenhouse gas emissions leading to a 9˚F (5˚C) temperature increase by 2100. This is broadly consistent with the Intergovernmental Panel on Climate Change high-emission scenario, also known as RCP 8.5 (see Chapter 1.2 for details about RCPs). In contrast, the low emission scenario assumes a 3.6˚F (2˚C) increase in average global temperature by 2100 as is called for in the 2015 Paris Climate Agreement. This scenario corresponds with a higher benchmark than the RCP 2.6 scenario, which would require a dramatic cut in current greenhouse gas emissions. Finally, there is a moderate scenario that is a composite of the high and low scenarios and roughly corresponds to a 6.3˚F (3.5˚C) increase in average global temperatures, slightly higher than temperatures projected under RCP 4.5. In determining the relative sea level changes in New Jersey, the STAP report accounts for such factors as glacial isostatic adjustment, sediment compaction, movement of land ice to the oceans, and changes in ocean circulation, temperature, and salinity.

The STAP sea-level rise projections are based on a probabilistic model that associates likelihood of occurrence (or probability) of sea-level rise heights and rates over time and are directly tied to the three future climate scenarios (Kopp et al. 2019). For example, given a specific emission scenario, a 50% likelihood, or a central estimate, of sea-level rise scenario suggests that there is a 50% chance that sea-level rise will meet or exceed a given level at a certain point in time. As such, the central estimate for 2070 under a moderate emission scenario represents a 50% probability that sea-level rise will meet or exceed 2.2 feet (0.7 meters). The central estimate includes an inherent risk that future sea-level rise may still exceed the given level. A likely range, consistent with definitions by the Intergovernmental Panel on Climate Change, is also presented. The likely range includes projections between the 17th and 83rd percentile and thus represents a 66% probability that future sea-level rise will be within that range. For example, the likely range for 2070 under a high emission scenario represents a 66% probability that sea-level rise will be between 1.5 feet (0.73 meters; lower end) and 3.5 feet (1.07 meters; upper end). The projections represent a 19-year average centered on the given year and are based on sea levels in the year 2000 and therefore already incorporate some of the rise included in these projections; approximately 0.2 feet (0.06 meters) through 2010.

4.3-2 Sea-Level Rise Projections for New Jersey

The sea-level rise values in Table 4.3 and Figure 4.6 represent projections made by the STAP to the year 2150 (Kopp et al. 2019). The projections through 2050 do not project to low, moderate, or high projections because differences in sea-level rise projections between emissions scenarios are minor in the first half of the century where low emissions projections for 2050 are about 0.1 ft lower than high emissions projections.

Increasing rates of sea-level rise are also expected. By 2050, the local rate of sea-level rise will likely increase from the current rate of approximately 0.2 in/yr to 0.5 in/yr (5.1 – 13 mm/yr) (Kopp et al. 2019). Under the moderate emission scenario, the likely range of increased rates of rise are between 0.2 to 0.8 in/yr (5.1 – 20 mm/yr) over 2060 to 2100. The likely ranges under low and high scenarios are 0.2 to 0.6 in/yr (5.1 – 15mm/yr) and 0.3 to 1.1 in/yr (7.6 – 28 mm/yr), respectively between 2060 and 2100.

4.3-3 Coastal Flooding

Especially low-lying coastal areas of NJ already experience tidal flooding on sunny days, in the absence of precipitation events. This occurrence of high tide floods has increased in recent years (Kopp et al. 2019). In Atlantic City, NJ, the frequency of tidal flooding events has increased from an average of less than one per year in the 1950s to an average of eight per year from 2007 to 2016 (Figure 4.7).

Future high-tide flooding days in Atlantic City under a moderate emissions scenario were modeled with alarming results (Kopp et al. 2019). By the year 2100, it is extremely likely (>95% chance) that Atlantic City will experience high-tide flooding at least 95 days a year, and likely (50% chance) that Atlantic City will experience high-tide flooding 355 days per year. This study highlighted one particularly vulnerable area of NJ but similar projections of "sunny day flooding" and increased flooding from storms is expected across the entire coastal area of the state. In addition to flooding solely from increased sea levels, an increase of tropical cyclones along the mid-Atlantic coast has the potential, modeled under a high (RCP 8.5) emission scenario, to increase the recurrence frequency of the historical 100-year flood level to as often as on an annual basis by the end of the century (Marsooli et al. 2019).

Table 4.3. Sea-level Rise Projections (ft. above year 2000 average sea level) for New Jersey From 2030 to 2150 Under Low, Moderate and High Emissions Scenarios. The likely range represents the range of levels between which there is 66% chance that SLR will occur (Kopp et al. 2019).

	Chance SLR Exceeds	2030	2050	2070 Emissions			2100 Emissions			2150 Emissions		
				Low	Mod.	High	Low	Mod.	High	Low	Mod.	High
Low End	*> 95% chance*	*0.3*	*0.7*	*0.9*	*1.0*	*1.1*	*1.0*	*1.3*	*1.5*	*1.3*	*2.1*	*2.9*
Likely Range	*> 83% chance*	*0.5*	*0.9*	*1.3*	*1.4*	*1.5*	*1.7*	*2.0*	*2.3*	*2.4*	*3.1*	*3.8*
	~ 50 % chance	*0.8*	*1.4*	*1.9*	*2.2*	*2.4*	*2.8*	*3.3*	*3.9*	*4.2*	*5.2*	*6.2*
	< 17% chance	*1.1*	*2.1*	*2.7*	*3.1*	*3.5*	*3.9*	*5.1*	*6.3*	*6.3*	*8.3*	*10.3*
High End	*< 5% chance*	*1.3*	*2.6*	*3.2*	*3.8*	*4.4*	*5.0*	*6.9*	*8.8*	*8.0*	*13.8*	*19.6*

*2010 (2001-2019 average) Observed = 0.2 ft

Notes: All values are 19-year means and are measured with respect to a 1991-2009 baseline. Projections are 19-year averages based on Kopp et al. (2014), Rasmussen et al. (2018), and Bamber et al. (2019). Moderate (Mod.) emissions are interpolated between the high and low emissions scenarios. Rows correspond to different projection probabilities. For example, the 'Likely Range' rows correspond to at least a 2-in-3 (66-100% chance) chance of sea-level rise from the relevant projections considered, consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al. 2010). Note alternative methods may yield higher or lower estimates of the chances of low-end and high-end outcomes.

THE EFFECTS OF CLIMATE CHANGE
SEA-LEVEL RISE

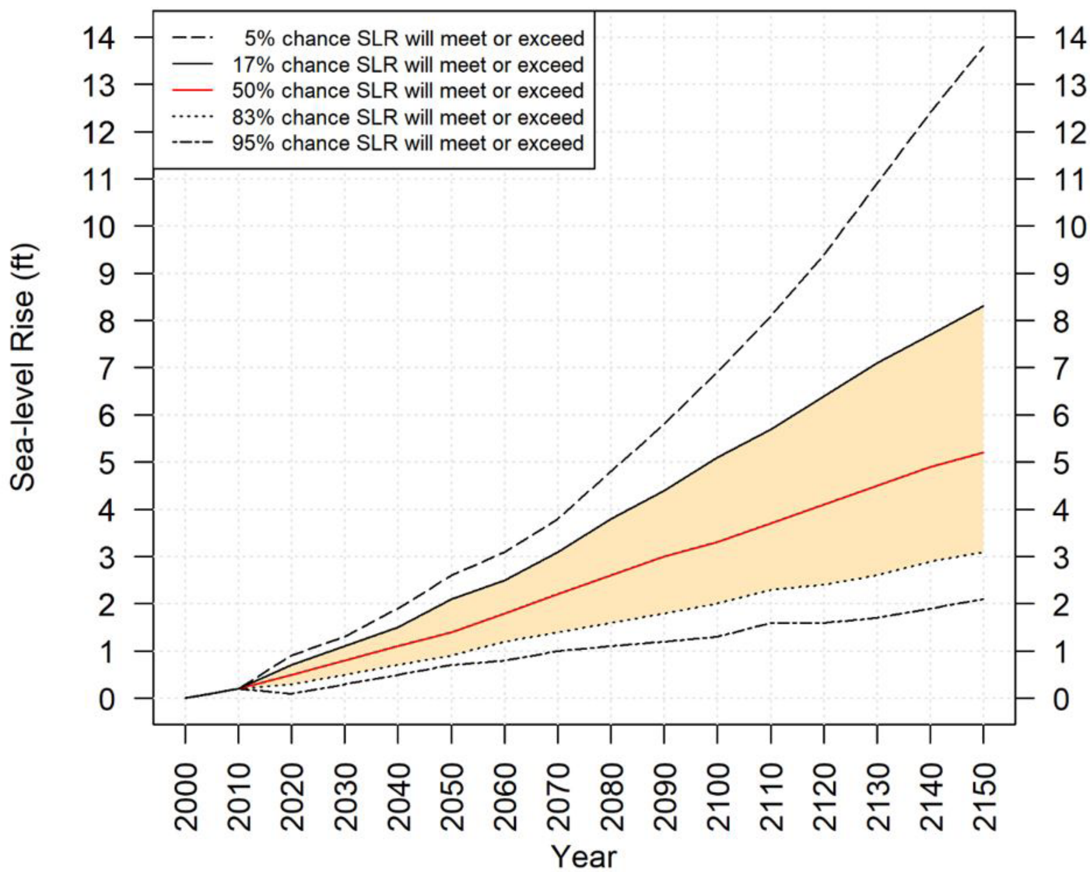


Figure 4.6. Diagram of Sea-Level Rise Projections Curve Under Moderate Emissions Scenario (Kopp et al. 2019). There is a 50% chance that sea-level rise will exceed the level displayed by the red line, and a 66% chance that sea-level rise levels will be between the solid black line and the dotted black line (i.e., tan area).

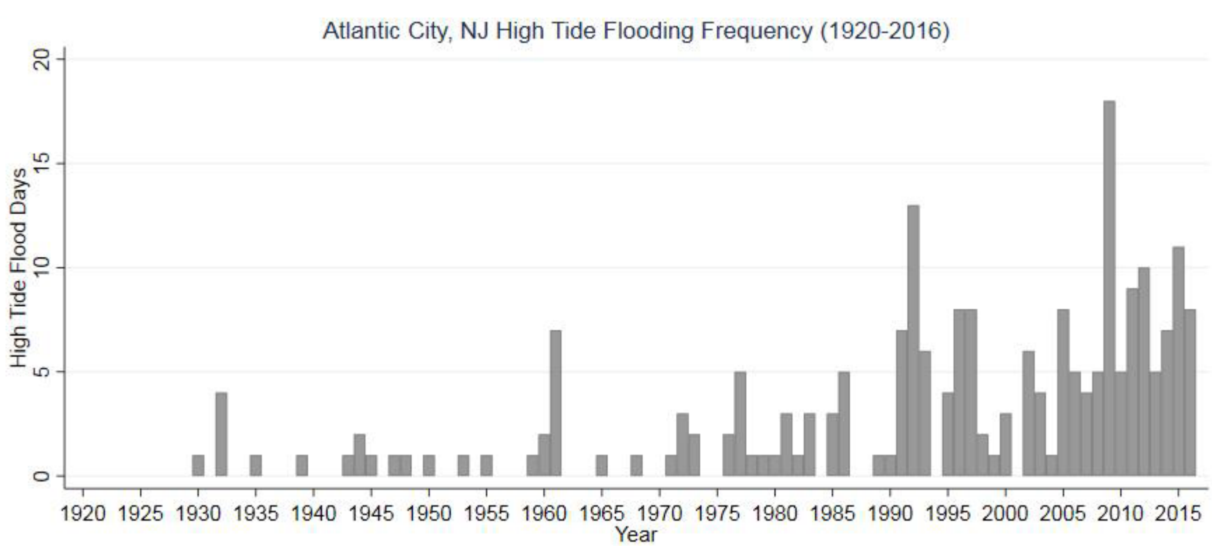
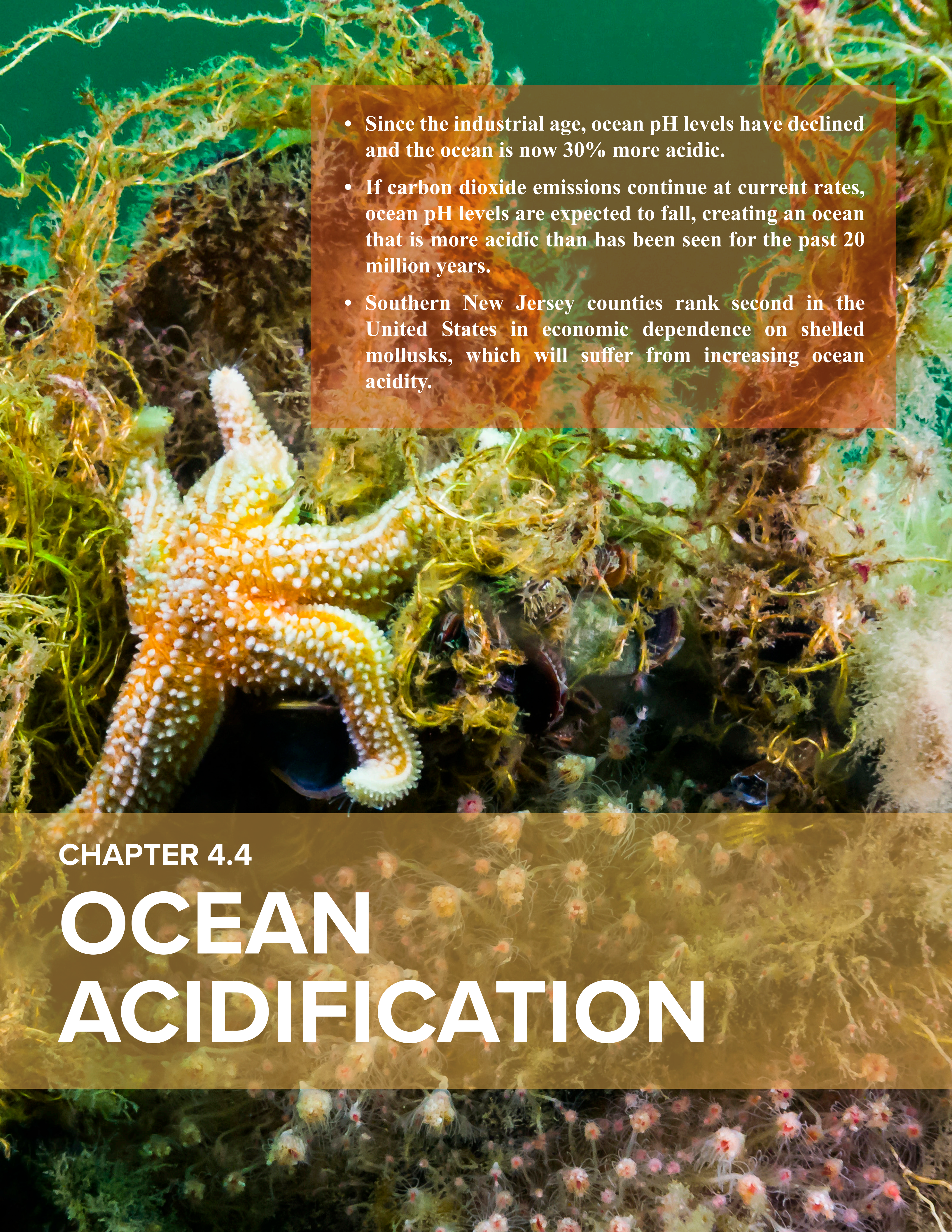


Figure 4.7. Historical High Tide Flood Frequency (number of Flood Days) for Atlantic City, New Jersey. The number of high-tide flooding days has continued to rise in Atlantic City, NJ since 1930 (Kopp et al. 2019).



- Since the industrial age, ocean pH levels have declined and the ocean is now 30% more acidic.
- If carbon dioxide emissions continue at current rates, ocean pH levels are expected to fall, creating an ocean that is more acidic than has been seen for the past 20 million years.
- Southern New Jersey counties rank second in the United States in economic dependence on shelled mollusks, which will suffer from increasing ocean acidity.

CHAPTER 4.4

OCEAN ACIDIFICATION

4.4 Ocean Acidification

Earth is over 70% water, and roughly 97% of that water can be found in the oceans which are being threatened by climate change. Ocean acidification is a marine and coastal specific aspect of climate change. Carbon dioxide (CO_2) has detrimental effects on the environment not only as a greenhouse gas, but also in its lesser known role in ocean acidification. In the most basic terms, CO_2 dissolves in seawater, beginning a chain reaction leading to more acidic conditions. Consequently, many marine organisms will be negatively impacted by ocean acidification, including species who will build weaker shells in a more acidic environment such as many species of shellfish and coral.

4.4-1 Ocean Acidification: The Chemistry

Ocean acidification can be thought of as "climate change's equally evil twin" as it is a significantly harmful consequence of excess CO_2 with effects neither seen nor felt, occurring underwater (NOAA Ocean Acidification Program 2019). When CO_2 gas from the atmosphere is absorbed by seawater, several chemical reactions occur that result in a reduction of seawater pH, the concentration of carbonate ions, and the saturation states of calcium carbonate minerals which are biologically important to many ocean organisms (NOAA 2011). These chemical reactions are collectively referred to as ocean acidification (NOAA 2011). Increasing levels

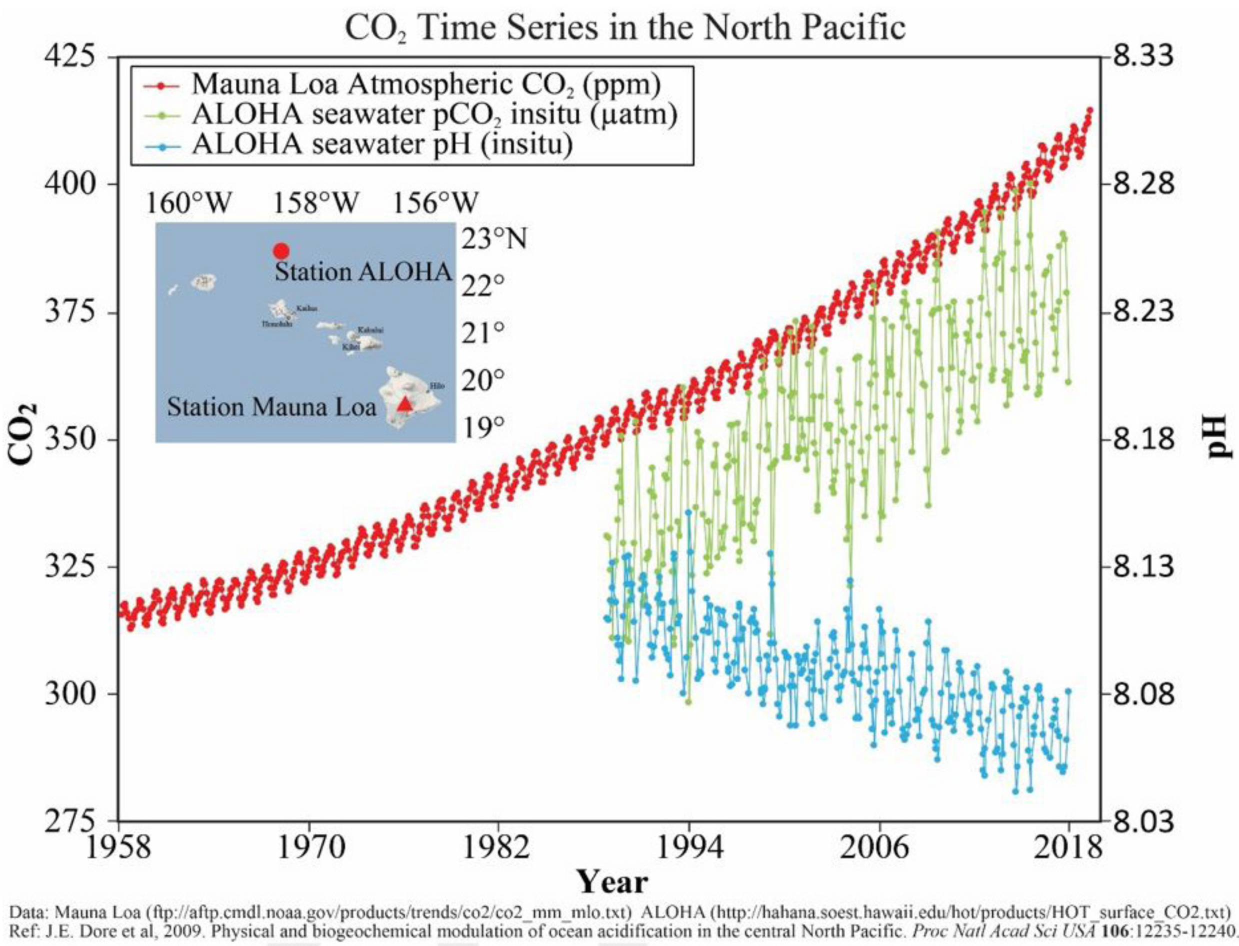


Figure 4.8. Time Series of Carbon Dioxide and Ocean pH at Mauna Loa, Hawaii (Feely et al. 2018).

of atmospheric CO_2 from the burning of fossil fuels, changes in land use, and other human activities are having a direct effect on ocean carbonate chemistry (NOAA 2011, Jewett and Romanou 2017). Since the industrial revolution, atmospheric concentrations of CO_2 have increased from around 280 to over 400 ppm (Figure 4.8) (NOAA Ocean Acidification Program 2019). The surface of the world's oceans are tightly linked with the atmosphere and the ocean has absorbed roughly 30% of global emissions of CO_2 since the preindustrial era ended (Feely et al. 2004). This exchange of CO_2 with the ocean helps in part to regulate atmospheric concentrations, but at a cost to ocean life (NOAA Ocean Acidification Program 2019). Since the industrial age, pH levels have declined by 0.1 pH units, from a global average of 8.2 to 8.1. This may not seem like very much, but the pH scale is logarithmic, so a decrease of 0.1 represents a 30% increase in acidity in the ocean (NOAA 2020b). If CO_2 emissions continue at current rates, ocean pH levels are expected to fall another 0.3 to 0.4 pH units by the end of the century to 7.8 or 7.7, representing another 120% drop and creating an ocean that is more acidic than has been seen for the past 20 million years (Ocean Portal Team 2018). It is not only surface ocean waters that have become more acidic over the last 150 years, anthropogenically (human-caused) sourced

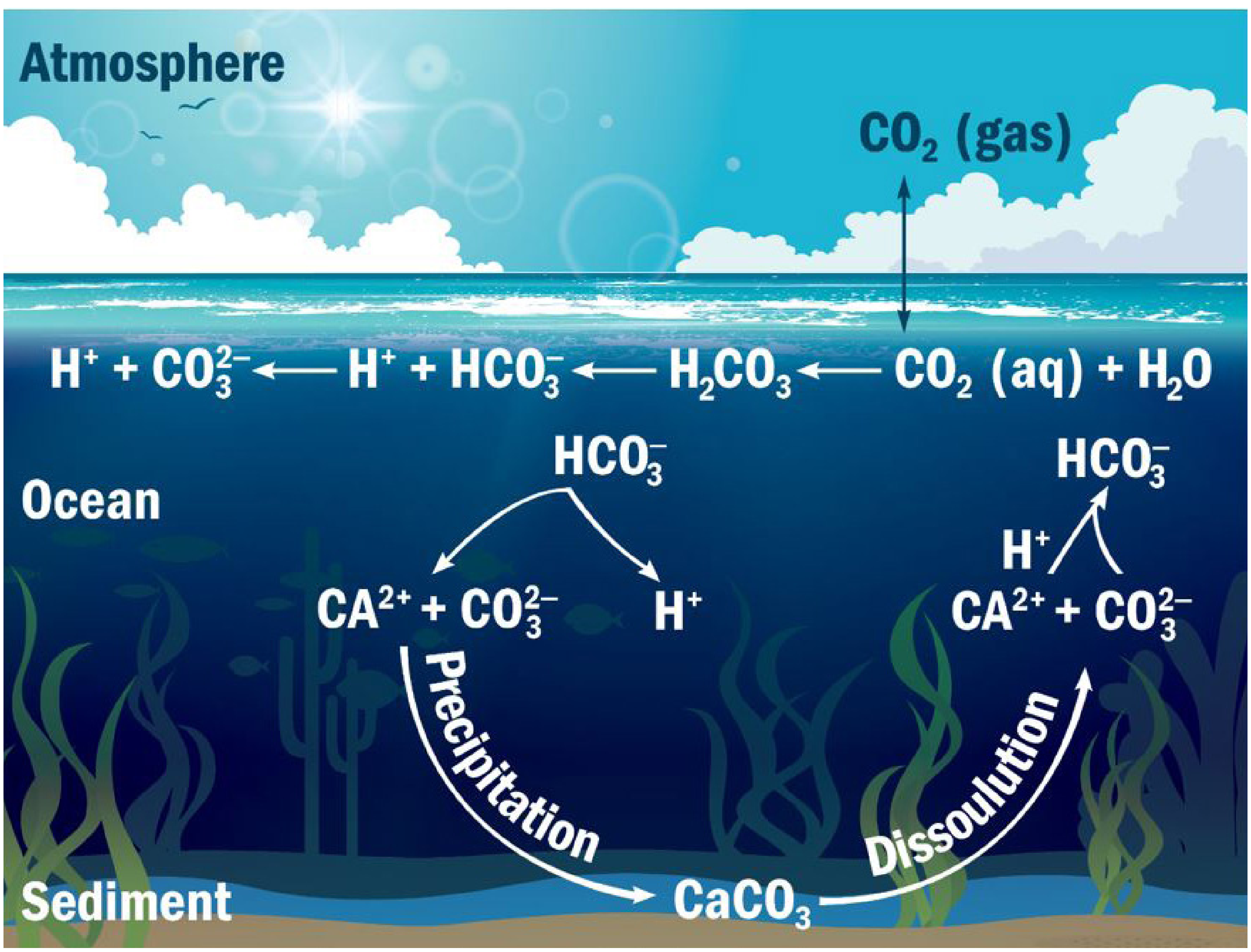


Figure 4.9. Process Contributing to Ocean Acidification. The Chemical Reaction That Leads to Ocean Acidification with the Introduction of CO_2 Into the Ocean.

CO_2 is also penetrating into the waters of the deep ocean (Jewett and Romanou 2017). If not for this ocean uptake of CO_2, atmospheric levels would be increasing at an even greater rate than they are at present (NOAA Ocean Acidification Program 2019).

Increased concentrations of hydrogen ions (H+) in seawater due to increased absorption of CO_2 leads to ocean acidification (Orr et al. 2005, Doney et al. 2009). The measurement of acidity (pH) refers to the concentration of free H+ in aqueous solution (NOAA 2011). In seeking equilibrium, substances will naturally move from an area of greater concentration to an area of lesser. In this way, increased global concentrations of atmospheric CO_2 are driving corresponding increases in concentrations of dissolved CO_2 (called partial CO_2 or pCO_2) in surface ocean waters since seawater naturally contains less CO_2 than the atmosphere (NOAA Ocean Acidification Program 2019). Dissolved CO_2 reacts with seawater (H_20) and forms carbonic acid (H_2CO_3). H_2CO_3 dissociates, or breaks apart, to form bicarbonate (HCO_3-) and H+ ions. (Ferguson et al. 2015). The free H+ ions are therefore increasing the acidity (lowering the pH) of the ocean. This process can be seen in Figure 4.9. Certain projections indicate that by the end of this century, under higher scenarios (RCP8.5), the average surface pH of the open ocean will decline from the current 8.1 to a possible 7.8 (Jewett and Romanou 2017).

In addition to increased concentration of H+ lowering seawater pH, its presence causes a decrease in the availability of carbonate ions (Jewett and Romanou 2017). The concentration of carbonate ions in the ocean affects the saturation state and the availability of the calcium carbonate minerals that many shell-building species need to build their skeletons. A lower pH results in a lower bicarbonate concentration and a lower calcium carbonate concentration that may dramatically effect a wide range of important species, including bivalves (oysters, clams, mussels, scallops, and surfclams), lobsters, crabs, sea urchins, plankton, and coral reefs (NOAA 2011, Dupigny-Giroux et al. 2018). Fisheries and aquaculture industries rely on many of the species that will suffer from increasing ocean acidity (Dupigny-Giroux et al. 2018). Of particular importance is the ability to maintain the aragonite saturation state (ΩAr) in seawater which is used as a measure and proxy for calcifying conditions. Aragonite is a mineral form of calcium carbonate used by corals, bivalve larvae, and other mollusks to build their exoskeletons, making it an ecologically relevant marker of ocean acidification (Ekstrom et al. 2015).

4.4-2 Open Ocean Acidification vs. Coastal Acidification

Open ocean acidification is a global change in ocean chemistry, primarily from increased inputs of atmospheric CO_2 (NOAA Ocean Acidification Program 2019). However, the surface waters of the open ocean experience carbonate chemistry changes from larger-scale physical processes, including both the uptake of CO_2 and the upwelling of naturally acidic, colder subsurface waters from deeper depths (Jewett and Romanou 2017). Generally, open ocean acidification rates on a decadal timescale closely approximate the rate of increased atmospheric CO_2.

Coastal acidification is affected by the same processes as the open ocean (such as CO_2 absorption and upwelling) as well as several additional local-level processes (Jewett and Romanou 2017). These processes include local changes in water from naturally acidic freshwater river input as well as an influx of nutrient run-off from the land, such as nitrogen (N_2) and organic carbon (NOAA Ocean Acidification Program 2019). Excess nutrients from pollution and fertilizers cause increased phytoplankton or algal growth (Jewett and Romanou 2017, NOAA Ocean Acidification Program 2019). The resultant algal blooms then die and are eaten by bacteria, which consume oxygen (O_2) and respire CO_2, increasing acidification (see Chapter 5.10 for more information about Harmful Algal Blooms) (Jewett and Romanou 2017). The input of freshwater into coastal waters changes the seawater chemistry making it more susceptible to acidification. These freshwater inputs contribute varying amounts of dissolved inorganic carbon (DIC), dissolved and particulate organic carbon, total alkalinity (TA), and other nutrients from riverine and estuarine sources. Overall, coastal acidification is subject to higher-frequency variability and short-term episodic events than the open ocean.

4.4-3 Ocean Acidification in the Mid-Atlantic

For the purposes of this section, the Mid-Atlantic is the region south of Long Island Sound, NY to Virginia, bordered by the U.S. Northeast Shelf (NES) (Goldsmith et al. 2019). The ecosystems of the Mid-Atlantic coasts and oceans support not only human recreation and commerce, but protect coastlines from storms, flooding, and erosion. The Mid-Atlantic is defined and bordered by a broad continental shelf (NES) several hundred kilometers offshore. Compared to other coastal environments, the NES undergoes one of the most extreme seasonal ocean temperature changes, varying surrounding ecological processes.

The coastal states in this region (New York, New Jersey, Delaware, Maryland, and Virginia) frequently work together cooperatively to manage and study this shared resource. The Mid-Atlantic Coastal Acidification Network (MACAN) is co-coordinated by the Mid-Atlantic Council on the Ocean (MARCO) and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) in order to address regional coastal and ocean acidification. A recent MACAN study reviewed and summarized current acidification and ecological research, identified research gaps, and provided recommendations for further studies to improve understanding in the Mid-Atlantic region (Saba et al. 2019). Current insights from acidification research indicate that the aragonite saturation state will be reduced further as a consequence of increased OA. Reduced calcifying conditions challenge the ability of bivalves, lobsters, crabs, sea urchins, plankton, and coral reefs to deposit shells. It has also been observed that increased acidification affects the success of hatching, larval development, organ development, immune response, acid-base regulation, metabolic processes, and olfaction (smell) in calcifying as well as non-calcifying species. Marine life responses to acidification in the Mid-Atlantic are highly variable and species-specific, with the potential for acclimation or adaptation leading to relative "winners" and "losers" in a future acidic ocean. Groups of organisms that can expect neutral, at best, to negative impacts from OA include corals, crustaceans, mollusks, echinoderms, bony finfish, and calcified algae. Younger, larval stage shelled organisms tend to be more at risk than adults due to reduced growth and impaired development. Adults, however, tend to be susceptible to changes in behavior and metabolism that can make them easy prey and increase physiological stress. As further summarized by Saba et al. (2019), studies are inconclusive as to whether rooted vascular plants,

"The long-term economic impacts of ocean acidification are predicted to be the most severe not just in regions where seawater will acidify soonest, but also where communities rely heavily on local shellfish industries for their livelihoods."

collectively termed submerged aquatic vegetation (SAV), could benefit from OA. Short-term increases in the amount of CO_2 dissolved in the SAV tissue can yield higher rates of photosynthesis. However, elevated amounts of dissolved CO_2 may also enhance SAV vulnerability to grazing, disease, and decomposition through the decreases in phenolic compounds, compounds that help reduce biotic and abiotic stressors. Also, increased photosynthesis does not necessarily equate to whole-plant productivity as other climate change factors come into play, such as light availability.

Furthermore, MACAN compiled a review of current monitoring, available technology, existing infrastructure, and areas of ecological and economic importance in order to inform the development of collaborative monitoring in the Mid-Atlantic (Goldsmith et al. 2019). This paper highlighted the significance of OA in the Mid-Atlantic by detailing the unique topography, geography, economy, seasonality, and ecological variability of the region. This densely populated, urbanized, and developed Mid-Atlantic coastline washes nutrients and other pollutants into its estuarine systems, exacerbating OA. Extreme precipitation events as well as overall annual precipitation amounts are predicted to increase for the Mid-Atlantic. This will cause more acidic freshwater to runoff into the ocean. This region also faces an above average risk from SLR and storm surge, creating the potential for compounding impacts associated with rising sea water temperatures, OA, and higher precipitation amounts that can threaten vulnerable aquatic species and dependent communities.

4.4-4 Ocean Acidification in New Jersey

Regions along the northern west coast and northern east coast of the United States are expected to experience the earliest impacts from ocean acidification (Ekstrom et al. 2015). According to an assessment of the most vulnerable communities in the United States to ocean acidification, New Jersey is considered to be at high risk of economic harm (NRDC 2015) (see Figures 4.10 and 4.11). New Jersey is not predicted to see unfavorable conditions to shellfish resulting from anthropogenic ocean acidification until 2100 according to global ocean models (Ekstrom et al. 2015), however, New Jersey is expected to see a high social impact as conditions evolve (NRDC 2015, Ekstrom et al. 2015) (Figure 4.11). Communities that are highly dependent on shellfish resources are either already experiencing effects of ocean acidification or will be in the near future.

New Jersey is at an increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests and vulnerability to discharge from rivers (NRDC 2015). The long-term economic impacts of ocean acidification are predicted to be the most severe not just in regions where seawater will acidify soonest, but also where communities rely heavily on local shellfish industries for their livelihoods. New Jersey has both a thriving commercial fishing industry and aquaculture community. In the United States, southern New Jersey counties rank second in economic dependence on the shelled mollusks.

In addition to economic vulnerabilities, marine ecosystems along the east coast will experience the results of ocean acidification due to local amplifiers such as eutrophication and the potential for increases in discharge of freshwater inputs (Ekstrom et al. 2015) (see Figure 4.11). Poorly buffered rivers (those least able to resist changes in pH), such as the Delaware River and coastal drainages of the Pinelands region, introduce relatively more acidic freshwater to coastal waters, reducing both pH and the availability of carbonate minerals needed by shellfish to build their shells. The effects on developing oysters (for example) have already been seen on the west coast of the United States, suggesting that commercial shellfisheries along the east coast and New Jersey are at risk as similar conditions arise (Weis et al. 2015). Also, excess nutrients such as N_2 make their way into coastal New Jersey waters from farms, lawn chemicals, and poorly maintained sewage systems (NRDC 2015). These nutrients can lead to excess algae growth or algal blooms. Decomposing algae release more

CO_2 into the system when they die, further reducing pH. New Jersey has a history of nutrient pollution and algal blooms in its estuaries including Barnegat Bay (see Chapter 5.10 for more information about Harmful Algal Blooms). As a result of these factors, coastal and marine waters of New Jersey are susceptible, with medium-high social vulnerability, to the impacts of ocean acidification.

In addition to ocean acidification occurring due to dissolved atmospheric CO_2 and local amplifiers, periodic summer upwelling events can occur off of New Jersey's coasts and transport deeper, colder, and more acidic water up to the surface (Goldsmith et al. 2019). This low pH, low aragonite-soluble seawater can impair shellfish production. Not only are shell-building species at risk, but so too are fish populations that depend on estuaries during part of their life cycles, including summer flounder *(Paralichthys dentatus)*. The ecological impacts of ocean acidification on marine organisms require further research.

Despite decades of ongoing ocean monitoring in New Jersey, there is a lack of consistency both in sampling technology and methods that make developing a clear picture of the level of acidification of coastal and marine waters difficult. New Jersey coastal waters have been monitored for pH and DO (dissolved oxygen) since the mid-1990's to some extent, and more extensively since the early 2000's (Weis et al. 2015). Monitoring stations with sensors

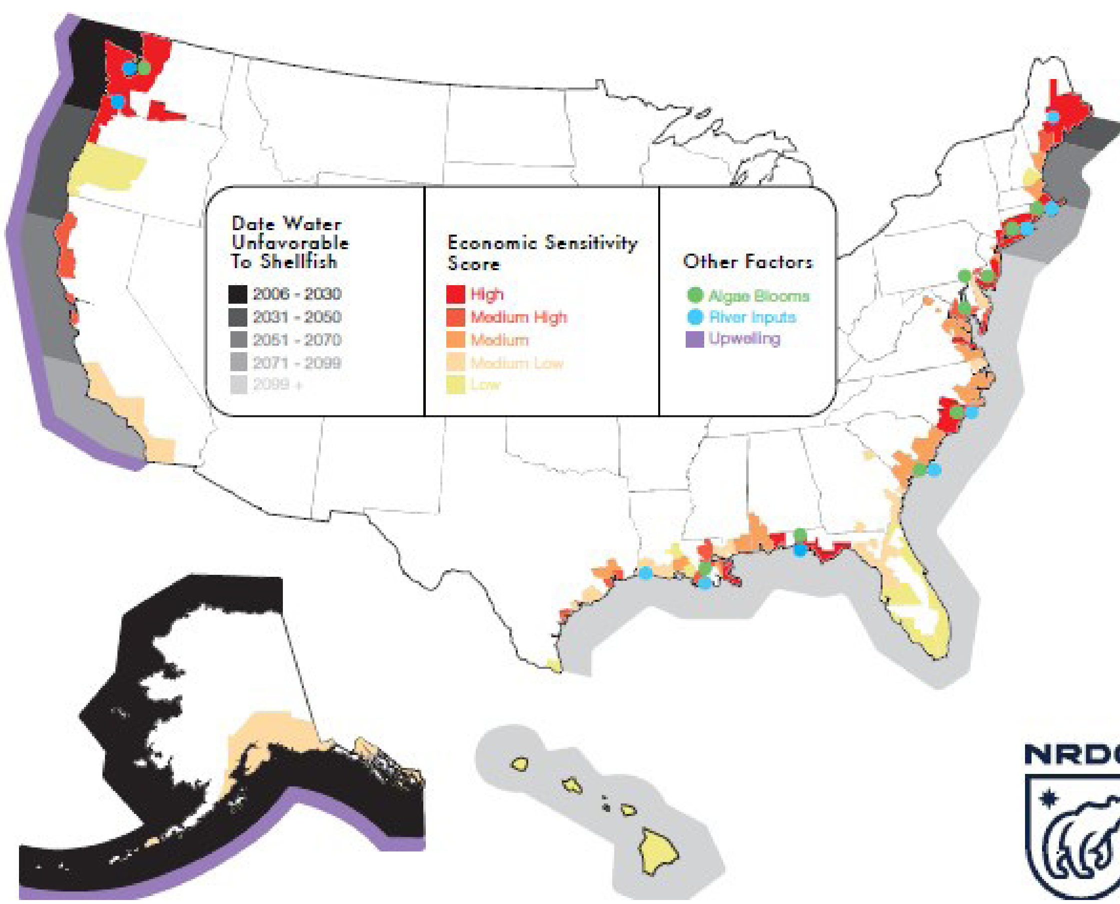


Figure 4.10. Vulnerability Ranking of United States Communities to Ocean Acidification. The most severe long-term economic impacts from ocean acidification are expected in the areas where the ocean is acidifying the soonest (black) and where there is a high reliance on shellfish for livelihood (red). Adapted from (NRDC 2015, Ekstrom et al. 2015).

from the National Estuarine Research Reserve System are included in the Atlantic coast database with data that does not extend prior to the 2000's. The DEP conducted submersible glider studies in the mid-2000's in order to look at ocean chemistry over an extensive area. NOAA has taken oceanic samples in the Mid-Atlantic area including New Jersey, as well as its regional estuaries since the 1970's, but sampling did not include ocean pH until the mid- to late-2000's. New Jersey's most comprehensive dataset is from the Barnegat Bay and includes pH and DO data from the 1970's to present (Weis et al. 2015).

The New Jersey area is uniquely susceptible to the impacts of ocean acidification. New Jersey's marine ecosystems, and particularly fisheries, are economically and ecologically important resources that provide services for local communities and the much wider populations they support (Murray et al. 2015).

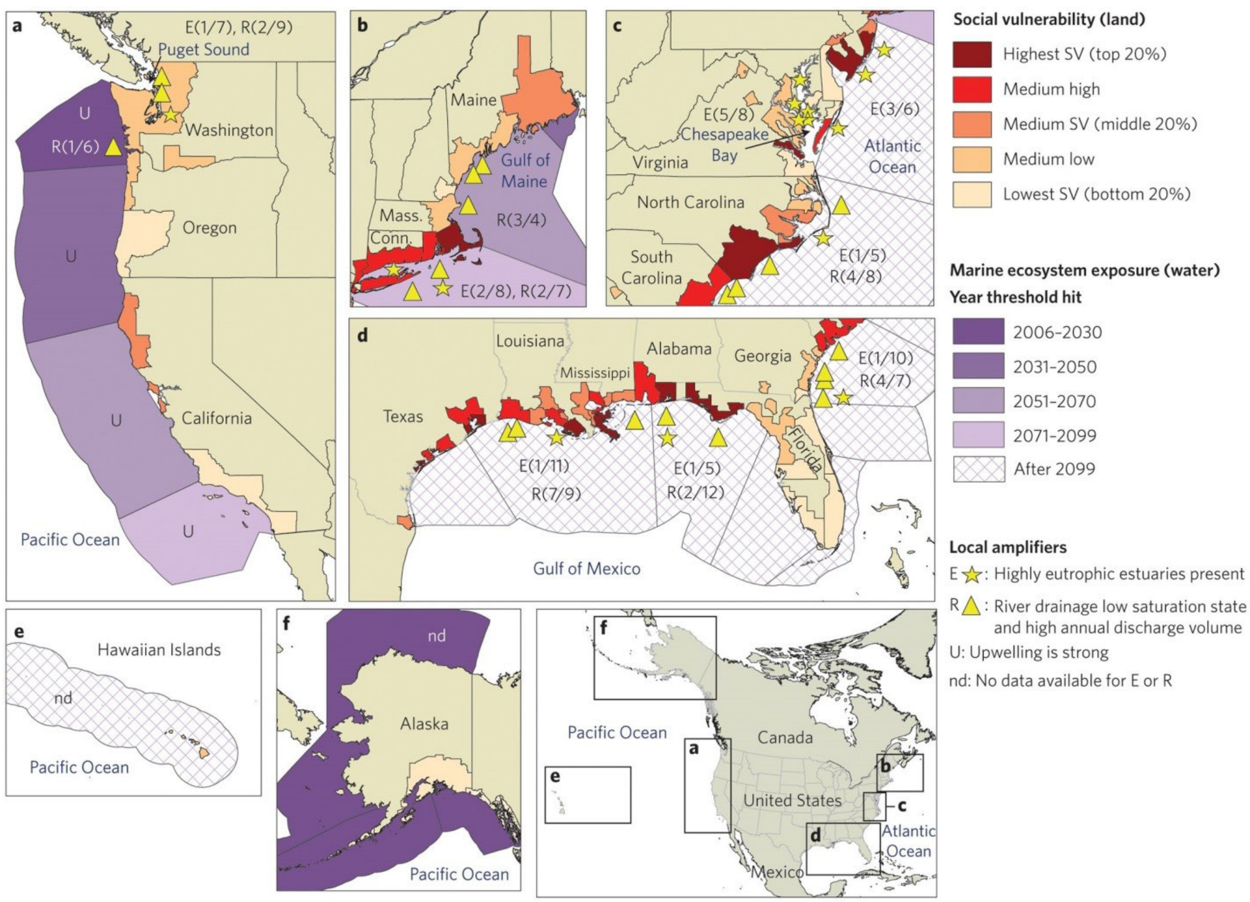
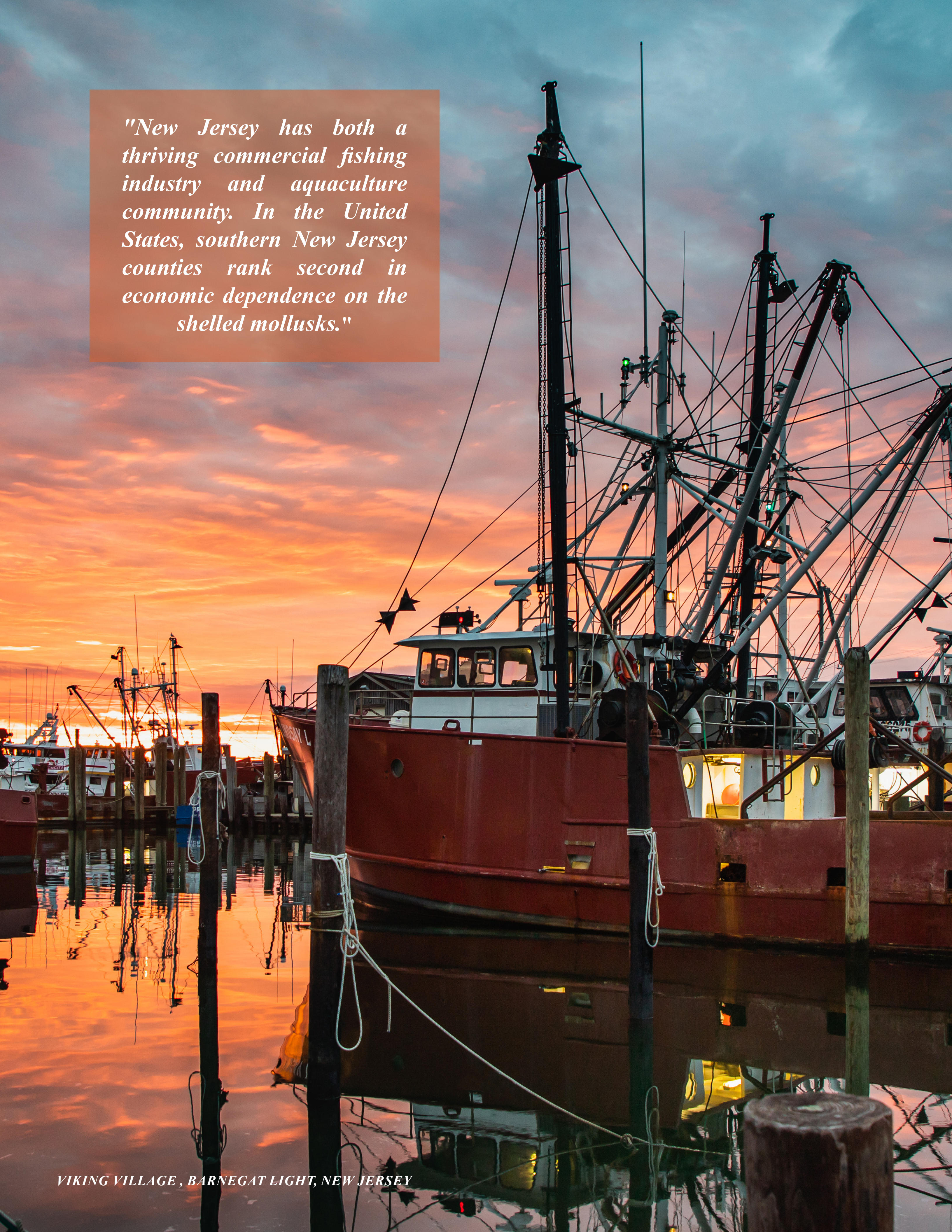
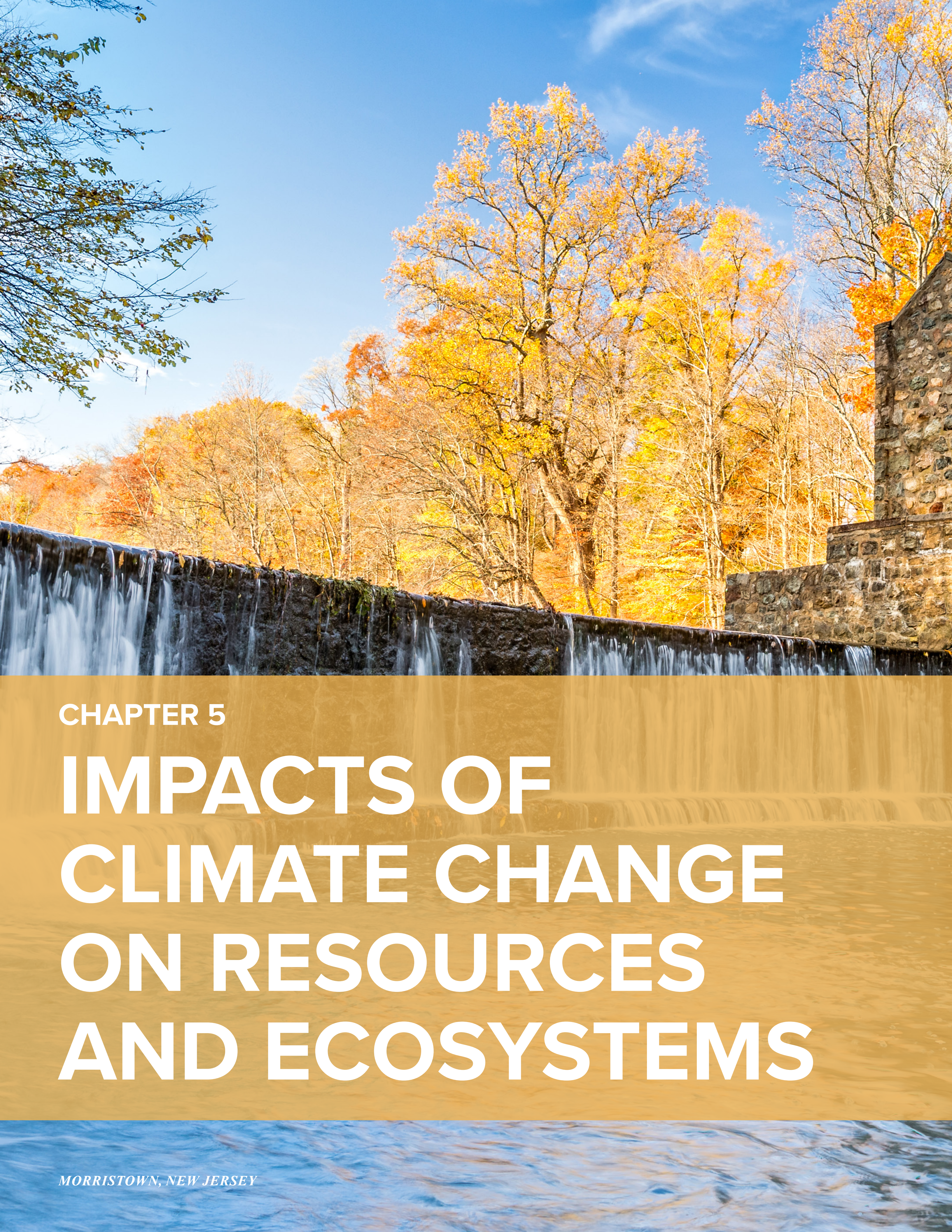


Figure 4.11. Exposure and Vulnerability of United States Communities to Ocean Acidification (Ekstrom et al. 2015).

"New Jersey has both a thriving commercial fishing industry and aquaculture community. In the United States, southern New Jersey counties rank second in economic dependence on the shelled mollusks."



VIKING VILLAGE , BARNEGAT LIGHT, NEW JERSEY



CHAPTER 5

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEMS

MORRISTOWN, NEW JERSEY

This chapter will discuss how the primary driver of climate change, greenhouse gas emissions, will impact and affect New Jersey's environmental and natural resources as well as ecological communities. The impacts of climate change to natural resources in New Jersey, particularly from increasing temperatures, changing precipitation patterns, and rising sea-levels, are already apparent. The following sections describe these impacts of climate change on New Jersey's air quality, water quality and quantity, agriculture, forests, wetlands, and wildlife species in terrestrial, freshwater, and marine systems.

Chapter 5 is divided into the following sections:

- **The effects of climate change are likely to contribute to an increase in air pollution, lead to increased respiratory and cardiovascular health problems, like asthma and hay fever, and a greater number of premature deaths.**
- **Environmental degradation from climate induced increases in air pollution will reduce visibility and cause damage to crops and forests.**

CHAPTER 5.1

AIR QUALITY

NEAR PORT NEWARK, NEW JERSEY

5.1 Air Quality

The quality of air affects all aspects of life. When air is polluted it can cause adverse health effects on humans, the environment, and other life. Air pollutants can be found indoors and outdoors, and in urban, suburban, and rural areas. National health-based standards exceed air pollution levels for over 100 million United States residents, including all New Jersey residents, (Nolte et al. 2018). The effects of climate change will not only contribute to an increase in air pollution but will also lead to increased respiratory and cardiovascular health problems and even a greater number of premature deaths. In addition, higher air pollution levels will result in increased environmental degradation such as reduced visibility and damage to crops and forests.

The chemical and physical processes that generate, transport and eliminate air pollution will be affected by climate change. The changes to these processes are likely to increase levels of air pollutants (outdoor and indoor) as well as increase exposures to aeroallergens (i.e., airborne substances that cause allergic reactions). The primary pathways by which climate change will influence air pollution are summarized in Figure 5.1 which shows that climate change will alter chemical and physical interactions (black bold text) that create, remove, and transport air pollution (red text and gray arrows) (Nolte et al. 2018). Human activities and natural processes release precursors for ground-level ozone (O_3) and particulate matter with a diameter less than 2.5 micrometers (PM2.5), including methane (CH_4),

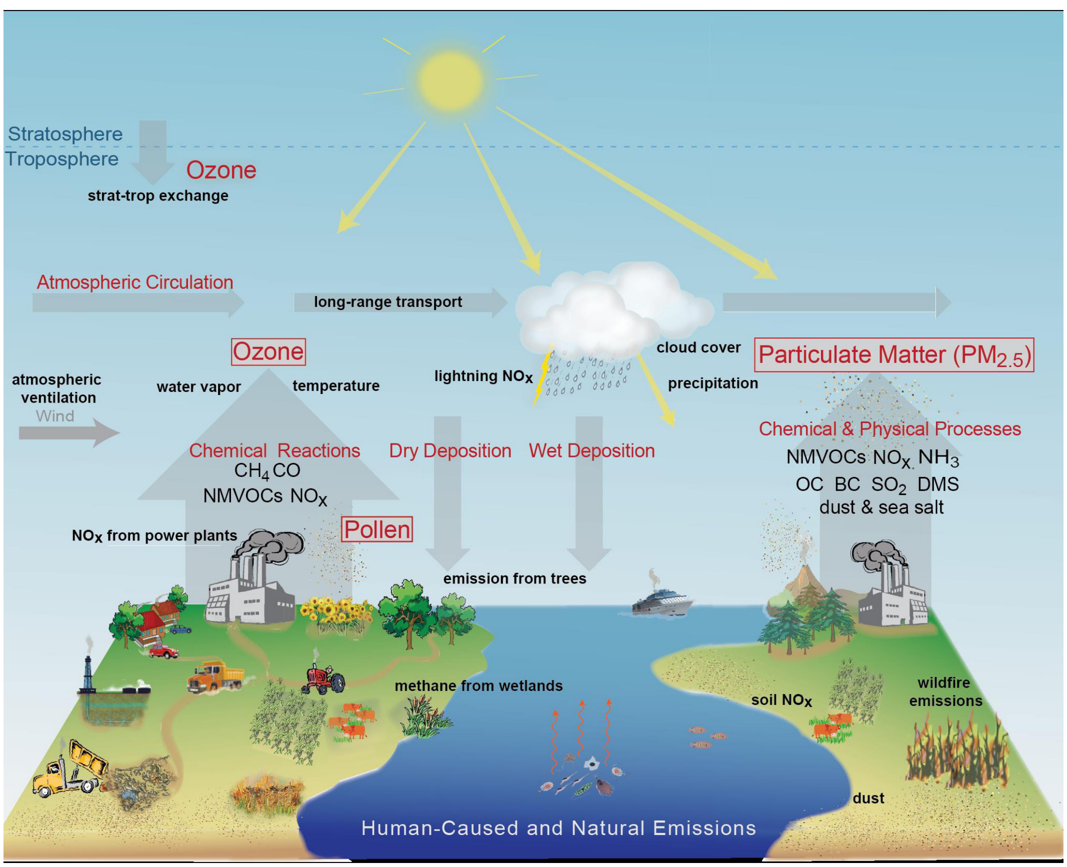


Figure 5.1. Air Quality and Climate Connections. This figure shows the primary pathways by which climate change will influence air pollution. The black bold text shows when climate change will alter the chemical and physical interactions that create, remove, and transport air pollution, which are shown in red text and gray arrows (Nolte et al. 2018).

carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO2), ammonia (NH3), organic carbon (OC), black carbon (BC), and dimethyl sulfide (DMS); and direct atmospheric pollutants, including mineral dust, sea salt, pollen, spores, and food particles (Fiore et al. 2015).

5.1-1 Outdoor Air Quality

Outdoor pollutants that threaten air quality include ground-level ozone, particulate matter, aeroallergens, greenhouse gases (see Chapter 3), and various other hazardous air pollutants. This section will focus on ground-level ozone, particulate matter, and aeroallergens.

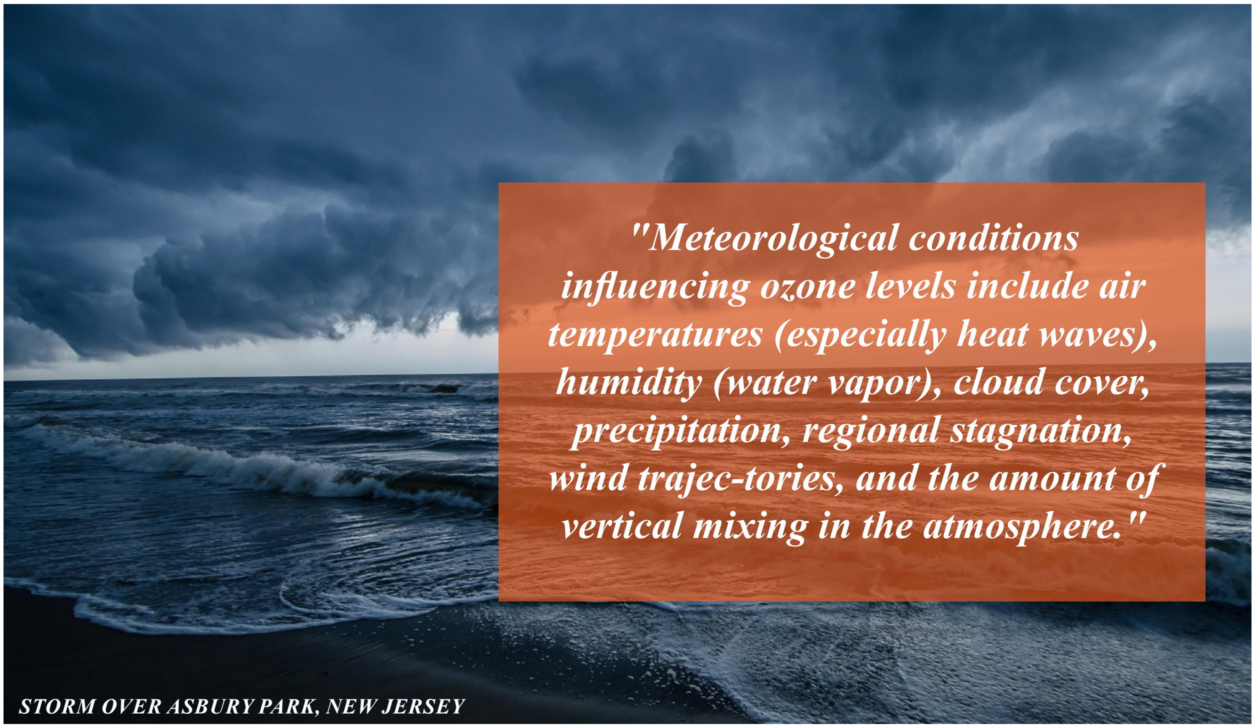
5.1-1.1 Ground-Level Ozone

Ozone (O_3) is a colorless and odorless gas that is formed in the layer of the atmosphere called the stratosphere (i.e., the layer of the atmosphere 6-30 miles above Earth's surface) (NOAA 2008) which provides protection from the harmful ultraviolet rays of the Sun. Ozone can also be created in Earth's lower atmosphere, or troposphere, by chemical reactions of pollutant gases, known as the precursor pollutants, such as nitrogen oxide (NOx) and volatile organic compounds (VOCs) interacting with heat and sunlight, as seen in Figure 5.2 (NJDEP 2020d). This ground-level ozone will be the focus of this section of the report. The atmospheric conditions that generate high ozone levels are high temperatures, plenty of sunshine, and stagnant air masses, and often result in elevated levels of particulate matter and/or other colored gases that may appear visually as haze or smog, which is why ground-level ozone is sometimes referred to as smog. The primary ozone precursor pollutants are NOx and VOCs. Sources of NOx emissions can be natural, but the primary source is human-made emissions from motor vehicles that use internal combustion engines (gasoline and diesel), construction equipment, power plants, and industrial, commercial, and residential fuel combustion (NJDEP 2016). The primary sources of human-made VOCs are household cleaners, paints and solvents, motor vehicles, lawn and garden equipment, and gasoline stations, but can also be emitted from trees and plants.

For decades, New Jersey has implemented numerous measures to control emissions of ozone precursors and has made significant progress in the reduction of ozone levels. However, the entire state currently is classified as "non-attainment", meaning air pollution levels are above the national ozone health-based air standards of 70 parts per billion (ppb) established by the Federal Clean Air Act and United State Environmental Protection Agency (EPA) (NJDEP 2020b).

Many factors contribute to ground-level ozone concentrations at any given time and location and extensive studies have been performed that evaluate how climate change will impact ground-level ozone air pollution. These factors can be broadly separated into two categories: sources that emit ozone precursor pollutants and meteorological conditions that are conducive to ozone formation (Fann et al. 2016). Although climate change is expected to have some effect on precursor emissions, emissions of ozone precursors are expected to continue to decline overall in the

Figure 5.2. How Smog is Formed. Ground-level ozone, also known as smog, is formed when oxides of nitrogen (NOx) and volatile organic compounds (VOCs) react in the presence of sunlight (NJDEP 2020d).



STORM OVER ASBURY PARK, NEW JERSEY

United States while remaining high in dense urban areas (NASA 2014). The primary climate change impacts on ozone formation are expected to result from changes to meteorological conditions, often referred to as the ozone-climate penalty which is "the deterioration of air quality due to a warming climate, in the absence of anthropogenic (human-caused) polluting activates" (Fu and Tian 2019). This means, that even as emissions are reduced, ozone formation may still increase due to the warmer climate, suggesting that it will be more difficult in the future for New Jersey to meet and maintain federal health-based air quality standards.

Meteorological conditions influencing ozone levels include air temperatures (especially heat waves), humidity (water vapor), cloud cover, precipitation, regional stagnation, wind trajec-tories, and the amount of vertical mixing in the atmosphere (Fu and Tian 2019). Additional ozone related processes that are impacted by climate change include wildfires (NOx and VOC source), lightning (NOx source), stratospheric ozone transport, soil NOx emissions, background methane levels, and release of VOCs from vegetation. An important feedback affect is the increase in NOx emissions from electric generating units at fossil fuel power plants when the demand for electricity increases due to the climate change impacts of higher temperatures and increased humidity levels. The scientific consensus is that the impact of climate change due to the above-mentioned processes (except for increased humidity/precipitation) will tend to generally increase ground-level ozone levels.

Additionally, climate change is expected to play a role in increases in the frequency and severity of wildfires, but as discussed in Chapter 5.4-5, forest management decisions may outweigh climate change impacts (Nolte et al. 2018). The air pollution from wildfire smoke degrades air quality and increases adverse health effects for tens of millions of United States residents. Wildfire smoke impacts air quality in New Jersey from both in-state and upwind wildfires as far away as the western United States and Canada. The degraded air quality due to wildfire smoke increases incidences of respiratory illness, reduces visibility, and disrupts outdoor activities.

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Changing wind patterns is another example of meteorological conditions being affected by climate change and leading to impacts on ozone (Fann et al. 2016). For New Jersey, and over much of the United States, the worst ozone episodes occur when ozone and ozone precursor emissions accumulate in a specific location when the local air mass does not change over a period of several days. Parts of the United States are already seeing an increase in frequency of this type of episode and it is expected to become even more common in the future. These episodes will be even more frequent in New Jersey's urban areas where locally emitted pollutants and high levels of ozone near the ground, do not get diluted because of the downward movement of air that occurs in densely developed locations.

To better understand how meteorology influences ozone formation compared to the effects of changes in emissions of ozone precursors, researchers use quantitative modeling that simulates regional chemical transports over multiple years (Fann et al. 2016). These models show that large portions of the United States, including New Jersey and surrounding states, are likely to see larger levels of ozone due to direct meteorological impacts from climate changes such as accelerated rates of photochemical reactions and increased occurrence of stagnate air mass events like those described above.

High ground-level ozone concentrations have been found to have a varying degree of impact on

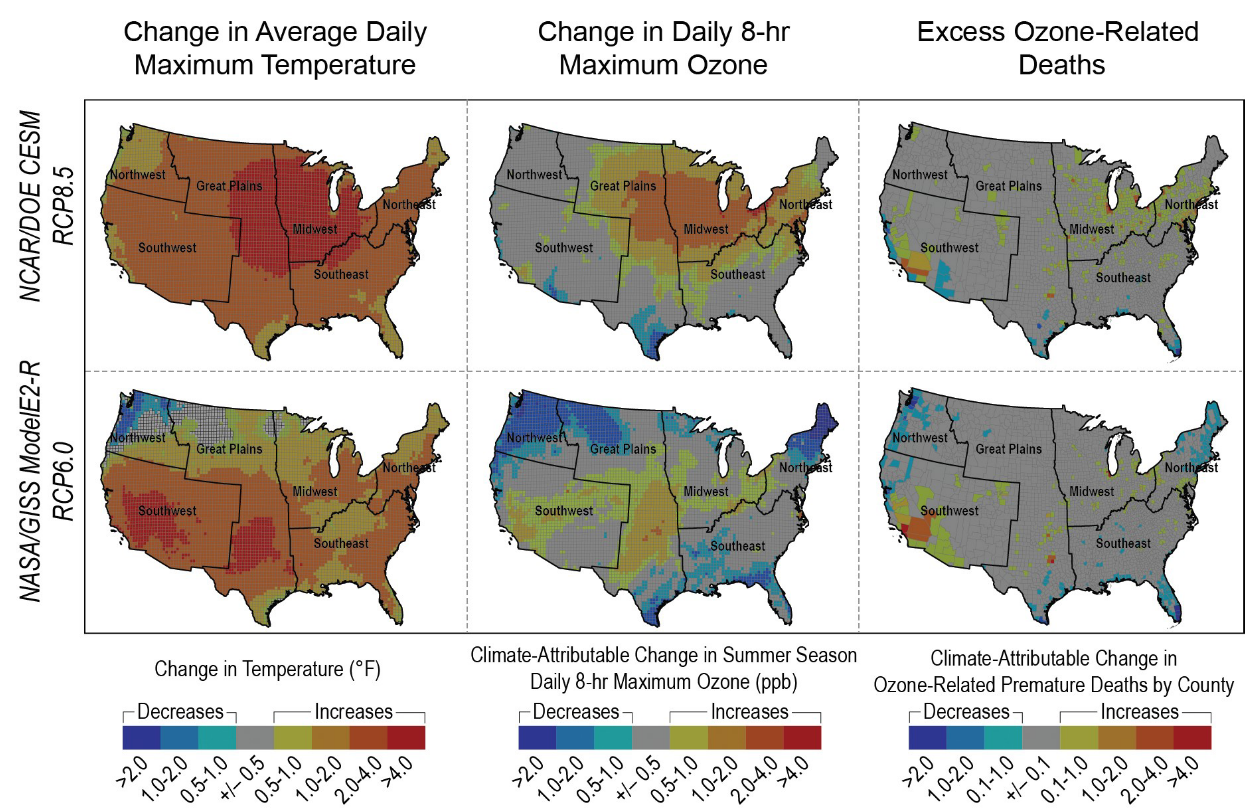

Figure 5.3. Projected Change in Temperature, Ozone, and Ozone-Related Premature Deaths in 2030. Projected changes in average daily maximum temperature (degrees Fahrenheit), summer average maximum daily 8-hour ozone (parts per billion), and excess ozone-related deaths (incidences per year by county) in the year 2030 relative to the year 2000, following two global climate models and two greenhouse gas concentration pathways. The top panels are based on the National Center for Atmospheric Research/Department of Energy (NCAR/DOE) Community Earth System Model (CESM) following RCP8.5 (a higher greenhouse gas concentration pathway), and the bottom panels are based on the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) ModelE2-R following RCP6.0 (a moderate greenhouse gas concentration pathway) (Fann et al. 2016).

human health, ranging from eye irritation to severe respiratory distress and can lead to chronic illness or premature death (NJDEP 2016). Numerous epidemiology studies have found that the risk of adverse health impacts is linked to a population historically being exposure to air pollutants (Fann et al. 2016). Specifically, there is a greater risk of being admitted to the hospital for respiratory issues, being admitted to the emergency room, suffering from aggravated asthma, and other health impacts in populations that are exposed to ozone air pollution. This is believed to occur because ground-level ozone damages lung tissue, intensifies heart and lung diseases, causes coughing and throat irritation, and lowers resistance to diseases such as colds and pneumonia (NJDEP 2016). While even healthy adults who work outdoors can be impacted by ozone, children, the elderly, and people with asthma are most at risk. By 2030 in the United States, it is expected that the human health impacts attributed to increases in ozone due to climate change will lead to a significant increase in pre¬mature deaths, hospital admissions, and cases of acute respira¬tory illnesses per year.

Specifically, recent modeling provided quantitative estimates of the projected change in temperature, ozone, and ozone-related premature deaths in 2030 for the United States (Fann et al. 2015, 2016). Study results shown in Figure 5.3 resulted in an increase in daily 8-hour maximum ozone and an increase in 1.8°F (1°C) to 7.2°F (4°C) in average

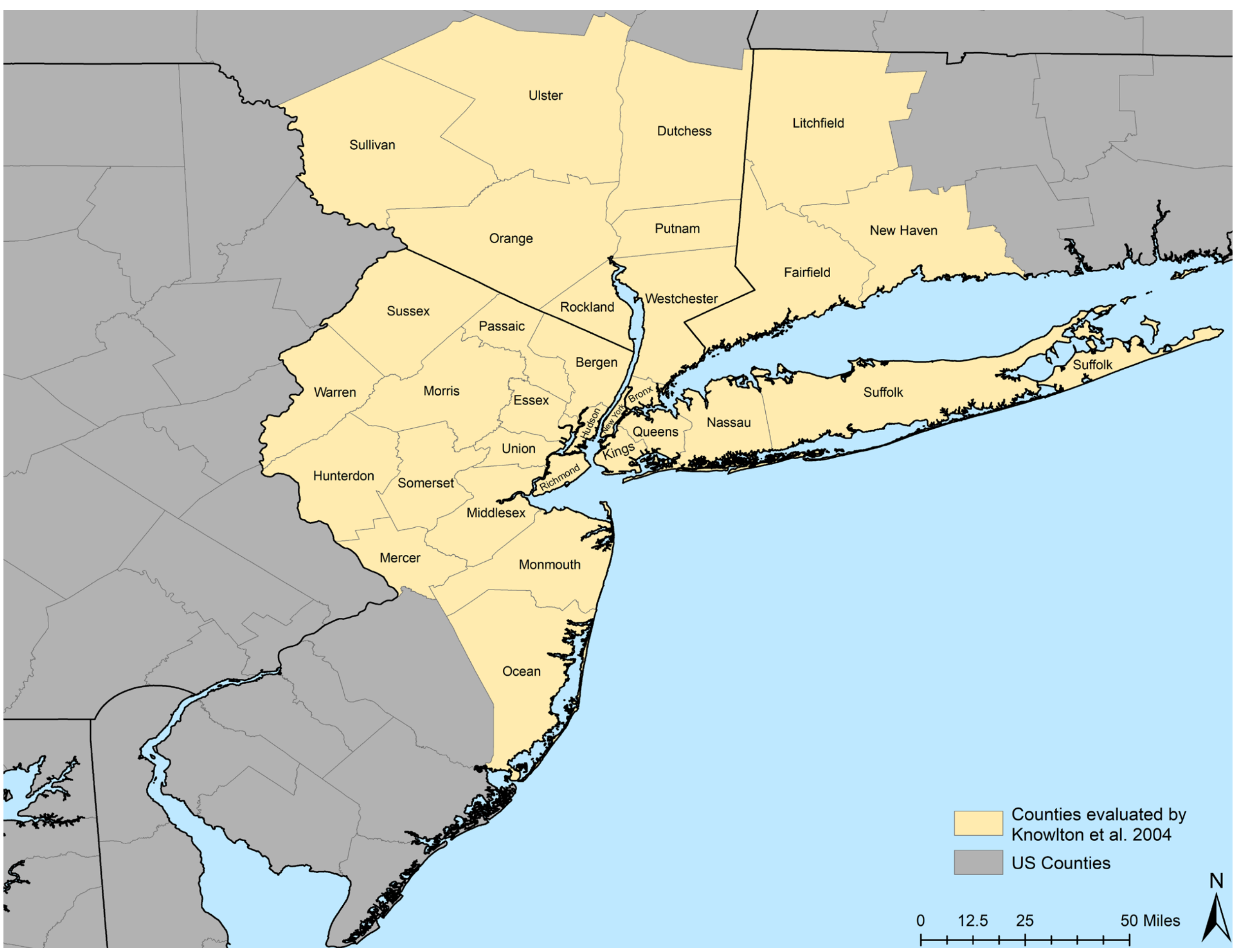

Figure 5.4. Map of the 31-County New York Metropolitan Area. Figure modified from Knowlton et al. 2004.

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daily maximum temperatures. While the change in air quality across the United States will be specific to regional conditions, the increase in ozone concentration due to climate change is predicted to result in a significant increase in additional ozone-related illnesses and premature deaths per year. The economic value of these additional premature deaths, respiratory related hospital admissions, acute respiratory symptoms, and missed days of school illnesses were also estimated by the authors of this study (Fann et al. 2015). These nation-wide costs were estimated to range from $320 million to $1.4 billion for the GISS/RCP 6.0 scenario and from $3.6 to $15 billion for the CESM/RCP 8.5 scenario.

Based on the national results seen in these studies, the impacts for New Jersey are generally more severe than many other states. The specific impacts for New Jersey can be estimated. For the two cases analyzed, average New Jersey temperatures will increase by about 2 - 4˚F (1.1 - 2.2˚C), ozone levels will increase by up to 2-4 ppb in the most affected counties, while other counties were not projected to see these results. It should be noted that numerous important climate change impacted processes that increase ozone levels were not included in the above analysis. For example, emissions from electrical generation units and wildfires were held constant between the current and future periods. Knowlton et al. (2004) modeled ozone deaths in the New York/New Jersey/Connecticut metropolitan area and determined 18 additional ozone-related deaths would occur in 2050 compared to 1950 in the 14 New Jersey counties in the study areas where 80% of the New Jersey population resides, see

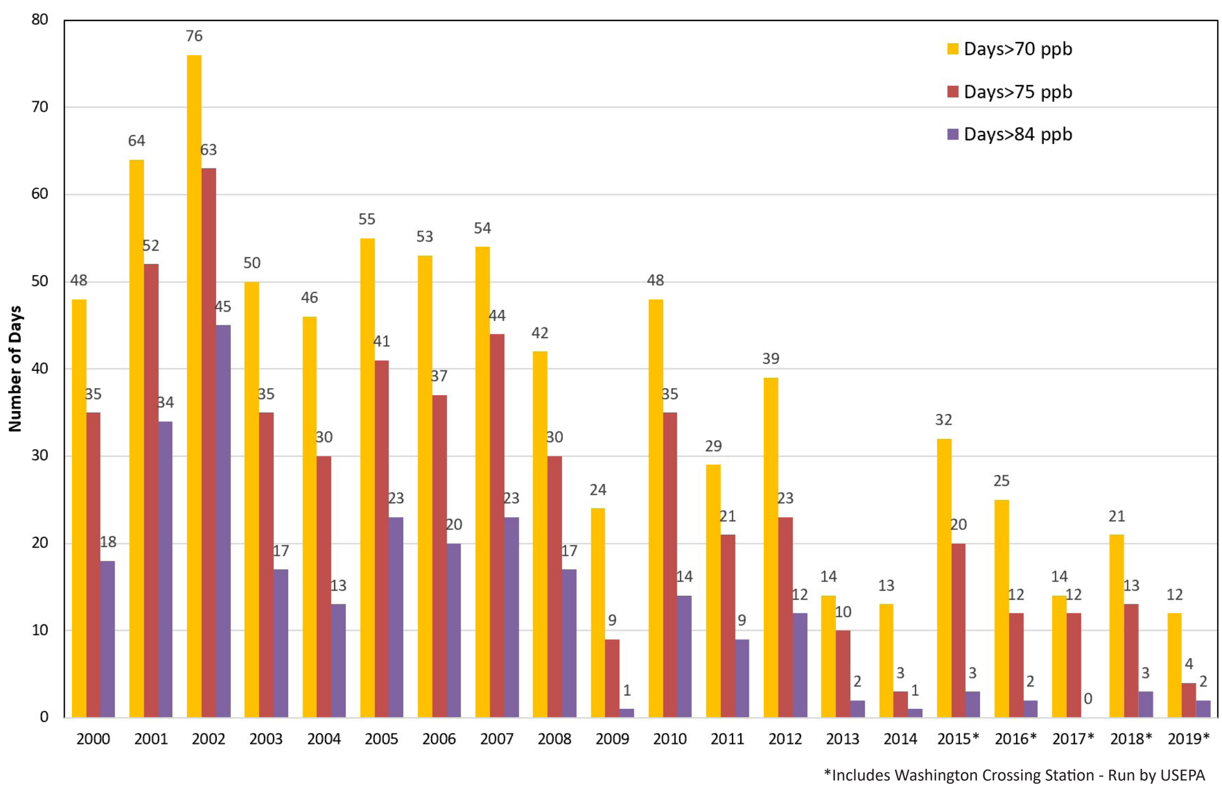


Figure 5.5. The Number of Ozone Exceedance Days in New Jersey. The chart shows the number of ozone exceedance days above the 8-Hour 70 parts per billion (ppb) (2015 standard), the 75 ppb (2008 standard), and 84 ppb (1997 standard) at 16 sites in New Jersey (NJDEP 2020e).

Figure 5.4. Accounting for the remaining counties and their population, it is fair to extrapolate to 22 additional ozone related deaths (range of 13-35 deaths) over the 1950s number. The consensus of the most recent literature is that there generally are climate change penalties for ozone, however the magnitudes are generally lower than earlier studies (Fu and Tian 2019). However, many of the known processes and feedbacks that increase ozone levels due to climate change impacts are still not included in recent modeling studies.

The above analysis focuses on ozone and does not include any increases to human health impacts due to the combined effects of greater air pollution and higher temperatures. There is emerging scientific evidence that the human physiological response to air pollution can be more severe when individuals are also subject to climate-related stressors such as elevated temperature (Fann et al. 2016, Nolte et al. 2018). For example, exposure to a heat wave may increase the risk of dying from exposure to elevated ozone levels (Fann et al. 2016). In urban areas, such as many areas in New Jersey, the hottest days are also often associated with high concentrations of local and transported air pollutants including ground-level ozone (Fann et al. 2016, Nolte et al. 2018). Vulnerable groups that include young children, elderly, socially or linguistically iso¬lated, economically disadvantaged, and those with preexisting health conditions will be more at risk to health impacts from the combination of heat stress and poor urban air quality (Dupigny-Giroux et al. 2018).

In New Jersey, the ozone monitoring season currently lasts from March 1 to October 31, peaking from June 1 through August 31st. Ozone is mainly a problem during the daytime (2 p.m. to 8 p.m.) in summer months when temperature and sunlight are at their peaks (NJDEP 2016). As explained above, meteorological conditions have a significant effect on ozone formation and as climate change results in higher temperatures and drying conditions, New Jersey will likely see an increase in ozone. The Department of Environmental Protection currently measures ozone at 16 sites around the state and has seen a substantial decrease over the last decade in the number of ozone exceedance site days over the 8-hour standard as seen in Figure 5.5.

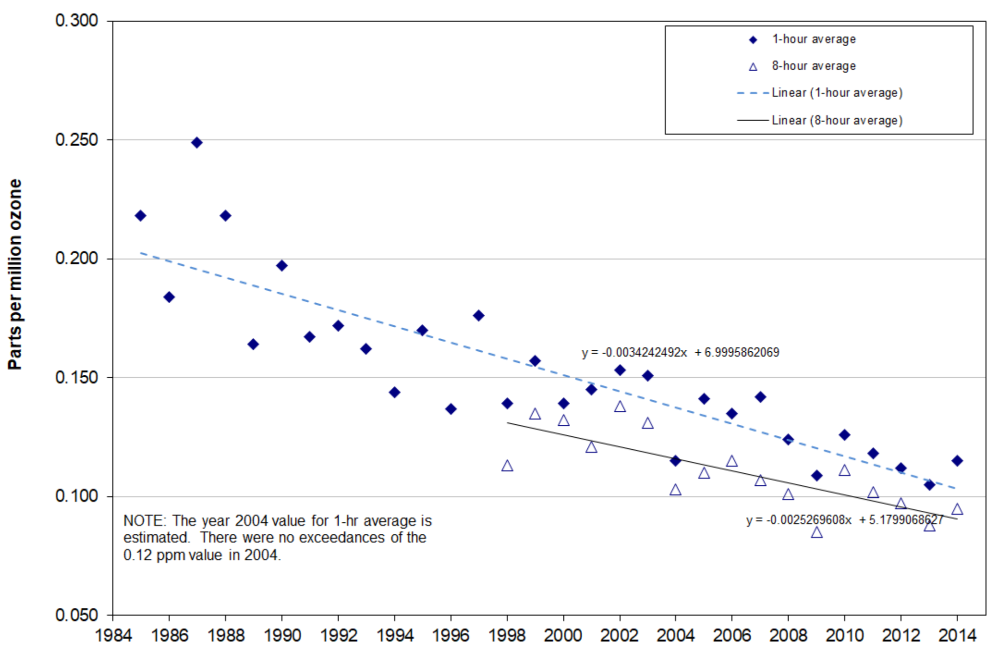


Figure 5.6. Maximum Ozone Concentrations per Year at All Monitoring Sites in New Jersey (1985 – 2014). The solid and dashed lines represent statistically significant linear trends with time (NJDEP, 2016).

Monitoring sites have also shown a decrease in the annual maximum ozone concentrations for the 1-hour and 8-hour periods, as seen in Figure 5.6.

Ground-level ozone is not only harmful to human health, but is also harmful to the environment (NJDEP 2016). Plant life is particularly susceptible, and an increase in ozone exposure has the potential to cause losses in crops and forests.

5.1-1.2 Particulate Matter

In addition to ozone, another important air pollutant for New Jersey is particulate matter (PM). In the atmosphere, PM consists of very small solid or liquid phase matter that is either directly emitted or formed from other pollutants, including ozone precursors (Fann et al. 2016). Sulfate, nitrate, ammonium, organic carbon, elemen¬tal carbon, sea salt, and dust are all examples of the many types of PM. These particles, also known as aerosols, are especially harmful to human health, especially PM smaller than 2.5 microns in diameter (PM2.5) which is associated with serious chronic and acute health effects including premature death, lung cancer, chronic obstructive pulmonary disease (COPD), cardiovascular disease, and asthma development and exacerbation. It is still unclear if changes in PM2.5 or ozone will be the dominant driver of air quality-related health effects due to climate change (Fann et al. 2016, Nolte et al. 2018).

Historically, many New Jersey counties have experienced PM2.5 pollution levels that have exceeded federal health-based air quality standards. New Jersey has taken many actions to address PM2.5 pollution and as a result, the entire state was determined by the Environmental Protection Agency (EPA) to have met the health standard in 2013 (Federal Registry Volume 78, Number 171. September 4, 2013. New Jersey: Resignation of Areas for Air Quality Planning Purpose). However, compliant levels may not occur in populated areas as localized exposure can be orders of magnitude higher than spatially averaged values. Despite this, concentrations of PM2.5 remain higher than they would be without human-caused, or anthropogenic, sources. Consequently, PM2.5 will continue to cause significant health effects for New Jersey residents because there is no level of PM2.5 that will not cause negative human effects.

Meteorological conditions and emissions also affect PM2.5 levels in the atmosphere (Fann et al. 2016, Nolte et al. 2018). While regulatory controls are expected to continue to reduce emissions of sulfur dioxide (SO2), NOx, and black carbon in the United States, PM2.5 concentrations are still expected to increase due to wildfires, dust generation from droughts, increased heat causing increased evaporation of PM2.5 components such as ash, dust, sea salt, water, organic carbon, and elemental carbon, and increased emissions from certain anthropogenic sources. There is no consensus yet if the meteorological changes that will cause increases in PM2.5 emissions will lead to a net increase or decrease in PM2.5 levels in the United States because of the many factors involved in this type of projection (Fann et al. 2016). The changing meteorological conditions that have the most impact on PM levels include increased stagnation, altered frequency of weather fronts, and more frequent heavy rain events.

As discussed later in this report, the number and magnitude of wildfires are expected to increase in the United States and possibly in New Jersey (see Chapter 5.4-5) as a result of climate change (Fann et al. 2016). Wildfires are currently a major source of PM2.5, especially in the western United States, during the summer months (Fann et al. 2016, Nolte et al. 2018). Release of PM2.5 and ozone precursors from wildfires can be transported significant distances and can cause impacts to air quality in these downwind locations.

Air quality in New Jersey has recently been impacted by air pollution from wildfires in the western United States and Canada (NJDEP 2017b). For example, a wildfire in Alberta, Canada, from May 1 to July 5, 2016 consumed about 1.5 million acres (which is an area 1.5 times bigger than New Jersey's Pinelands), forced over 80,000 residents out of their homes, and destroyed about 2,400 buildings. Because of the emissions from this Canadian wildfire, 16 out of 17 air quality monitors in New Jersey recorded exceptionally high ozone levels that exceeded the ozone health-based standard on May 25, 2016. Concentrations of PM2.5, which are also associated with fires, were also elevated during the elevated ozone event. These levels were similar to the levels found in New Jersey's air when a nearby wildfire earlier in the month caused elevated levels of PM2.5. (Letter from Mr. John Filippelli, Director USEPA Clean Air & Sustainability Division to Mr. Francis C. Steitz, Director NJDEP Division of Air Quality, October 24, 2017.)

5.1-1.3 Aeroallergens

An aeroallergen is any airborne substance that triggers an allergic reaction caused by hypersensitivity of the immune system to certain substances. Examples of aeroallergens include tree, grass, and weed pollen; indoor and outdoor molds; and other allergenic proteins associated with animal dander, dust mites, and cockroaches. People in the United States are most commonly affected by the pollen from ragweed. Allergic diseases resulting from aeroallergens include hay fever and allergic asthma (Fann et al. 2016).

Allergies or allergic diseases develop in response to complex interactions, including genetic and non-genetic factors, environmental exposures, and socioeconomic and demographic factors (Fann et al. 2016, Nolte et al. 2018). The scientific literature indicates a high likelihood that the concentration, allergenicity, season length, and spatial distribution of various aeroallergens will increase with climate change (Nolte et al. 2018), posing serious health risks with respect to asthma, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis (Fann et al. 2016, Nolte et al. 2018).

An example of this is that within the United States over 34 million peopled have been diagnosed with asthma and about one-third of the population is affected by an allergic illness (Fann et al. 2016). According to New Jersey State Health Assessment Data (2019), the prevalence of hay fever and asthma have increased over the years. Approximately 30% of the population in 2000 had hay fever, up from approximately 10% in 1970. Asthma rates have increased from about 8 to 55 cases per 1,000 people to about 55 to 90 cases per 1,000 people during the same time period. In New Jersey, over 600,000 adults (9.0% of the populations) and 167,000 children (8.7% of the population) are estimated to have asthma. Children, African American, Hispanic, and urban residents are most likely to be affected by asthma. Health risks may increase for individuals who are exposed simultaneously to both aeroallergens and air pollution, especially particulate matter (Nolte et al. 2018). Related symptoms can cause individuals to miss work or school (NJ DOH 2019). Serious asthma attacks may result in hospitalization; though most are successfully managed without it. Many people with asthma prevent serious attacks by avoiding known triggers, but that could become more difficult due to climate change.

Asthma and hay fever are expected to worsen due to the effects of climate change which will increase airborne allergen exposures (Nolte et al. 2018). The longer frost-free seasons, changes in precipitation, and higher levels of atmospheric CO_2 are expected to result in increased exposure to pollen allergens in New Jersey and elsewhere (Fann et al. 2016).

There is substantial evidence that supports the conclusion that climate change and rising CO_2 concentrations affect major facets of aeroallergen biology (Nolte et al. 2018). These facets include production rates, timing of releases, and the potential for the severity of allergic reactions to aeroallergens. Changes in seasonal exposure times for allergenic pollen have been observed and correlate with rising CO_2 levels, higher temperatures, and altered precipitation patterns. Trends show climate change has extended the growing season for some allergenic pollens by lengthening the frost-free period (Fann et al. 2016). Increases in CO_2 and temperature result in acceleration of flowering, increased pollen production and floral numbers, as well as allergenicity of pollen. These changes result in more exposure to aeroallergens, which in many cases cause increases in allergic disease. As discussed in Chapter 4.1-3, over the period of 2000-2015 in New Jersey, months with a top-5 average temperature have occurred 32 times while none of the months in that same period record a top-5 coldest average temperature (Runkle et al. 2017). This is supported by the observation that annual precipitation over the most recent 10-year period in New Jersey was 8% above the long-term average. Allergy symptoms can be exacerbated by the changes in local weather patterns, such as rainfall and changes to minimum and maximum temperatures (Fann et al. 2016).

5.1-2 Indoor Air Quality

Climate change is likely to worsen indoor air problems as outdoor air can enter buildings through open windows, under doors or through cracks in the building (Fann). When air infiltrates a building this way, it bypasses filtration systems exposing inhabitants to air pollutants. Poor indoor air quality is linked with adverse respiratory and other health effects.

Outdoor weather conditions can also affect indoor air quality through the same infiltration described above. As droughts and dust storms become more frequent, dust particles carrying dust-borne pathogens are more likely to infiltrate buildings and increase the allergic potential of indoor air (Fann et al. 2016). In addition, as climate change results in weather events of increased severity and increases in humidity, the affect is an increase in potential water/moisture damage to buildings and a higher potential for dampness and condensation indoors, creating more ideal environments for mold and bacteria growth. More extreme weather events could cause additional power outages, disabling any control systems meant to regulate air conditions such as temperature, humidity or circulation (Runkle et al. 2017), further worsening these conditions. This was the case in 2012, when New Jersey experienced Hurricane Sandy. Powerful storm surges and the accompanying rainfall caused substantial damage and allowed water to infiltrate structures in the impacted area. The conditions the storm created were ideal for numerous molds and bacteria. Power loss rendered heating, ventilation, and air conditioning systems useless, making it difficult for many buildings to maintain indoor temperature, humidity and keep up ventilation, filtration and circulation. Additionally, the use of portable generators to power appliances in lieu of normal power supply can lead to carbon monoxide poisoning if used improperly. As discussed previously in this report (Chapter 4.2-4), it is generally believed that climate change related factors such as ocean temperatures and increasing sea levels will strengthen storms and their impacts.

- Water supplies will be stressed from the increase in the growing season and extreme temperatures expected due to climate change.
- Rising sea levels may lead to increased saltwater intrusion in New Jersey aquifers where wells are over pumped.
- Freshwater intakes and aquifer recharge areas may be threatened if sea-level rise pushes the salt front further upriver.
- Combined sewer overflow communities may be further challenged as sea-level rise and/or increased rain events submerge discharge points that are currently above the waterline.
- Surface and groundwater quality will be impaired as increased nutrients and contaminants enter waters due to runoff from more intense rain events.

CHAPTER 5.2

WATER RESOURCES: SUPPLY AND QUALITY

STOKES STATE FOREST, NEW JERSEY

5.2 Water Resources: Supply and Quality

Climate change has been shown to have a multitude of effects on our planet and specifically to New Jersey. Of particular concern to New Jersey water supply managers are temperature (Chapter 4.1), precipitation (Chapter 4.2), and changes to sea-level (Chapter 4.3). These three factors have a significant effect on the amount of available water, where and when it is available, and on its quality. They can place additional or new stresses on the treatment and infrastructure for drinking water, wastewater, stormwater, and on aquatic ecosystems. It is thus critical to update procedures within any planning process to ensure that the most recent scientific consensus, data, and models are considered.

Throughout the United States, aging public water supply infrastructure and demands are vulnerable to the consequences of climate change. According to the 2017 Statewide Water Supply Plan, New Jersey citizens withdraw on average 1.8 billion gallons of water per day, with 75% coming from surface water, 17% from groundwater from unconfined aquifers (water table aquifer; aquifers where water can directly recharge from precipitation), and 8% from confined aquifers (aquifers where recharge is restricted by impermeable layers) (NJDEP 2017a). In 2015, about 70% of the withdrawals were used for potable (drinking water) supply, with power generation, commercial/industrial/mining, and agricultural/irrigation making up the remaining 30%. The source and use of water vary across the State in response to climatic conditions and over time. Sub-annual use patterns vary depending upon the specific use type and socio-economic factors. In addition, the fraction of consumptive and depletive use varies by season, use type, and individual user. Even with these variations, withdrawals have generally been sustainable due to a combination of abundant rainfall (on average), a physiography which allows for water storage, and adequate management and regulatory actions. Additionally, apart from power generation, total water use has remained relatively stable over the last decade (NJDEP 2017a). While New Jersey receives what many regions would consider a significant amount of precipitation, 46 inches (117 cm) per year on average, it also has an ecology and economy that are dependent upon those average amounts. Climate change has the potential to change the quantity and quality of water available and increase the variability of each, which in turn can create both environmental and water supply stresses.

New Jersey's water supply, from both ground and surface water, will be continually subjected to and at risk of the effects of climate change. The increase in the growing season and extreme temperatures will put more stress on water supplies while peak water demands will last longer. Water quality changes are also likely to require additional drinking water treatment and monitoring and may limit the use of water supplies for some industrial, agricultural, or recreational uses. Longer periods of low-flow conditions in streams, punctuated by more frequent and intense extreme precipitation events, will result in challenges to maintain water quality. Changes in temperature ranges, nutrient loads (nutrients inputs into the water), and reductions in dissolved oxygen levels will have the greatest effect on sensitive aquatic life. These changing conditions are likely to alter the species assemblages that reside in New Jersey (see Chapter 5.8-1 for more information).

5.2-1 Groundwater

5.2-1.1 Groundwater Supply

Groundwater is an important source of water in New Jersey (Figure 5.7). In addition to sustaining baseflow in streams, it supplies 25% of the total statewide water supply needs. In some regions, like in the Atlantic Coastal water region, it accounts for over half of the total withdrawal. For smaller self-supplied users, groundwater is the only economical source of water available. This is especially true for the almost 400,000 private domestic wells spread across the state.

Groundwater resources are extracted from either unconfined or confined aquifers. Unconfined aquifers receive recharge from precipitation and direct infiltration. They may also gain water from or lose water to underlying aquifers. Confined aquifers are those where recharge is restricted by impermeable layers. Confined aquifers ultimately get their water from groundwater recharge, but the age of the water can be thousands of years old and travel times can be centuries for deeper units. Not all aquifers are created equal; some are barely productive enough to meet potable domestic well needs while others can produce thousands of gallons per minute for large industrial, irrigation, or public water supply sources. Groundwater availability is a complex function of the timing

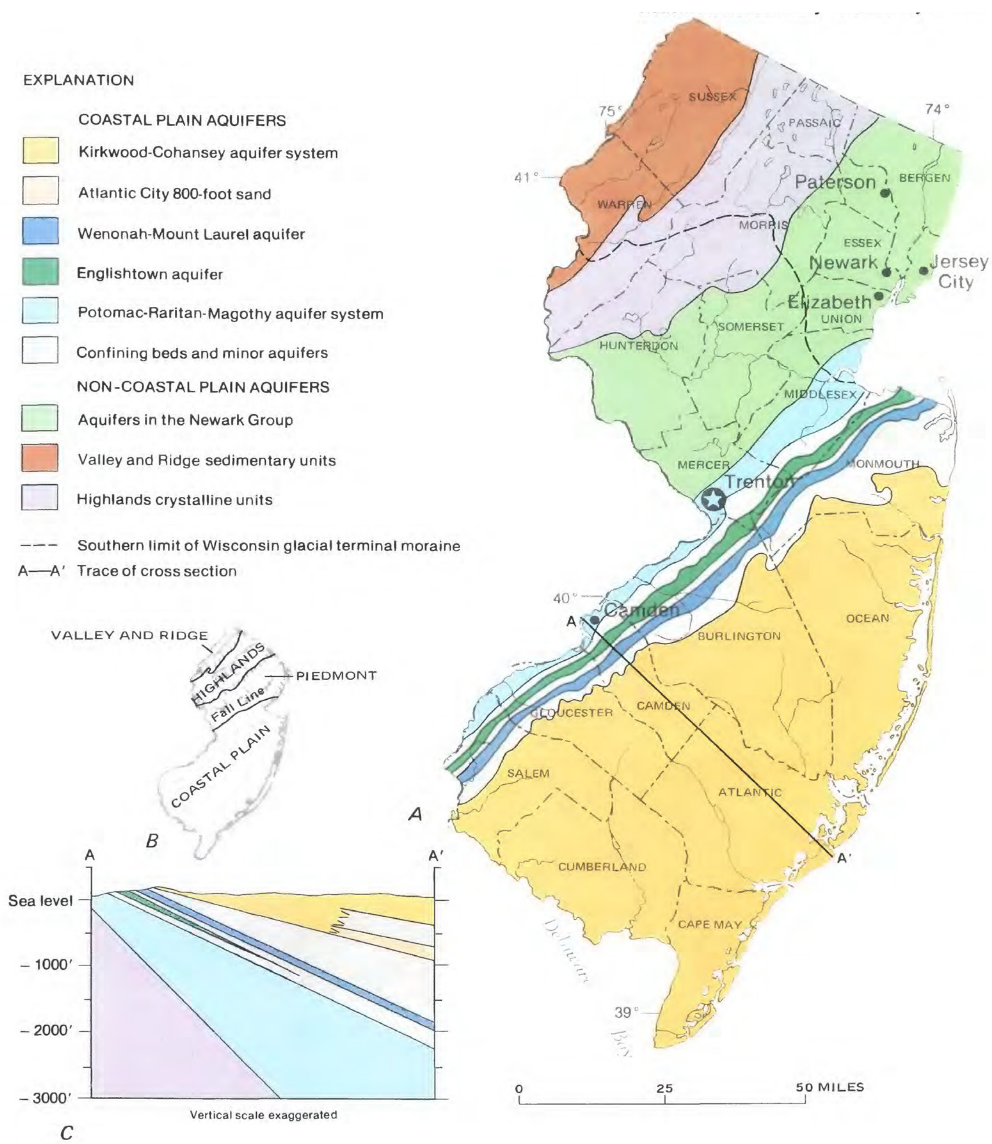


Figure 5.7. Principle Aquifers of New Jersey. Adapted from (USGS 1985).

and magnitude of recharge and the aquifer's hydrogeologic properties. Groundwater recharge is the mechanism that conveys precipitation to our aquifers. It is an even more complex function of the timing and magnitude of precipitation, surface water runoff, land cover, evapotranspiration, and the soil moisture (New Jersey Geological and Water Survey 1993).

Due to concerns with over pumping and depletion of aquifers during normal and drought conditions, New Jersey passed the Water Supply Management Act in 1981, giving the State the authority to respond to those concerns though a variety of regulatory, planning and scientific actions. These include a robust water allocation and well permitting program, the declaration of two groundwater-supply critical areas, water supply master plans, numerous scientific reports on groundwater recharge including water level assessments conducted within a relatively short period and under specific hydrologic conditions.

Climate change will influence the volume and rate of groundwater recharge in several ways. As temperatures increase and the growing season lengthens, there will be greater demand for water for irrigation use (e.g., crop, nursery, golf course, and outdoor residential), putting more stress on the water supply. Water demands peak in warm weather, and even more so during heat waves. These peaks occur the same time that natural resources are typically most limited. Changing precipitation patterns (frequent, intense rainfall with extended dry periods) coupled with increased temperatures will affect groundwater recharge and hence discharge. Groundwater recharge projections are closely related to projected changes in precipitation. Predicting how the combination of precipitation and temperature change will affect recharge is difficult because model results vary greatly due to the unpredictability of future precipitation events. More intense precipitation will hit the Northeast United States, but it is not certain how daily rainfall (or lack thereof) will affect recharge. An Australian study predicts that with the increased precipitation, evapotranspiration will increase due to more plant growth resulting in less recharge (Taylor et al. 2013). Under both a low emission and high emission scenario, a USGS study (Bjerklie and Sturtevant 2018) of potential climate change impacts on a glacial unconfined aquifer system in New Hampshire (similar to those present in northern New Jersey), predicted that overall groundwater levels and baseflow in rivers will decrease, but that the changes varied over the year. While temperature and precipitation increases are predicted to change the quantity of available groundwater supplies across the United States, another looming threat is the impact to the quality of groundwater, particularly saltwater intrusion, due to overuse and sea-level rise. More work is needed to evaluate the range of potential changes to groundwater recharge from climate change.

5.2-1.2 Groundwater Quality

Groundwater is susceptible to various sources of contamination that can ultimately impair the water quality. Few studies detail the effects that climate change may have on groundwater quality and those that do often include high levels of uncertainty due to the complexity in coupling climate models with the multitude of factors that govern groundwater dynamics (Green et al. 2011). Of concern is the potential for contamination from the mobilization of microbial pathogens, pesticides, and fertilizers rich in nitrogen and phosphorus from agricultural fields (Hamilton and Helsel 1995, USGS 2012) following heavy rains. Additionally, increased periods of wet and dry conditions, have the potential to influence the release and mobilization of contaminants, including arsenic (Bondu et al. 2016, Levitt et al. 2019) in the bedrock region of the state. Shifts in subsurface geochemistry (redox and desorption of contaminants) can lead to water chemistry and ultimately groundwater quality changes. Such changes may stem from changes in groundwater pumping rates due to drought; including a need for pumping from deeper depths or shifts to groundwater as surface water sources are reduced. Alternatively, reductions in the depth-to-groundwater due to increased precipitation and subsequent infiltration/recharge, can influence water quality. Additionally, increased sea levels

> ***"Changing precipitation patterns...coupled with increased temperatures will affect groundwater recharge and hence discharge."***

may also threaten coastal groundwater quality as the interface between fresh groundwater and saline groundwater will likely move inland, posing a specific threat to the Kirkwood-Cohansey Aquifer (Fiore et al. 2018). Degradation of water quality due to increased groundwater salinity may prevent certain wells from being used as drinking water sources, and effectively limit use to agricultural or industrial purposes (Green et al. 2011). New Jersey has an extensive systematic monitoring network to evaluate chemical and physical parameters in groundwater. This network aids in assessing water quality as well as potential impacts on the water supplies.

5.2-1.3 Saltwater Intrusion

Increased rates of groundwater pumping are known to, and rising sea levels associated with climate change may lead to, increased saltwater intrusion in New Jersey aquifers . The magnitude and extent of those impacts will vary depending on the hydraulic connection between the source of saltwater and the freshwater portion of the aquifer, the magnitude of sea-level rise, and the proximity to water supply wells. To date, most saltwater intrusion issues are associated with over-pumping of wells near either seawater or connate saline water (saltwater trapped in rock pores).

Not all of the aquifers used in New Jersey coastal areas are connected or proximate to saline water sources. For those that are, the distance to the salt front can vary, so the risk of saltwater intrusion is not solely a function of proximity to the ocean or bay but rather more dependent on groundwater pumping and withdrawals in these areas (McAuley et al. 2001, Lacombe and Carlton 2002). Areas that have already experienced saltwater problems due to overpumping include:

- Diversions in Cape May County south of the county airport from deeper wells and along the Delaware Bayside from shallower wells. These issues are due primarily to over pumping of groundwater sources near saltwater.
- The Raritan Bay communities of Union Beach, Keyport, and Keansburg were over pumping wells in the Potomac-Raritan-Magothy (PRM) aquifer system, (see Figure 5.7) so they moved to inland sources. These aquifers have water levels below sea-level and the aquifer appears to be connected to the bay.
- The PRM aquifer system in the Camden-Gloucester County region is affected by increased salt concentration in some wells where over pumping has occurred in the areas of inland connate sources.
- Recharge of the PRM aquifer system primarily occurs from the freshwater reaches of the Delaware River in much of the Camden-Gloucester County region. As sea-level rise moves the salt front further upstream in these recharge areas, saltwater intrusion may occur.

An increased use of water supplies will, and sea-level rise may, lead to saltwater intrusion problems in some parts of the State. Along the coast, aquifer withdrawal limits have been established to address increasing saltwater intrusion concerns (Millsaps 2016). Efforts to combat saltwater intrusion, like the construction of desalination plants, may be complicated if systems are vulnerable to coastal flooding and storm surges. Injecting water into aquifers has been shown to buffer saltwater from freshwater in California and Florida (USGS 2020).

Saltwater intrusion poses a potential risk to New Jersey groundwater supply and more analysis is needed to determine the magnitude and extent of that risk. The DEP and the USGS currently monitor and map water levels and chloride concentrations in New Jersey confined coastal plain aquifers. This mapping was first produced in 1978 and is remapped on a 5-year cycle. Future updates to the Water Supply Plan will further evaluate the potential for sea-level rise induced salt-water intrusion.

5.2-2 Surface Water

5.2-2.1 Surface Water Supply

Surface water withdrawals represent about 75% of New Jersey's total water use. This is especially true for more populated areas where demands exceed the available supply of groundwater, like the central and northeastern regions of New Jersey (NJDEP 2017a). Climate change has the potential to change the timing and magnitude of streamflows, as well as increase the variability of flows over multiple timescales. Warming air temperatures will increase water temperatures, which along with increased extreme precipitation events, will lead to water quality changes. Such changes, like increased turbidity and excess nutrient inputs and subsequent eutrophication to reservoirs and drinking water supplies may pose treatability issues. Some of those changes may stress the water treatment processes required by the Safe Drinking Water Act or limit use for other non-potable uses. Sea-level rise will push the saltwater-freshwater interface (location where salt and freshwater meet in a waterbody or the saltwater front) further upriver and threaten intakes, aquifer recharge areas, and the aquatic ecology. Extreme dry periods or flash droughts may temporarily push the salt front even further upstream.

The advancement of the salt front is of particular concern because existing surface water intakes and treatment plants are not designed to treat elevated salt levels. Increased salinity can lead to corrosion within older lead drinking water service lines and may release lead if not properly controlled. Additionally, there are no primary drinking water standards for chloride and sodium, both components of saltwater, although secondary standards do exist.

In the Delaware estuary, there are large potable supply intakes in Delran, New Jersey, and Philadelphia, Pennsylvania, as well as numerous industrial intakes. Historically, the salt front on the Delaware River came within eight miles (13 km) of those intakes during the 1960's drought. A repeat of those drought flows under a warmer climate and exacerbated by sea-level rise will move the salt front even further upriver. Along the Delaware River, the salt front is predicted to move 6.8 miles (11 km) upstream based on a scenario where sea

OVERFLOWING MANHOLE

"As precipitation events become more intense, the design of current stormwater infrastructure will be less efficient and the size of stormwater management systems will need to be modified to minimize the risk to communities from increased nuisance flooding and reduce the risk of ecological impacts."

level rises 2.4 ft (73 cm) by 2100 (Najjar et al. 2000). The Delaware River Basin Commission and USGS are currently modeling the flow management programs and the possible effects of sea-level rise on the salt-front to understand how much further it might move upstream and what other resources might be at risk (Delaware River Basin Commission 2019). During drought the Delaware River Basin Commission regulates upstream reservoir releases to help maintain the location of the salt front in the Delaware estuary. In the event of a drought, the effectiveness of these releases would likely be reduced, and saltwater could impact the water supply. There are similar concerns along smaller estuaries along the Atlantic Coast and Barnegat Bay where infrastructure could also be impacted. In the Hudson River waterfront and Newark Bay region of New Jersey, most water supplies are piped in from the New Jersey Highlands region, so while the source water in these areas may not face the same risks, the infrastructure that delivers the treated drinking water to its customers may.

5.2-2.2 Streamflow

The regional hydrologic systems in the Northeastern United States will be affected by the increase in precipitation events (Melillo et al. 2014) that are expected to result from the climate changes discussed so far in this report. However, when and how intense those events will be is uncertain. An increase in extreme precipitation events and annual precipitation has the likelihood to alter streamflow patterns and impact surface water supplies. Competing climatic forces complicate the ability to predict future annual streamflow. Increased precipitation alone would increase streamflow, especially following significant isolated heavy rains. In a warmer climate, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) is expected to increase while soil moisture will decrease. Both evapotranspiration and soil moisture will collectively reduce and perhaps offset streamflow increases (DeWalle et al. 2000, Luber et al. 2014, Wasko and Sharma 2017). Although, a study by Milly and Dunne (2017) strongly suggest that drying conditions due to increased evapotranspiration are being "systematically and substantially" overestimated in streamflow analyses and thereby masking potential streamflow increases.

The hydrologic dynamics of waterways can also be greatly altered by the sediment load in streams and rivers that result from runoff and in-stream erosion (IPCC 2018b). While long term increases of high streamflows have been reported in New Jersey, the trends do not appear to be directly related to increases in precipitation, especially in undeveloped watersheds (Watson et al. 2005). Some of the observed increases are likely due to increases in urbanization or associated increases from runoff (Melillo et al. 2014). The uncertainty between these forces complicates the ability to predict the magnitude and extent of future streamflow.

A projected increase in winter precipitation and temperature is expected to reduce snow accumulations and effectively shift the timing and extent of winter and spring flows in the Delaware River Basin (Williamson et al. 2016). Accordingly, winter flows will increase due to reduced snowpack and subsequent additional rainfall. Spring snow melt will occur earlier with less volume resulting in reduced spring flows. Additionally, short duration streamflow spikes and three-day peak flows are projected to increase as a result of more intense precipitation events while low-flows, including the 7-day low-flows, are expected to decrease, exasperating low-flow conditions (Demaria et al. 2016). The length of the low-flow season, defined as May through October, is projected to increase by up to five days on average by mid-century.

Evapotranspiration is expected to increase in the Northeastern United States with greater rates during the summer and fall leading to reduced soil moisture storage and ultimately altering runoff patterns and streamflow responses.

Temporal changes to regional groundwater levels also need to be considered when evaluating potential climate-induced changes to streamflow. Reductions to groundwater recharge, due to increased rates of evapotranspiration or drought conditions, can greatly influence surface water flows since a significant proportion of baseflow can come from groundwater discharging to the stream. In New Jersey, this a particular concern especially in the Pinelands region where groundwater can constitute over 80% of annual flows (Rhodehamel 1998). While historic streamflow trends that evaluate average, high, and low flows are present for specific monitoring stations throughout New Jersey (Watson et al. 2005) with a future update expected to include trends through 2017 (Broccoli et al. 2020), it is not appropriate to assume such changes are due solely to changes in precipitation or climate. While both are contributing factors, historic changes may be driven primarily by temporal changes in land-use, agriculture, and water withdrawals and diversion (Watson et al. 2005).

Climate-driven simulations of projected streamflow and precipitation were evaluated in the Northeast United States. One particular study projected a slight increase in streamflow under mid-range greenhouse gas emissions (RCP 4.5) and showed no statistical increase in streamflow under higher long-term emissions (RCP 8.5) despite a projected increase in precipitation (Demaria et al. 2016). The United States Geologic Survey (USGS) used a Precipitation Runoff Modeling System (PRMS) in New Hampshire that estimated monthly projected changes to the state's streamflow (Bjerklie and Sturtevant 2018). The results showed that streams will see a larger range of high flows to lower flow as a result of climate change. Overall, the study shows that New Hampshire's rivers and streams will become more unpredictable due to localized changes in precipitation (Bjerklie and Sturtevant 2018). Similar unpredictability can be assumed for New Jersey.

5.2-2.3 Reservoir Systems

Reservoir systems are designed to capture high flows and store that water for later use when the natural flows are not adequate to meet demands. In New Jersey, an extensive reservoir network has been established and management of this network dates back to the late 1800s (NJDEP 2017a). This intricate network of reservoirs is ideally suited to meet the increased streamflow variability likely under future climate change. There are limits to what those systems can store, treat, and deliver. It is quite possible that future variability and increased floods can overwhelm the capacity of each system. Systems that rely on water being pumped to the reservoir for storage are likely to be more at risk due to the nature of streamflow variability predicted under climate change. For example, reservoirs may be filled to higher than usual capacity following floods and lower low-flow conditions in streams may prohibit pumping to fill reservoirs for longer periods of time. Over the last decade, the DEP has developed computer models for the major surface water reservoir systems that can be used to evaluate the impact of hydrologic changes. Under current drought-of-record flows (varies according to system), the research and preliminary modelling conducted by the DEP Division of Water Supply & Geoscience shows that coordinated operations and the ability to move water between systems is key to maintaining adequate supplies and preventing unwanted shortages (NJDEP 2007). These drought responses are also likely to be valid under climate change, at least in the near term, where there is more variability, more variance between high and low flows and short, intense drought periods.

5.2-2.4 Surface Water Quality

New Jersey's streams, rivers, and lakes will be affected by changing weather patterns. In areas where temperature increase has been the largest climate change driver, organic matter, nitrates, and phosphorus have affected water quality (IPCC 2018b). Increased variability in precipitation, will also pose significant threats to the State's waters. Wetter winters and springs, for example, will lead to greater seasonal runoff, transport excess sediment and contaminants, and increase in-stream erosion. Changes in precipitation, especially increases, will increase the rate of streambank erosion. Changes would be more likely in alluvial (loose sediment) stream channels while bedrock channels will be less sensitive to increased rates of erosion. Increased rates of erosion will ultimately lead to an increase in sediment delivery downstream and subsequent increases in total dissolved solids (TDS), conductivity, and turbidity (Goudie 2006). In turn, the increased sediment load can alter the stream discharge or volume of water passing a point per second. Collectively, increased water temperature along with increased nutrients and TDS amplifies the potential for reduced dissolved oxygen levels in waterways, especially in summer (USGCRP 2017).

Increased precipitation will likely mobilize nutrients, which will cause an increase in surface water nutrient loading. Within these waters, this will lead to eutrophic conditions (the condition when excess nutrients in water from runoff causes excess plan growth, that leads to a lack of oxygen, and results in species death in the system) in watersheds of the Northeastern United States. The magnitude of nutrient mobilization and the increase in eutrophic conditions is uncertain (Sinha et al. 2017). This nutrient loading and warming of waters also poses the potential to stimulate rapid and excessive growth of harmful algal blooms (HABs; see Chapter 5.10 for more information) (Sinha et al. 2017, Ho et al. 2019). Due to increased runoff, surface waters and water supplies in proximity to agriculture practices are at particular risk for nutrient loading because of the additional input of microbial pathogens and nutrients. In an effort to track changes in stream quality, New Jersey has an extensive systematic monitoring network to evaluate chemical and physical parameters in lakes and streams which will aid in assessing surface water quality and impacts on the State's water supplies and aquatic biology.

Besides posing increased challenges and risks to drinking water operations, changes in water quality and quantity will also impact aquatic habitats. Aquatic habitat and populations are strongly guided by hydrogeomorphic variables and channel characteristics including streamflow variability, substrate size, bedload sediment, and flooding frequency (Resh et al. 1988). Environmental factors, including water temperature and water chemistry also contribute to the maintenance of suitable habitat (Richter et al. 1996). Changes in any of these factors can lead to changes in species diversity and habitat availability (Beschta and Platts 1986, Poff et al. 1997, Bunn and Arthington 2002, Kennan and Ayers 2002) and may lead to community shifts (Vannote et al. 1980, Junk et al. 1989). Changes in the natural flow regime, primarily the magnitude and frequency of streamflow, may lead to alterations to the stream channel form (Wolman and Miller 1960) and structure (Leopold et al. 1964) which may also ultimately contribute to altered aquatic ecosystems (Poff et al. 1997, Postel 2000, Arthington et al. 2006, McKay and King 2006). This is shown specifically in the Pinelands area of New Jersey (Laidig et al. 2010, Procopio 2012, Laidig 2012).

5.2-3 Stormwater and Discharges to Surface and Groundwater

As a result of changing climatic conditions, surface water bodies may experience increased nutrient and other pollutant loads from groundwater and surface water sources including stormwater runoff. As precipitation events become more intense, the design of current stormwater infrastructure will be less efficient (Wright et al. 2019) and the size of stormwater management systems will need to be modified to minimize the risk to communities from increased nuisance flooding and reduce the risk of ecological impacts. Based on recent and expected changes to precipitation patterns, precipitation depths associated with current storm probabilities may not adequately represent current or near-future conditions (Kunkel et al. 2013, Marsooli et al. 2019). For example, a 100-year 24-hour storm, which describes the depth of rain that has a 1% chance of occurring within a 24-hour period, is based on the

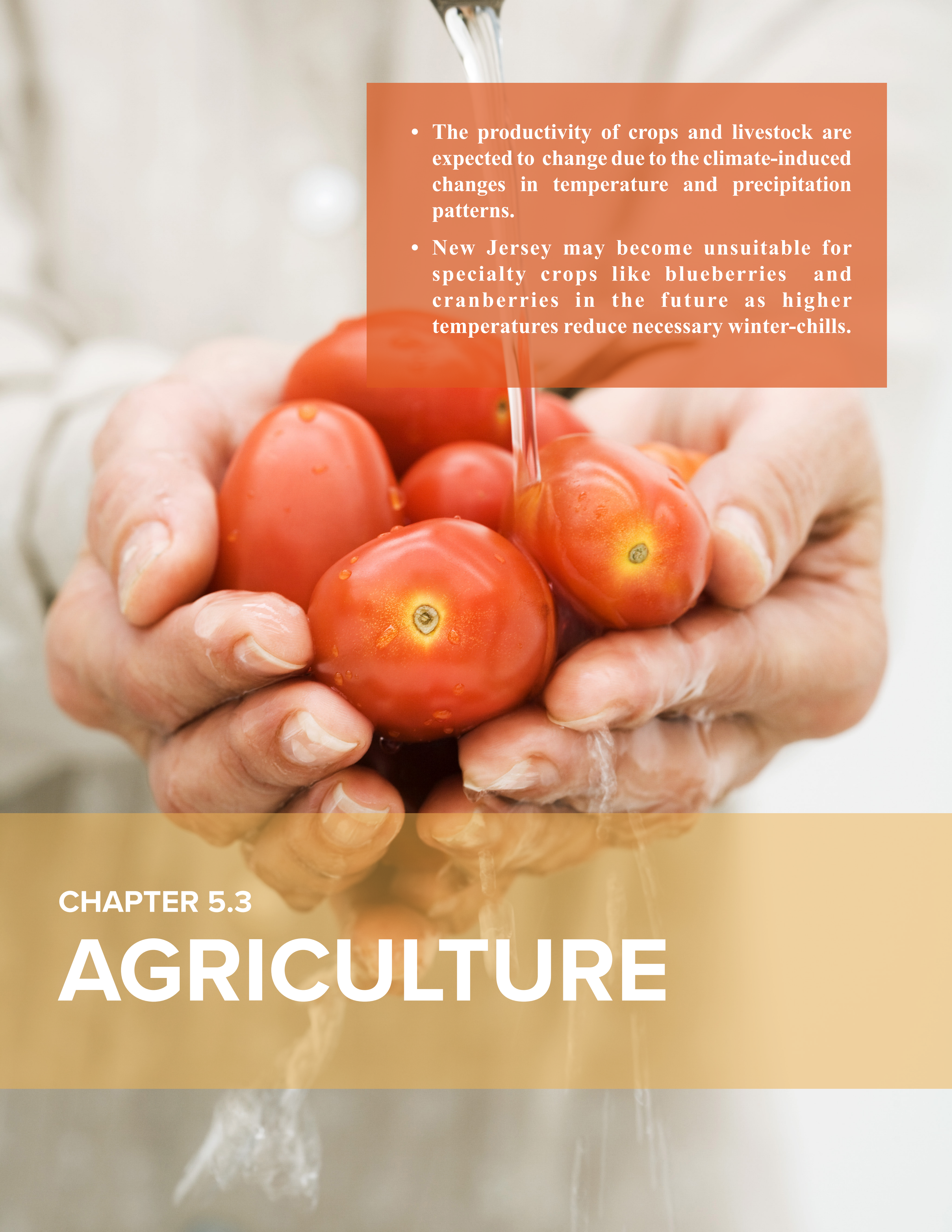
"…changes in temperature, more intense precipitation events, and rising sea-levels will impact New Jersey waters."

likelihood of occurrence as measured from historic data (Bonnin et al. 2006). As future precipitation events become more intense, this historic data may no longer represent actual or current conditions. To ensure storm and flood mitigation measures are met into the future, Wright et al. (2019) suggest using the upper bound of the confidence interval (90%), rather than the average, to describe the precipitation depth, associated with storms of interest.

Stormwater recharge will become a challenge in communities as flooding will likely increase over time, requiring additional investment in infrastructure and other solutions. Discharge to surface water systems that combine stormwater and sewage into one collection system, with combined sewer overflow (CSO) points, may discharge combined effluent more frequently due to increased flooding, increasing the load of nutrients and pollutants entering waterways. Discharge points in CSO communities that are currently submerged have effective strategies in place, such as tide gates and pump stations, to overcome this issue. Rising sea levels mean existing CSO outfalls will be further submerged during rain events and may function less efficiently. As such, additional measures may have to be taken as sea levels rise. In similar fashion, discharges from industrial sites near coastal areas may be inundated more often, resulting in the direct discharge of unintended or contaminant materials. In areas where groundwater tables rise, including areas where rising sea-levels influence the water table, septic systems may become ineffective, requiring more mounded systems or other treatment solutions. All such impacts will require a reevaluation of design standards and current best management practices.

Overall, changes in temperature, more intense precipitation events, and rising sea-levels will impact New Jersey waters. The DEP, which oversees the Pollutant Discharge Elimination System permitting programs, anticipates several impacts to these programs due to climate change factors and recognizes that adaptive design specifications for collection systems and treatment units will need to be implemented in order to continue to protect the waters of New Jersey.

LEBANON, NEW JERSEY



- The productivity of crops and livestock are expected to change due to the climate-induced changes in temperature and precipitation patterns.
- New Jersey may become unsuitable for specialty crops like blueberries and cranberries in the future as higher temperatures reduce necessary winter-chills.

CHAPTER 5.3

AGRICULTURE

5.3 Agriculture

Agriculture consists of crops, livestock, and nursery plants. The health and well-being of plants, pasture, rangeland, and livestock, is directly impacted by the changes in weather that are expected due to climate change (NJ Climate Adaptation Alliance 2014). Changes in temperature, precipitation, carbon dioxide (CO_2) concentrations, and amount of water that is available change the productivity of crops and livestock and their exposure to insects, disease, and weeds. How these factors will exactly impact farmers across the Northeast United States is unknown, but it is certain that they will need to adapt to the effects of climate change.

The ability for plants to grow efficiently depends upon climate conditions, of which temperature is one of the major factors (NJ Climate Adaptation Alliance 2014) (see Chapter 4.1 for more details about temperature). Increased temperatures during critical growth and reproductive stages can result in crop stress and loss in profits due to a change in flavor or visual appeal. This can occur when daytime maximum temperatures reach over 90˚F (32˚C), even if only for a few hours.

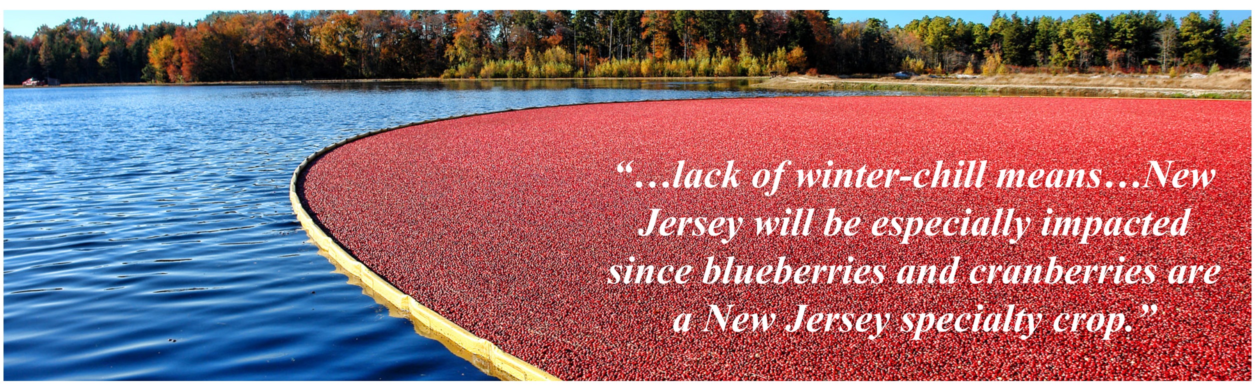
Increases in temperatures mean there will be a longer growing season (NJ Climate Adaptation Alliance 2014). The growing season occurs when the soil temperature and moisture conditions are right for plants to grow (Zommers and Alverson 2018). This will be beneficial for melon, okra, and sweet potatoes, which do well in warm temperatures (NJ Climate Adaptation Alliance 2014). However, those crops that do not do well in warmer conditions will experience shorter growing seasons, including potato, lettuce, broccoli, and spinach.

As winter season temperatures increase, there are parts of the Northeastern United States that will not see the periods of winter-chill needed for certain species to produce fruit (NJ Climate Adaptation Alliance 2014). This lack of a winter-chill means areas will become unsuitable to some varieties of apples, blueberries, and cranberries by late this century. New Jersey will be especially impacted since blueberries (*Vaccinium corymbosum & Vaccinium angustifolium*) and cranberries (*Vaccinium macrocarpon*) are a New Jersey specialty crop and depend on a long winter chill for optimum flowering and fruit development (Frumhoff et al. 2007). Alternately, higher winter temperatures also mean there will be an extended frost-free period (NJ Climate Adaptation Alliance 2014) that will benefit crops that need longer growing seasons including peach, melon, and peppers. There may be some economic gains from a longer growing season, however, as temperatures continue to rise above the optimal conditions of even the heat-tolerant crop varieties, those gains will be lost (NJ Climate Adaptation Alliance 2014).

Plant growth will also be impacted by increases in the concentration of CO_2. Some plant species are able to increase growth when CO_2 is elevated (NJ Climate Adaptation Alliance 2014), which could lead to increases in agricultural harvests. However, weeds, particularly invasive weeds, have an even more positive response to increased levels of CO_2 which will lead to an increase in the number of weeds that crops will need to compete against for resources, negatively impacting harvests and profits. Additionally, as temperatures and CO_2 levels continue to rise, farmers will turn to herbicides to combat the issue. This will lead to the use of pesticides of greater concentrations and more frequent uses, which will cause an increase in costs and environmental concerns. Of particular note is that some research suggests that weeds growing at higher CO_2 levels will be less affected by glyphosate, which is one of the most widely used herbicides in the United States (NJ Climate Adaptation Alliance 2014).

Insects and pathogens are also both expected to expand their ranges northward as temperatures continue to rise (NJ Climate Adaptation Alliance 2014). This is due to the fact that insects are able to mature and reproduce faster in warmer temperatures. The decrease in winter temperatures also means a greater number of insects will survive the winter (NJ Climate Adaptation Alliance 2014). Similar to herbicides, there are indications that some pesticides will also experience a reduced efficacy (USGCRP 2016). This potential for reduced efficacy of pesticides and increased pressures from insects will lead to more pesticides being used. Increased concentration of ground-level ozone reduces the growth rate of crops, increases the susceptibility to disease, and reduces overall agricultural productivity (Zommers and Alverson 2018).

Changes in precipitation will also present increased challenges to agricultural practices. As discussed in Chapter 4.2-5, due to higher temperatures much of the United States is projected to see changes the frequency and severity of drought, longer growing seasons, and longer dry periods (NJ Climate Adaptation Alliance 2014). While the amount of total annual precipitation is not projected to change significantly in the Northeastern United States, it is reasonable to expect annual precipitation to increase as average temperatures increase (Trenberth 2011, Kunkel et al. 2013). Additionally, the frequency and intensity of precipitation will change, including variation in precipitation between seasons with a small decrease in summer months and small decreases in winter months (Fan et al. 2014). If there is increased heavy precipitation that occurs during the growing season, then there will also be longer dry periods (Sweet et al. 2017a). If these dry periods occur when crops need the most water, irrigation will be required to sustain crop yields (NJ Climate Adaptation Alliance 2014). The water demand of crops will also increase due to longer growing seasons. Currently in the Northeast United States farms use some irrigation as needed during the summer season, mostly for fruit and vegetable production. The water for irrigation comes from local streams, farm ponds, or wells which are not able to cope with prolonged summer drought. In New Jersey, water use for agriculture and irrigation accounts about 9% of statewide usage (NJDEP 2017a). As more water is pulled from wells and other groundwater sources, those areas in need of irrigation along tidally flowed waters may see the intrusion of saltwater into freshwater sources (NJ Climate Adaptation Alliance 2014). As discussed in Chapter 5.2-1.3, saltwater intrusion of New Jersey's coastal aquifers is usually a result of over pumping. As the need for irrigation increases due to the frequency of short-term drought and warmer temperatures, the cost of production will also increase.



As changes in the intensity and frequency of precipitation occurs, either through heavy downpours or hurricanes, the excess water that results will negatively impact plants through reduced growth, delayed spring planting, and flooding which will cause wetter soils that cause increased susceptibility of root diseases and increased compaction from farm equipment (NJ Climate Adaptation Alliance 2014). For those farms located near tidal waterways, there is an additional risk of flooding from storm surges. As sea-levels rise (Chapter 4.3) storm surges will reach farther inland and present an elevated risk of saltwater impacts to fields. Increased salinity decreases crop production. Wind damage from these storms also present a problem for agriculture.

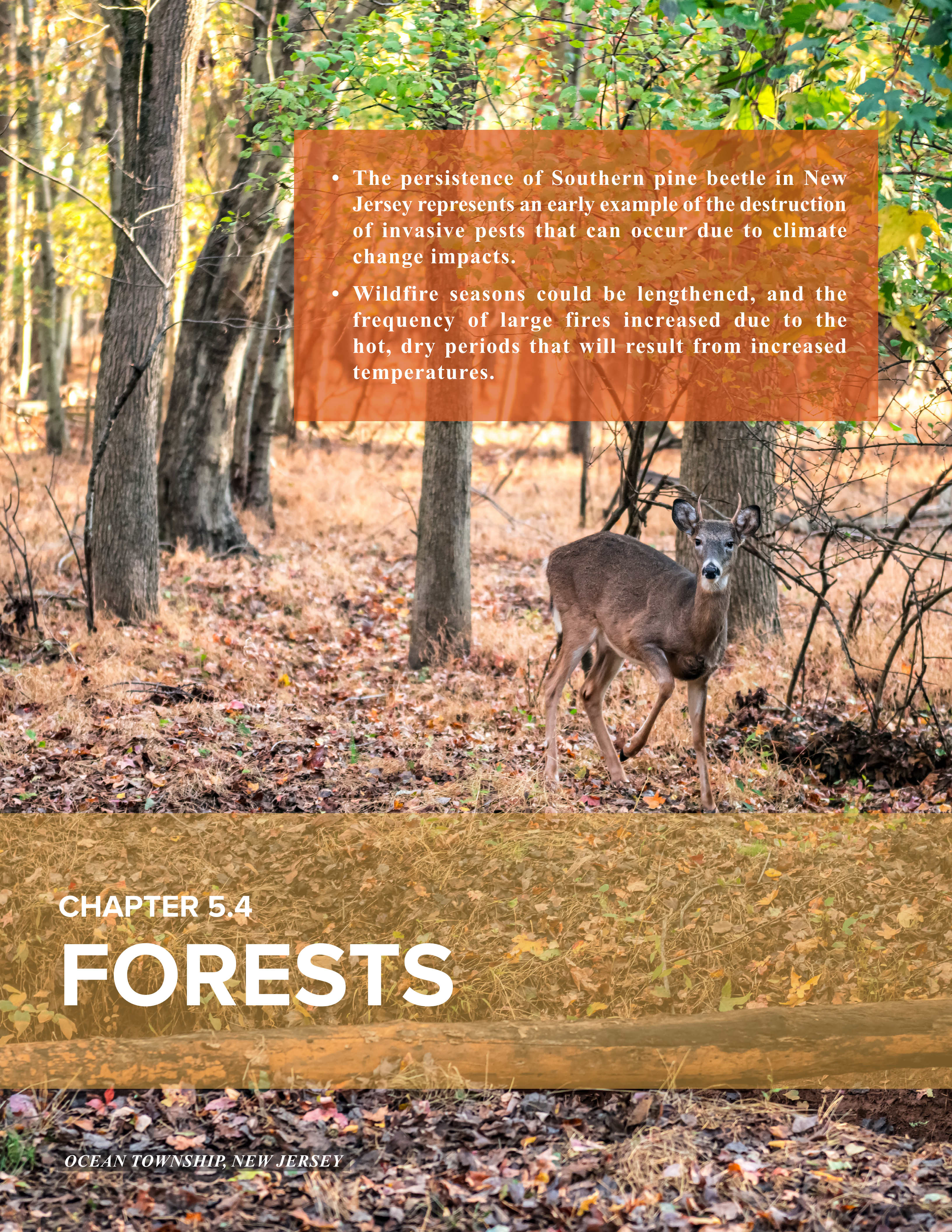
As the impacts from climate change increase in New Jersey, research and management efforts work to address possible actions to mitigate the effects. As previously mentioned, blueberries and cranberries are especially at risk and are a substantial portion of the New Jersey agricultural economy (NJ Climate Adaptation Alliance 2014). Research is already underway in the State to inform crop management decisions. The Rutgers Philip E. Marcucci Center for Blueberry and Cranberry Research is developing heat tolerant cranberry cultivars to better understand the reactions of crops to heat stress.

Higher temperatures will also very likely negatively impact livestock through a loss of productivity in summer months (NJ Climate Adaptation Alliance 2014) and increased exposure to vector-borne diseases (USGCRP 2016). When conditions exceed 75˚F (24˚C) dairy cows must work harder to stay cool, which results in less milk production. In the Northeastern United States, it is predicted that milk production will decline by 5 and 20% in certain months, with a 10% loss by 2100. In New Jersey, this is estimated to result in a $3.3 million loss to the industry.

However, an increase in productivity during warming winter months may offset the loss in production seen during summer months (NJ Climate Adaptation Alliance 2014). As warmer temperatures produce warmer winters and springs conditions to occur earlier in the year, pathogens and parasites will be able to better survive through the winter season and reproduce at higher rates, increasing pressure on livestock. To offset these impacts, use of parasiticides and other animal health treatments may increase to keep livestock healthy (USGCRP 2016). Unfortunately, these practices could lead to an uptake of pesticides in the food chain and cause long-term resistance to treatment (USGCRP 2016).

Operations and management will be affected by climate change due to changes that will be seen in the foraging plants consumed by livestock (NJ Climate Adaptation Alliance 2014). As temperatures increase and growing conditions change, plants will be less productive and there will be a shift in the types of plants that can grow. Additionally, the nutritional content of plants is likely to change as a result of climate change. As atmospheric CO_2 concentrations increase, there is likely to be a decline in the amount of protein, increase in the amount of carbohydrates, and reduction in the concentration of essential micro- and macronutrients found in food crops, including those fed to livestock (USGCRP 2016).

As a result of climate change there is expected to be major impacts to the growth and productivity of New Jersey crops and livestock due to an increase in dry spells, heat waves, and sustained droughts (NJ Climate Adaptation Alliance 2014). Crop yields are expected to decrease for a number of economically important crops by mid-century due to increasing summer temperatures and heat stress. Crops will be additionally stressed due to agricultural pests and weeds (such a kudzu) moving northward as winter temperatures continue to rise. All of this will increase pressure on farms, which will likely result in an increased use of herbicide and pesticide use.



- The persistence of Southern pine beetle in New Jersey represents an early example of the destruction of invasive pests that can occur due to climate change impacts.
- Wildfire seasons could be lengthened, and the frequency of large fires increased due to the hot, dry periods that will result from increased temperatures.

CHAPTER 5.4

FORESTS

5.4 Forests

Roughly 40% of New Jersey's land is covered by forests. Climate change is expected to bring stress and change to forests, and that stress is expected to be amplified by the non-climate stressors forests face due to human decisions.

5.4-1 Forest Characteristics in New Jersey

The United States Department of Agriculture Forest Service, Forest Inventory and Analysis Program, provides a comprehensive overview of New Jersey's forest resource. The Forest Inventory and Analysis Program data estimates that just under 2 million acres of land in New Jersey is forested, which is nearly 40% of the total land area. Although much of New Jersey is covered in forest, including portions of urbanized areas, most of this forested land is located within the northwestern and southeastern portions of the state as seen in Figure 5.8.

In the northwestern region of the State, the majority of forested land is located within the *Ridge and Valley and Highlands* physiographic provinces, which is a geographic region with a specific subsurface rock type or surface features. In this region, the most dominant forest-type group is the oak-hickory forest-type group (USDA 2020), see Figure 5.9. A forest-type group is a collection of tree species that are closely related or have similar requirements. White oak (*Quercus alba*), red oak (*Quercus rubra*), and hickory (*Carya*) trees are the most represented species within the oak-hickory forest-type. Other important species in the northern part of the state include yellow-poplar (*Liriodendron tulipifera*), chestnut oak (*Quercus prinus*), scarlet oak (*Quercus coccinea*), eastern red cedar (J*uniperus virginiana*), and black gum (*Nyssa sylvatica*), as well as northern hardwoods like red maple (A*cer rubrum*), sweet birch (*Betula lenta*), sugar maple (*Acer saccharum*), and American beech (*Fagus grandifolia*) (Crocker et al. 2017).

In the southeastern region of the state, the majority of the forested land is located within the Coastal Plain physiographic province, more specifically, in the Pinelands of New Jersey. In this area, the dominant forest-type group, as seen in Figure 5.9, is the loblolly-shortleaf pine forest-type group. Pitch pine trees (*Pinus rigida*) are the most represented species within this group. Other species that dominate southeastern New Jersey include Atlantic white-cedar (*Chamaecyparis thyoides*), and red maple. For more information on Atlantic white-cedar, see Chapter 5.5-3.

New Jersey forests, while having fewer trees per unit area, are becoming composed of trees of greater size and age, representing the maturation of New Jersey forests. As forests age without disturbance, the canopy gets denser and less sunlight reaches the forest floor. The result is mesophication, which pushes the forest environment to be cooler, damper, and more shaded with larger and older trees. The forest floor becomes less flammable, and there is a community shift toward shade-tolerant and less drought resistant species (Nowacki and Abrams 2008). These patterns will affect the trajectory of the forest as it increasingly encounters a warmer, more drought-prone climate.

5.4-2 Changes in New Jersey Forest Composition

Forests are dynamic and at any time usually include trees within all stages of life – from seed to decomposition – all shaped by species life history processes. Life history processes are growth, rooting habit, resource partitioning, and vegetative reproduction. Specific changes to the life history process of individual species will play key roles in how different species respond to a warming climate and will play a role in how climate change will impact New Jersey forests. For example, a species that can leaf-out early and extend its growing season may seem to be a better competitor with warmer springs, but sensitivity to late-season frost may make this behavior a liability compared to a more conservative or frost-hardy neighbor (Hufkens et al. 2012).

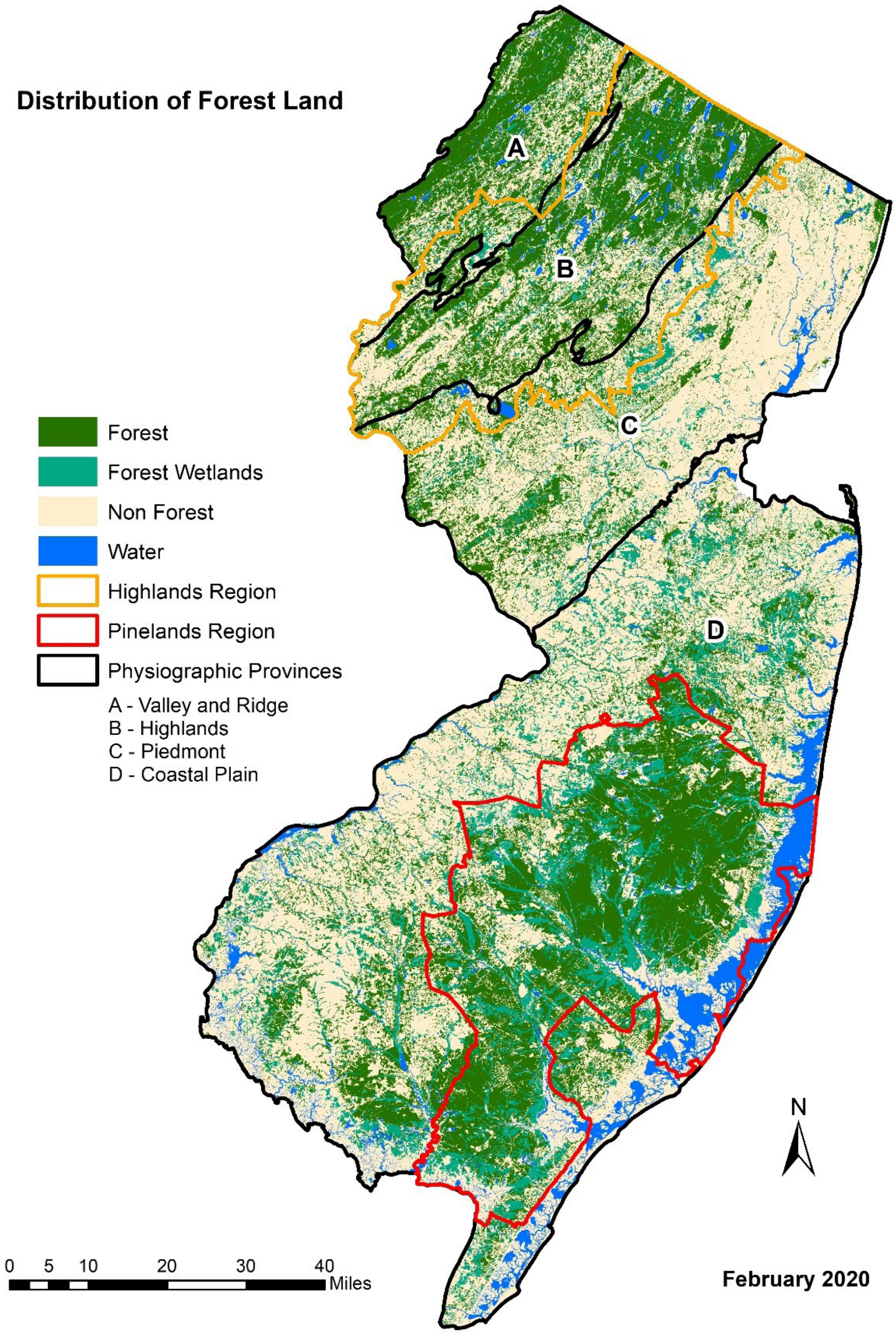


Figure 5.8. Distribution of Forest Land in New Jersey, 2015. This map shows the distribution of forested and non-forested land throughout New Jersey, the boundary lines of the Highlands and Pinelands Region, and the boundary lines of the physiographic provinces in the State (NJ Geologic Survey 2002, NJ Highlands Water Protection & Planning Council 2011, NJ Pinelands Commission 2018, NJDEP 2019b).

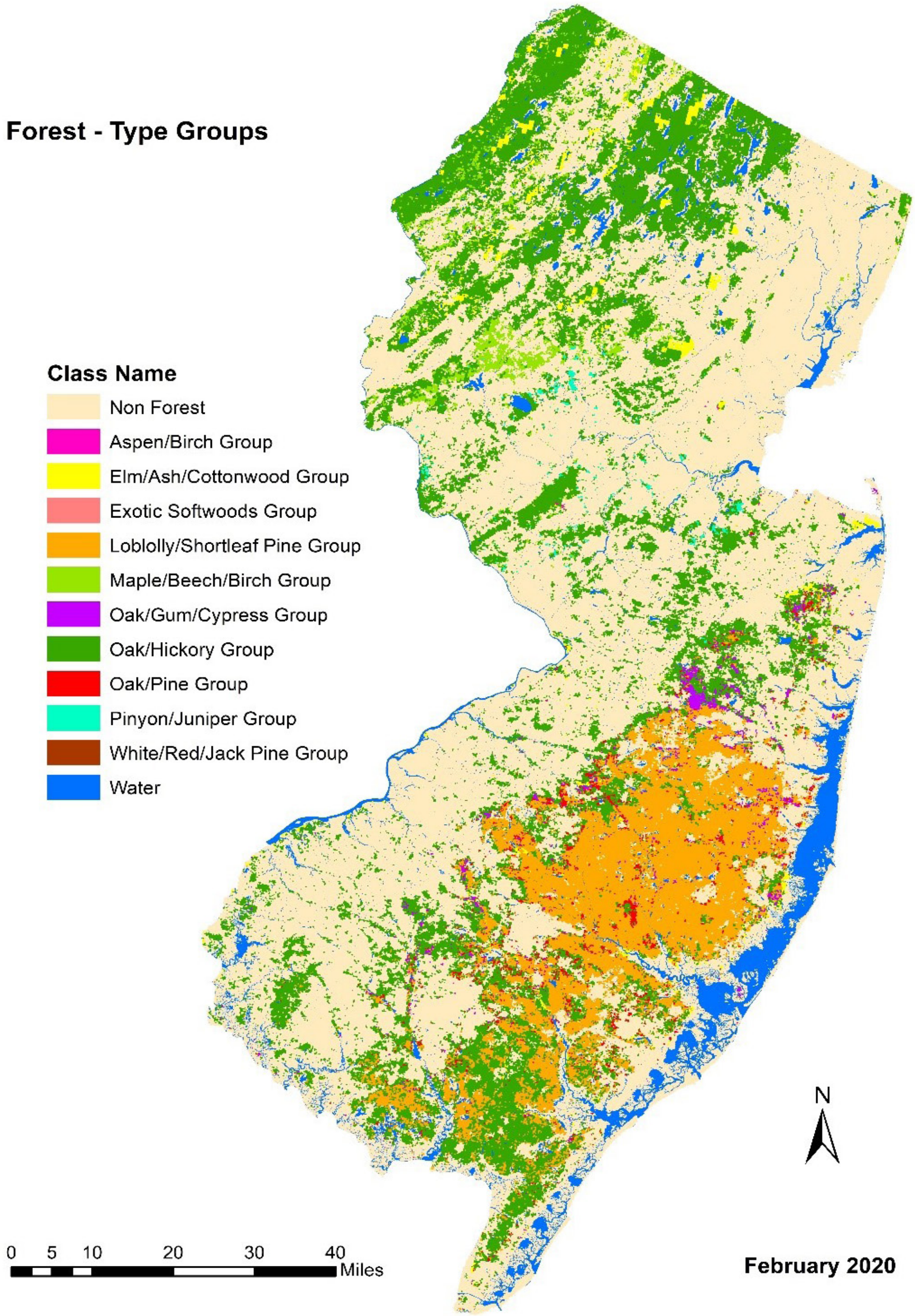


Figure 5.9. Forest-Type Group Map for New Jersey. This map shows the current distribution of each forest-type group located within New Jersey. (Data from US Forest Service, Forest Inventory and Analysis.

To help understand how forest composition will be altered over time and as the climate changes, it is necessary to consider all factors that influence forest conditions. The United States Forest Service, Climate Change Tree Atlas has attempted to provide species-level predictions for how suitable tree species habitat will be depending on different climate change scenarios (Prasad et al. 2007). Predictions from the Climate Change Tree Atlas describe a significant southern shift to New Jersey forest's composition, where sweetgum, pitch pine, red maple, and white oak will still be some of the most abundant species. Loblolly pine will become even more abundant than it currently is, with post oak (*Quercus stellata*), winged elm (*Ulmus alata*), water oak (*Quercus nigra*), and black hickory (*Carya texana*) also becoming more abundant. Red maple, while still abundant, is expected to be less so in the future along with sugar maple (*Acer saccharum*) and red oak. Some relatively minor species currently in New Jersey are expected to become more abundant, like persimmon (*Diospyros virginiana*), shortleaf pine (*Pinus echinata*), and blackjack oak (*Quercus marilandica*), see Figure 5.10.

These predictions seem to provide clear narrative: as New Jersey's climate becomes more similar to current southern conditions, forest composition will comparatively shift. However, in actuality

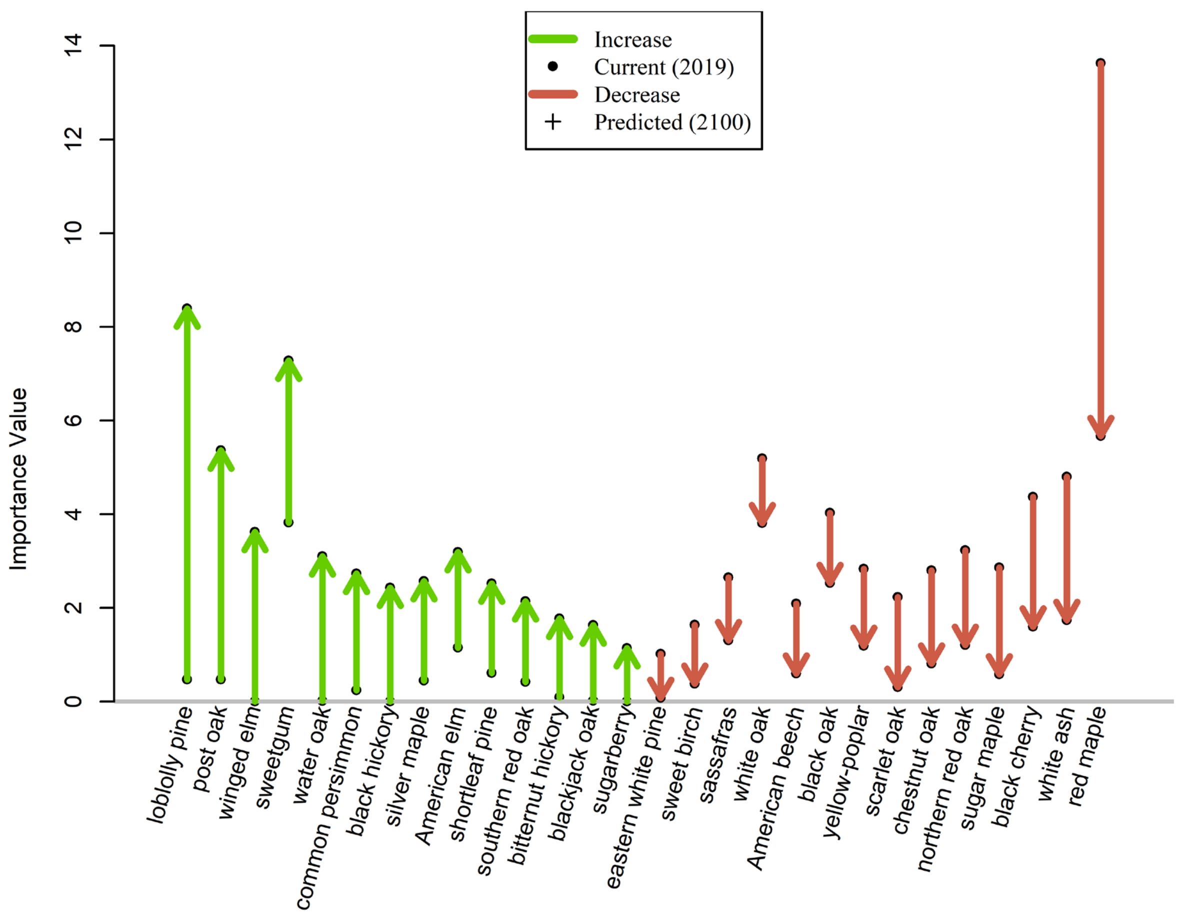


Figure 5.10. Changes in Abundance for Selected Tree Species in New Jersey. This figure shows the importance value assigned to each tree species in the United State Forest Service Climate Change Atlas. The importance value is based on both tree basal area and the number of tree stems. The species with higher importance values are more abundant in New Jersey and are expected to be more suited to climatic growing conditions in the years indicated. Data from (Prasad et al. 2007).

forests are not changing as rapidly as the climate and climate change (Woodall et al. 2018), and climate is not the only factor that has shaped or will continue to shape New Jersey forests (Foster and D'Amato 2015). Human choices about how land is used is a dominant force in shaping forest composition. These choices include past and current land use decisions, both of which have shaped the composition of today's forests. Additionally, the land use choices made today and into the future will determine the forest composition and structure for future forests (Butler-Leopold et al. 2018). Climate change will similarly be an influential factor that determines future forest composition.

The processes that shaped forests over the last 10,000 years are and have historically been heavily dependent on human actions and human choices (Abrams and Nowacki 2008). For example, across the northeast United States and Great Lakes states, forest age-class distribution show a remarkably consistent pattern, the result of simultaneous farmland abandonment (Oswalt et al. 2019). Social-economic changes from early in the 20th century gave rise to much of the forest we have today, the result of technological improvements in farming, the transition towards fossil fuels, and the relaxation of pressure on forests for fuelwood. These human actions and choices have impacted forest composition in New Jersey and resulted in trees being allowed to grow older, leading to forest canopies that are denser which reduce the amount of sunlight reaching the forest floor, creating the dark and wet conditions that are more favorable to mesophilic northern hardwood species, such as red maple, that exist in New Jersey forests today. In this way, changing conditions, including those that are human-caused and those that are due to climate change, allow certain species to expand their range and distribution and will cause other species to be reduced.

As previously discussed, oak-hickory forests are the dominant forest-type group in northern New Jersey (Crocker et al. 2017). Current successional trends in New Jersey are tilting much of the oak-hickory forest toward moisture and shade-tolerant generalists, like red maple (Brose et al. 2014). This trend is in part due to the land use decisions that have resulted in the reduction in low-intensity fire, high pressure from deer herbivory, and reduced sunlight on the forest floor producing moisture rich forest conditions (Lorimer 1984, Nowacki and Abrams 2008, Thompson et al. 2013, Gundy et al. 2015). Other causes for this trend include natural succession, competition from invasive species, and lack of disturbance. Low-intensity fire and disturbance is needed to maintain oak ecosystems (Nowacki and Abrams 2008, Brose et al. 2014) and without these disturbances, succession and replacement by shade-tolerant generalists is the eventual fate of eastern oak forests (Lorimer 1984, Abrams and Downs 1990). This means the current composition of New Jersey forests will not be as suited to the warmer forest conditions that are expected with climate change.

"Southern pine beetle behavior...foreshadow massive mortality events covering tens of thousands of acres of New Jersey's pine forests."

The expected future climate is likely to favor oak- and pine-dominated systems as these species are thought to be more resilient to drought and compete better under physiologically drought-like conditions, which are conditions that emulate drought such as sandy soils that do not retain moisture. Conversely, northern hardwood communities are more likely to be stressed by rising temperatures (Swanston et al. 2018). It is unclear whether fine-scale processes such as the ability of individual trees to adapt to changing conditions will be enough to mitigate possible mortality from drought or whether droughts in currently oak-dominated systems will be significant enough to cause more than minor compositional changes (Gustafson and Sturtevant 2013, Coble et al. 2017) due to mortality of northern hardwoods.

The Climate Change Tree Atlas predictions indicate that the ranges of current moisture tolerant understory and co-dominant species are most strongly affected by climate factors (Prasad et al. 2007). It is expected that these species will be negatively impacted by climate change relative to areas made up of oaks, hickories, and pines which can thrive in warm, dry soil conditions.

5.4-3 New Jersey Forests' Role in the Water Cycle

Vegetation plays a key role in the water cycle. In southern New Jersey, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) currently consumes about half of the water budget. (Sloto and Buxton 2005, Walker et al. 2011). Water that reaches the ground is either used by plants, evaporates, or makes its way to groundwater and streams through infiltration and runoff. Transpiration by plants occurs when water travels from the ground through the plant and is released into the atmosphere as vapor through tiny leaf pores, called stomata. Transpiration through stomata keeps leaves cool, and by keeping stomata open, the leaves are also able to accept atmospheric CO_2. Under a warmer climate, forests are expected to increase their water use to maintain comfortable leaf temperatures (Lévesque et al. 2014).

Global-scale models predict that increases in vegetative water demand will not surpass the amount of available water in New Jersey due to increased extreme precipitation (Mankin et al. 2018). However, local models show that under expected climate changes, a modest decrease in surface water for southern New Jersey results from the increased demand of vegetation (Sun et al. 2015).

Finer-scale processes are also likely to unbalance the water budget to the detriment of water resources. The trend to wetter forest conditions is causing a shift away from water-sipping oaks/hickories and towards the water-guzzling northern hardwoods like maple (Ford et al. 2011, Caldwell et al. 2016). More sudden loss of keystone species (i.e., species with a larger effect on the environment than expected relative to its abundance) to emergent pests, like the near-eradication of hemlock by hemlock wooly adelgid, will cause permanent reductions in surface water yield because water-sipping hemlocks will be replaced by water-guzzling northern hardwoods (Brantley et al. 2013, 2014).

Climate-induced declines in available groundwater could have profound effects on the composition of the New Jersey forested landscape. In the Pinelands, plant community composition is strongly related to the depth of the water table (Laidig et al. 2010). Water table declines are expected to cause shifts in the patterns of plant communities in the Pinelands, with wetland communities disfavored (Lathrop et al. 2010). Even if subsurface recharge remains in balance under a changing climate, longer periods between rainstorms will still put stress on upland forest communities.

5.4-4 Changes in Insect and Disease Pests

Some forest pest species native to North America are expected to take advantage of the warmer temperatures caused by climate change. As an insect's development is closely tied to the temperature, a warmer climate allows insect pests to mature faster, achieve more generations per year, and move into new habitats that no longer have a winter season cold enough to be lethal. The effect of warming on native insect species is expected to be even more dramatic as these species will disperse into forests that have not before experienced the pressure of these pests (Olatinwo et al. 2014).

Of particular concern for New Jersey's forests is the southern pine beetle (*Dendroctonus frontalis*). Southern pine beetle is native to the southern coastal plain pine forest and is one of the most important bark beetle pests in the United States, affecting southern yellow pines like pitch and shortleaf pine. In landscapes where southern pine beetles are native, populations are always present in low numbers and survive by killing isolated unhealthy trees. As populations build up, however, even healthy trees succumb to the mass attack of congregating beetles. This causes a positive feedback loop that creates population eruptions, where outbreaks of the insect kill tens of thousands of acres of forest (Coulson and Klepzig 2011).

Southern pine beetle behavior in New Jersey represents an early example of the current impacts of climate change. The southern pine beetle has long been present, but its role was insignificant. Starting in the early 2000's New Jersey began to experience spot outbreaks of the beetle that have moved progressively northward, especially along the coast (Hassett et al. 2018). Rising winter minimum temperatures are thought to be responsible for this northward movement (Trần et al. 2007) since insects are killed when temperatures drop below 3.2˚F (-16˚C) (Ungerer et al. 1999). As that thermal control on southern pine beetle moves north, we can expect populations of the beetles to build and the range and population size to increase. These alarming developments foreshadow massive mortality events covering tens of thousands of acres of New Jersey's pine forests.

Other pests are likely to experience range shifts, increased vigor, or increased impact as a result of changing climate, making the future more challenging for New Jersey's forests. Invasive insects like the sirex woodwasp (*Sirex noctilio*) are expected to eventually reach New Jersey, as their range expands faster in warmer environments (Lantschner et al. 2014). Lethal diseases like annosus root disease (*Heterobasidion annosum*) and bacterial leaf scorch (*Xylella fastidiosa*) as well as less virulent ones like fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) may become more prevalent in New Jersey as temperatures warm and eventually match those to the south of New Jersey. Host species shifts may additionally increase prevalence of pests (Olatinwo et al. 2014). As a consequence, other invasive species may take hold in areas where the forest community has little evolutionary defense.

5.4-5 Forest Fires

The New Jersey Office of Emergency Management defines a wildland fire "as any non-structural fire that occurs in the wildland", and can occur in forested, semi-forested, or less developed areas (State of New Jersey 2019). Wildfires can occur naturally, can be set purposely for management purposes as in the case of prescribed burns, or can be human caused. Fires that occur naturally can ignite from lightning or from power lines downed by wind-fallen trees. In New Jersey, wildfires are most frequently caused by humans and can result in the destruction of forests, brush, grasslands, field crops, and private and public property. As New Jersey population expands into more rural areas the threat of wildfires increases.

New Jersey is at the highest risk from wildfires in spring (March through May) when vegetation is at its driest but can also experience fires in the summer and fall or in any month of the year. Figure 5.11 depicts the wildfire fuel hazards throughout the State. Regionally, the Pinelands (Pine Barrens) area of southern New Jersey is the most susceptible to forest fire and much of the area is classified with a high to extreme fire hazard level. This region has a tremendous propensity toward burning (Forman and Boerner 1981, Buchholz and Zampella 1987) and that tendency to burn hot and often has shaped this unique landscape (Little 1998).

The length of the fire season depends on local weather conditions, drought, and the amount of precipitation that occurred through the winter as snow. To date, an average of 1,500 wildfires damage or destroy 7,000 acres of State forests; in 2016, 1,047 wildfires burned approximately 4,444 acres and in 2017, 731 fires burned approximately 5,142 acres.

How climate change will impact wildfires in New Jersey forests is uncertain based on existing literature and models, which there are few that focus on New

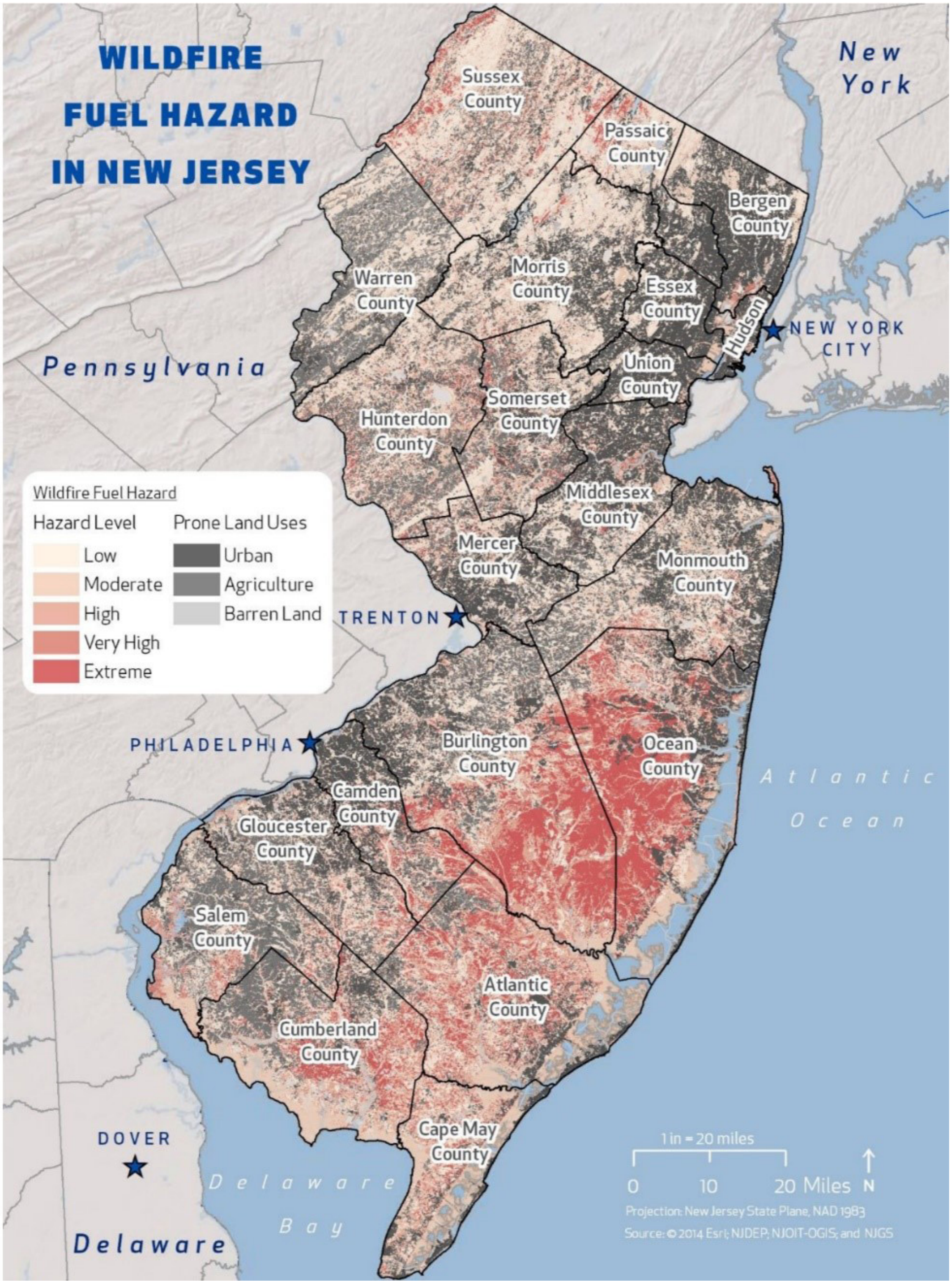
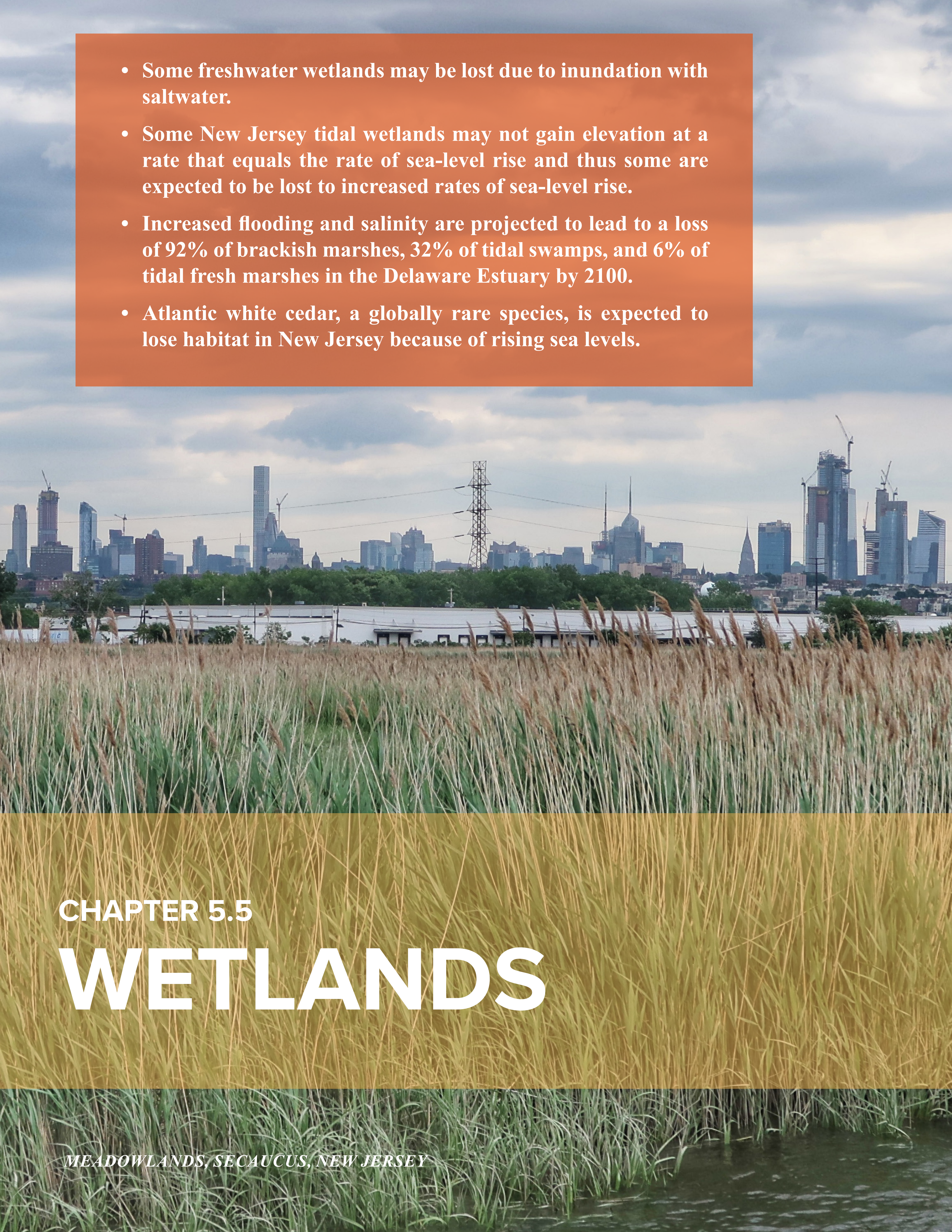


Figure 5.11. Wildfire Fuel Hazard in New Jersey. This figure depicts wildfire fuel hazards throughout New Jersey. (State of New Jersey 2019).

Jersey specific conditions. As discussed in Chapter 4.1 and 4.2, climate change is expected to cause increased temperatures and changes in extreme precipitation events and drought that make it uncertain when a drought, or drought-like conditions may occur. Wildfire seasons could be lengthened, and the frequency of large fires increased from the warmer springs and longer summer dry periods that are expected with climate change due to these conditions causing drier soils and vegetation (Nolte et al. 2018). Global- and national-scale assessments of fire risk for the Mid-Atlantic United States predict an increased occurrence of fire, but local-scale forecasts do not mirror this increase (Butler-Leopold et al. 2018). This is due to the fact that Mid-Atlantic coniferous forests are anticipated to experience increased precipitation during the fire-season that will counteract increased chances of fire (Moritz et al. 2012). National level predictions of climate and forest disturbance patterns predict that New Jersey will see the establishment of southeastern mixed pine-oak, which will bring with it an increase in the chance of fire (Bachelet et al. 2001). Regionally, forests in the Northeast United States are predicted to see minor increases in the magnitude of fires (Scheller et al. 2012, Guyette et al. 2014).

The potential for factors that cause stress and disturbances to a forest, such as insects, to impact the potential for forest fires has not been considered (Scheller et al. 2012). Trees stressed from insect infestations provide an increased fuel source which makes them easier to burn and is more likely to occur as insect populations expand in warmer temperatures (State of New Jersey 2019). Additionally, climate change does have the potential to increase drought-like conditions through warmer temperatures, increases in evapotranspiration, and decreased soil moisture. Areas susceptible to burning are very likely to increase if increases in summer precipitation do not occur. Factors like current successional trends, patterns of land ownership, patterns of land use, forest fragmentation, and wildfire control activities all exert strong controls on fire behavior in the state, and are expected to continue (Clark et al. 2014). These factors are expected to maintain the existing wildfire regime, especially in the most fire-prone areas. Providing predictions on wildfires is challenging due to all the factors and conditions that contribute to when or where a fire may start (State of New Jersey 2019). However, given predictions about how climate change will impact New Jersey temperatures (Chapter 4.1), precipitation, and storms (Chapter 4.2), and that fire is determined by climate variability, some general statements can be made about how climate change will impact wildfires in New Jersey. Increases in temperature, and the hot, dry periods that result, may intensify the danger of wildfires by drying out vegetation and soil. With increases in the frequency and severity of storms, there is increased potential for lightening to occur and ignite a fire. Also, any increase in winds, which could occur from weather changes due to climate change, would also increase the spread of fires. Due to the dry sandy soils and fire prone nature of the New Jersey Pinelands, this area is susceptible to increased fire threats, especially along the wildland-urban interface (Scheller et al. 2011, Buchanan et al. 2018).

- **Some freshwater wetlands may be lost due to inundation with saltwater.**
- **Some New Jersey tidal wetlands may not gain elevation at a rate that equals the rate of sea-level rise and thus some are expected to be lost to increased rates of sea-level rise.**
- **Increased flooding and salinity are projected to lead to a loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100.**
- **Atlantic white cedar, a globally rare species, is expected to lose habitat in New Jersey because of rising sea levels.**



CHAPTER 5.5

WETLANDS

MEADOWLANDS, SECAUCUS, NEW JERSEY

5.5 Wetlands

Several types of wetlands exist in New Jersey including tidal, freshwater, and cedar swamps. As the climate changes in New Jersey, potential changes to wetland habitats will include shifts in carbon sequestration, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration), fire frequency, and acidification. Sea-level rise is of particular concern for wetlands, as freshwater wetlands may be lost due to inundation with saltwater.

5.5-1 Freshwater Wetlands

Freshwater wetlands are found at the interface between terrestrial upland and aquatic ecosystems, distinguished by the presence of freshwater at the surface and in the root zone, saturated soils conditions, and flood-tolerant vegetation adapted to seasonal or perennial wet conditions. In addition, seemingly isolated freshwater wetlands can be connected hydrologically to groundwater and therefore influenced by seasonally dynamic water level fluctuations. While most freshwater wetlands in New Jersey are located inland, freshwater tidal wetlands occur at the landward end of coastal estuaries and are influenced by both freshwater stream flow and coastal lunar tides that push the fresh water back and forth. The location of the fresh-saltwater boundary fluctuates with seasonal precipitation and river volume as well as sea-level influence.

All freshwater wetlands are productive ecosystems providing critical habitat for plants and animals that depend on water for breeding, foraging, and living. Humans also benefit greatly by the ecosystem services and functions that freshwater wetlands provide.

5.5-1.1 Ecosystem Services and Functions

Freshwater wetlands are complex habitats that provide important ecosystem services and functions in the landscape. Wetland ecosystem services are the link between the biological functions and the social value of wetlands, often reported in terms of economic worth as defined in the Ramsar International Wetland Conservation Treaty (Ramsar Treaty 1971). Wetland ecosystem services include:

- Flood control (floodplain water storage/flood attenuation)
- Groundwater replenishment (recharge/discharge)
- Sediment and nutrient retention and export (carbon sequestration)
- Water purification (filtering nutrients and pollutants)
- Reservoirs of biodiversity (supporting food chains)
- Wetland products (food, peat, fuel, textiles, medicine)
- Cultural values (art, aesthetics)
- Recreation and tourism (ecotourism)
- Climate change mitigation and adaptation (carbon sequestration, sea-level rise buffer)

Wetland functions are processes or series of processes that take place in a wetland that relate to an ecological condition such as water quality, hydrology, and habitat. Wetland functions depend upon the location of the wetland within a watershed. Wetland functions include:

- Surface-water detention
- Coastal storm surge detention (including freshwater tidal wetlands)
- Streamflow maintenance
- Nutrient transformation (including carbon sequestration)
- Sediment and particulate retention
- Shoreline stabilization
- Provision of habitat for fish, shellfish, waterfowl, amphibians and other wildlife
- Conservation of biodiversity

"While freshwater wetland ecosystems are generally resilient, environmental and human stressors may reduce the natural capacity of wetlands to rebound."

Clearly there is overlap in wetland functions and ecosystem services they provide. Wetland functional assessments are used to evaluate changes in wetland function over time (e.g., historical vs current) as well as in landscape or watershed scale assessments (e.g., carbon sequestration by wetland type). The temporal and spatial evaluations of wetland function can inform wetland mitigation, restoration, regulation, and protection as well as assessing vulnerability of freshwater wetlands to climate change.

5.5-1.2 Types of Freshwater Wetlands in New Jersey

New Jersey supports a remarkable diversity of inland and freshwater tidal wetlands across the landscape including glacial bog, calcareous fen, wet meadow and marsh, sinkhole pond shore, floodplain forest, hardwood peat swamp, Atlantic white cedar swamp, pine barren riverside savanna, freshwater tidal marsh and swamp, coastal interdunal swale, coastal plain intermittent pond and sea-level fen (see Figure 5.12). Excellent descriptions of freshwater wetlands can be found in books such as "Plant Communities of New Jersey: A Study in Landscape Diversity" (Collins and Anderson 1994), "Wetlands of New Jersey" (Tiner 1985), "Pine Barrens: Ecosystem and Landscape" (Forman 1979), and "The Highlands: Critical Resources, Treasured Landscapes" (Lathrop 2011).

The ecological driver in all wetlands is hydrology, sourced by water through precipitation, surface water, groundwater, or a combination thereof. Soil characteristics are directly influenced by hydrology and the development of organic peat and muck over time is one way that carbon is sequestered in freshwater wetlands. Wetland plants, including trees, shrubs, vines, forbs, grasses, sedges, ferns, mosses, fungi and lichens have developed special adaptations to living in wet environments. The type of freshwater wetland that forms on the land depend on source of water, landscape position, topography, geologic history, soils and local climate. The diversity of freshwater wetlands in New Jersey is influenced strongly by the four physiographic provinces: Valley and Ridge, Highlands, Piedmont, and Coastal Plain (Inner and Outer). The hydrogeomorphic classification of wetlands provides a useful way to assess the impacts of climate change on functions and ecosystem services.

The classification of freshwater wetlands into broad categories is a useful way to understand and identify the variety of types found in New Jersey. The United States National Vegetation Classification (USNVC) is a floristic classification that groups freshwater wetland vegetation into four formations: Flooded & Swamp Forest, Freshwater Marsh, Wet Meadow & Shrubland, Bog & Fen, and Aquatic Vegetation (Federal Geographic Data Committee 2008, Faber-Landendoen et al. 2016). The National Wetland Inventory (NWI) groups freshwater wetlands into Palustrine, Riverine and Lacustrine systems (Cowardin et al. 1979). The hydrogeomorphic (HGM) classification groups freshwater systems by the Riverine, Depression, Slope, Mineral Soil Flats, Organic Soil Flats, and Lacustrine Fringe (Smith et al. 1995, Natural Resources Conservation Service

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
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Table 5.1. Acreage and Percentage of Freshwater Wetlands by Land Cover Type in New Jersey

LU15 Code	LULC 2015 Freshwater Wetland Type	Acres	Hectares	% Freshwater Wetlands
Forested Wetlands				
6210	*Deciduous Wooded Wetlands*	342,687	138,683	48%
6220	*Coniferous Wooded Wetlands*	72,602	29,382	10%
6252	*Mixed Wooded Wetlands (Coniferous Dom.)*	73,092	29,580	10%
6251	*Mixed Wooded Wetlands (Deciduous Dom.)*	59,621	24,128	8%
6221	*Atlantic White Cedar Wetlands*	41,910	16,961	6%
Shrub Wetlands				
6231	*Deciduous Scrub/Shrub Wetlands*	39,250	15,884	6%
6233	*Mixed Scrub/Shrub Wetlands (Deciduous Dom.)*	12,575	5,089	2%
6234	*Mixed Scrub/Shrub Wetlands (Coniferous Dom.)*	8,142	3,295	1%
6232	*Coniferous Scrub/Shrub Wetlands*	6,517	2,637	1%
Herbaceous Wetlands				
6240	*Herbaceous Wetlands*	30,657	12,407	4%
6241	*Phragmites Dominated Interior Wetlands*	11,852	4,796	2%
Freshwater Tidal Marshes				
6120	*Freshwater Tidal Marshes*	8,194	3,316	1%
	Total Freshwater Wetland Area In New Jersey	***707,100***	***286,159***	***100%***

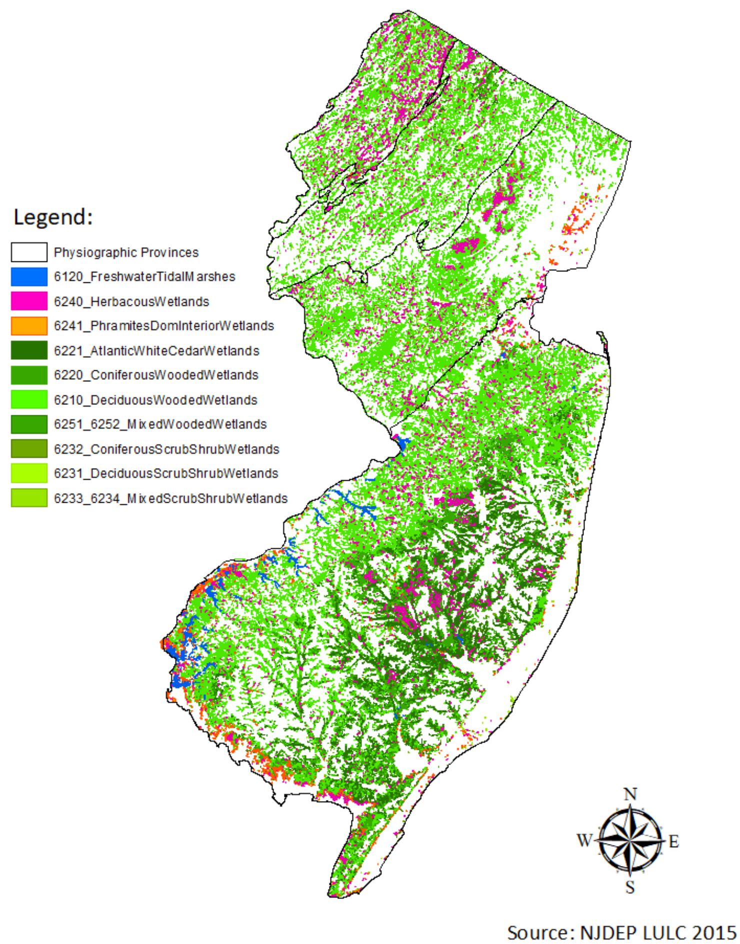

Figure 5.12. Map of Freshwater Wetlands in New Jersey. This map shows the diversity of freshwater wetland types throughout the State (NJDEP 2019b).

2008). In each of these broad categories there are many local freshwater wetland community types, described in detail in the books referenced above. Total area by freshwater wetland type is presented in Table 5.1. Forested wetlands represent 83%, shrub wetlands 10%, inland herbaceous 6%, freshwater tidal marsh 1% of natural freshwater wetlands mapped by the DEP (Anderson et al. 1976, NJDEP 2019b).

5.5-1.3 Climate Change Impacts on Freshwater Wetlands

Climate influenced changes to hydrology impact all of the critical functions and ecosystem services provided by freshwater wetlands. Two key indicators of a changing climate, temperature and precipitation, impact freshwater wetlands directly. Climate driven changes in precipitation amount, periodicity, severity and timing of storm and drought events, rates of evapotranspiration, and vulnerability to fire directly impact wetland hydrology, soils and vegetation (Mitsch 2016, Wardrop et al. 2019). Temperature directly affects evapotranspiration and ground water levels, particularly in productive ecosystems like forested swamps, where increased temperatures and lower water levels allow for the oxidation of organic soils and subsequent release of carbon. Conversely, increased flooding and waterlogged organic soils increase the potential storage or sequestering of carbon. Seasonal and annual fluctuations in the timing and intensity of precipitation complicate the response of ecosystems, creating the potential for wetlands to serve both as carbon source and sink. With predictions for changes in precipitation, sea-level rise, rising temperatures, and extreme weather, the response of freshwater wetlands to these changes will be complex and is not well understood.

While freshwater wetland ecosystems are generally resilient, environmental and human stressors may reduce the natural capacity of wetlands to rebound. Threats to the integrity of freshwater wetlands in New Jersey include landscape fragmentation, alterations to hydrology by ditching, soil erosion, saltwater intrusion, deer browse, and invasive species (Walz and Faber-Langendoen 2019). The condition of wetlands and their landscape context affect the long-term viability, resiliency, and adaptability of these systems in the face of a changing climate. Table 5.2 provides a look at climate change drivers, hazards and impacts, and the potential impact on freshwater wetland ecosystem services.

New Jersey supports a remarkable diversity of freshwater wetland types throughout the state, from glacial bogs on the Kittatinny Ridge to Atlantic white cedar swamps in the Pine Barrens. All freshwater wetlands provide critical functions in the landscape and ecosystem services to the public. Climate change will affect these functions and ecosystem services in various ways and the challenge will be to understand the vulnerability, resilience, and adaptive capacity of different wetland types in order to manage these systems effectively for the better good.

5.5-2 Tidal Wetlands

Tidal wetlands exist along rivers, estuaries, and coasts where low-lying areas are influenced by the tide. The New Jersey Wetlands Act of 1970 defined the term "coastal wetlands" to include banks, marshes, swamps, meadows, flat or other low land subject to tidal waters whose surface is at or below an elevation of 1 foot above local extreme high water. In New Jersey, more than 200,000 acres of tidal marsh form a charismatic green band of herbaceous vegetation spanning most of the Delaware River and Bay, the Atlantic Coast behind barrier islands, along the Raritan River, and up into the Meadowlands near New York City. In addition, there are 40,000 acres of tidal swamps and a few remaining sea-level fens (Figure 5.13). New Jersey coastal wetlands belong to two main categories: (1) back-barrier wetlands, protected by island barriers and lagoons located mainly on the Atlantic coast, and (2) wetlands that are not protected by a barrier island and receive direct impact from the ocean force, located mainly on the northern shore of the Delaware River and Bay.

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
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Table 5.2. Impacts of Climate Change on Freshwater Wetland Functions and Ecosystem Services. Primary climate change and natural hazards interactions and impacts to wetland functions and ecosystem services in New Jersey.

Climate Change Drivers	*Climate Change and Natural Hazards Impacts*	*Freshwater Wetland Functions & Ecosystem Services Impacted By Climate Change*
Increase in Greenhouse Gas Emissions (Carbon Cycle)	▪ *Carbon Sequestration* ▪ *Methane Emissions*	▪ *Sediment and particulate retention and export* ▪ *Nutrient transformation* ▪ *Surface-water detention*
Rising Temperatures	▪ *Increased Evapotranspiration* ▪ *Increased Fire Frequency and Intensity* ▪ *Freezing Precipitation & Ice Damage* ▪ *Lack of snowpack* ▪ *Increase in groundwater temperature*	▪ *Groundwater replenishment* ▪ *Surface-water detention* ▪ *Streamflow maintenance*
Sea-level Rise	▪ *Increase Salinity in Groundwater and Coastal Fringe* ▪ *Landward Migration*	▪ *Nutrient transformation* ▪ *Shoreline stabilization*
Changes in Timing and Amount of Precipitation	▪ *Drought* ▪ *Decreased rainfall during growing season* ▪ *Increased severity and duration of Storms* ▪ *Increased rainfall during growing season* ▪ *Flooding* ▪ *Groundwater Recharge* ▪ *Groundwater Discharge* ▪ *Acidification (Acid Rain)*	▪ *Flood control* ▪ *Groundwater replenishment* ▪ *Nutrient transformation* ▪ *Sediment and particulate retention and export* ▪ *Streamflow maintenance* ▪ *Surface-water detention* ▪ *Water purification*
Extreme Weather	▪ *Hurricanes & Tropical Storms* ▪ *Severe Winter Storms & Nor'easters* ▪ *Tornadoes* ▪ *Extreme Precipitation* ▪ *Strong Wind*	▪ *Coastal storm surge detention (including freshwater tidal wetlands)* ▪ *Flood control* ▪ *Shoreline stabilization* ▪ *Surface-water detention*
Ecological Linkages - Ecosystem Shifts	▪ *Hydrological Cycle* ▪ *Shifts in phenology* ▪ *Pollinators* ▪ *Invasive species* ▪ *Pests and Diseases*	▪ *Reservoirs of biodiversity* ▪ *Provision of habitat for fish, shellfish, waterfowl, waterbird, amphibians and other wildlife*

Tidal wetlands are among the most valuable habitats in New Jersey, providing more than $1.24 billion per year in ecosystem services (Liu et al. 2010). Tidal wetlands buffer coastal communities from storms; filter nutrients and sediment out of the water, helping to make water fishable and swimmable; provide nursey habitat for commercially important fish; draw ecotourists interested in fishing, crabbing and birding; mitigate climate change by sequestering carbon in the soil; provide critical habitat for rare and endangered species; and beautify the coast (Woodward and Wui 2001, Costanza et al. 2006, Mitsch and Gosselink 2007, Liu et al. 2010, Barbier et al. 2011, Narayan et al. 2017).

In recognition of the high value of tidal wetlands, both federal and state laws were enacted in the 1970s to protect tidal wetlands in New Jersey (Clean Water Act; Wetlands Act of 1970, N.J.S.A. 13:9A-1 et seq., Waterfront Development Act N.J.S.A. 12:5-3, Coastal Area Facility Review Act, N.J.S.A. 13:19, Coastal Zone Management Rules, N.J.A.C. 7:7). These laws have been very successful in conserving the acreage of tidal wetlands in the state. Prior to the enactment of these laws, tidal wetlands were routinely filled and dredged, but between 1986 and 2012 the losses due to land use change were less than 0.5% (Lathrop et al. 2016).

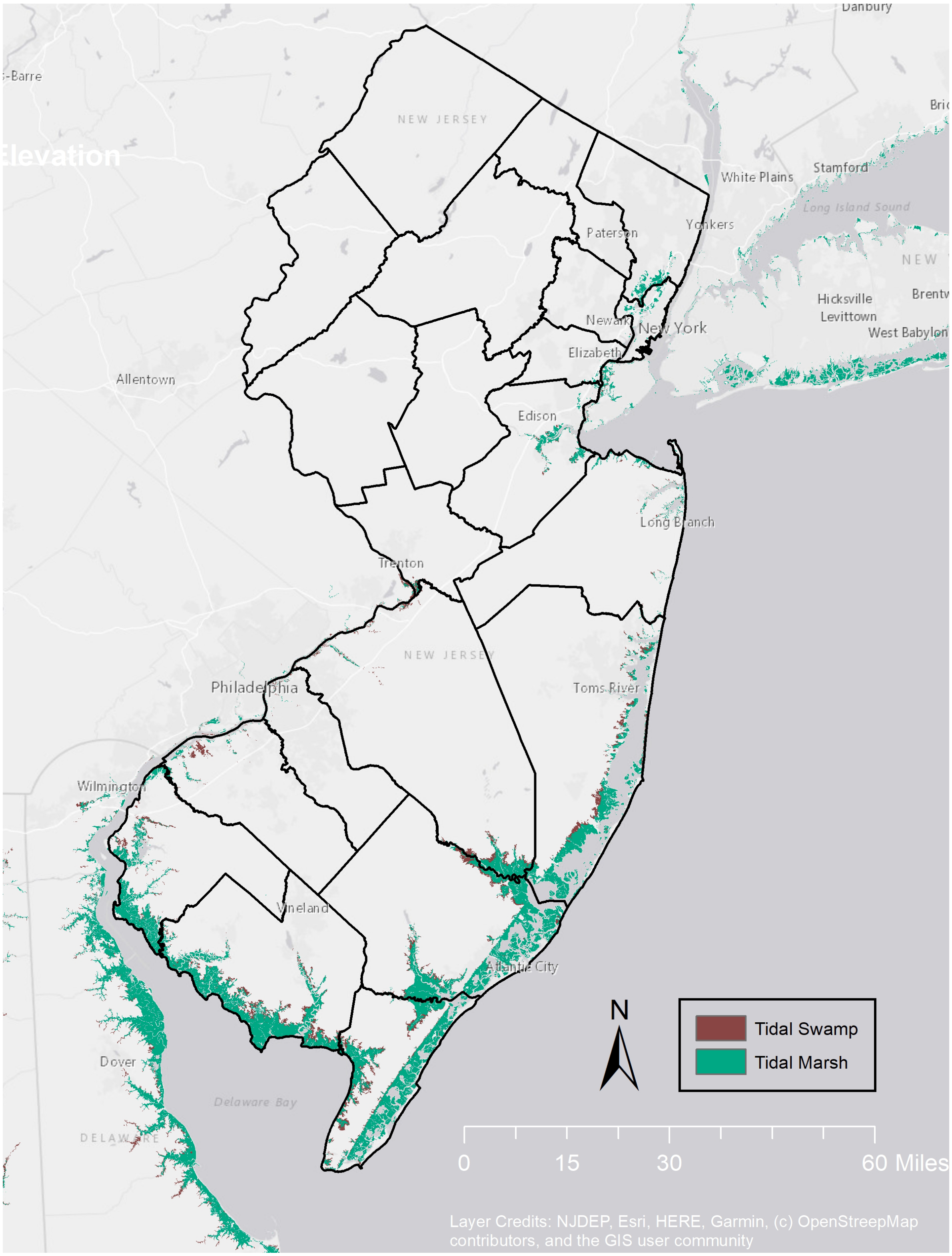


Figure 5.13. Location of Tidal Marsh and Tidal Swamps in New Jersey. Data from Terrestrial Habitat Map for the Northeast US and Atlantic Canada (The Nature Conservancy 2015).

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
WETLANDS

Located at the ocean-land interface, tidal wetlands are inherently highly dynamic and stressed habitats. The plants and animals that live there must be able to deal with alternately being flooded and exposed to the air, often for variable amounts of time driven by seasonal and lunar cycles. Tidal wetlands are often exposed to intense erosive forces from rivers, tides, storms, and boat wakes - making their shape and size naturally variable. In addition, in saltwater and brackish marshes, plants and animal have adapted to living in salty water. Because of the stressful and dynamic nature of tidal wetlands, the habitats themselves are surprisingly resilient to natural disturbances.

However, current rates of climate change are sparking changes that are unprecedented in the 2000-year history of New Jersey tidal wetlands. It is unknown how resilient tidal wetlands will be in the face of increases to atmospheric carbon dioxide, increased rates of sea-level rise, increased severity and frequency of storms, changes in rain patters, and coastal acidification. In addition, human activities like dredging, shoreline hardening, and pollution have already decreased the resilience of tidal wetlands.

In order to provide the best protection to New Jersey coastal wetlands, it is necessary to understand the processes that contributed to their formation since the Holocene marine transgression (about 10,000 years ago) and acquire knowledge on their natural variability and capacity to withstand the ocean force effects, as described above. The first theories for the evolution of New Jersey lagoons from open-water to marsh-filled systems were proposed in 19th century (Shaler 1895). Other authors afterwards studied the geological processes and physical characteristics leading to the development of modern salt marshes (Knight 1934, Frey and Basan 1978).

There is geological evidence that approximately 125,000 years ago the sea-level was similar to its present-day level. The evidence is provided by the presence of late Pleistocene (i.e., a geological epoch that lasted from 2.5 million to approximately 12,000 years ago) marine and fluvial sediments constituting the Cape May formation, which is present east of the Cape May peninsula (MacClintock 1943). This formation is 125,000 years old and is overlain by the younger Holocene barrier and back-barrier. Later on, during the subsequent glaciation episodes and maximum ice loading, southern New Jersey was located on the forefront ice cap bulge. Between 80,000 and 18,000 years ago, the southern New Jersey climate conditions resembled those from today's Alaska, Canada, and Siberia, with temperatures below freezing levels for most of the year. The main consequence of glaciation episodes was a dramatic sea-level retreat, and approximately 18,000 years ago at maximum glaciation, the sea-level was more than 130m (426 feet) below the present-day level (Dillon and Oldale 1978), the coast line was 80 miles east from its present position, while the coastal plain occupied twice its surface today (Tiner 1985).

About 10,000 years ago, the Holocene warming period started the northern hemisphere melting of the ice cap which resulted in a continuous but fluctuating rate of sea-level rise throughout the Holocene (Kemp et al. 2013). Rapid sea-level rise (~12 mm/year) began following early Holocene glacial melting. About 6,500 years ago, the rate of sea-level rise gradually decreased. A marked decrease in sea-level rise to about 2-mm/year occurred 2,000 years ago permitting the coastal wetlands to establish. Fluvio-deltaic sediments deposited during the early Holocene marine transgression provided the foundation for intertidal sediment deposition and subsequent marsh formation. A gradual increase in sea-level rise reached present-day rates that vary in different New Jersey locations.

With current rates of climate change generating unprecedented changes (at least over the last 2000 years, as revealed by sediment and ice core investigations) to atmospheric carbon dioxide, increased severity of storms, and sea-level rise that outpaces what New Jersey tidal wetlands have experienced before, it is unknown how resilient tidal wetlands will be in the future. Sea-level rise is a contributor to the global loss of thousands of hectares of tidal wetlands each year (Hartig et al. 2002, Langley et al. 2009). The current knowledge and predicted future effects of climate change on the tidal wetlands of New Jersey is explored next.

5.5-2.1 Increased CO_2

The concentration of carbon dioxide (CO_2) in Earth's atmosphere is higher than has been in the past 800,000 years. In 2018, it reached 407.4 ppm which is more than an 80 percent increase over pre-industrial times (Blunden et al. 2019). Carbon dioxide is used by plants during photosynthesis to store the Sun's energy as sugars in plant tissue. Increased CO_2 is likely to facilitate a shift in the plant communities of New Jersey's tidal wetlands by stimulating growth in some plants, while having no effect on others. In turn, some of that increase in plant growth will be stored in soil, helping wetlands gain elevation at a more rapid rate (Cherry 2009, Langley et al. 2009). For example, in experiments conducted in the Chesapeake Bay with CO_2 elevated to levels projected for 2100, an increase in plant productivity was found to increase the rate of soil elevation gain in brackish marshes by 0.15 in/year (3.9 mm/year) (Langley et al. 2009). An increase of 0.15 in/year would nearly double current average accretion rates for tidal wetlands in New Jersey.

Certain plants are better able to take advantage of elevated levels of carbon CO_2, increasing their ability to compete with other species. As CO_2 levels increase, the makeup of tidal wetland plant communities is likely to change, favoring sedges and grasses that use C3 pathways in photosynthesis, which are more limited by the amount of available CO_2, than plants that use C4 pathways for photosynthesis (Curtis et al. 1990, Rozema et al. 1991, Erickson et al. 2007). Studies on tidal wetland plants in the Mid-Atlantic and New England have found that biomass is increased in C3 plants when CO_2 is increased, but there is no effect on C4 plants when CO_2 is increased. However, this boon to C3 plants may be muted by C4 plants' adaptations to the higher temperatures and drought conditions during the growing season projected as a result of climate change.

In New Jersey, the dominant native salt marsh plants are all C4 plants (*Spartina alterniflora, Spartina patens, and Distichlis spicata*), while the primary invasive species to tidal wetland systems, *Phragmites australis*, is a C3 plant. Increases in CO_2 and increases in temperature have been found to increase the biomass of *P. australis* especially with elevated levels of nitrogen (Mozdzer and Megonigal 2012, Eller et al. 2014). In addition, the combination of elevated CO_2 and increase temperature decreased *P. australis* sensitivity to salt, allowing it to encroach into more saline areas that it had been excluded from before (Eller et al. 2014).

5.5-2.2 Temperature Increase

Over the past century, the average annual temperatures in New Jersey have increased by 3.5˚F (1.9˚C) (Chapter 4.1). Winters have warmed more rapidly than summers, decreasing the number of days that drop down into freezing temperatures. Looking into the future, average annual temperatures are expected to continue to rise. With a high emissions scenario the hottest years may be up to 10˚F (5.6˚C) warmer than past years (Chapter 4.1-4). Warmer air temperatures have led to warmer water temperatures and longer ice-free seasons (Dupigny-Giroux et al. 2018).

Increases in the average air temperatures and decrease in the number of frigid days has lengthened the growing season, allowing plants to be more productive. The longer growing season and increases in temperatures will continue to facilitate the northern migration of plant and animal species. In addition, temperature increases and species migration are expected to result in a decrease of plant species diversity in tidal wetlands (Tiner 2013, Baldwin et al. 2014).

The effect of warmer weather on carbon sequestration in tidal wetlands is complex. Tidal wetlands excel at capturing carbon dioxide from the air and sequestering it in the soil. Increased plant productivity as a result of climate change would also increase the rate of carbon storage in the soil. However, the soil carbon density may actually decline as temperatures increase because rates of decay also increase at higher temperatures (Chmura et al. 2003). In addition, benefits to increased plant production from a longer growing season and warmer temperatures may be offset as the heat and summer droughts (also projected as part of climate change in New Jersey) reduce the moisture content of the soils, consolidating salts and other chemicals (Kreeger et al. 2010). Changes in soil moisture can cause rapid shifts in soil chemistry, which is stressful for the plants and animals that live there. These extreme shifts in soil chemistry can contribute to marsh loss (Bason et al. 2007, Kreeger et al. 2010, Elmer et al. 2013).

5.5-2.3 Current Effects Of Sea Level Rise On Tidal Wetlands

Tidal wetlands exist between where the water meets the land at elevations that are alternately flooded and exposed by tidal waters. These habitats are resilient to moderate rates of sea-level rise; they gain elevation by trapping sediment brought in by the tide and building organic matter from plant roots and leaves (Nyman et al. 2006, Mitsch and Gosselink 2007, Cahoon and Guntenspergen 2010, Kirwan and Megonigal 2013). Wetland areas that are flooded deeper and longer generally accrete and add elevation at a faster rate than wetland areas at higher elevations (Payne et al. 2019).

Although tidal wetlands can keep up with moderate increases in sea-level rise, it is expected that there are tipping points after which habitats will begin to change. The amount of sea-level rise that can be tolerated is thought to be influenced by salinity, shallow subsidence, tide range, accretion rates, and the amount of sediment in water (Partnership for the Delaware Estuary 2017). When a tipping point is reached, the species composition of plant communities will shift from less flood tolerant to more flood tolerant species (Donnelly and Bertness 2001, Erickson et al. 2007, Cameron Engineering and Associates 2015). For example, high salt marsh -- an infrequently flooded habitat dominated by saltmeadow cordgrass (*Spartina patens*) that is critical to the Black Rail (*Laterallus jamaicensis*), the American Black Duck (*Anas rubripes*), and others -- are already giving way to the more regularly flooded middle and low marsh dominated by smooth cordgrass (*S. alterniflora*). Smooth cordgrass dominated marsh appears to be more resilient to sea-level rise (Payne et al. 2019). The low marsh provides habitat for ribbed mussels and crabs. When flooded for too long, even low marsh plants cannot persist, and the habitat will convert to mud flats and open water. Plants are the keystone of tidal wetlands habitats. Plants trap sediment and produce roots and leaves that allow the sites to gain elevation and their roots bind the soil together preventing erosion and sequestering carbon. Plants also provide food for the marine food web, and nesting structure for birds. The common reed, *Phragmites australis*, has been found to protect tidal marshes from erosion associated with sea-level rise and violent storms (Theuerkauf et al. 2017). The height and dense growth of *Phragmites* provide some protection from the erosive effects of storm surge and wind. Without plants, tidal wetlands would disappear.

In light of increasing rates of sea-level rise, scientists and researchers have been studying tidal wetlands to determine how they are responding to current conditions and to make predictions about future states of tidal wetlands. They want to understand what the critical thresholds are for habitat conversion and under what scenarios and timescales the thresholds will be reached. Such work is underway in the New Jersey Meadowlands (MERI 2020) and elsewhere around the state. Answering these questions can help inform management decisions in New Jersey coastal zones.

Tidal wetlands in New Jersey began to form when rapid sea-level rise (~0.47 in/year; ~12 mm/year) decreased to around 0.08 in/year (2 mm/year). In the 20th century, rates of sea-level rise increased to an average of 0.16 in/yr (4 mm/year) (NOAA 2019). Sea-level rise is a contributor to the global loss of thousands of hectares of tidal wetlands each year (Hartig et al. 2002, Langley et al. 2009). There is evidence in New Jersey that tidal wetlands are already being negatively impacted by that rates of sea-level rise we are currently experiencing, although the effects are not uniform across all marshes.

The majority of salt marshes in the United States and more specifically in New Jersey are not gaining elevation at a rate that equals local relative sea-level rise (Cahoon 2015, US EPA 2019). A recent study in the Delaware Estuary and Barnegat Bay found that 94% of the thirty-two wetlands studied were not keeping pace with the rates of sea-level rise observed between 2000-2018. This accumulation deficit, the difference between the rate of elevation gain in the marsh and long-term sea-level rise trends, was as much as 0.16 in/yr (4 mm/year) in the Delaware Estuary Bay marshes and 0.26 in/yr (6.5 mm/yr) in Barnegat Bay marshes (Haaf et al. 2019). Similar studies conducted in the Meadowlands indicate that tidal wetlands are gaining elevation near current rates of sea-level rise, ranging between 0.16 in/yr and 0.23 in/yr (3.18 and 5.84 mm/year) (MERI 2015). Monitoring stations to track elevation changes in tidal wetlands on the Raritan River have been added in the past few years, but more data is needed prior to summarizing findings.

Recently, the DEP conducted sediment core investigations along the New Jersey coast exploring the environmental conditions over the last 500 to 2,000 years. These investigations revealed how much environmental conditions such as nutrients, salinity, and exposure to ocean tides naturally varied, as well as changes that were induced by the European settlers (NJDEP 2018b). All examined sediment cores revealed that the sea-level rise is negatively impacting the New Jersey coastal wetlands included in this study, with exposures to tides higher than during the previous centuries or millennia encompassed by the stratigraphic record.

Historic and current land use practices make New Jersey tidal wetlands more vulnerable to sea level rise than they would be naturally. For example, tidal wetlands have historically been diked for farming or waterfowl. These practices left wetlands at lower elevations than the surrounding marshes. Sea-level rise and diking are blamed for the decreasing health of tidal wetlands in the Delaware Bay (Kearney et al. 2002, Smith et al. 2017).

Sea-level rise also affects other important hydrological factors. The first effect is that the tidal range (the difference in elevation between high and low tides) is projected to change in New Jersey, increasing in some areas and decreasing in others (Flick et al. 2003, Hall et al. 2013). Generally, it is considered that wetlands with larger tide range are expected to be more resilient to sea-level rise, but there is little research on whether an increasing tidal range will be beneficial.

The second effect is that mean high-water levels are rising at a faster rate than mean sea-level (Flick et al. 1999). Recent studies from New England have found that marshes situated below mean high water are experiencing greater losses than marshes sitting well above mean high water (Watson et al. 2017). Rates of increase in mean high water were several mm/year higher than rates of mean tidal levels in the Barnegat Bay and Delaware Estuary (Haaf et al. 2019). If mean high water is a critical threshold for tidal wetland resilience, then tidal wetlands in New Jersey are likely to face increased threats due to sea-level rise.

A third effect is that the sea-level increase results in increased water depth, which allows for larger and stronger wave formation. Larger and stronger

waves will increase erosion of tidal wetland shorelines. Wetlands in the Delaware Bay are not as protected as the back-barrier wetlands along the Atlantic Coast of New Jersey and thus have higher rates of erosion. Average erosion of tidal wetland edges in the Delaware Bay between 1940 and 1978 was 0.13 in/yr (3.3 mm/year) (Phillips 1986); this number has likely increased as a result of sea-level rise. In addition, creeks and ditches in tidal wetlands are also eroding, making these water conveyances wider (Smith et al. 2017). Changes in creek size, depth, and density alter the hydrology of the marsh and change the edge to interior marsh ratios which is important for fish production (Cameron Engineering and Associates 2015).

Sea-level rise is also creating new tidal wetlands through marsh migration. Marsh migration (also referred to as marsh retreat) is the process by which new tidal wetlands form in upland areas as sea-level rises. New Jersey's gently sloping coasts are ideal for marsh migration. While New Jersey may have ideal slopes for marsh migration under natural conditions, 29% of potential migration areas were found to be blocked by roads and other development in 2007 (Lathrop and Love 2007). The more developed regions of New Jersey coasts, like Raritan Bay, northern and central sections of the Barnegat Bay, the Meadowlands, and the wetlands associated with barrier islands have little room to move due to development (Lathrop and Love 2007). In the less developed Delaware Bay, as much as 75% of tidal wetlands loss has been compensated by increases in new wetlands area (Hardisky and Klemas 1983, Phillips 1986, Smith 2013, Watson 2019). However, these newly formed wetlands are largely dominated by the invasive *P. australis* and thus are not replacing the same high habitat that has been lost (Smith 2013, Cameron Engineering and Associates 2015, Dorset 2018). In addition, the newly formed tidal wetlands often replace other important habitats, like non-tidal cedar swamps, further calling into question the quality of the new tidal habitats (Dupigny-Giroux et al. 2018).

5.5-2.4 Future Responses To Sea Level Rise

Sea-levels are expected to rise 0.9 to 2.1 feet (274 to 640 mm) between 2000 and 2050 and then an additional 1.4 to 4.2 feet between 2050 and 2100 in New Jersey (Kopp et al. 2019). When these estimates are converted into units that are more useful for tidal wetlands, the likely rate of change in sea-level from 2000 to 2050 is an increase of 0.02 to 0.04 ft/year (5 to 13 mm/year). From 2050 to 2100, the rate increases to 0.03 to 0.08 ft/year (9 to 26 mm/year). The majority of tidal wetlands studied in New Jersey are not keeping pace with recent rates of sea-level rise which have a mean of 0.24 in/yr (6 mm/year) from 2000 to 2018 (Haaf et al. 2019) when 0.39 in/yr (10mm/year) has been suggested as a tipping point resulting in catastrophic loss of tidal wetlands (Orson et al. 1985).

> ***"Although tidal wetlands can keep up with moderate increases in sea-level rise, it is expected that there are tipping points after which habitats will begin to change."***

Future projections of tidal wetland response to sea-level rise in New Jersey vary by region, salinity, sediment load, and tide range. One of the main models used to predict tidal wetland vulnerability to sea-level rise is SLAMM (Sea-level Affecting Marsh Model, Warren Pinnacle Consulting, Inc, Waitsfield, VT). Although SLAMM is limited by data inputs, uncertainty associated with input factors, and general oversimplification of the system, the model can provide important insights into how the New Jersey coast may be impacted by sea-level rise. SLAMM has been run for portions of the New Jersey coast several times. The following summarizes what is projected for tidal wetlands in New Jersey:

- In the Delaware River and Bay, many tidal wetlands were classified as high marsh (flooding one time or less per day). High marsh habitats are expected to be especially hard hit by rising sea-levels, leading to a decrease in high marsh acres of 85-95% in the four watersheds studied. The rate of conversion is expected to increase rapidly after 2050. Under moderate rates of sea-level rise, current high marsh areas convert to low marsh (flooded twice daily) and new high marsh areas would be created in transition zones (marsh migration) with a net increase in total marsh area projected. Under high rates of sea-level rise (6.6 feet between 2000 and 2100), the current areas of high marsh largely convert to low marsh or open water, but new wetlands would be projected to form in transition areas resulting in little loss of total wetlands areas. Tidal swamps and tidal freshwater marshes are also projected to decline in acreage with moderate and high rates of sea-level rise, assumedly converting to salt marsh (US EPA 2019).
- Another recent SLAMM run for the entire coast of New Jersey predicted that tidal wetlands in New Jersey would be resilient to low rates of sea-level rise as of 2050 (1 foot between 2000 and 2050), potentially even increasing in area by more than 17,000 acres due to marsh migration. However, with moderate rates of sea-level rise (2 feet increase between 2000 and 2050) the picture changes. The Delaware and Raritan Bay wetlands generally seem resilient to 2 feet increase, although the higher upstream the model traveled, the higher the likelihood of conversion from vegetated marsh to mudflat or open water. From Cape May north to Atlantic City is dominated by wetlands with a moderate likelihood of conversion by 2050. From Great Bay north to Toms River, many tidal wetlands would be projected to convert to mudflats with 2 feet of sea-level rise. In addition, there is far less room for tidal marshes to migrate on the Atlantic Coast of New Jersey (Rutgers University 2019).

5.5-2.5 Decreased Rainfall During The Growing Season

Salinity is expected to increase upstream (i.e., inland) and in coastal aquifers as a result of sea-level rise and droughts during the growing season (US EPA 1986, Fiore et al. 2018). Increased salinity is expected to change the composition of plant communities in tidal wetlands and change the rates of carbon storage and mineralization (release of carbon from dead plant material back into the water and air). Plants that dominate tidal fresh and brackish marshes as well as freshwater tidal swamps tend to be intolerant of increases to salinity. Based on mesocosm studies (i.e., outdoor experiments designed to examine the natural environment in a more controlled setting) and long-term studies done in the Mid-Atlantic regions, where the seedbank is available, more salt tolerant species are likely to shift upriver with sea-level rise (Spalding and Hester 2007). Increased flooding and increased salinity have been projected to lead to the loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100 with 2.3 feet (0.7 meters) of sea-level rise (Glick et al. 2008). The extremely rare sea-level fens are also at risk. In addition to changes in plant communities, the loss of these habitats would have major impacts to the birds, fish, crabs, and mammals that use them. Brackish marshes are important feeding spots for bald eagles and provide habitat for herring, shad, Atlantic menhaden and drum species (Strange et al. 2008). Tidal freshwater marshes support a diverse range of bird species as well as frogs, turtles, and snakes that cannot tolerate saline or brackish conditions. The effect of increased salinity can already be seen in tidal swamps and non-tidal coastal forests of New Jersey. Saltwater intrusion, salinity increases in tidal water, and storm surges have created “ghost forests,” stands of dead trees surrounded by transitional marshes.

5.5-2.6 Increased Frequency, Severity, And Duration Of Storms

Storm erosion events have been observed in wetland sediment sequences from Delaware Bay. Sediment cores collected from Sea Breeze and Fortescue, on the northern shore of Delaware Bay revealed that these wetlands have received blunt force impacts from prolonged periods of heavy storms over the past 2,000 years. A group of scientists led by Dr. Daria Nikitina from Westchester University collected sediment cores from these sites and found that sharp changes in sediments from organic to inorganic and void of vegetation layers correspond to erosion events that eradicated the vegetated marsh (Nikitina et al. 2014). Radiocarbon dating revealed the age, duration and frequency of these storm erosion events as well as the wetland recovery process.

For example, in Sea Breeze, the sediment cores revealed under the wetlands surface a sediment record that formed during the last ~2,300 years. This sediment record is represented by six lithostratigraphic units (i.e., rock layers) which were associated with erosive boundaries that are considered to be formed during strong storm events (Nikitina et al. 2014). The erosive boundaries occur above high saltmarsh peat layers and are sharp [~0.04 in (1 mm)], suggesting an abrupt change in the sedimentation regime and environment of deposition, which were interpreted as marsh erosion caused by powerful storm events. These erosion events are followed by deposition of a gray mud layers and represents tidal-flat and low salt-marsh depositional environments. Vertical stems of *S. alterniflora* deposited above the tidal mud illustrate colonization by low salt-marsh vegetation.

Similar lithostratigraphic changes were observed in two cores from the Fortescue wetlands, showing that the wetlands from Delaware Estuary have been subjected to cyclic storm events and marsh erosion since their formation more than 2,000 years ago. The sediment core record also revealed the time span for marsh recovery from vegetation of tidal flat with *S. alterniflora* to high marsh of approximately 200 years but in some cases may take longer. See Figure 5.14 for an example of storm events in a sediment core from Fortescue. Other sediment cores collected from Barnegat and Cheesequake State Park (Raritan Bay) did not display erosion discordances and sediment layer successions associated with storm events; this is possibly due to the wetlands benefiting from natural protection by barrier islands or other forms of protection. These findings may imply that present-day wetland protection practices, such as living shorelines for example, may help preserve the wetlands from erosion impacts from storms and/or other ocean forces.

5.5-2.7 Flooding

Climate change is expected to increase the frequency, severity, and duration of coastal storms. Increased flooding during storms appears to have variable effects on tidal wetlands. The increased turbidity and inundation times associated with storms tends to increase sedimentation on the marsh, causing elevation to increase and helping the marsh keep pace with sea-level rise. However, this increase in sedimentation is offset by increased compaction from the weight of flood waters during a storm. For example, one study of the elevational effects of Hurricane Sandy on tidal wetlands found that wetlands on one side of where the storm made landfall had an overall increase in elevation, indicating that the added sediment outweighed any compaction effects of the storm surge (Cahoon et al. 2019). On the other side of where the storm made landfall, the marshes tended to have an overall loss of elevation, indicating that compaction of the marsh was greater than the accretion benefits of the storm surge. This was explained by a larger storm surge in areas where the marshes had an overall loss in elevation. A larger storm surge moved farther inland, passing the marshes before dropping the majority of its sediment load and was heavier and had a longer residence time (Cahoon et al. 2019).

5.5-2.8 Coastal Acidification

The current extent of coastal acidification affecting tidal wetland ecosystems in New Jersey or the Mid-Atlantic region has not been well studied. Expert opinions on current and future effects on estuarine systems range from insignificant to extreme.

Those presenting arguments on why coastal acidification may be insignificant cite the high variability in pH in estuarine systems and the terrestrial drivers of acidification. Some research

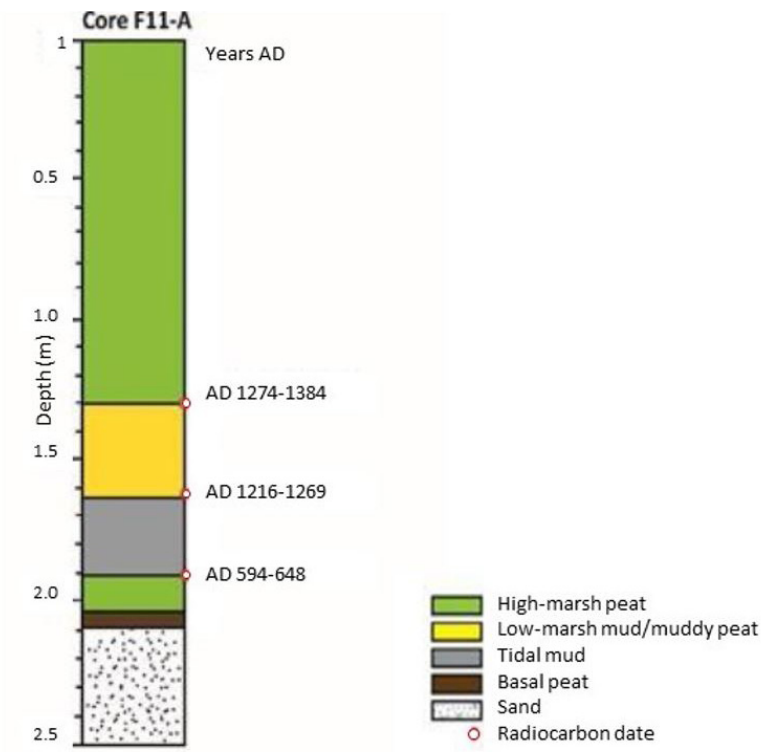


Figure 5.14. Example of a Sediment Core Lithology from Fortescue, Delaware Estuary Wetland Displaying a Storm Erosion Event Followed by Mud Flat Deposition. Radiocarbon ages were calibrated using data from (Stuiver and Reimer 1993, Reimer et al. 2009). Figure modified from (Nikitina et al. 2014).

suggests the typical range in estuarine pH is higher than the change expected in the ocean from CO_2 inputs (Duarte et al. 2013a). For example, based on a small handful of studies conducted on the east coast of the United States, the change in pH in salt marsh can range from 1 or even 2 pH units daily (Duarte et al. 2013a). These daily fluxes greatly exceed the 0.1 pH unit change documented in the open ocean since the mid-eighteenth century and exceed the predicted pH change in the open ocean for the next few centuries (NJDEP 2018a).

The major drivers of pH flux in estuarine systems are from natural and anthropogenic (human-caused) sources running off the landscape and from nutrient fluxes within the estuary itself. Eutrophication plays a major role in the acidification of rivers and estuaries (Cai et al. 2011). The increase in river alkalinity over time in New Jersey has helped to offset some of the new sources of acidity in river and estuarine systems (Kaushal et al. 2013). However, there are indications that pH in portions of major estuaries in the United States have already decreased to a point of harming invertebrates. Those who warn of harmful impacts from coastal acidification stress that multiple acidic sources, relatively small volume, and low frequency of flushing make estuaries especially susceptible to acidification (Guinotte and Fabry 2008, Ross and Adam 2013). Larval and juvenile stages of invertebrates are especially sensitive to lower pH which can weaken their shells, making them more susceptible to predation and decreased growth rates. Thus, small changes in estuarine pH that might result from acidification could have large impact on the estuarine food chain. The pH has declined significantly in the Chesapeake Bay. In some regions, it has declined to such low values that juvenile oyster shells dissolve (Waldbusser et al. 2011). The pH has also declined significantly in portions of the Puget Sound in Washington State. In this case, scientists have estimated that acidification

"The composition of coastal wetland forests will likely be altered under a changing climate…Atlantic white cedar…will suffer disproportionately compared to other native New Jersey species due to rising seas."

currently accounts for 24-29% of the change in pH from pre-industrial levels. Based on future projections of coastal acidification under a scenario where CO_2 doubles, the contribution could increase to 49-82% of the pH decrease.

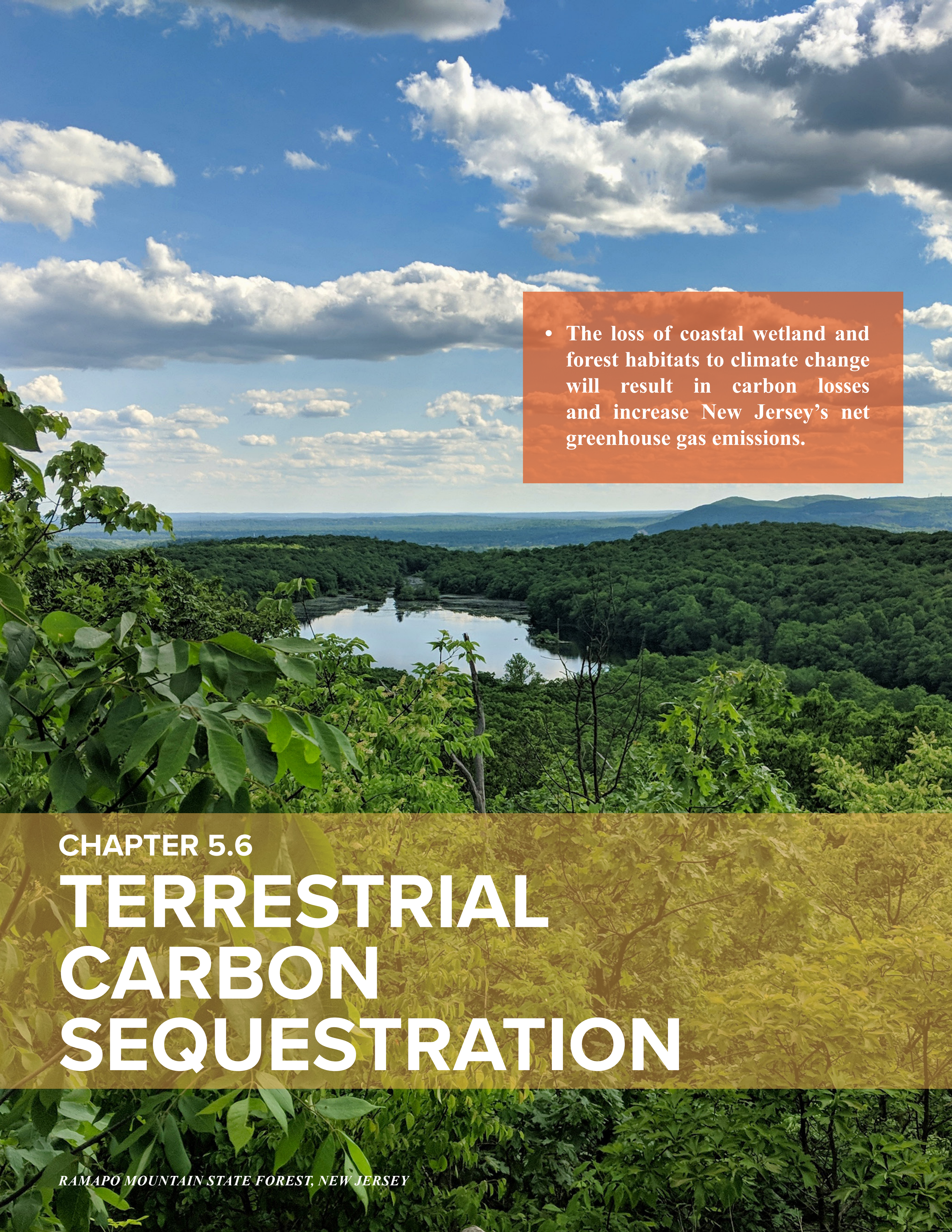
5.5-3 Coastal Wetland Forests

The composition of coastal wetland forests will likely be altered under a changing climate. For instance, Atlantic white cedar (*Chamaecyparis thyoides*), long a high-value species throughout its range, will suffer disproportionately compared to other native New Jersey species due to rising seas. Atlantic white cedar typically occurs within one hundred miles of the Atlantic coast, from Maine to Mississippi. It competes well against other trees in wetlands, which are often the lowest-elevation features on the landscape. However, it is completely intolerant of saltwater inundation, although it does have a capacity to reestablish on salted sites if enough salt is leached from the soil (Little Jr. 1950). In New Jersey, it mainly grows in wetlands with muck soils on the outer coastal plain. This low-lying coastal distribution and utter intolerance of salt makes the species particularly susceptible to rising seas. Persistent inundation from direct sea-level rise is not needed to eliminate cedar from a site: periodic and unpredictable flooding from saltwater storm surges are all that is needed to kill a forest. Hence, loss of area and range of this globally rare species is expected with rising seas.

Cedar swamps dying and being colonized by marsh species is not new: losses to saltwater have been noted for this species since the 1850s, attributed then to coastal subsidence (Cook and Kitchell 1857). The immense decay resistance of the species has left evidence of the longer-term impacts of rising seas by way of buried cedar stumps well into coastal marshes and shallow bays. These examples show that Atlantic white cedar forests have been retreating with rising seas since the last glacial period.

For cedar forests to maintain their presence on the landscape despite losses on the coast, the conditions that created the establishment of those forests must also be maintained. For cedar, that disturbance process was mainly driven by fire. Cedar can be an excellent competitor as a colonizer of sites left open by disturbance like fire, provided that the disturbances occur, and cedar can get to the openings.

Compared to historical levels, the current diminished extent of this species makes the threat from sea-level rise that much more pressing, as cedar will likely find difficulty in establishing itself in new sites to replace those lost to salt. In forested wetlands that no longer have a cedar component, disturbance of those areas will not increase the chance for cedar to establish (Sheffield et al. 1998, Mylecraine and Zimmermann 2000). Hundreds of years of cutting of the species has reduced its abundance, reducing it to a minor canopy component in almost all of the forested wetlands outside the Pinelands National Reserve. Combined with changes to the behavior, frequency, and extent of fire on the landscape, it is not expected that cedar forests will have suitable habitat to retreat to in response to rising seas.



- **The loss of coastal wetland and forest habitats to climate change will result in carbon losses and increase New Jersey's net greenhouse gas emissions.**

CHAPTER 5.6

TERRESTRIAL CARBON SEQUESTRATION

RAMAPO MOUNTAIN STATE FOREST, NEW JERSEY

5.6 Terrestrial Carbon Sequestration

New Jersey natural lands, including forests, woodlands, salt marshes and wetlands, seagrasses, and agricultural lands, are large carbon sinks and can provide important mitigation against greenhouse gas emissions. Carbon that is removed from the atmosphere is stored in live trees and plants, standing dead trees, understory and marsh vegetation, downed dead wood, forest floor litter, and soil organic carbon. It is estimated that in 2018, New Jersey's land sector of forests and associated land cover sequestered the equivalent of 8.1 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) resulting in net greenhouse gas emissions of 97.0 $MMTCO_2e$ (NJDEP 2019a). It is important to note that this is an estimate as there is limited New Jersey specific data about the sequestration capabilities of the State's lands. As described further in Chapter 3.2, CO_2e which is a term used to compare the emissions from various greenhouse gases based on their Global Warming Potential to the reference gas of CO_2, which has a Global Warming Potential of 1. Changes in land use can contribute to changes in how much carbon is stored in ecosystems, also known as carbon storage, and can cause the release of greenhouse gases.

The Intergovernmental Panel on Climate Change (IPCC) defines a *sink* as any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere (IPCC 2014). *Terrestrial carbon sequestration* is a process that involves the capture of CO_2 from the air by plants through photosynthesis, and storage of that carbon in woody biomass and in plant-derived soil organic carbon (United States Department of Energy and the National Energy Technology 2010). New Jersey has large areas of permanently preserved lands, which already serve as carbon sinks (NJ Climate Adaptation Alliance 2014, Lathrop et al. 2016, Crocker et al. 2017) and include state parks, forests, wildlife management areas, and natural areas; preserved farmland; county and municipal parks; nongovernmental organization nature preserves; and federal wildlife refuges, parks, and military installations.

Blue Carbon ecosystems, such as salt marshes, tidal wetlands, seagrass beds, and mangroves are particularly important to fight against climate change (Howard et al. 2014). These ecosystems capture and store atmospheric carbon at rates up to 10 times greater than forests on a per area basis (Pidgeon 2009). In forest habitats, most of the carbon storage occurs in soils, where it can remain locked up for centuries or more (Pidgeon 2009). Additionally, the high salinity in many blue carbon systems limit production of methane, which is a potent greenhouse gas (Kroeger et al. 2017).

Terrestrial carbon sequestration in New Jersey has incrementally increased over the last decade. Between 2006 to 2015, New Jersey realized a 2.1 $MMTCO_2e$ increase in carbon sequestration see Table 5.3. Minor gains are attributed to carbon accumulation in biomass and soil due to continued maturation of New Jersey forests and wetlands. However, despite this fact between 1986 and 2015, New Jersey saw a 360,000 acre increase in developed (urban) land, and experienced decreases in upland forests, cropland, grassland, and wetlands (NJDEP 2019b). As seen in Figure 5.15, from 2012 to 2015 New Jersey lost almost 10,000 acres of forest, over 9,000 acres of wetland, and over 2,000 acres of crop/grassland (NJDEP 2019b). The rate of urban growth has slowed in more recent years, due in part to the Great Recession of 2008, changes in housing market preference, and New Jersey's strong land preservation polices (Lathrop et al. 2016). These historical land use decisions have reduced New Jersey's carbon pool and impacted the annual rate of sequestration.

The ability of land to sequester carbon is impacted by land use and changes in land use (United States Department of Energy and the National Energy

Table 5.3: Greenhouse Gas Sequestration Trends in New Jersey 2006-2018. This table shows the increased trend of greenhouse gas sequestration from forests and associated land cover in million metric tons carbon dioxide equivalent ($MMTCO_2e$) in New Jersey from 2006-2018. (NJDEP Greenhouse Gas Emission Inventory, 2018).

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
-6.0	-7.6	-7.6	-7.6	-7.6	-7.6	-7.6	-8.1	-8.1	-8.1	-8.1	-8.1	8.1

Technology 2010). The conversion of land from a natural to a developed or disturbed condition is well documented as causing significant, direct, as well as secondary and cumulative, environmental impacts. Environmental impacts associated with land conversion and alteration, beyond limiting carbon sequestration, include habitat loss (NJ DFW 2019), fragmentation (McGuire et al. 2016), the introduction of invasive species (Anderson et al. 2016), and changes to the energy budget like the urban heat island effect (Solecki et al. 2004). Urban/developed land includes both land with houses, buildings and pavement, and other areas; these are essentially impervious to infiltration of rainfall, reducing evaporative cooling, and reflect less solar energy while absorbing more than rural surfaces (US EPA 2008).

Looking forward to 2030 and 2050, under a high emission scenario, terrestrial carbon sequestration in New Jersey will reach 8.6 $MMTCO_2e$ by 2030 and 9.5 $MMTCO_2e$ by 2050, as seen in Figure 5.16. This emission scenario assumes no significant changes in recent land use data and a decline in land clearing due to development being concentrated in already developed or built up areas of the state. This projection also does not take into account recent sea-level rise projections, which predict upwards of 2.1 feet (0.6 meters) of sea-level rise by 2050 (Kopp et al. 2019). The rising sea level could critically endanger coastal wetlands and forest habitat that currently serve as key carbon sinks (Lathrop 2014).

Additionally, the sequestration ability of New Jersey forests and wetlands may be threatened not only by sea-level rise, but also from other climate change factors such as the southern pine beetle. Forests killed by beetles will regrow and over time will adapt in response to this disturbance, but this regrowth and adaptation is a long process and the carbon losses from such an event will cause forests to become a net carbon emitter, like those of the mountain west have become in response to the mountain pine beetle.

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
TERRESTRIAL CARBON SEQUESTRATION

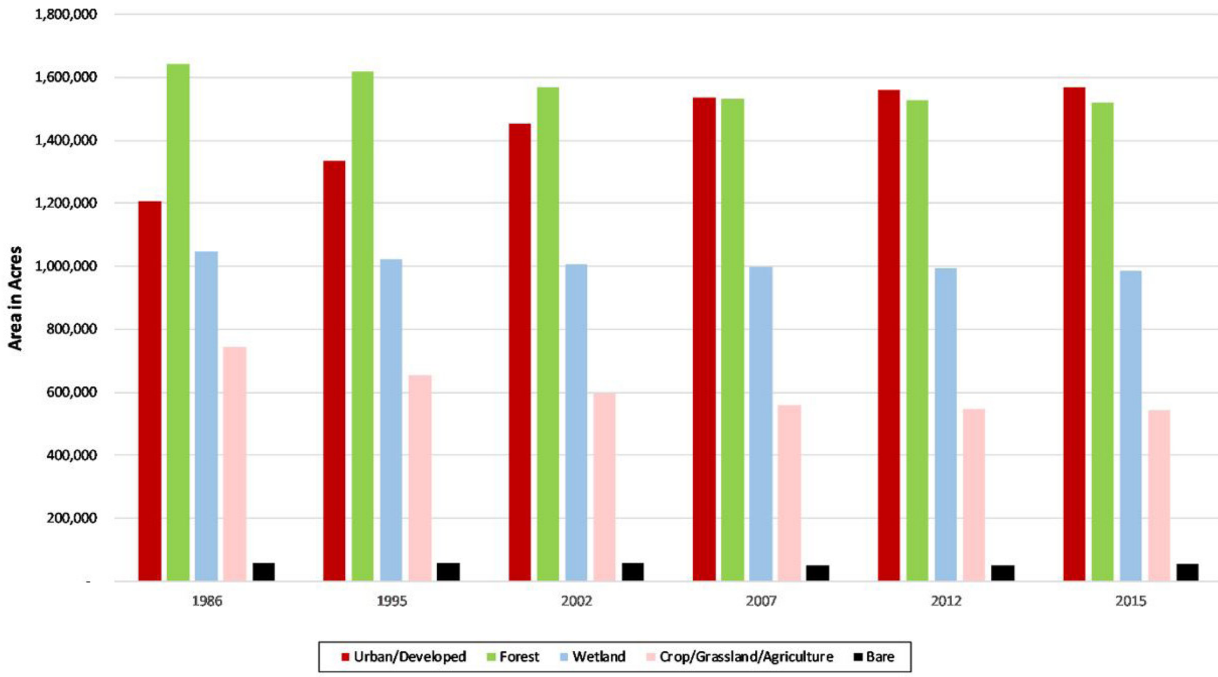


Figure 5.15. New Jersey Land-Use Trends, 1986-2015. This figure shows the acres (y-axis) in New Jersey between 1986 and 2015 that increased in developed/urban land and decreased in crop/grassland/agriculture, wetlands, and forest. (NJDEP, 2019).

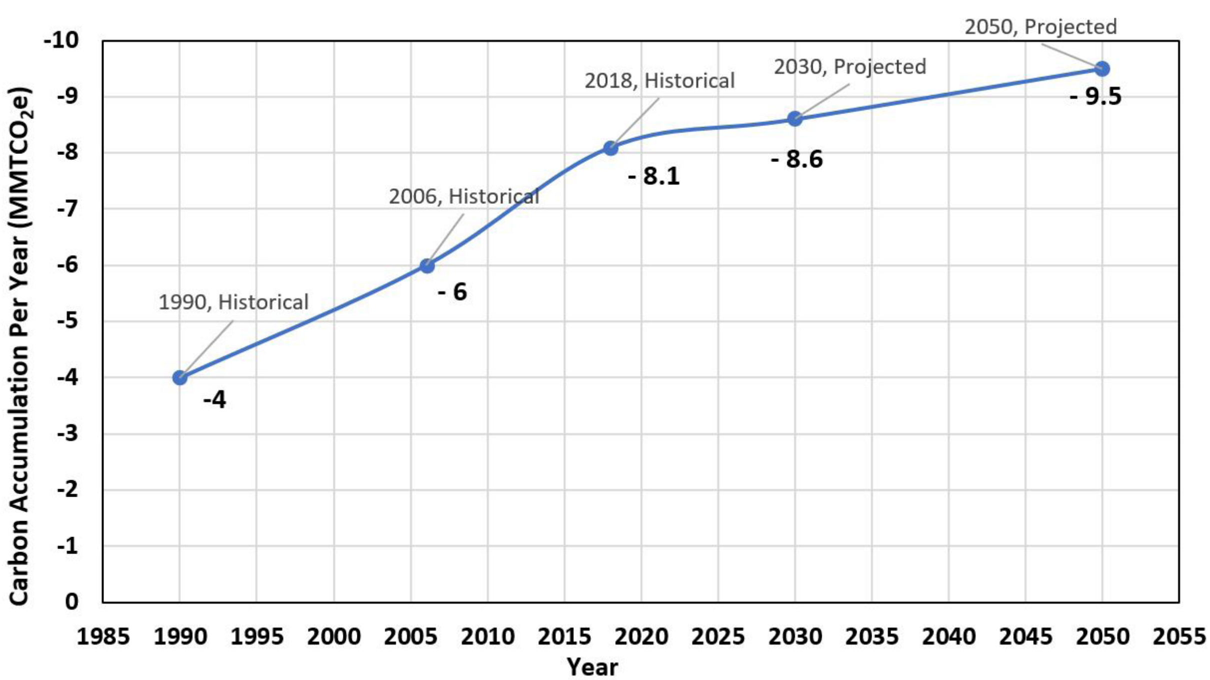
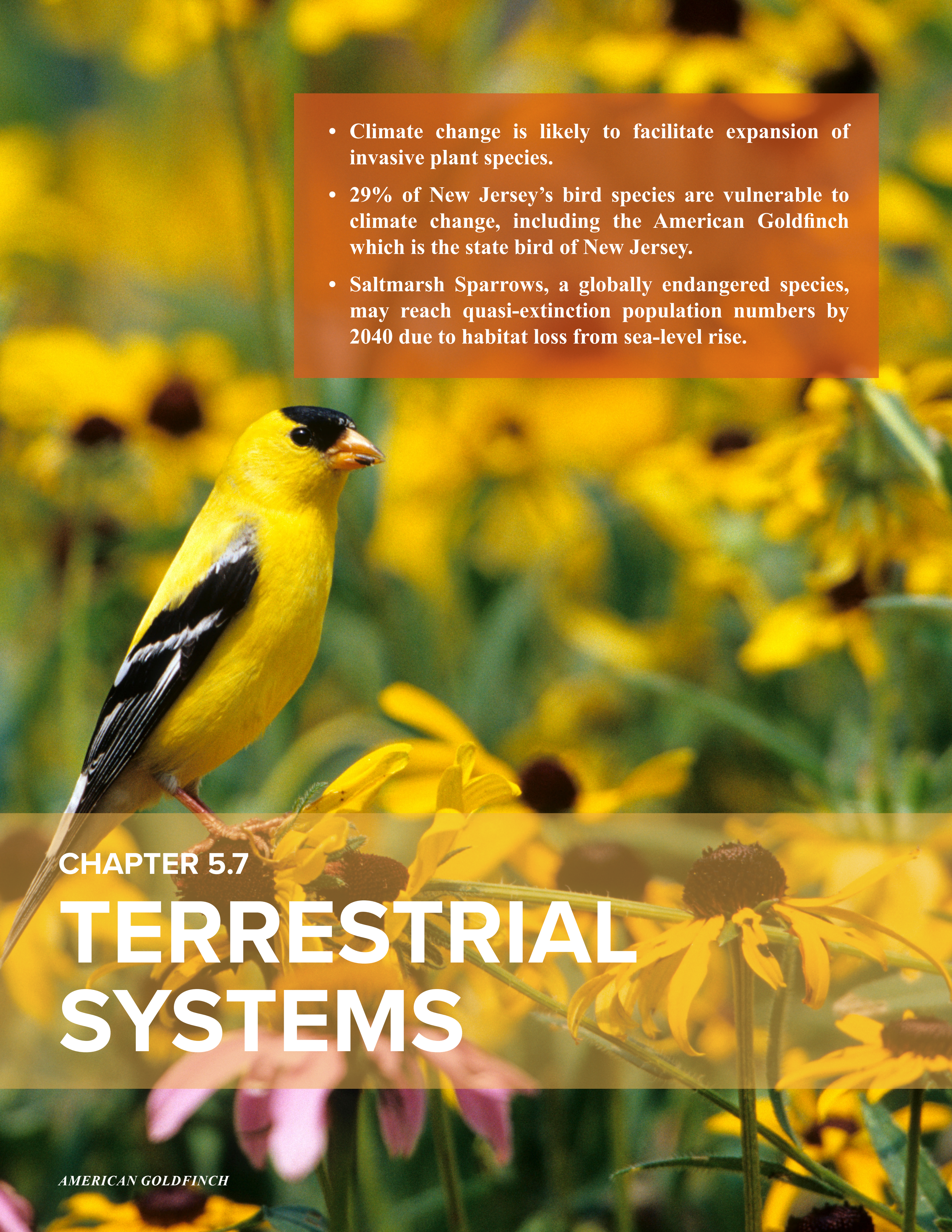


Figure 5.16. Trend of New Jersey Terrestrial Carbon with Projections Through 2050 Under a High Emissions Scenario. This figure shows the projected trend of carbon accumulation per year in $MMTCO_2e$ from 1990 through 2050 (NJDEP 2019c).

- **Climate change is likely to facilitate expansion of invasive plant species.**
- **29% of New Jersey's bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey.**
- **Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 due to habitat loss from sea-level rise.**

CHAPTER 5.7

TERRESTRIAL SYSTEMS



AMERICAN GOLDFINCH

5.7 Terrestrial Systems

The plants and animals that reside in terrestrial systems throughout New Jersey will be impacted by the effects of climate change. In particular, rising sea-levels, changing precipitation regimes, and increased severity and frequency of storms will affect terrestrial plant and animal species.

5.7-1 Plants and Forests (*Flora*)

New Jersey occupies a unique place in both the Mid-Atlantic and Northeast regions of the United States. The five physiographic provinces in New Jersey (ridge and valley, highlands, piedmont, inner coastal plain, and outer coastal plain) give the state an astounding geographic and geological diversity and give rise to an equally astounding biodiversity. These unique conditions mean that New Jersey is home to several globally rare communities such as sea-level fens and Atlantic white cedar swamp. There are over 2,100 native plant species in New Jersey. Several of these species are found nowhere else in the world. This number is comparable to states significantly larger, especially considering that New Jersey is the most densely populated and fifth smallest state in the United States. Climate change poses a significant threat to New Jersey plants and plant communities. Changes brought on by a warming climate, namely earlier springs, hotter summers, inconsistent precipitation, and rising CO_2 concentrations, will challenge the resilience of New Jersey's natural systems (Snyder and Kaufman 2004).

Under the effects of anthropogenic (human-caused) climate change, New Jersey plants and plant communities will be subjected to a variety of stressors and changes, some gradual, others rapid. Plants, in general, respond disproportionately to changes in average temperature and are, thus, indispensable for monitoring the impacts of climate change (Cook et al. 2012). Specifically, changes in plant phenology are major indicators for a changing climate. Phenology is the study of cyclic events in the life stages of plants and animals and how seasonality and habitat can affect these events. Phenological events such as germination, leaf emergence, and flowering have become earlier, following temperature increases in temperate areas worldwide (Parmesan and Hanley 2015). While there is little New Jersey specific data available, trends for the Mid-Atlantic and Northeastern Unites are clear: winters are becoming milder and springs are arriving earlier every year, with ever higher mean temperatures (Parmesan and Hanley 2015, Hoegh-Guldberg et al. 2018, Lipton et al. 2018).

Long-term datasets concerning dates of first flowering, leaf emergence, and local temperature trends offer a wealth of information regarding the effects of climate change. One such dataset is from Mohonk Lake, in Ulster County, New York (Cook et al. 2008). An analysis of local temperature records beginning in 1895 combined with first flowering dates of 19 native plant species beginning in 1920 reveal that most spring blooming herbaceous plants flowered 0.12 to 0.19 days earlier per year following a roughly linear trend in mean temperature increase. The analysis indicates a 1.9 day/decade change in spring flowering date. Similarly, a dataset from Washington D.C. spanning roughly 30 years and containing 100 species, both woody and herbaceous, showed that between 1970 and 1999, 85% of species had advanced flowering dates by an average total of 5.6 days (Abu-Asab et al. 2001). Many species in the list had advanced first-flowering dates by more than 10 days, indicating that some species are more sensitive than others to rising spring temperatures. In Massachusetts, record breaking spring temperatures in 2010 and 2012 resulted in the earliest recorded flowering of 27 different species (Ellwood et al. 2013). Mean flowering time in 2010 was a full three weeks earlier than the mean flowering time in 1852, and mean spring temperature (52°F; 11°C) in 2010 was higher than the mean spring temperature in 1852 (42°F; 5.5°C). Individual species show even more extreme change. Vaccinium corymbosum (highbush blueberry), for example, was recorded flowering on April 1 in the spring of 2012, six weeks before it was observed blooming in the 1850's. Leaf emergence also known as the spring "green up" is advancing at a similar rate and shows strong associations with maximum daytime temperature in the spring and late winter (Piao et al. 2015). With warming trends expected to continue and even accelerate, wild plants will be pushed into earlier first flowering dates. Multiple studies have concluded that for every 1.8˚F (1˚C) increase in average temperatures, flowering time will advance by roughly 4 days (Primack et al. 2004, Ellwood et al. 2013).

> ***"Changes brought on by a warming climate, namely earlier springs, hotter summers, inconsistent precipitation, and rising CO_2 concentrations, will challenge the resilience of New Jersey's natural systems."***

While there is a substantial body of research showing that climate change is causing plants to bloom earlier, a nagging minority of species exhibit seemingly counterintuitive or insignificant responses to spring warming. Species that exhibited no response were considered to be insensitive to warming springs while species with delayed responses were often dismissed as statistical noise or a product of unknown variables. These responses lend to the complexity of the issue and, when investigated, shed light on unexpected ways in which plants can respond to climate change. An additional analysis of the Washington D.C. dataset coupled with year-round temperature records revealed that many of the "unresponsive" species actually were responding quite strongly to climate change due to a process called vernalization (Cook et al. 2012). Vernalization is the period of cold weather required by some plant species before they begin the physiological changes associated with emerging and flowering. With winters becoming milder and shorter, some plants are not receiving the required period of cold weather needed. Vernalization is well studied in model and crop species but is not as well understood in wild plants. Plants that showed a significant response to warmer springs likely require little to no vernalization during the winter months. The combined effects of warmer springs and milder winters essentially "pulled" plants that require vernalization, but were also sensitive to spring warming, in equal and opposite directions (divergent response), resulting in what appeared to be a lack of response to climate change. Out of 106 species, 73% showed significant responses only to spring warming. Meanwhile, 10% previously assumed to show no response at all, showed a divergent response, indicative of both spring warming sensitivity and vernalization sensitivity. Less than 4% exhibited delayed flowering dates due to vernalization sensitivity and the remaining 13% showed no response to warming in any season. New Jersey is especially susceptible to this phenomenon as annual temperatures have risen by 3.5˚F (1.9˚C) with winter temperatures rising more than 4˚F (2.2˚C) since the beginning of the last century and significant future increases expected (Chapter 4.1-4). The unearthed complexity of plant responses to climate change indicates that current estimates are likely underestimating the magnitude of the effect climate change is having on wild plants.

Despite the considerable body of evidence suggesting that climate change is profoundly affecting phenological events in wild plants, the mechanisms surrounding these changes are not well understood. Controlled warming experiments often fail to mirror results found in real world studies and, on occasion, showcase responses that directly oppose those of observational studies (Wolkovich et al. 2012, Parmesan and Hanley 2015). These discrepancies highlight the need for more comprehensive controlled experiments and models that accurately represent the complexity of the real-world observations. There are a multitude of factors influencing plant phenology, some known and some unknown. Temperature plays a disproportionately large role, but the conflicting results of small-scale warming experiments show that it is far from the only factor involved in phenological changes (Cook et al. 2012). These studies also demonstrate that despite the relatively rapid changes, wild plants do not appear to be reaching their physiological limits in terms of flowering dates as of yet (Ellwood et al. 2013).

"If a plant flowers well before or after its associated pollinators are active, it is likely that both plant and pollinator species will experience a drastic decline in reproductive success."

While wild plants show little sign of stress due to earlier flowering dates, there are other potential complications and threats associated with phenological changes and the earlier arrival of spring. Pollinator-plant mismatch is chief among those threats. If a plant flowers well before or after its associated pollinators are active, it is likely that both plant and pollinator species will experience a drastic decline in reproductive success (Memmott et al. 2007, Lipton et al. 2018). The literature, however, is not conclusive. Simulated changes in the flowering dates of 429 species predicted that between 17-50% of pollinator species will experience a decline in food supply under a warming scenario. Moreover, the more dramatic the changes in flowering date, the more pollinator species were likely to experience a lack of or inconsistency in food supply (Memmott et al. 2007). There is also evidence that an increase in average spring temperatures can reduce the overall springtime longevity of important pollinators such as butterflies (Lepidoptera) and bees (Hymenoptera) (Bosch et al. 2000, Karlsson and Wiklund 2005). However, literature concerning real world observations is relatively lacking; pollinator response to warming still is not completely clear. Controlled experiments and simulations do not always match in situ observations. The results of a study of 10 generalist bee species native to eastern North America indicate that long-term trends of spring bee emergence are near identical to those of plants and that phenological mismatch has not yet occurred. A majority of the phenological advancement for both plants and bees took place between 1970 and 2010, suggesting that alterations in phenology are accelerating in response to worsening climate change. The authors still warned that future warming, particularly in more urbanized regions, could facilitate phenological mismatches detrimental to both plants and pollinators (Bartomeus et al. 2011). However, if pollinators are exhibiting parallel responses to spring sensitive plant species, phenological mismatches may become an even larger issue for plants subject to a delayed flowering due to insufficient winter chilling. While long-term generalizations cannot necessarily be made based on the long-term emergence trends of just 10 bee species, the conflicting results of these studies are a reminder that responses to climate change are difficult to forecast and are often more complex and less understood than expected.

Additional consequences of shifts in plant phenology include susceptibility to frost and soil drying induced by higher daytime temperatures and inconsistent precipitation (Ellwood et al. 2013). There is also some evidence that earlier emergence and flowering can have a negative effect on seed production in spring ephemerals (plants with short life cycles) (Kudo et al. 2004). Furthermore, winter warm spells are projected to increase under all emission scenarios (Frumhoff et al. 2007, Hoegh-Guldberg et al. 2018). In addition to winter warm spells, winter precipitation in the form of rain is projected to increase in the Northeastern United States as climate change progresses (Frumhoff et al. 2007). Winter warm spells combined with an increase in winter precipitation have the potential to trigger premature seed germination, which could lead to increases in seedling mortality as average winter temperatures return (Walck et al. 2011, Parmesan and Hanley 2015). Short lived warm periods followed by a rapid return to winter temperatures could force seeds back into dormancy, potentially delaying their germination when spring actually arrives (Walck et al. 2011).

An increase in temperature, growing season length, and frequency of droughts will put a considerable amount of strain on New Jersey plants and plant communities. Changes in winter precipitation can have far reaching effects into the growing season as well. With earlier snowmelt and more winter precipitation in the form of rain, streams will reach maximum spring flow one to two weeks earlier than in the past. In addition to early stream flow peaks, summer rain events are becoming less frequent, but more severe. As a result, periods of low summer stream flows are arriving earlier and lasting longer. The growing season is also expected to last longer in New Jersey. Between 1915 and 2003, the duration of the growing season in Northeast New Jersey expanded 0.7 day/decade, with a rapid acceleration to 2.5 days/decade between 1970 and 2000. Warmer average temperatures can spur a dramatic increase in evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) from the leaves of plants and from the soil (Parmesan and Hanley 2015). This increase in average summer temperature combined with a deficit of soil moisture could have detrimental effects on seedling establishment and spur dramatic shifts in plant communities (Butler-Leopold et al. 2018). Drier forest soils will lead to declines in interior forest plants such as *Osmorhiza spp.* (sweet cicily), *Caulophyllum thalictroides* (blue cohosh), *Clintonia borealis* (blue-bead lily), and *Trillium spp.* (trillium); *C. borealis* and two species of Trillium are listed rare species in New Jersey, Trillium grandiflorum being endangered (Rustad et al. 2012). Drought resistant generalists and invasive species will likely expand and dominate under these conditions (Frumhoff et al. 2007, Parmesan and Hanley 2015). There is also evidence of poleward shifts of plant species in response to climate change, but little New Jersey specific information is available (Parmesan and Hanley 2015). It stands to reason that certain plant species reaching their southern terminus in New Jersey will likely no longer be present due to conditions brought on by climate change (Pitelka 1997, Ring et al. 2013).

> ***"With warming trends expected to continue and even accelerate, wild plants will be pushed into earlier first flowering dates."***

The increase in summer temperatures can have dramatic effects on plant physiology. However, there is little New Jersey specific or even Northeastern United States data available. Rather, most information comes from experiments with model and agricultural species, but the findings can still offer clues to the types of effects climate change will have on wild plants in New Jersey. It is also important to highlight the fact that not all plants will respond in the same way and that some species are more sensitive than others. A comprehensive literature review examining physiological responses to warming found that, under warmer conditions, certain species of plants would produce fewer or no flowers at all, while others underwent mass flowering. Similarly, the plants that did produce flowers exhibited traits such as smaller flowers and shorter corollas (petals), which can affect pollinator attraction. Increased temperatures also negatively affected pollen production and viability in a variety of plants. Certain species exhibited 35-50% lower pollen production under experimental warming (Scaven and Rafferty 2013). Experimental warming was shown to cause changes in the nectar properties of flowers as well: changing overall volume, ratios of sugar molecules, and a decrease in compounds responsible for floral scent production. Changes in flower shape, size, and nectar availability could affect pollinator visitation. Moreover, a marked decrease in pollen production or viability could hinder reproduction and gene flow among plant populations.

In addition to significant warming during all seasons, high concentrations of CO_2 will affect New Jersey plants, both native and invasive. Atmospheric CO_2 concentrations are currently the highest they have been in over 800,000 years (Lindsey 2019). Curiously, *Toxicodendron radicans* (poison ivy) has responded to higher CO_2 concentrations by not only increasing its growth rate, but by synthesizing even greater amounts of urushiol, the compound responsible for the dermatitis experienced after contact (Ziska et al. 2007). An increase in atmospheric CO_2 can enhance plant growth through a process known as CO_2 fertilization, but these benefits are often short lived, largely dependent on water, and limited by nutrient availability in the soil (Parmesan and Hanley 2015). Increases in CO_2 also have the potential to cause draw downs in soil nitrogen, a limiting nutrient in many ecosystems. Furthermore, higher levels of atmospheric CO_2 have been shown to benefit invasive plant species over native species (Bradley et al. 2010, Sorte et al. 2013, Parmesan and Hanley 2015). Temperature and CO_2 concentrations are far from the only factors involved in the spread of invasive plants, but they do play relatively large roles (Parmesan and Hanley 2015).

The spread of invasive plants under the conditions of climate change is extremely difficult to predict. Specific predictions in scientific literature are fraught with uncertainty, but the overall consensus seems to be that invasive plant species stand to benefit from climate change be it directly or indirectly (Frumhoff et al. 2007, Bradley et al. 2010, Rustad et al. 2012, Butler-Leopold et al. 2018, Hoegh-Guldberg et al. 2018). Invasive plants can easily take advantage of a wide array of environmental conditions, outcompete native plants, and rapidly reproduce and evolve to new climates and habitats (Rustad et al. 2012). *Frangula alnus* (alder buckthorn), for example, is unlikely to expand due to direct factors such as CO_2 and temperature but will likely take advantage of land use changes associated with climate change (Dukes et al. 2009, Burnham and Lee 2010). Invasive vines, such as the Asian bittersweet (*Celastrus orbiculatus*), are poised to directly benefit from factors such as higher CO_2 concentrations, higher temperatures, and higher average precipitation (Dukes et al. 2009). A recent analysis of 13,575 plant species and their potential ranges concluded that invasive plants, compared to natives, have not even begun to reach their hypothetical range limits within the continental United States (Bradley et al. 2015). It is highly likely that the effects of climate change will help facilitate the range infilling and expansion of invasive plant species (Pitelka 1997, Bradley et al. 2015, Hoegh-Guldberg et al. 2018).

> ***"An increase in temperature, growing season length, and frequency of droughts will put a considerable amount of strain on New Jersey plants and plant communities."***

Alongside more frequent heatwaves and drought, New Jersey will be subject to more severe storms during both winter and summer months (Frumhoff et al. 2007, Butler-Leopold et al. 2018). Intense and severe ice storms, thunderstorms, hurricanes, and nor'easters will become more powerful and, in some cases, increase in frequency as climate change progresses (Rustad et al. 2012, Rustad and Campbell 2012, Butler-Leopold et al. 2018). These storms have the potential to cause high intensity disturbance to the forests of New Jersey, creating large canopy gaps and littering the ground with woody debris (Rustad and Campbell 2012, Butler-Leopold et al. 2018). Under natural conditions, these gaps would create opportunities for shade intolerant species of trees, shrubs, and herbaceous plants to establish and thrive, adding to the diversity of the forest and creating a heterogeneous (diverse) community of forest plants (Massad et al. 2019). However, many forests in New Jersey are subject to unnaturally high deer densities and inundated with a large number of invasive plant species (Van Clef 2004, Rustad et al. 2012). Gaps created by severe storms will likely create opportunities for invasive plants to establish and crowd out any native regeneration, reducing the diversity of native herbaceous plants, shrubs, and trees (Rustad et al. 2012, Butler-Leopold et al. 2018). Older, more intact forest plant communities are not immune to this threat. For example, multiflora rose (Rosa multiflora), a prolific and aggressive invasive shrub, frequently utilizes gaps as "springboards" to invade intact interior forest (Dlugos et al. 2015). Another invasive shrub, *Frangula alnus*, is also known to rapidly occupy the forest floor directly beneath canopy gaps (Burnham and Lee 2010). Invasive plant species are a substantial problem, constituting one of the largest threats to native regeneration within canopy gaps (Massad et al. 2019). Invasive plants also pose a substantial threat to the rare plant species of New Jersey (New Jersey Natural Heritage Program 2019). There are over 1,000 non-indigenous plant species established in New Jersey (Snyder and Kaufman 2004). Forest damage caused by more severe storms will only serve to facilitate the further spread of non-native and invasive plants in New Jersey.

Increasingly severe storms threaten more than just forest plant communities. Coastal plant communities such as maritime forests, beaches, and coastal plain forests are at an increased risk as sea-levels rise in response to climate change (Frumhoff et al. 2007, Butler-Leopold et al. 2018). Maritime forest is a unique habitat found on the barrier islands of New Jersey and characterized by dense thickets of stunted trees, shrubs, and a sparse herbaceous layer (Anderson et al. 2013). Trees and shrubs such as *Prunus serotina* (black cherry), *Quercus coccinea* (scarlet oak), *Pinus rigida* (pitch pine), *Quercus ilicifolia* (scrub oak) and *Ilex opaca* (American


ALDER BUCKTHORN

holly) are common in this habitat. Relatively large and intact stretches of maritime forest can be found in areas like Gateway National Recreation Area, Island Beach State Park, and Cape May. In New Jersey, the endangered shrub *Amelanchier nantucketensis* (Nantucket serviceberry) is only found in the openings of coastal forests, putting it at risk to the effects of climate change and sea-level rise (Anderson et al. 2013, New Jersey Natural Heritage Program 2019). Maritime forests are the most vulnerable communities in the coastal plain region to sea-level rise, as frequent and prolonged saltwater inundation can increase tree mortality and spur shifts in species composition (Butler-Leopold et al. 2018). In New Jersey, maritime forest habitat is already fragmented and uncommon due to development along the coast; it is projected that erosion of barrier islands, rising sea-levels, and more frequent coastal flooding will contribute to further loss of this habitat. Beach habitat in New Jersey is expected to suffer from a dramatic increase in erosion and inundation (Frumhoff et al. 2007). New Jersey beaches are home to several rare plant species including *Polygonum glaucum, Honckenya peploides var. robusta, and Amaranthus pumilus*. All three species are critically imperiled in the state of New Jersey and are rare globally (New Jersey Natural Heritage Program 2019). The increase in erosion and flooding has the potential to destroy important beach habitat and negatively affect all three species.

As sea-levels rise, so too will saltwater intrusion in coastal plant communities. Cape May is home to several rare plant communities and is expected to erode and flood heavily due to rising sea-levels and more severe storms. Cape May is home to unique and rare plant communities like intermittent ponds and the Cape May lowland swamp, both of which are considered globally rare. A substantial number of rare plant species are found in these unique wetland communities. Rare and endangered species include but are not limited to *Rhexia aristosa, Rhynchospora niten, Coelorachis rugosa, Helonias bullata, and Hottonia inflata* (Heimerdinger 2011, Ring et al. 2013, New Jersey Natural Heritage Program 2019). Sea-level rise and erosion associated with climate change are direct threats to these globally rare plant communities. Further, an increase in droughts will enable saltwater to intrude further and further inland for longer periods of time as rivers draw down. More severe flooding caused by hurricanes and nor'easters will penetrate further inland, affecting freshwater swamps. Many coastal swamp communities can withstand raised salinity levels for short periods of time, but an increase in the frequency and duration of saltwater intrusion will likely lead to mortality among plant and tree species with lower tolerances to salinity. Inland plant communities that rarely experience changes in salinity can be severely affected by saltwater intrusion (Middleton 2016, Butler-Leopold et al. 2018). Following Hurricane Sandy, freshwater

"It is highly likely that the effects of climate change will help facilitate the range infilling and expansion of invasive plant species."

ASIAN BITTERSWEET

swamp trees and shrubs such as *Acer rubrum* (red maple), *Liquidambar styraciflua* (sweet gum) and *Ilex spp.* (holly) were all left dead by an increase in salinity that remained in the soil for over two years (Middleton 2016).

In New Jersey, there are over 2,100 native species of plants, a little over 800 of which are rare or endangered (Breden et al. 2006). The unique and varied geography and geology of New Jersey grants the state incredible plant diversity. Many species such as *Claytonia virginica var. hammondiae* (Hammond's yellow spring beauty) and *Narthecium americanum* (bog asphodel) are found nowhere else in the world. Climate change represents a substantial threat to a large number of these rare species. A recent study of 70 rare plant species in New Jersey found that 50 of the 70 species were vulnerable to climate change. Of these 50 species, 41 were ranked as moderately vulnerable, 8 were ranked as highly vulnerable, and 1 was ranked as extremely vulnerable to climate change. Species were divided into two groups depending on the region they were found in: the Skylands of northern New Jersey or the Pinelands of southern New Jersey. Species were further subdivided into four specific habitat types found within those regions. These four habitats will be among the hardest affected by climate change in New Jersey. Habitat types included calcareous fens and calcareous sinkhole ponds in the Skylands, and Pine Barrens Savannas and Coastal Plain Intermittent Ponds in the Pinelands. Vulnerability of many of the species stemmed from a projected drying of their wetland habitat, a risk factor consistently projected to increase under climate change scenarios. Another significant risk factor, particularly for species found in the northern New Jersey Skylands, was that of range shifts associated with climate change. Many of those species, such as rush aster (*Aster borealis*) and bog birch (*Betula pumila*), reach their southern termini in New Jersey and will likely experience a poleward range shift in the future (Ring et al. 2013). Another significant risk consistently projected to increase for many of these species relates to dispersal ability. Rare plants often depend on specific habitat requirements and are, thus, scattered, fragmented, and found in small, precarious populations (Pitelka 1997). Southern species within savannas and intermittent ponds, often at the northern edges of their range, face sea-level rise as well as natural and anthropogenic barriers to dispersal (Ring et al. 2013). Due to the relatively low number of populations and specific habitat requirements, rare plants are severely limited in their ability to disperse or migrate in the face of climate change. It is likely that many of the vulnerable plant species in New Jersey will no longer be present or severely reduced by the effects of climate change.

One of the largest risk factors for the 34 vulnerable species found in the Skyland region was related to changes in the historical hydrological niche (Ring et al. 2013). While this specific study only examined 41 Skyland species with sufficient data, there are over 120 rare plant species in northern New Jersey that exist in similar habitat types (New Jersey Natural Heritage Program 2019). These species will probably be vulnerable to the hydrological changes brought on by climate change as well. Furthermore, *Tsuga canadensis* (Eastern hemlock), already reduced in New Jersey due to the invasive woolly adelgid, is projected to fare even worse due to climate change (Rustad et al. 2012). *T. canadensis* is an important component in the swamps and forests of northern New Jersey, and plays a vital role regulating microclimate and soil moisture. Compared to hardwood forests, stands of *T. canadensis* lose 50% less moisture to evaporation during the summer months and provide significantly more shade year-round. The combination of drier overall conditions, warmer summers, and the loss of many more T. canadensis stands will negatively affect rare plants that have specific thermal and hydrological requirements (Ring et al. 2013, New Jersey Natural Heritage Program 2019).

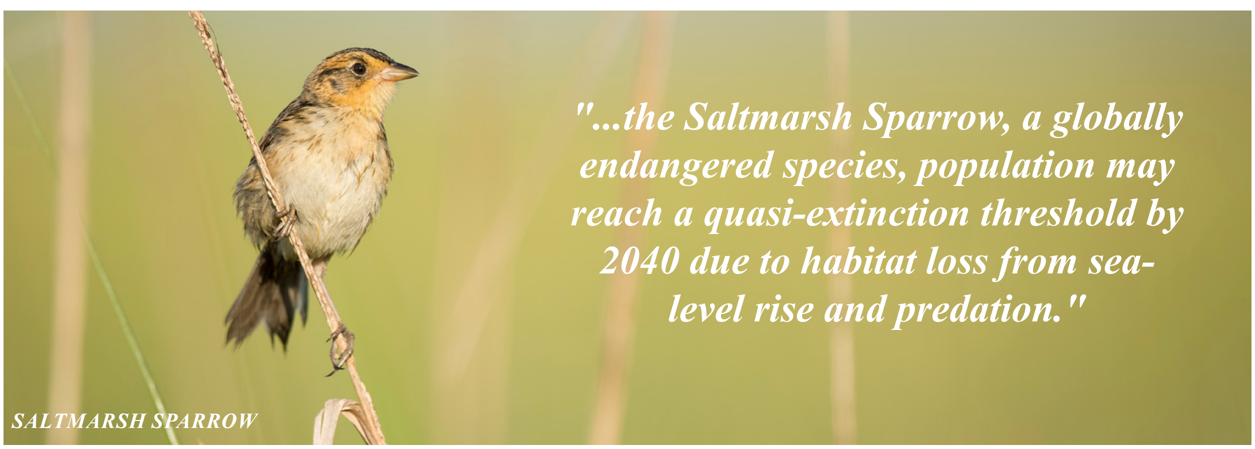
Wild plants and communities in New Jersey face a myriad of challenges and changes associated with climate change. Certain changes, such as shifts in spring phenology, do not seem to be negatively affecting wild plants yet. Other changes, such as rising sea-levels, less consistent precipitation regimes, and more severe storms represent substantial threats. Mitigation of climate change in New Jersey lies in continued research and observation, as well as taking steps to decrease greenhouse gas emissions in an effort to curb future warming. Ultimately, that effort will depend on cooperation with other states as well as the federal government.

5.7-2 Animals (*Fauna*)

In New Jersey and elsewhere, rising sea-levels will inundate animal habitats, particularly in low-lying areas such as wetlands and beaches. This will lower the amount of habitat available for terrestrial animals, especially as coastal communities continue to armor coastlines and prevent systems from migrating naturally. After storm and erosion events, replenishment of ocean and estuarine beaches may also impact habitat availability and/or quality for species. Moreover, as temperatures and precipitation patterns shift, species compositions may also change, particularly at the edges of their current ranges.

are expected to occur because of climate change could lead to population declines, relocation of species, and local extinctions (Audubon 2019). Additionally, bird species are good indicators of ecological change and are early responders to climate changes. One recent study on the Edwin B. Forsythe National Wildlife Refuge estimated that the Saltmarsh Sparrow (*Ammospiza caudacuta*), a globally endangered species, population may reach a quasi-extinction threshold by 2040 due to habitat loss from sea-level rise and predation (Roberts et al. 2019). Similar results were found regarding Saltmarsh Sparrow population decline along the rest of coastal New Jersey, as far north as the Meadowlands (Correll et al. 2017). According to an Audubon study (Audubon 2019), 29% of New Jersey's 248 bird species are vulnerable to climate change, including the American Goldfinch (*Spinus tristis*), which is the State bird of New Jersey.

Of all avian species, shorebirds are particularly sensitive to the effects of climate change. Of 49



SALTMARSH SPARROW

Many bird species will be affected by climate change worldwide. Population declines have occurred across much of the North American avifauna (birds) over the past 50 years (Rosenberg et al. 2019). This biodiversity loss is due to habitat loss and modification, agricultural intensification, coastal development and direct anthropogenic mortality, all of which are exacerbated by climate change. The rapid climatic and habitat changes that

species that were evaluated in one study, 90% were predicted to experience an increased risk of extinction (Galbraith et al. 2014). Shorebirds are more highly vulnerable to climate change than other bird species for a few reasons. First, the majority of shorebird species migrate, breed, or winter in areas that will be severely affected by climate change such as low-lying, coastal breeding areas. For example, the population of Common

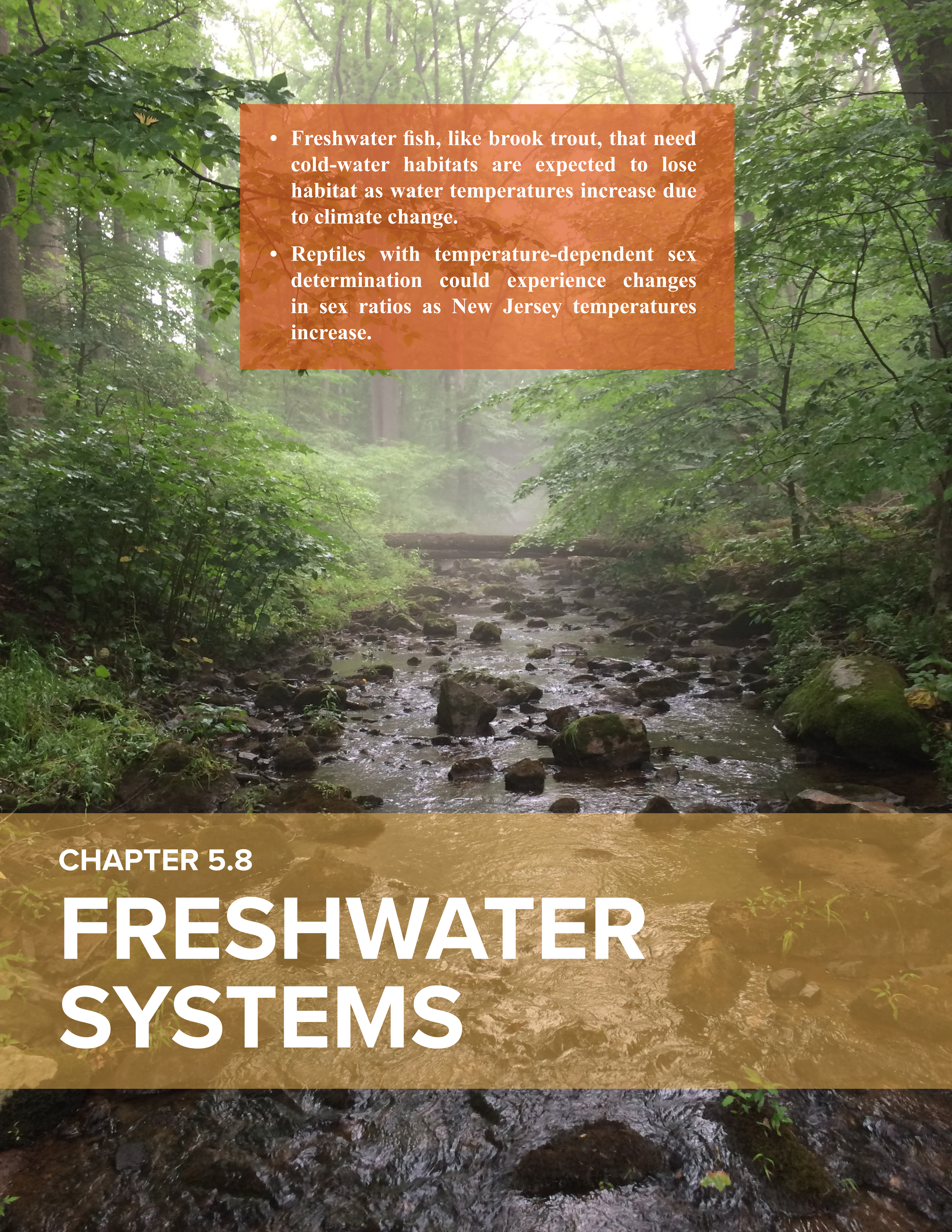
Terns (*Sterna hirundo*) in Barnegat Bay, New Jersey has been experiencing poor productivity (a measurement of how many chicks were raised per breeding pair) and a decline in the number of breeding pairs (Palestis and Hines 2015). Common Terns are ground nesters and the most likely cause of the declines is frequent flooding due to sea-level rise and subsidence. Second, migration exposes shorebird species to high risks of changing weather patterns including the increase in intensity of storms. Third, ecological synchronicities are necessary for many species, especially regarding the availability of food sources. For example, shifts in spatial and temporal overlap between horseshoe crabs and red knots could be problematic (Smith et al. 2011). Horseshoe crab spawning and shorebird stopover must match temporally in Delaware Bay for eggs to be available as food for red knots. However, onshore winds can result in reduced spawning activity by horseshoe crabs during shorebird stopover. Climate change-induced increases in severe storm frequency, and changes in onshore winds, could impact food availability (i.e., horseshoe crab eggs) for shorebirds.

Shorebirds and other migratory bird species must arrive and depart from their breeding grounds in synchronization with the peak food and nesting site availability. Shifting temperatures across seasons could alter the phenologies (life cycle events) of bird species so that they are no longer synchronized. This lack of synchronization could lead to lower reproductive rates for migrants (Carey 2009). Non-migratory birds will also be impacted by mismatches in food and nesting site availability due to changes in precipitation and/or temperature.

Although many of the effects of climate change will be negative for animal species, at first glance, some effects may appear to be positive. For instance, coastal storms can benefit species by creating new habitat (Maslo et al. 2019). Specifically, in New Jersey, Hurricane Sandy created nesting habitat for three of four avian species studied (American Oystercatcher, *Haematopus paliatus*; Least Tern, *Sternula antillarum*; and Piping Plover, *Charadrius melodus*). Black Skimmers (*Rynchops niger*) were the only species assessed where nesting habitat decreased as a result of the hurricane. Unfortunately, much of this newly formed nesting habitat was located outside of existing reserve boundaries and in areas that are inhabited by humans. In many of these non-protected areas, natural resources were not the main concern because infrastructure (e.g., roads, houses, access points, etc.) were damaged by the hurricane. Since most of the new nesting habitat created by the storm was located in developed areas, these areas were rebuilt for human use instead of conserved for wildlife.

Many non-avian species will also be affected by climate change, including insect species. Monarch butterflies (*Danaus plexippus*) have declined in North America over the last two decades (Thogmartin et al. 2017). This decline in Monarch butterfly populations is in part attributed to climatic factors. In particular, breeding season temperature is an important determinant of annual variation in abundance for Monarch butterflies. Bumblebee populations are also being negatively affected by climate change (Kerr et al. 2015). For many species, geographical ranges are expanding toward the poles in response to climate change. Unfortunately, bumblebees have been unable to expand their northern range limits to track the recent warming trends.

The effects of climate change on animals will likely include loss of habitat, population declines, increased risk of extinction, decreased reproductive productivity, and shuffled species distribution. Although some effects of climate change may be positive (such as the increased habitat availability for avian species following Hurricane Sandy), conservation managers will need to allow for more fluidity as the spatial distribution of animal species change and to be prepared to help these species with the adjustment.



- Freshwater fish, like brook trout, that need cold-water habitats are expected to lose habitat as water temperatures increase due to climate change.
- Reptiles with temperature-dependent sex determination could experience changes in sex ratios as New Jersey temperatures increase.

CHAPTER 5.8

FRESHWATER SYSTEMS

5.8 Freshwater Systems

In freshwater systems, fish, reptile, and amphibian species will be negatively impacted by climate change. As temperature and precipitation patterns shift, the ecology of freshwater systems will also change, particularly in shallow streams were these changes will be the greatest. Habitat fragmentation problems will likely increase as some aquatic areas become too warm for cold-water species. Increased frequency and duration of droughts will also be problematic as habitat availability of vernal ponds decrease. Adaptation strategies will need to focus on improving connectivity between habitats to decrease fragmentation.

5.8-1 Fish

In response to increasing temperatures and fluctuations in precipitation, the ecology of freshwater systems will change. Fluctuating extremes in precipitation are expected in New Jersey as a result of climate change (Chapter 4.2). More intense precipitation events will cause flooding and erosion in streams altering current habitat conditions (Chapter 5.5-2.2), and these issues may be exacerbated in areas already impacted by stormwater runoff. Moreover, flooding events can create connectivity and be a vector for distribution of invasive species. Drought, in comparison, will likely promote crowding, increased competition, physiological stress, and mortality. In particular, seasonal weather patterns affect brook trout (*Salvelinus fontinalis*) population dynamics (Kanno et al. 2016). Young-of-the-year abundance is a key driver of brook trout population dynamics that is mediated by seasonal weather patterns. Increased winter precipitation will have negative impacts on young-of-the-year abundance and population dynamics of brook trout, whereas changes in other seasons may have positive or negligible effects. Timing of life history events, such as migration and spawning, will be altered as well. For instance, American Shad in the Columbia River now begin Spring migration earlier in response to warmer springs and summers (Quinn and Adams 1996).

Furthermore, the amount of cold-water habitat available for freshwater fish is expected to decrease in part due to reductions in precipitation (Jones et al. 2013). Changes in stream temperatures, flows, and spatial extent of suitable thermal habitats for freshwater fish have been modeled using a range of projected changes in temperature and precipitation caused by increased greenhouse gases. In general, the spatial distribution of cold-water fish species is projected to decrease and be replaced by warmer-water tolerant fish. Nonnative brown trout, established throughout New Jersey, are more tolerant to warmer temperatures than native brook trout. Besides displacement, stream warming may have other implications. Another native cold-water species, slimy sculpin (*Cottus cognatus*), has coexisted with brook trout, but brown trout populations have shown evidence of altering slimy sculpin population structure (Zimmerman and Vondracek 2006). The study suggests that native and nonnative trout do not fill the same niche and expansion of nonnatives, facilitated through climate change, will have additional community-level effects. Moreover, many of these warm-tolerant species are considered less desirable by recreational fisheries. Accounts of New Jersey trout streams showing cold-to warm-water tolerant species shifts because of direct or indirect thermal impacts have already been documented and will likely increase as temperatures rise. Under the highest greenhouse gas emissions scenario, cold-water fisheries are projected to decline by approximately 50% by 2100 and to be confined to mountainous areas in the western United States and the Appalachians. In New Jersey, the majority of current cold-water fisheries are projected to be warm-water fisheries by 2100 regardless of climate scenario (Zimmerman and Vondracek 2006).

Climate change will also lead to increases in average air temperatures in New Jersey (Chapter 4). Brook trout will experience growth and physiological stress responses if subjected to increased surface water temperatures (Chadwick and McCormick 2017). Although, surface water temperatures are not expected to increase at the same rate as air temperature since a significant portion of stream water is derived from more temperature-moderated groundwater inputs (Kaandorp et al. 2019). When brook trout were subjected to chronically elevated or daily oscillating temperatures and then monitored for growth and physiological stress responses, growth rate decreased at temperatures above 60.8˚F (16˚C) (Chadwick and McCormick 2017). Plasma cortisol, a stress hormone, increased with temperature and was 12 to 18-fold higher at 71.6 to 75.2˚F (22 and 24˚C), respectively, than at 60.8˚F (16˚C). Elevated temperatures induced cellular and endocrine stress responses and provided a possible mechanism by which growth was limited at elevated temperatures.

As with many other species, warming temperatures can also alter the distribution and abundance of freshwater fish. Higher temperatures could further warm rivers and streams, making them less suitable for cold-water fish (Trumbo et al. 2014). However, freshwater fish species in some areas may be buffered from the immediate impacts of air temperature change due to the thermal inertia of water (Snyder et al. 2015, Culler et al. 2018). Air temperatures tend to increase at a greater rate than stream temperatures, especially in areas with groundwater inputs. However, even small increases in water temperature extended the duration of physiologically stressful conditions for fish. These changes in water temperature are likely to be highly site specific, as additional key determinants appear to be shading from riparian vegetation, cold water input from springs, surrounding land use, and elevation (Trumbo et al. 2014). A follow-up study developed a framework to estimate the effects of groundwater seepage on stream temperature in un-sampled locations (Johnson et al. 2017). Geomorphological (e.g., stream slope, elevation, network length, etc.) and precipitation predictors of groundwater influence varied in their importance between watersheds, suggesting differences in spatial and temporal controls of recharge dynamics and the depth of groundwater source.

Overall, habitat fragmentation may occur because of an increase in thermal barriers, especially for cold-water species. Therefore, preserving thermal heterogeneity and allowing access to thermal refuges by identifying suitable areas for restoration projects and management may be essential for the persistence of freshwater fish populations. In New Jersey, climate will likely affect headwater streams more spatially than temporally because of geophysical feature variation but anthropogenic (human-caused) factors, such as land-use changes and dams, may confound where thermal refuge will ultimately be located.

BROOK TROUT

5.8-2 Reptiles and Amphibians

As with many other species, climate change will affect reptile and amphibian populations in multiple ways. Higher temperatures and altered precipitation patterns will warm freshwater and brackish water systems leading to negative consequences for reptiles and amphibians in New Jersey. An increase in droughts throughout the state will decrease availability of freshwater habitats, such as vernal ponds for amphibians. Also, as the sea-level continues to rise, shoreline erosion will increase, low-lying coastal areas will flood, and wave heights will be increased during storms. These impacts of sea-level rise will decrease habitat available for reptiles and amphibians, especially those species located close to the coast. Many reptiles and amphibians have limited dispersal abilities, and thus they are particularly vulnerable to rapid changes in habitat availability (Whitfield Gibbons et al. 2000, Butler 2019). The overall vulnerability of reptiles and amphibians to the effects of climate change have not been assessed in New Jersey; however, an assessment has been performed in a neighboring state.

Severe changes in weather, including an increased number and intensity of storms and more extreme temperatures than typical, will impact many species. For example, increased storms and extreme temperatures could contribute to unusual mass mortality and cold stunning events in diamondback terrapins, *Malaclemys terrapin* (Egger 2016). Wood turtles (*Glyptemys insculpta*) will be directly impacted by changes in temperature and precipitation by influencing their seasonal ecology (mating, emergence, nesting), reproductive success, overwintering physiology, and foraging efficiency (Jones et al. 2018). Increasing winter and summer temperatures and a changing precipitation regime will change habitat quality for wood turtles by elevating stream temperatures and reducing dissolved oxygen content of streams. Moreover, increased temperatures could lead to changes in sex ratios in reptiles with temperature-dependent sex determination (Schlesinger et al. 2011, Butler 2019).

Many amphibian species depend on the availability of vernal pond habitat; however, vernal ponds may disappear for periods due to drought and altered precipitation patterns from climate change (Brooks 2009). Some vernal ponds may even disappear because of droughts. Not only may some ponds disappear, but the remaining ponds will become increasingly isolated and less likely to properly support amphibian metapopulations that depend on connectivity between ponds. Sea-level rise will also introduce saltwater into coastal freshwater systems, including vernal ponds. Some low elevation freshwater wetlands may become brackish, particularly if groundwater withdrawal is high in the area (Werner and Simmons 2009). This increase in salt content of the water in vernal ponds may negatively affect amphibian species, many of which are already at risk of extinction. Coastal amphibian populations will be especially at risk because the increased frequency and intensity of storms may also increase saltwater over-wash into vernal ponds (Schlesinger et al. 2018).

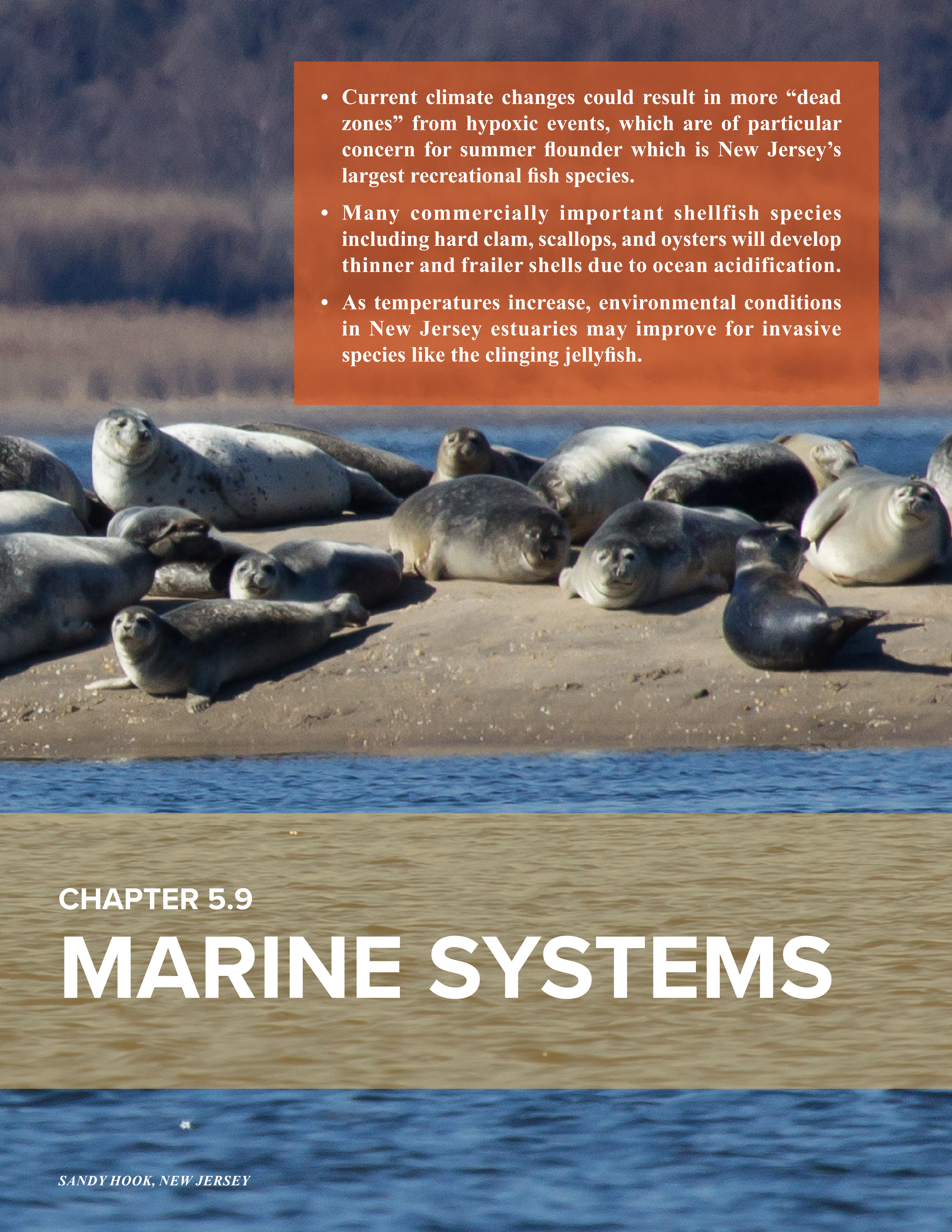
Sea-level rise will decrease the amount of habitat available for some reptile and amphibian species. For example, diamondback terrapins, an estuarine species, depend on the availability of salt marsh areas for nesting (Egger 2016). As sea-levels rise, the amount of habitat available on nesting beaches will likely decrease. Atlantic Coast leopard frogs (*Rana kauffeldi*) will also be susceptible to the impacts of sea-level rise because their preferred freshwater habitats tend to be located in close proximity to the coast (Schlesinger et al. 2018).

The vulnerability of reptiles and amphibians, and other at-risk species, to climate change has been evaluated in New York (Schlesinger et al. 2011). This vulnerability assessment assumed that climate change vulnerability was the result of two factors: exposure and sensitivity. Exposure parameters included temperature, moisture, and sea-level rise, in addition to other factors, and sensitivity included genetic diversity, dispersal capability, past climate regime, phenology, and other factors. Overall, most reptile populations were rated as stable or likely to increase, with the exception of

"...increased storms and extreme temperatures could contribute to unusual mass mortality and cold stunning events in diamondback terrapins."

bog turtles (*Glyptemys muhlenbergii*) and mud turtles (*Kinosternon subrubrum*) which were listed as extremely vulnerable and highly vulnerable, respectively, to the effects of climate change. Likewise, two amphibian species were listed as extremely vulnerable (eastern tiger salamander, *Ambystoma tigrinum*; hellbender, *Cryptobranchus alleganiensis*) and three as highly vulnerable (marbled salamander, *Ambystoma opacum*; mink frog, *Rana septentrionalis*; and eastern spadefoot, *Scaphiopus bolbrooki*). Many of these vulnerable species also reside in New Jersey, with the exception of hellbenders and mink frogs.

In conclusion, some reptile and amphibian populations in New Jersey may experience shifts in distribution range, reproductive ecology, and habitat availability as the climate continues to change. The expected, continued increases in temperatures, frequency and intensity of precipitation, droughts, and sea-level rise will all continue to decrease habitat availability for reptiles and amphibians. Not only will the overall amount of habitat available decrease, but there will be problems with connectivity between habitats (i.e., fragmentation). Climate change adaptation strategies will need to focus on creating a well-connected landscape to allow reptile and amphibian species to move to appropriate habitats (NJ DFW 2019).



- **Current climate changes could result in more "dead zones" from hypoxic events, which are of particular concern for summer flounder which is New Jersey's largest recreational fish species.**
- **Many commercially important shellfish species including hard clam, scallops, and oysters will develop thinner and frailer shells due to ocean acidification.**
- **As temperatures increase, environmental conditions in New Jersey estuaries may improve for invasive species like the clinging jellyfish.**

CHAPTER 5.9

MARINE SYSTEMS

SANDY HOOK, NEW JERSEY

5.9 Marine Systems

Marine resources are expected to be impacted in a variety of ways by climate change, particularly because of increases in temperature, severity and frequency of storms, and acidification. This is of noteworthy concern due to the State's many commercially and recreationally important marine fisheries; however, other marine species including mammals, invertebrates, and vegetation may also be affected.

5.9-1 Mammals

Specialized diets, restricted ranges, or reliance on specific sites make many marine mammal populations particularly vulnerable to climate change (Silber et al. 2017). Marine mammal species play an important role in maintaining healthy habitats because any loss or change of habitat will not only affect these predatory species directly but will also ripple throughout various ecological systems (Askin et al. 2017). Despite being resilient animals, climate change has impacted marine mammals, their food sources, and their habitats. In particular, rising ocean water temperature will impact predator-prey relationships, which in turn will impact migration, range and distribution shifts, as well as breeding success, and susceptibility to disease (Learmonth et al. 2006). However, the direct and indirect stressors that could potentially have dire consequences for marine mammals are unknown and only predictions exist due to a lack of data. Marine mammals are probably one of the best sentinel organisms (i.e., organisms utilized to detect potential risks to humans by providing early warnings) in aquatic and coastal environments because many species have long life spans, feed at a high trophic level (i.e., mammals are high up on the food chain), and have extensive fat stores that can serve as depots for anthropogenic (human-caused) toxic chemicals (Reddy et al. 2001). Direct observations have been made of several marine mammal populations that illustrate responses to climate change. Marine mammal populations have been, and are expected to continue to be, affected by changing climate conditions (Lettrich et al. 2019).

Humpback whales (*Megaptera novaeangliae*) are seasonal migrants that utilize primary breeding sites in the West Indies and primary feeding sites in the Gulf of Maine, eastern Canada, western Greenland, Iceland, and Norway (Brown et al. 2018). However, some humpback whales feed in less well-studied areas, including the New York-New Jersey Harbor Estuary. From 2011 to 2016, there were 46 humpback whale sightings in this area. The number of humpback whale sightings increased over this time period; however, more effort was extended to locate whales as the study progressed and thus this trend is likely biased. Alternately, humpback whales feed on Atlantic menhaden (*Brevoortia tyrannus*), and there have been documented increases in larval menhaden along the Atlantic coast from 2000 to 2013 which may explain the increase in whale sightings (Simpson et al. 2016). Climate change may lead to mismatches between the arrival times of migrants and their food source. However, in this case, this interpretation should be made with caution because of the changes in effort by researchers in sighting humpback whales over time (Brown et al. 2018).

Common bottlenose dolphins (*Tursiops truncatus*) are found throughout the world in both coastal and offshore waters. The dolphins found along the coast of New Jersey are part of the Western North Atlantic Northern Migratory Coastal stock and are considered depleted under the Marine Mammal Protection Act. New Jersey has been the approximate northernmost range of the stock in the northwest Atlantic Ocean and the northernmost destination of these seasonal migrants (Toth et al. 2011, Waring et al. 2011). When assessing the effects of climate change on animals, it is essential to study the species at the extent of their range because the changes from climate change may first be detected in the expansion or reduction of this range. Although the direct effects of climate change on bottlenose dolphins were not directly assessed, photo-identification surveys were conducted in southern New Jersey to determine seasonal occurrence, distribution, and movement patterns. From 2003-2005, 205 individuals were identified, with almost half of the sightings being near the southern part of the Jacques Cousteau National Estuarine Research Reserve in Little Egg Harbor, New Jersey. It is unlikely that the seasonal appearance of bottlenose dolphins in New Jersey is directly determined by water temperature because bottlenose dolphin populations occur in water temperatures as low as 48 to 50˚F (9 to 10˚C) (Ross and Cockcroft 1990, Sykes 2002). Rather, water temperature more directly affects the movements and temperature tolerances of prey. Steep-sided valleys like the New York and New Jersey Bight (coastal area off New York and New Jersey) drive warmer waters towards the coastline and that may be drawing in both the dolphins and their prey. The primary prey of bottlenose dolphins along the east coast of the United States is sciaenid fishes (Barros and Odell 1990, Gannon and Waples 2004) and noise making fish such as drums, croakers, weakfish, mackerel, and mullet. These species occur along the New Jersey shoreline during the summer months, seasonally migrate to and from New Jersey during spring and fall, and overwinter south or offshore during winter months (Able and Fahay 1998). Future studies plan to determine how climate change will affect distribution of prey, water temperatures, and high-quality dolphin habitat.

Western Atlantic harbor seals (*Phoca vitulina concolor*) will also be impacted by climate change. From 1996 to 2011, Western Atlantic Harbor Seals were monitored on their regional overwintering grounds in the Great Bay–Mullica River estuary in southern New Jersey (Toth et al. 2018). This overwintering ground is the southern limit of routing occupancy for Atlantic harbor seals in the Northeastern United States, and thus is an important population to assess in light of potential climate change impacts. Over the 15-year time frame, the maximum number of individuals counted at one time increased from 100 individuals in 1996 to 160 seals in 2011. Since 2011, additional counts have been conducted using a spotting scope at the Rutgers University Marine Field Station (pers. comm. with Roland Hagan; Feb. 2020). In February 2020, a record high 230 harbor seals were observed at Fish Island in Great Bay, New Jersey. These results are valuable in monitoring future changes in habitat use, potentially resulting from climate change.

In conclusion, some of the effects of climate change on marine mammal populations will be direct, such as a decrease in availability of seal haul-out sites due to rising sea levels. However, there will also be many indirect effects of climate change such as changes in prey availability, abundance, and migration patterns. In general, marine mammals tend to be fairly tolerant of changes in water temperature. Therefore, the main concern for marine mammal populations in New Jersey is likely the potential shift in distribution of prey sources because of ocean warming.

> ***"…climate change has impacted marine mammals, their food sources, and their habitats."***

5.9-2 Finfish

Finfish species will be impacted by climate change in many different ways. Changing temperature and precipitation patterns may lead to shifts in species spatial distribution, decreased survival, and loss of habitat. Water chemistry shifts, including changes in acidity and dissolved oxygen levels, will also impact finfish populations by decreasing larval populations, changing growth rates, and changing predator-prey interactions. Diseases may become more common, and some invasive species may move into New Jersey waters.

5.9-2.1 Effects of Changing Temperature And Precipitation Regimes

Changes in temperature and precipitation regimes will lead to many changes for finfish species. In particular, spatial distribution of species may shift in response to the changing climate. In a seminal study, trends over the time period from 1968 to 2007 were analyzed for average biomass, depth, temperature, and the area occupied by each of 36 fish stocks along the Northeastern United States continental shelf (Nye et al. 2009). Clear shifts in spatial distribution were demonstrated for the majority of fish stocks examined as 24 of the 36 stocks had statistically significant changes associated with large-scale warming. Projections of habitat shifts due to temperature changes (Morley et al. 2018) and climate vulnerability assessments (Hare et al. 2016) are critical to predicting the impacts of climate change on marine stocks. Of stocks assessed by the Northeast Climate Vulnerability Assessment, about half of the species were forecast to experience a negative effect due to climate change (Hare et al. 2016). Other studies noted that populations that may be projected to respond positively to warming are unlikely to maintain productivity gains and will reach a peak where continued warming drives these populations past their optimal thermal range (Free et al. 2019).

In addition to experiencing large-scale range redistributions, marine resources are also experiencing increased physiological stress (Deutsch et al. 2015) and altered food availability (Stock et al. 2017). Shifting stocks can mean ecological functions of a species may change as they move into new areas. For instance, there could be a mismatch between predatory species and their typical prey species as predator and prey shift poleward and/or into deeper waters to remain in their optimal thermal range instead of attempting survival under suboptimal conditions.

In many populations, it remains difficult to disentangle the effects of climate change with those of other human-generated influences. This is especially true of populations that may change in abundance or distribution in ways that could be attributed to either climate-induced and/or harvest-induced impacts. For instance, shifts in black sea bass and scup, two economically important species in the Mid-Atlantic and New Jersey, have been identified as climate-driven, while summer flounder distribution shifts have been attributed to a decrease in fishing pressure (Bell et al. 2015). Regardless of cause, movement of fisheries will create significant obstacles to the industry due to increased distances fishermen must travel to reach productive fishing grounds which results in raising fuel, food, and maintenance costs (Morley et al. 2018). Summer flounder are an economically important species in New Jersey. In 2018, the Atlantic Coastal Cooperative Statistics Program estimated that the New Jersey commercial summer flounder fishery landed over 4.5 million dollars in fish. Catch location for summer flounder has shifted latitudinally Northward from 1996 to 2014 (Dubik et al. 2019). These shifts have entered directly into ongoing policy debates about appropriate management response for summer flounder. Preventing overfishing and developing management strategies that are robust to temperature-driven changes in productivity are essential to maintain and rebuild fisheries capacity and support livelihoods in a warming ocean.

> ***“More frequent high-intensity events could lead to more widespread damage of coastal habitats that are vital fish nursery habitat…”***

Furthermore, altered precipitation patterns (drier, wetter, more storms, more droughts) could affect various marine species. Heavier or more frequent rain may lead to increased issues related to runoff. Runoff causes degradation of water quality and pollution by means of rain or snow carrying harmful nutrients, metals, chemicals, and other debris into a waterbody (Center for Climate and Energy Solutions 2019). Finfish can experience negative biological effects related to polluted runoff. For instance, studies on striped bass have shown decreased survival correlated with rainfall and pollution stressors (Uphoff 1989).

A range of other potential threats exist with the possibility of altered precipitation patterns in New Jersey. Heavy freshwater inputs to seawater will directly reduce the pH. Increased rainfall in New Jersey could lead to exacerbated negative effects of ocean acidification on important marine species (Pörtner et al. 2014). Increased storm activity or drought can cause physical damage or losses of fish spawning areas or wetlands. Physical and chemical water changes could alter fish spawning and juvenile survival. More frequent high-intensity events could lead to more widespread damage of coastal habitats that are vital fish nursery habitat, coastal flooding buffers, and natural pollutant filters.

Different fisheries may respond to changes in precipitation regime in different ways. Some species have more successful survival after wet years, while others show better success during dry years in the same environment (Meynecke et al. 2006). Some species may benefit from higher flood lines, as habitat may be expanded to new areas of rivers or bays. Studies have shown species of diadromous fish (those that spend part of their lives in freshwater and part of their lives in saltwater) have exhibited higher biomass and more productive fisheries correlated to years of both higher and lower than average precipitation. Hence, it is largely unclear how our marine ecosystems may respond to climate-driven changes to rainfall or drought.

Overall, continued research will help to better understand the future of New Jersey's marine ecosystems in the face of climate change. High-intensity storms are likely to occur more often, which can have several damaging effects on coastal environments. More frequent runoff from rain events or dry periods could change salinity profiles, leading to altered community structure and population dynamics. Profitable fisheries may experience declines if water quality changes in our bays and estuaries. Nevertheless, some species may thrive in newly created habitats or more suitable aquatic environments. There remains considerable uncertainty about how climate change may drive temperature and precipitation patterns in New Jersey, and how it might affect marine resources.

5.9-2.2 Effects of Changing Water Chemistry

Many marine finfish populations may also be threatened by acidification (pH below pre-industrial levels) and hypoxia (lower than optimal dissolved oxygen concentrations) as a result of climate change. Ocean acidification, loss of oxygen, and changes in nutrient supply have already affected the distribution and abundance of marine organisms in the ocean (Bindoff et al. 2019). Ocean acidification not only threatens the health of the oceans, but also the economic value that people and industries depend on.

Exposure to higher CO_2 levels (and decreased pH levels) lead to marine fish expending more energy in ventilation to consume oxygen needed rather than eating and other essential survival behaviors (Ishimatsu et al. 2008). Growth rates may also be reduced due to this energy cost. Otolith density and mass have also been shown to be affected by elevated CO_2 levels (Bignami et al. 2013). Otoliths are ear bones in marine fish made of gelatinous matrix and calcium carbonate to help sense gravity and movement. Alterations to these ear bones can directly influence sensory function. Ocean acidification increased the otolith size (about 49% greater volume and 58% greater relative mass) and density (about 6% higher) of larval cobia otoliths, which can influence their dispersal, survival, and recruitment.

Early life stages of fish are very important because they are the most vulnerable time during their life cycle. A major concern is that these increased CO_2 levels are greatly affecting reproductive output, particularly egg and larval survival rates. Increased CO_2 drastically decreased the survival rate of larval clownfish (Munday et al. 2010). At 700 parts per million (ppm) CO_2, behavior of the larvae was altered, which can potentially attract more predators. Clownfish larvae became more active, and less aware of potential threats as their ability to sense predators was completely impaired.

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
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As a result of these elevated CO_2 levels, they had a five to nine times higher mortality rate due to predation which reduces their recruitment success rate. Recruitment is the process of adding new individuals to a population by birth and maturation. Increased mortality rates of other egg and larval species (such as the inland silverside) have been directly related to elevated CO_2 levels as well (Baumann et al. 2012).

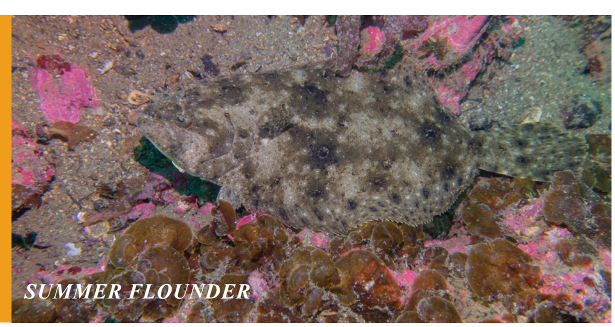
Adult fish exposed to elevated CO_2 levels are affected behaviorally as well. Orange clownfish lose their natural fear of the odor from predators and lost their ability to distinguish between predators and non-predators when exposed to olfactory cues in seawater simulating ocean acidification, such as pH 7.8 and 1,000 ppm CO_2 (Dixson et al. 2010). Brown dottyback avoided the smell of injured prey, increased activity levels, and decreased feeding activity when exposed to two different levels of CO_2 that are predicted to occur by 2100 (Cripps et al. 2011).

Five-lined cardinalfish have impaired homing behavior, which was found using a displacement experiment in which the fish were released approximately 650 ft (200 m) from their respective home site after being exposed to elevated CO_2 levels for four days (Devine et al. 2012). Although these studies suggested behavioral changes in fish due to elevated CO_2 levels, a new study cast doubts on this connection demonstrating that end-of-century ocean acidification levels have negligible effects on coral reef fish behavior (Clark et al. 2020). Thus, further study will be necessary to determine whether CO_2 levels will impact fish behavior.

Biological alterations to economically important marine fish due to ocean acidification will directly impact recreational and commercial fisheries, jobs, and revenue associated with these fisheries, as well as tourism. Summer flounder, the largest recreationally fished species in New Jersey, has been shown to be sensitive to drops in pH (Ferguson et al. 2015). Summer flounder (also known as fluke) embryos experience increased mortality when exposed to high levels of CO_2. When fluke embryos were exposed to a lowered pH of 7.5, mortality reached 52%. At an extremely low, 7.1 pH, fluke embryo mortality reached 84%. Although there are large data gaps, monitoring of pH in New Jersey estuaries and ocean has occurred since the mid-1990's.

Reducing CO_2 emissions are necessary, nationally and internationally, to significantly influence this rapid occurrence of ocean acidification. When the ocean is warmer, it is more acidic and less productive. By 2100, according to model predictions, the ocean will absorb two to four times more energy under low CO_2 emission scenarios and five to seven times more under high emissions scenarios (Bindoff et al. 2019). Oxygen levels in the ocean, having equal importance to community dynamics, are projected to decline 1.3 to 2.0% for low emissions and 3.2 to 3.7% for high emissions by 2081-2100 (Bindoff et al. 2019). Relative to 2006 to 2015, increased CO_2 emissions and decreased oxygen levels will lead to a decline in primary productivity of 4 to 11% by 2081-2100. Ocean acidification will greatly impact our oceans, both biologically and economically.

"Summer flounder, the largest recreationally fished species in New Jersey, has been shown to be sensitive to drops in pH."



SUMMER FLOUNDER

Changes in dissolved oxygen (DO) in coastal water bodies may also impact the State's marine resources as a result of climate change. Dissolved oxygen is vital for the survival and maintenance of a healthy subsurface environment. Current climate change trends suggest the possibility of more frequent hypoxia events (i.e., dissolved oxygen concentration is too low to support aquatic organisms) in New Jersey's coastal waters, which could lead to a complicated range of changes to the State's marine resources and fisheries.

Depleted dissolved oxygen level causes unsuitable, stressful, and sometimes lethal conditions for aquatic life. "Dead zones" and fish kills are commonly documented results of rapidly-occurring hypoxia, but less dramatic responses still show impacts on individual fish and populations (Breitburg 2002). Though different species respond differently to low dissolved oxygen, there are several general effects that hypoxia has on fish. Short term responses to sublethal levels of dissolved oxygen include reduced respiration, reduced activity, reduced feeding, and reduced escape behavior to hide from predators. Longer-term impacts include slower growth, delayed egg hatching, and varied developmental issues (Weis et al. 2017). Summer flounder are especially sensitive to low dissolved oxygen and exhibit slow recovery to other stressors in hypoxic conditions (Brady and Targett 2010). Black seabass have poor tolerance to hypoxic conditions, particularly in increased water temperatures (Slesinger et al. 2019). Anadromous species like striped bass, river herring, and the threatened Atlantic sturgeon may suffer reduced recruitment as a result of more frequent hypoxic events, especially in upstream spawning habitat.

The larger-scale impacts of hypoxia on fisheries are quite complicated, and generally not well understood. Some research has shown the possibility of positive fishery responses because of the increased fish biomass. Increased nutrients and growth in a system (which ultimately causes hypoxia) can allow for high prey abundance, providing more food for fish on higher trophic levels, many of which might include commercially or recreationally important species (Breitburg 2002). Nevertheless, this theory is dependent on the survival of lower trophic-level species in hypoxic conditions, and the prey-predator interactions that follow. Other research suggests a possibility of higher fisheries catch because of high density of target species on the fringes of a hypoxic zone (de Mutsert et al. 2016). However, this grouping behavior is unlikely in New Jersey's highly developed, shallow bay ecosystems, where there would be very little refuge area in event of a large-scale hypoxic zone. Additionally, reduced feeding behaviors in fish could be expected to cause a reduction in recreational catch, particularly rod-and-reel¬, as fish would be less likely to feed on bait and lures.

Overall, hypoxia is a considerable issue in discussing impacts of climate change on New Jersey marine resources. While the coastal ecosystems of New Jersey (i.e., Delaware River and Bay, Barnegat Bay, and Great Egg Harbor Bay) do not commonly experience hypoxic conditions, current climate change trends could result in future hypoxic events (Kennish 2007). The greatest concern is the uncertainty of how hypoxia may affect our coastal ecosystems in the future.

5.9-2.3 Occurance of Diseases

As New Jersey marine populations are subjected to the varying effects of climate change, another category that could rapidly impact New Jersey marine fisheries is the occurrence of diseases. As the environment changes, not only does it affect marine fisheries resources, but also the diseases themselves as climate change alters or extends the natural ranges of organisms (Lafferty 2009). Marine organisms that have expanded their ranges or altered the timing of their migration are more likely to encounter new diseases. The area of influence a disease has is directly related to their hosts' range of influence. As the climate changes, the opportunity for disease transference may increase as previously uninhabitable areas for parasites could become inhabitable (Lafferty 2009). An outbreak of a disease can occur rapidly once conditions are optimal for the disease to thrive and spread. Outbreaks can leave ecosystems and fisheries in critical conditions, taking years to recover, if at all.

Marine species are subjected to and operate under a variety of environmental conditions. Intense weather events, mixing with higher temperatures and other environmental and anthropogenic factors, are likely to degrade fish habitat and adversely affect water quality (Brander 2007). Generally, subjecting an organism to an environment outside of its optimum environment or range of conditions causes the individual to function at a depressed capacity (Marcos-López et al. 2010). This will stress and compromise the health of the organism, possibly resulting in death, depending on the severity of the shift. Temperature is one of the key factors involved in whether an infection results in disease and mortality or immunity and recovery (Short et al. 2017). Changes to temperature, salinity, pH, and dissolved oxygen are all elements that directly impact the marine environment and the immune systems of inhabiting organisms. Moreover, these diseases or disease carriers also have ideal ranges. The chance of an outbreak is increased when an environment that compromises marine populations' immune systems but is optimal for a disease occurs (Marcos-López et al. 2010).

Parasite, bacteria, and virus infections are more effective when their host's health is compromised. In addition, these infections will be a bigger threat in an environment where these diseases are in their optimum ranges. Optimum conditions for diseases make for a situation where they can flourish, multiplying and infecting at higher rates (Marcos-López et al. 2010). Pathogenic organisms that rapidly reproduce will also have a high rate of mutations in future generations. Mutations will enable pathogens to adapt and respond rapidly to novel opportunities created by climate change, such as establishment in new host species (Gale et al. 2009). Pathogen evolution lowers the species barrier so new strains are more likely to extend their host range (Kuiken et al. 2006). When the right mutation is created, the defenses of the host organisms can be by-passed. Species that were previously resistant may encounter a new mutated disease that is now able to infect. The diseases that infect and multiply may develop lethal mutations and kill large portions of a population in a relatively short amount of time. The effects of a lethal outbreak will impact large groupings of organisms and or ecosystems and if it is an exploited marine resource, can implicate human health, economics, and societies. An outbreak of disease in a short amount of time expanding across a large area is a probable outcome if marine populations are not able to acclimate to climate change and bolster their defense against the occurrence of diseases.

> ***"Due mainly to warming water temperatures, invasive marine species will expand their distributions."***

5.9-2.4 Non-Native Species

Yet another concern associated with climate change is the spread of non-native and invasive species and the detrimental impacts they may have on fishery and ecosystem resources along the coast of New Jersey. Invasive species are plants and animals that through intentional or accidental introduction by humans, or through natural dispersion, take hold in a habitat that they are not native to and compete with native species for resources. Due mainly to warming water temperatures, invasive marine species will expand their distributions. Warmer waters may allow invasive species to gain a foothold in environments they were previously excluded from by native species which could have cascading effects on food webs and trophic structures. Impacts to fisheries could be dramatic if drastic changes are seen in New Jersey marine environments as many commercially, recreationally, and environmentally important species may not be able to keep pace with the current rate of climate change.

One of the main factors driving the appearance of marine invasive species along the Atlantic coast is

ATLANTIC SURFCLAM

warming ocean temperatures causing a latitudinal shift northward of aquatic species distributions as well as creating suitable habitat for introduced invasives that otherwise could not successfully overwinter off the coast of New Jersey. This problem may prove to be especially severe in the marine waters of New Jersey as the latest modeling efforts as described by the National Oceanographic and Atmospheric Administration (NOAA) predict that the northwest Atlantic will be warming at nearly three times the global average (Saba et al. 2016). This predicted accelerated warming pattern will make it difficult for native species to adapt through evolution and natural selection and may allow invasive species to get a foothold and outcompete native wildlife.

The State has already begun to see the effects of these warming temperatures as fish traditionally viewed as southern or tropical species are starting to be encountered with some regularity. The red lionfish, *Pterois volitans*, a species of venomous fish native to the coral reefs of the central and Indo-Pacific, has now been encountered in and around New Jersey's natural and artificial reefs (Albins and Hixon 2008). This species has established confirmed breeding populations as far north as North Carolina and spread throughout the Caribbean and Gulf of Mexico after first being encountered off Florida in the early 1990s. This Indo-Pacific resident was most likely introduced to the Atlantic both intentionally and unintentionally through the aquarium trade. It is a voracious predator readily consuming all manner of finfish, cephalopods, and crustaceans. One study has shown that the presence of lionfish on an experimental patch reef caused a significant decrease in recruitment of native species by 79% over five weeks (Albins and Hixon 2008). The problem may be compounded because the lionfish has no natural predators in the Atlantic preventing any sort of natural population control. Given the rate of warming of the ocean waters off New Jersey and the species' pattern of establishment along the south Atlantic coast, there is a distinct possibility that a lionfish population may establish itself on New Jersey's natural and artificial reef structures. This voracious predator could have deleterious effects on populations of native recreationally, commercially, and ecologically important species.

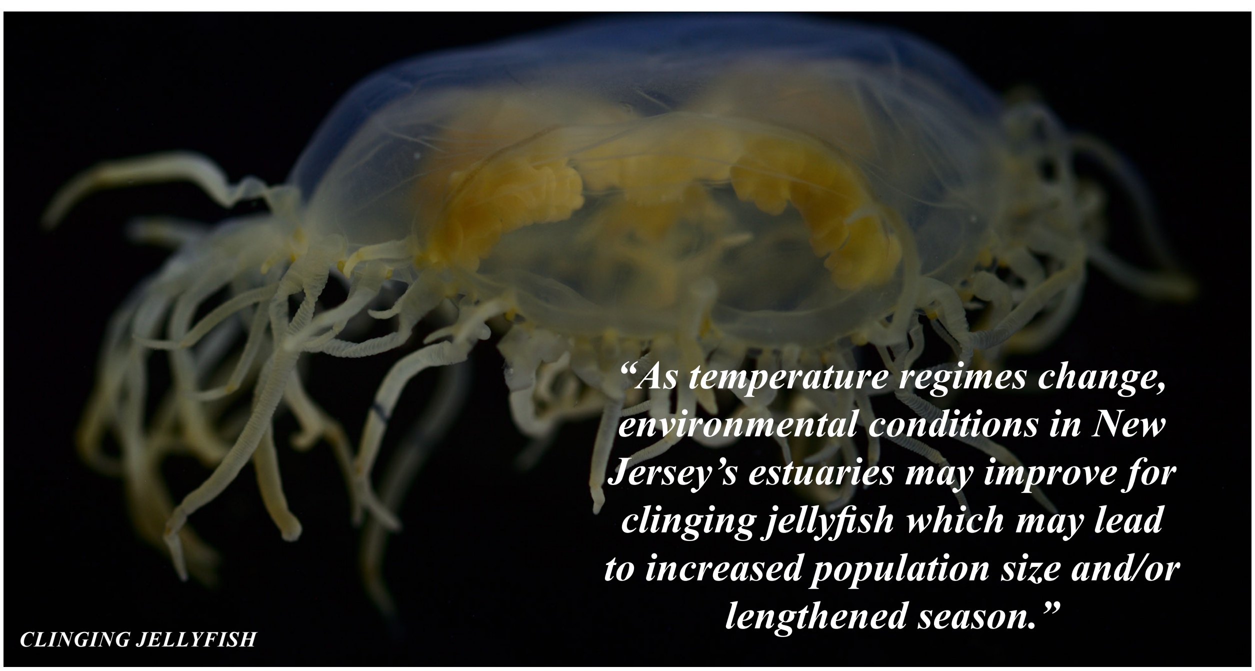
In addition to specific species such as the red lionfish, many other finfish species that are native to the south Atlantic coast may appear more regularly in State waters. Sheepshead, cobia, and triggerfish which were once late summer visitors to our waters but are now being reported by fishermen earlier in the year and with increasing regularity. These reports mirror the predictive modeling projections that project northward shifts of many fish stocks as waters warm and suitable habitats change (Kleisner et al. 2017, Morley et al. 2018). As thermal habitats change along New Jersey's coastline, south Atlantic species more suited to these warmer temperatures may begin to displace the native species that have long since supported many important commercial and recreational fisheries. Natural resource managers will need to take this into account when addressing the economic and ecologic impacts of climate change.

5.9-3 Invertebrates

In New Jersey, populations of invertebrate species such as shellfish, crustaceans, gastropods, and jellyfish will be impacted by climate change. Shifting temperature, precipitation, and water chemistry patterns will impact populations. The occurrence of diseases may increase, and more invasive species may move into New Jersey waters.

5.9-3.1 Effects of Changing Temperature and Precipitation Regimes

The Northeast Climate Vulnerability Assessment found that in relation to overall climate vulnerability, benthic invertebrate species (hard clam, eastern oyster, Atlantic surfclam, ocean quahog, and Atlantic sea scallop) exhibit the greatest vulnerability to climate change . Over the last two decades, the stocks of New Jersey surfclams have dramatically declined from all-time highs recorded in the mid to late 1990s (Normant 2009). Even though exploitation of the New Jersey surfclam resource has ceased over the last ten years, stocks continued to decline. This pattern appears to be a regional event, as declines in the surfclam population have also been documented within the Mid-Atlantic region. Thermal stress due to warmer waters are likely to have caused mortality of surfclams within the shallow waters and the southern limits of its range which resulted in a shift of the population to deeper offshore waters (Weinberg 2005). It is anticipated that this downward trend in New Jersey's surfclam population will continue (Normant 2009). The economic impacts of climate change could be concentrated on specific ports that rely on access to the availability of these fisheries.



CLINGING JELLYFISH

Changes in temperature may also produce longer breeding seasons for some invertebrate species as a result of summers lasting for a longer amount of time. For example, fiddler crabs (*Uca pugnax*) exhibited a much longer breeding season in the 21st century than had previously been reported in the 1970s (Bergey and Weis 2008).

Changes in salinity associated with rainfall and drought may be another factor impacting marine life. High freshwater inputs after precipitation reduce the salinity of a waterbody; whereas lack of freshwater discharge caused by drought results in increased salinity (Habib et al. 2008). Species specifically adapted to current salinity profiles may be unable to survive changes that may occur with altered precipitation patterns. This would result in a habitat that supports only species with the greatest range of salinity tolerance. Oysters are an example of a species that is sensitive and unable to survive significant changes in salinity due to precipitation (Levinton et al. 2011). Oyster aquaculture, an important industry for food and habitat restoration in New Jersey, could be threatened by changes in precipitation patterns. Also, as precipitation patterns change, heavy rain events and subsequent increases in stormwater runoff may cause more frequent contamination of estuaries and shellfish resources (Leight and Hood 2018). Rainfall events are often tied to detection of harmful bacteria in New Jersey bays, triggering shellfishery closures. Increased storm activity could thus lead to more frequent potential health risks and closures of the State's shellfisheries.

Shellfish and finfish populations will also be impacted by beach nourishment projects. As more frequent and intense weather events occur, communities may respond to the threat of flooding with beach nourishment projects where sand will be mined from offshore and placed on beaches. As a result, essential habitat for shellfish will be removed or changed. Sand lumps from where the sand is mined in New Jersey have a contoured bottom that houses key invertebrate species and attracts recreationally and commercially important species to these areas. This loss of habitat not only effects the ecology of the area but could also result in a loss of prime fishing grounds, adversely affecting the economic benefit New Jersey gains from its recreational and commercial fishing industries.

"The effects of climate change can…have major implications on…submerged aquatic vegetation..."

5.9-3.2 Effects of Changing Water Chemistry

Ocean acidification will also impact shellfish by reducing availability of important compounds, such as calcium carbonate, needed for a healthy marine environment. Calcium carbonate is crucial for many shellfish species (and corals) as they need it to build their skeletons and shells. By reducing the availability of calcium carbonate, these organisms will then expend more energy on shell-building and less energy on basic survival tasks like foraging.

Many commercially important shellfish including hard clam, scallops, and oysters, rely on carbonate availability in seawater to form their shells. Increased CO_2 levels in seawater has been found to adversely affect shellfish growth and larval development of commercially important shellfish species (Gazeau et al. 2007). The calcification rates of two commercially important shellfish species (edible mussel, *Mytilus edulis*; Pacific oyster, *Crassostrea gigas*) were found to decline as a function of decreasing pH and increasing CO_2. Increased CO_2 levels were also found to impact shell development, leading to thinner and more frail shells when exposed to projected CO_2 levels (Talmage and Gobler 2010). Larval stages are especially vulnerable life stages, resulting in potentially malformed, pitted, or softened shells, which increase the likelihood of death by predation or failure to reach adulthood. This could pose a significant risk to the survival of juvenile shellfish and their ability to combat predation in the wild and ultimately affect the distribution and densities of shellfish resources and the State's vibrant shellfish industry.

Throughout the United States, wild shellfish harvest and shellfish aquaculture industries are valued at $1.3 billion dollars (National Marine Fisheries Service 2018). The National Marine Fisheries Service stated that United States shellfish producers harvested 72 million pounds of eastern oysters (*Crassostrea virginica*) in 1952, but in 2012 the harvest yielded only 23.8 million pounds. A parasite known as Multinuclear Sphere X (MSX) was responsible for widespread mortality in Delaware Bay oysters in the 1950s; however, other pressures combined with parasites and diseases make it difficult for the oyster resource to expand to its historical proportions. While these shellfish species are known for their evolutionary skills, the current rate of ocean acidification may be too rapid for adaptation. In addition, shellfish may be vulnerable to negative impacts of future hypoxic events. Bay scallops and other bivalves exhibit slowed growth in the larval stage at low dissolved oxygen (Weis et al. 2017).

5.9-3.3 Occurrence of Diseases

In addition to concerns regarding ocean acidification and decreased dissolved oxygen concentration, diseases may become more common for shellfish species in New Jersey. For example, diseases such as Multinuclear Sphere X (MSX) and Dermo (also known as Perkinsosis) have become prevalent in oysters, when previously they were only found in warmer waters south of New Jersey (Najjar et al. 2000). The MSX disease has been present in oyster populations in the Mid-Atlantic since the 1950s; however, MSX became more common further north along the east coast of the United States starting in the 1980s (Hofmann et al. 2001). Climate warming is a contributing factor towards this northward movement of MSX disease.

5.9-3.4 Non-Native Species

There are several species of shellfish and parasites that are non-native species or have the potential to be invasive in New Jersey. Invasive shellfish species in New Jersey include Chinese mitten crab, Asian shore crab, European periwinkle, Wedge rangia, and European green crab. The European green crab (*Carcinus maenas*) has exceptionally flexible thermal physiology. It is substantially more heat tolerant than co-occurring native crustaceans. The European green crab was first introduced to the United States near the Long Island Sound, New York in approximately 1817. This initial population spread up and down the Atlantic Coast (Tepolt and Somero 2014). Since European green crabs are very adaptable to a range of temperatures, it is a threat to native populations. These crabs are good foragers and are very adept at opening bivalve shells. They are better at gathering food than other species of crab, and therefore may outcompete native species (MacDonald et al. 2007). Green crabs prey on clams, oysters, mussels, marine worms, and small crustaceans, which also makes them a competitor of the native bird species and finfish. Their diet is like that of shorebirds, making green crabs a direct threat.

Another possible invasive species as the water warms is the green porcelain crab, *Petrolisthes armatus* (Hollebone and Hay 2008). The green porcelain crab is a non-native filter feeder and scavenger currently invading oyster reefs in the South Atlantic Bight which is the coastal area from Florida to North Carolina. Green porcelain crabs have suppressed the growth of juvenile oysters, the recruitment of mud crabs, and the abundance of microalgae, in addition to promoting enhanced survivorship of oyster predators. As water temperatures rise, the current range of the green porcelain crab could expand. These crabs can move north and affect oyster communities in the Mid-Atlantic Bight, including Delaware Bay.

The veined rapa whelk (*Rapana venosa*) is another potential invasive species. This large predatory gastropod is located in the lower Chesapeake Bay and the James River, Virginia (Mann and Harding 2000). From New York to the Chesapeake Bay, water temperatures are capable of supporting larval development. The veined rapa whelk has

EUROPEAN GREEN CRAB

a broad dietary preference for bivalves. Lack of competition from other predatory gastropods and an abundance of prey species lead to this whelk's success. Expansion of the veined rapa whelk's current invasion is a cause for concern. This species produces viable pelagic larvae, consumes native species, and grows rapidly which all suggest its resilience. As waters around New Jersey become consistently warmer, this could lead to successful settlement of the veined rapa whelk.

Clinging jellyfish (*Gonionemus vertens*) are another example of a non-native species now inhabiting New Jersey waters. Although clinging jellyfish are native to the Pacific Ocean, they were initially introduced to the Atlantic coast around Woods Hole, Massachusetts in the 1890s, and now can be found in estuarine waters from Maine to New Jersey (Govindarajan and Carman 2016). In New Jersey, clinging jellyfish have been observed to emerge around mid-May when water temperature rises above 70˚F (21.1˚C) (NJDEP 2019d). In mid-July when water temperature exceeds 80˚F (26.7˚C), clinging jellyfish can no longer be found in New Jersey waters. Favorable conditions for clinging jellyfish include warm water temperatures, nutrients, and presence of zooplankton (Govindarajan and Carman 2016). As temperature regimes change, environmental conditions in New Jersey's estuaries may improve for clinging jellyfish which may lead to increased population size and/or lengthened season.

Non-native species invasion is affecting all aspects of local ecosystems. However, the rapid pace of invasions of non-native species threatens the function and maintenance of local marine communities and can fundamentally change these communities over large areas. Invasions can displace or completely disassemble native communities (Hollebone and Hay 2008). Natural resource managers will need to consider the impacts invasive species may have on native populations when planning for dealing with and/or mitigating the effects of climate change in the future.

5.9-4 Submerged Aquatic Vegetation

The oceanic and estuarine habitats are an essential part of Earth's climate. These important habitats face many anthropogenic stressors along New Jersey's coastal margins as a result of climate change, including those associated with sea-level rise. In New Jersey, sea level is projected to rise 0.8 feet by 2030 (Kopp et al. 2016). Sea-level rise can lead to several consequences on New Jersey's marine resources. Saltwater intrusion can alter upland habitats and modify salinity regimes that ultimately change estuarine habitats. Small increases in salinity within an estuary can have major impacts on shellfish populations by potentially increasing predation rates. The effects of climate change can also have major implications on other sensitive species including rooted aquatic plants, known as submerged aquatic vegetation (SAV), by increasing metabolic stressors and altering distributions throughout the state.

Submerged aquatic vegetation is an integral part of New Jersey's estuarine ecosystem and is critical to protecting the coast against flooding and erosion. For instance, SAV beds serve many purposes including regulating water column dissolved oxygen, modifying the physical and chemical environment, and reducing suspended sediments, chlorophyll, and nutrients in the water column (Short and Neckles 1999). They are primary sources of food for waterfowl, serve as indicators of local water quality conditions, affect key sediment processes, and decrease the potential for shoreline erosion by dampening nearshore water flow and waves (Moore and Orth 2008). SAV also serves as habitat for fish, crustaceans, and shellfish, which includes commercially and recreationally important species such as blue crab, hard clam, and juvenile striped bass (Arnold et al. 2017).

There are certain environmental conditions that determine the distribution of SAV species: salinity, light, temperature, nutrient levels, sediment type, and physical setting (Moore and Orth 2008). Extensive SAV beds provide valuable resources in shallow coastal waters, and due to increased temperature stress, distribution of seagrasses will shift. Changes in sea level, salinity, temperature, atmospheric CO_2, and UV radiation can alter seagrass distribution, productivity, and community composition (Short and Neckles 1999).

Increasing water temperatures will have negative effects on SAV. Higher water temperatures can lead to an increase in algal growth on seagrasses. This can affect growth and decrease or eliminate the population. Changes in temperature will also affect metabolism and carbon balance which could lead to changes in distribution and abundance of SAV (Short and Neckles 1999). Sea-level rise will also have negative effects on SAV. An increase in water depth due to Sea-level rise will reduce the amount of light reaching existing SAV beds resulting in reduced productivity and will also move the salt front further inland and affect SAV distribution. Changes in the distribution of SAV beds may have profound consequences for local and regional biota, nearshore geomorphology, and biogeochemical cycles.

Climate change will also lead to an increase in storm activity. Increased rainfall will increase sediment and nutrient input into estuaries, further decreasing light availability to the SAV beds (Moore and Orth 2008). SAV beds have a high capacity to dissipate wave energy (Duarte et al. 2013b). Increased frequency and intensity of storms will lead to erosion of SAV beds, reducing their ability to mitigate storm surge and wave action (Moore and Orth 2008).

Submerged aquatic vegetation beds also serve as a mechanism to capture and store CO_2. SAV can sequester approximately 10% of oceanic organic carbon globally (Arnold et al. 2017). Climate change will cause SAV habitats to experience

"Changes in climate patterns seem to be leading to an increase in the long-term detection range and season of Vibrio…"

reduced distribution, decreased productivity, altered bed structure, and reduced functional value (Short and Neckles 1999).

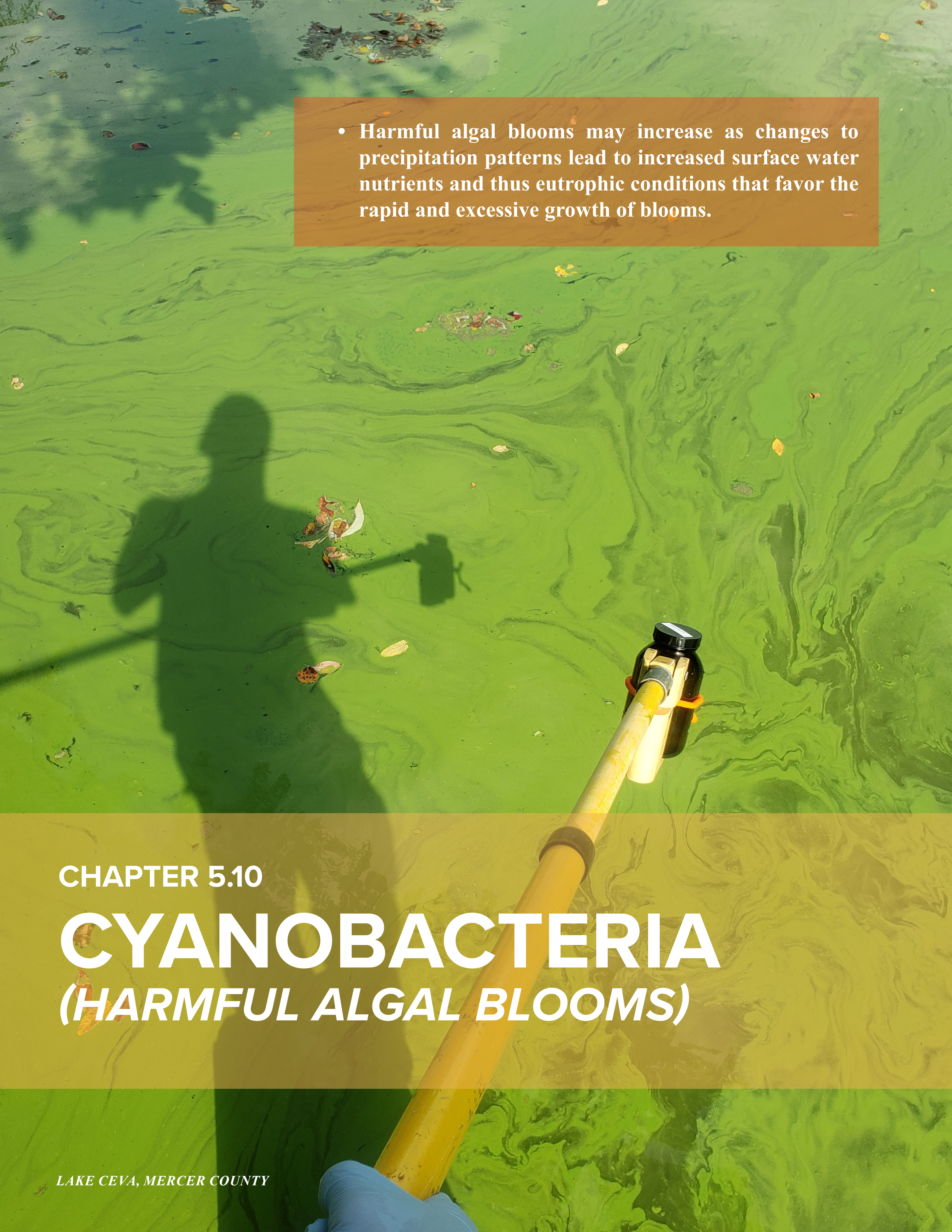
5.9-5 *Vibrio*

Pathogens of particular concern in marine systems of New Jersey are those associated with the bacterial genus *Vibrio*. *Vibrio* species are important microbial pathogens which are implicated in several transmitted freshwater and saline environmental illnesses. Notable examples of typical pathogenic *Vibrio* species are *Vibrio cholerae*, the causative agent of the disease cholera; *Vibrio parahaemolyticus*, which is found in brackish and saltwater and is a causative agent of foodborne illness when contaminated seafood is consumed; and *Vibrio vulnificus*, which can cause mild foodborne illness if consumed (similar to *V. parahaemolyticus*). *V. vulnificus* has been implicated in severe and often fatal cases of invasive wound infections known as necrotizing fasciitis. *V. vulnificus* is typically found in saline and saline influenced environments.

Historically *Vibrio cholerae* has played an important role in human disease, and due in large part to increases of disinfection of potable water and advances in wastewater treatment technology, cases of *Vibrio cholerae* have largely fallen around the globe (Safe Drinking Water Foundation 2017). While *Vibrio* related drinking water illnesses have decreased, *Vibrio* species can often cause infections from the consumption of contaminated seafood (Newton et al. 2014) or bathing in waters with an open wound (Dechet et al. 2008).

Bathing based events appear to be increasing, as both severe weather events and warming patterns seem to favor *Vibrio* species growth and habitat preference. Severe weather events such as hurricanes have resulted in increases in reports of fatal Vibrio cases (CDC 2005) and warming waters appear to increase the rate of *Vibrio* infections (Baker-Austin et al. 2013) Changes in climate patterns seem to be leading to an increase in the long-term detection range and season of *Vibrio*, which may lead to an increase of adverse *Vibrio*-based infection events (Martinez-Urtaza et al. 2010).

The DEP addresses *V. parahaemolyticus* and *V. vulnificus* through a detailed *Vibrio* Control Plan which was developed to reduce incidences of food-borne illness from the consumption of contaminated oysters. The *Vibrio* Control Plan includes program coordination, response to potential outbreak, post-harvest time and temperature controls, hours of harvest for tidal and intertidal waters, and Hazard Analysis and Critical Control Points (HACCP) plan requirements and recommends additional best management practices to be implemented to further minimize risk from these naturally occurring bacteria (Bryan 1992).



- **Harmful algal blooms may increase as changes to precipitation patterns lead to increased surface water nutrients and thus eutrophic conditions that favor the rapid and excessive growth of blooms.**

CHAPTER 5.10

CYANOBACTERIA

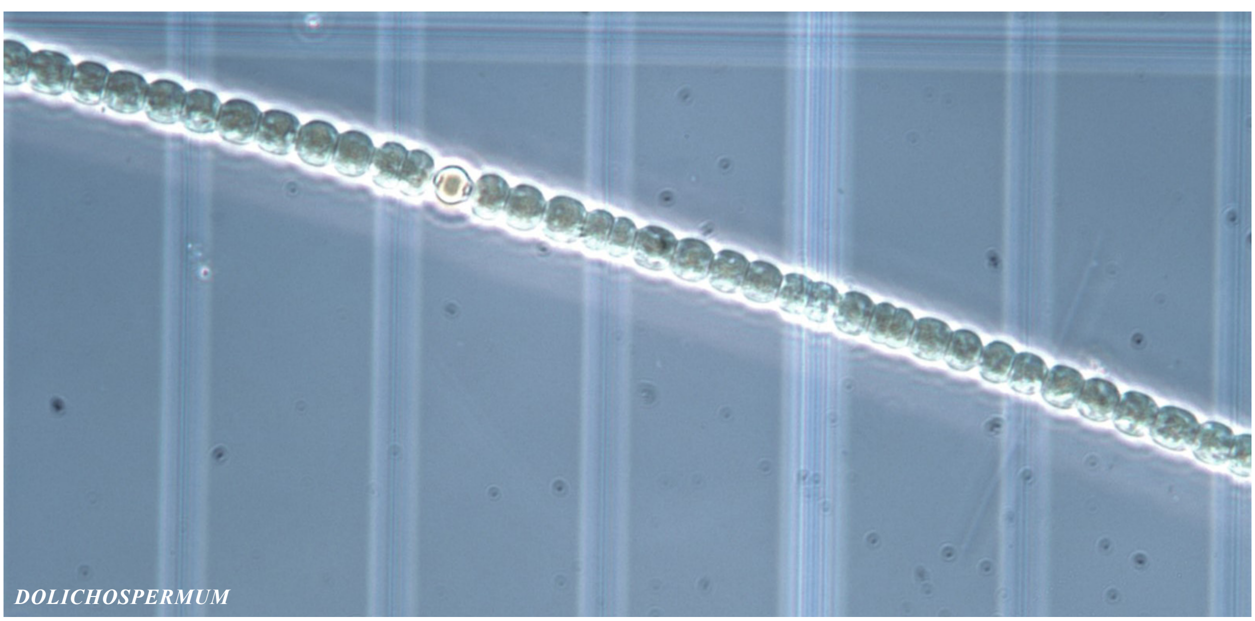
(HARMFUL ALGAL BLOOMS)

LAKE CEVA, MERCER COUNTY

5.10 Cyanobacteria
(Harmful Algal Blooms)

Microbiologists have been reporting the observation of increased survival and sustained photosynthetic activity in cyanobacteria at both high and low temperatures in lab and field samples since the late 1970s (Konopka and Brock 1978). Recent studies continue to note an increase in the incidences of intense toxic phytoplankton blooms worldwide and in the Northeast United States (Ho et al. 2019). In 2008, a landmark paper highlighted the notion that shifts in global climate trends can both spark and exacerbate conditions suitable for harmful bloom events to occur (Paerl and Huisman 2008). In general, increased nutrients in aquatic systems support the proliferation of cyanobacteria (Sinha et al. 2017, Ho et al. 2019) and they can survive significant temperature extremes. This is supported by the observation of survival in freezing conditions for cyanobacteria compared to other eukaryotic algae and zooplankton which usually experience a "die off" during freezing conditions (Seckbach 2007).

Harmful algal blooms can occur in freshwater, brackish, and marine systems. Increased surface water temperatures and nutrient inputs drive cyanobacteria dominance and increase the likelihood for a bloom to form. Observation and modeling data from Europe highlighted that predictive modeling forecasts increases in cyanobacteria directly due to increases in temperature (Joehnk et al. 2008). This is in part due to the increase in photosynthetic activity, and also the increased stability of the water column. This stability is known as thermal stratification and reduces the water's ability to vertically mix. This creates temperature zones in water which restricts mobility of key competing species for cyanobacteria. Cyanobacteria are able to regulate their buoyancy by structures know as gas vesicles. These allow a direct competitive advantage where the cyanobacteria can rise to the surface for photosynthesis during the day, and fall back down into cooler, nutrient dense water at night. Field work showed that blooms increase the stability of the water column and enhanced their growth compared to control areas where the water column was artificially mixed (Kumagai et al. 2000). Blooms have been observed to locally increase the surface temperature of impacted water, creating a positive feedback loop of dominance for cyanobacteria over other plankton species.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IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEM
CYANOBACTERIA (HARMFUL ALGAL BLOOMS)

The loss of diversity in the plankton community also has dire consequences for water quality, with modeling results of higher temperatures favoring the dominance of cyanobacteria in these populations over other photosynthetic organisms (Elliott et al. 2006). This ultimately has profound effects since data suggests that warmer spring water temperatures favor earlier uptake of nutrients by plankton species. This earlier uptake in nutrients can lead to nitrogen limitations and favor nitrogen fixation species of cyanobacteria in late spring and summer (Elliott 2012).

> ***"Conditions similar to those expected from a changing climate in New Jersey have been documented…and will favor cyanobacteria growth…"***

Nutrient loading and cycling in an aquatic system are impacted by changes in climate and precipitation (Sinha et al. 2017). As droughts and heavy rainfall events become more frequent, more biologically available nutrients may be introduced to an aquatic system which may reduce species biodiversity (Isbell et al. 2013). Species biodiversity appears to be impacted, with cold-water organisms being negatively affected the most and warm/warm-tolerant being positively affected (Heino et al. 2009). Patterns of intense rainfall and prolonged dry spells has been documented to cause massive cyanobacteria blooms in several water bodies (Paerl and Huisman 2008).

Conditions similar to those expected from a changing climate in New Jersey have been documented to impact several key dynamics in aquatic systems and will favor cyanobacteria growth , either directly or indirectly. The potential for increased HAB in drinking water reservoirs is equally as likely to occur as in other water bodies and will require careful monitoring and maintenance to avoid significant impacts to the drinking water sources of the state. Similarly, blooms with a significant cell density or toxin production have the potential to limit recreational opportunities. In 2009, there were 39 HABs confirmed in New Jersey which was the greatest number since the State started tracking blooms (NJDEP 2019e). There were 22 blooms confirmed in 2017 and 20 blooms confirmed in 2018.

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CHAPTER 6

RESEARCH AND DATA GAPS/NEEDS

The research summarized throughout this report is a vitally important component of New Jersey's strategy to understand the impacts the State will face due to climate change. An equally important component is identifying the information needed to inform the policies, guidance, and recommendations that will be made by the State to address the existing and future impacts of climate change. The following list includes those areas identified where further research is needed and/or where research does not currently exist.

For example, climate change may pose significant complications to public health but the science around these issues continues to evolve. Additional information is needed before conclusive statements can be made.

Greenhouse Gases

- Further exploration of the impact of reduction of short-lived climate pollutants is needed to understand their contribution to climate change and mitigation efforts.

Temperature

- Research is needed to provide a better understanding about why New Jersey is one of the fastest warming states in the country.
- Increased and continued monitoring and assessment of sea surface temperature data from New Jersey's coast is needed. Sea surface temperature is one metric of ocean warming and ecological health, so more data from various locations along the coast provides more coverage and is more representative of actual conditions.

Precipitation

- Increased confidence is needed on how the frequency and intensity of precipitation events will change. The

RESEARCH AND DATA GAPS/NEEDS

frequency and intensity of precipitation is necessary to inform and plan for flooding and storm water design.

- Improved modelling is necessary to better understand how increased precipitation, increased streamflows, and higher sea levels will interact in order to better plan for coastal and fluvial flooding events.
- An updated analysis is needed to accurately reflect current and future precipitation rates including the 100-year (1%) storm frequency and Water Quality Design Storm. Such information is needed to inform flooding and storm water design.
- Improved sub-daily (hourly) precipitation totals are needed as such storms may be more sensitive to climate warming than longer duration events.
- Further research is needed to understand how changes in tropical and extratropical cyclones patterns will impact the regional and state.
- Additional research is needed to understand how wind speeds in storm events (extratropical and tropical cyclones, etc.) may change as a result of climate change.
- Research is needed to better predict how future precipitation patterns will affect water supplies in New Jersey.
- Analysis is needed to determination if the snow regime in New Jersey has changed.

Sea-Level Rise

- The establishment of a long-term monitoring station for sea-level rise, including a surface elevation table, is needed in the northern coastal area of New Jersey; perhaps the Raritan Bay area.
- More research is needed to evaluate the movement of the salt-front in non-Delaware River estuaries, and how they may impact water supplies.
- Further coastal geomorphology modeling is needed to evaluate fluvial impacts from coastal flooding.
- Additional research is needed to evaluate the potential future costs of beach nourishment, coastal armoring (seawalls, groins, and jetties), and dune maintenance under future sea-level rise projections.

Ocean Acidification

- The ecological impacts of ocean acidification on marine organisms require further research as we are only beginning to understand the ramifications to species and ecosystems.
- Constancy in ocean acidification sampling technology and methods is necessary to create continuous and accurate timelines and data pools.
- Research to fill in information gaps in major taxa and regionally important species is needed to understand what it is we know and what we are missing.
- Improving of experimental methods are needed to account for realistic environmental variabilities and stressors.
- Additional research to determine the capacity of key species to acclimate or adapt to changing ocean acidification conditions is needed to understand how the ecosystem may change and evolve.

Air Quality

- High spatial resolution risk mapping and cumulative risk assessments is needed to determine vulnerability and exposure of communities at high risk.
- Additional research is needed to understand the effects of climate change on the meteorology of the Northeastern United States with respect to changes in weather patterns, such as stalled air masses, increases in humidity, and frequency of afternoon thunderstorms, that affect ozone levels.

Water Resources

- More research is needed to determine how water supply sources will be impacted by sea-level rise, droughts, changes in precipitation, and changes in local demands as a result of climate change.
- More research is needed to evaluate the movement of the salt-front in non-Delaware estuaries, and how they may impact water supplies.
- Additional research is needed to evaluate the range of potential changes to groundwater recharge from climate change.
- Additional research is needed to determine the magnitude and extent of that risk associated with saltwater intrusion to groundwater supply.
- Additional research is needed to evaluate the effects of precipitation and streamflow changes under future climatic conditions on the availability of water for surface water reservoirs.
- Additional research is necessary to evaluate the ability of water supply systems to adapt to the multitude of climate change related drinking water operation issues, in an economically feasible way.
- Additional research into how the future intensity and frequency of dry periods and warming trends will impact groundwater resources.

Agriculture

- Information is needed about the sequestration rates for crop land and the sequestration potential if preserved farmland is managed in ways to increase carbon sequestration.

Marine Fisheries

- Monitoring should be conducted to determine whether increased non-native fish species are negatively impacting native species.
- Although monitoring of pH and dissolved oxygen in New Jersey coastal waters has been performed since the mid-1990s, there are some gaps in the dataset. A standardized monitoring protocol should be developed and followed to allow assessment of the impacts of changes in pH and dissolved oxygen on fish populations.
- More research needs to focus on how shifting species distributions will impact the economics associated with New Jersey's commercial and recreational fisheries.
- New Jersey is in the process of developing offshore wind farms. Studies will need to be developed to determine how the wind farms will affect benthic and fish habitat, and subsequently the recreational and commercial fisheries.

Plants and Forests

- More New Jersey specific research is needed on Herbaceous plant communities' responses to climate change, invasive plants, rare plants, beach and dune species, phenology shifts (particularly the effects of warmer autumns on winter and spring phenology), and plant physiology. Plants respond disproportionately to changes in temperature making them indispensable for monitoring the impacts of climate change.
- How ice storms, less snow melt, less cold and fatal (to pests) temperature days – will impact New Jersey forests.
- While the report provides information about carbon pools in New Jersey forests, it does not cover the annual rate of sequestration by forest types. This information is needed.
- New Jersey has limited data on the sequestration capabilities of State lands. To more accurately quantify the capacity of New Jersey forests to sequester carbon, updated biomass carbon density factors are needed. New Jersey needs to continue to generate data on the sequestration capabilities of New Jersey State lands through improved monitoring and measurement.
- The likelihood of increased occurrence and

magnitude of forest fires in New Jersey is not clear and requires further study.

- High resolution remote sensing from New Jersey state aerial surveys, satellite imagery, computers and network resources is needed.
- More research is needed on the interaction between climate changes, such as higher temperatures and more variable precipitation, insect and pathogen outbreaks, and forest fires.

Wetlands

- More data is needed to reference wetland conditions, particularly in the northern parts of the State. In order to develop plans for ecological restoration, an understanding of wetland reference condition is essential.
- The magnitude and direction of change in wetlands must be assessed to determine whether marshes will be able to migrate inland.
- Wetland monitoring, both tidal and freshwater, across the State needs to be collected in a consistent way to allow for comparisons between sites.
- The impacts of atmospheric deposition of nitrogen and sulfur on tidal marsh habitat should be assessed to determine whether habitat will continue to be available for wildlife species.
- A map of brackish marshes in New Jersey needs to be developed. Additional water quality monitoring stations are needed in conjunction with freshwater and brackish tidal marsh vegetation monitoring to accurately map the continuum of freshwater to oligohaline to mesohaline (brackish) wetland resources. The saline “line” may shift temporally, thus long-term data is needed to document the impacts of climate change.
- Freshwater wetlands and aquatic systems should be monitored for the presence of invasive species which may negatively impact native species.

Animals

- The overall vulnerability of reptiles and amphibians to the effects of climate change need to be assessed in New Jersey. Vulnerability assessments are an essential tool in climate change adaptation planning.
- The impacts of climate change on habitat availability for shorebirds, particularly migratory species, should be assessed throughout the State.

Topics for additional consideration:

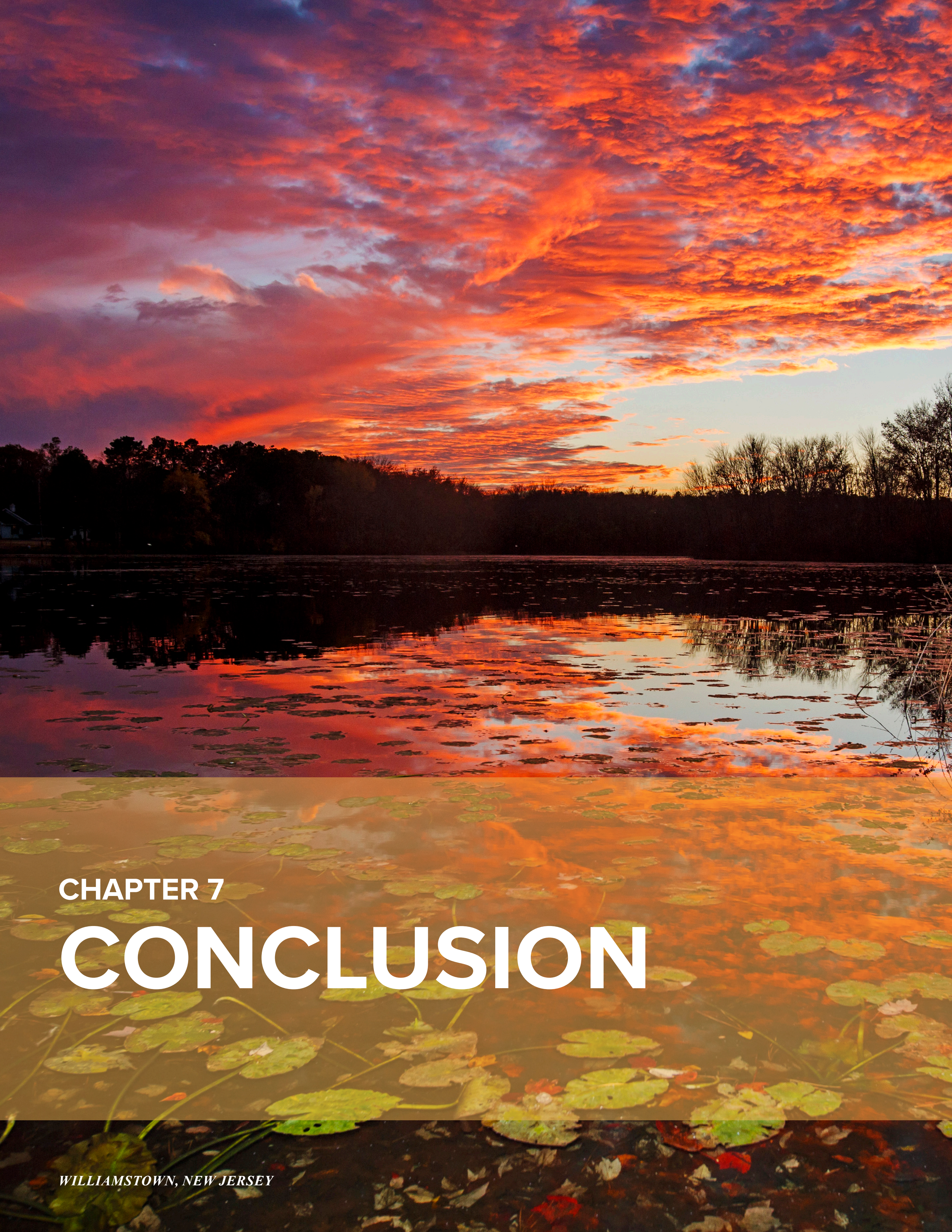
- More consideration needs to be given to greenhouse gases as an air quality concern themselves and what ecological impact will be caused from ozone on crop yields and forest ecosystems.
- Additional details should be provided on the other hazardous pollutants that are monitored in New Jersey.
- The impacts caused by climate change, specifically increased temperatures and air quality changes, on outdoor recreation and associated industries should be considered.
- Further consideration is needed on how the New Jersey aquaculture and fisheries industries will be affected by climate change.
- Further consideration is needed on the effects of forests in urban and suburban areas, and how they may be impacted by climate change.
- Further consideration is needed on the climate change impacts to New Jersey grasslands.

"...climate change may pose significant complications to public health but the science around these issues continues to evolve. Additional information is needed before conclusive statements can be made."

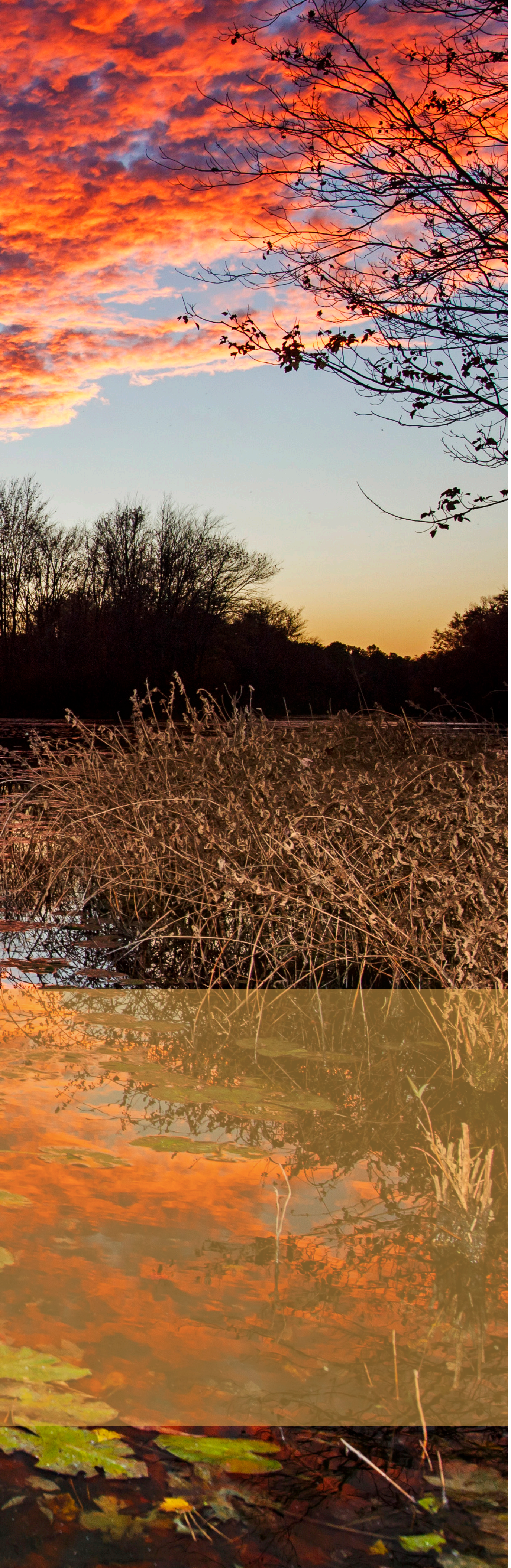
JERSEY CITY, NEW JERSEY

CHAPTER 7

CONCLUSION



WILLIAMSTOWN, NEW JERSEY



This report summarizes the advancements that have occurred in the scientific understanding of climate change as well as some of the current and anticipated impacts it will have on New Jersey's environment, natural resources, infrastructure, and communities. The report has shown how anthropogenic (human-caused) greenhouse gases are driving changes in temperature, precipitation, sea-level rise, and ocean acidification that are altering the way life on Earth interacts and exists.

Just how interconnected Earth's systems are becomes apparent when looking at the growing evidence of climate change - increasing global temperatures, driven by increases in the atmospheric concentration of greenhouse gases, and leading to more water vapor in the atmosphere. Excess water vapor can lead to an increase in precipitation as well as more intense weather patterns. These weather patterns not only bring on extreme precipitation events, but also conditions that cause droughts and settings favorable for wildfires. Higher temperatures will also increase the melting of land and sea ice which can alter ocean currents and amplify rising sea levels. Collectively, these changes in turn affect resources like air quality, the amount and quality of available water, the ability of the agricultural industry to provide food, and ecological systems like forests, wetlands, plants, and animals. These resources are vital to New Jersey and the anticipated impact from climate change will affect all aspects of life, including health impacts to human populations.

The impacts of climate change on the environment and human civilization will be significant. The natural range of ecosystems; migrations of species; impacts on society from severe storms and extreme weather events; the sensitivity of agricultural production; the intensity and frequency of wildfires, floods, and drought; and many other indicators make clear that both the environment and humanity are dependent on the state of the climate.

While a vast amount of expertise and knowledge exists within DEP, there is an even larger source of knowledge to be found within higher education institutions, other governmental and non-

CONCLUSION

governmental organizations, as well as the private sector within and around New Jersey. Through development of the Scientific Report, and in anticipation of future updates, the DEP is working to build relationships with these higher education institutions. DEP will continue to coordinate with these institutions, and look to engage other agencies and organizations, to gather the most current climate science available to inform the next iteration of this report.

As this report is being finalized, work is already underway to identify additional areas for consideration and inclusion in the next iteration of this report. As noted at the onset of the report, New Jersey is committed to having a comprehensive and forward-thinking response by all levels of government, economic sectors, communities and populations to address the impacts of climate change. As such, this report will be reviewed and updated in order to keep pace as the science behind climate change evolves.

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