NOVEMBER 2026

Teeing Up for Climate Change

Climate Change Vulnerabilities and Adaptation Opportunities of U.S. Golf Courses



Credit: USGA.

EcoAdapt™
Meeting the challenges of climate change

Arden Drake
Kathryn Braddock
Lara Hansen

Table of Contents

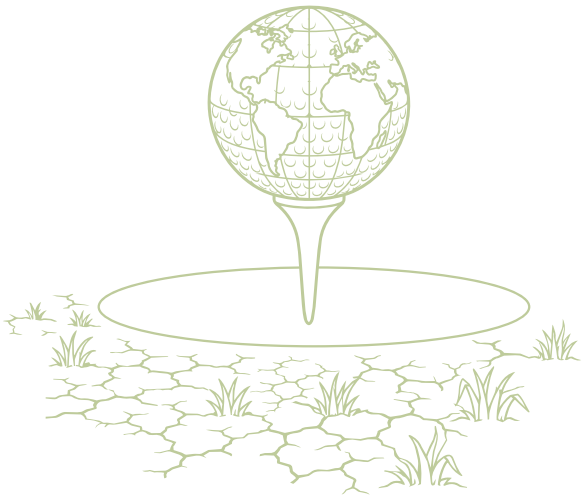
Executive Summary **3**
Key Findings 3
Introduction **5**
Methods 8
Literature Review 8
Survey 9
Interviews and Case Studies 13
Vulnerability of the Golf Industry to Climate Change **14**
Warmer Temperatures and Increased Extreme Heat 16
Changes in the Amount and/or Seasonality of Precipitation 20
Increased Drought 21
Increased Flooding and Storms 22
Sea Level Rise and Coastal Erosion 24
Adaptation to Climate Change in the Golf Industry **26**
Reducing Golf's Vulnerabilities to Climate Change 29
Adaptation Challenges 38
Future Opportunities for Adaptation 39
Literature Cited **41**
Appendix A. Efforts Toward Adaptation Implementation: Case Studies 48
The Kittansett Club's Response to Sea Level Rise in Buzzards Bay, MA 48
Palmer Hills' Strategy for a Climate-Resilient Course 51
Drought Adaptation and Landscape Transformation at La Rinconada Country Club 54
Advancing Climate Resilience Across Washington, D.C.'s Public Golf Courses 56
Appendix B. Regional Summaries **60**
Northeast U.S. 60
Midwest U.S. 62
Southern U.S. 64
Western U.S. (including Hawai'i and Alaska) 66

Acknowledgments:

Thank you to Daniella Rolle, who provided valuable background research and review and synthesis of the scientific literature for this report. Thanks also to Cole Thompson and the United States Golf Association (USGA) for their support of this important effort.

Recommended Citation:

Drake, A.E., K. Braddock, L. Hansen. Teeing Up for Climate Change: Climate Change Vulnerabilities and Adaptation Opportunities of U.S. Golf Courses. Bainbridge Island (WA): EcoAdapt; 2026.



Executive Summary



Credit: USGA.

Golf courses cover more than two million acres in the United States. In addition to opportunities for professional and recreational play, they promote tourism, support community connections, and contribute open space benefits. Because golf courses are widely distributed across all U.S. states and territories, they are already experiencing or will experience the full range of climate change effects—sea level rise, drought, flooding, fire, extreme heat, and hurricanes, among others.

To better understand climate vulnerabilities and adaptation opportunities for golf courses, course management, and users across the U.S., we surveyed members of the golf community to assess their concerns and ideas around climate change, reviewed the literature on golf course vulnerabilities, and conducted interviews to learn more about golf course climate adaptation actions to date. The goal of this project is to provide course managers and other stakeholders with the information they need to understand the types of climate changes that might occur and how those are likely to impact the golf industry, as well as opportunities for adaptation to reduce the negative impacts of climate change and maintain enjoyment of the game for everyone.

Key Findings

1. **Increased temperatures and more extreme heat** are likely to result in changes in the timing and length of the playing season, threats to the health and safety of players and staff spending time outdoors during periods of extreme heat and poor air quality, increased water consumption (and corresponding reductions in water availability), and damage and mortality in turfgrass and other course vegetation as a result of heat stress.

2. **Changes in precipitation amount, timing, and intensity** affect surface water and soil moisture availability, which in turn affect turfgrass and soil conditions as well as runoff volume/velocity and water quality. Frequent rain has been associated with decreases in play and can necessitate closures, both of which reduce revenue, while drier conditions increase the need for irrigation.

3. **Increased drought** reduces the availability of soil moisture and surface water, thus increasing water requirements and competition for water with other sectors (e.g., agricultural or municipal use). Drought also causes stress in turfgrass (and other plants), which limits growth and reproduction and, during severe or prolonged drought periods, causes turfgrass injury or mortality.

4. **Increased flooding and storms** are likely to cause a wide range of impacts, including stress in turfgrass, damage to course facilities, erosion and/or loss of access to portions of a course, and the need for postponing or canceling events to ensure player safety.

5. **Sea level rise and associated impacts** such as storm surge, coastal erosion, and saltwater intrusion are likely to result in damage or loss within coastal areas, along with stress in turfgrass inundated with seawater or exposed to higher salinity levels within water supplies for irrigation.

6 Climate changes such as warmer temperatures and shifts in precipitation patterns are likely to impact the growth and development, reproduction, and survival of problematic organisms such as **insect pests, pathogens, and invasive weeds.**

7 A wide range of options are available to address vulnerabilities to climate changes such as those listed above, which are called **adaptation actions**. Many of these are management actions that might already be occurring on golf courses, and those that are effectively reducing the impact of changes that are occurring or are likely to occur should be prioritized for continued use. In some cases, existing management actions may need to be shifted in terms of timing, location, or intensity to better address future climate conditions. There may also be new actions or activities that are not already taking place but that should be considered to help address emerging challenges.

8 Golf courses play a valuable role within their community and region, functioning as open space areas that can support ecosystem services (e.g., floodwater storage, water filtration, temperature regulation) and provide habitat for native plants and wildlife. Many of these characteristics can help ameliorate the impacts of climate change for the surrounding communities, and, as such, **golf courses can serve as valued partners within regional adaptation planning processes**.

9 Although climate change adaptation within the golf industry can be challenging due to factors such as lack of institutional and staff capacity, financial constraints, aesthetic expectations, **there are ample opportunities for golf courses to take the first steps towards preparing themselves for climate impacts**. Possibilities include conducting a course vulnerability assessment to better understand site-specific impacts, incorporating consideration of future climate change into current management plans, joining regional planning efforts, collaborating with other golf courses, and sharing lessons learned with others within the industry.



Credit: USGA.

With almost 16,000 golf courses in the United States covering more than 2 million acres,[1] golf accounts for a not-insignificant proportion of land use in the U.S. (Figure 1).[2,3] Their wide distribution across all U.S. states and territories suggests that, collectively, golf courses are already experiencing or will experience the full range of climate change effects—sea level rise, drought, flooding, fire, extreme heat, and extreme weather events such as hurricanes or other storms, among others. Because many of these changes will have significant impacts on golf course infrastructure, course access, and human health and safety, it is important for those in the golf industry to understand how climate change intersects with golf to effectively manage courses over the coming decades.

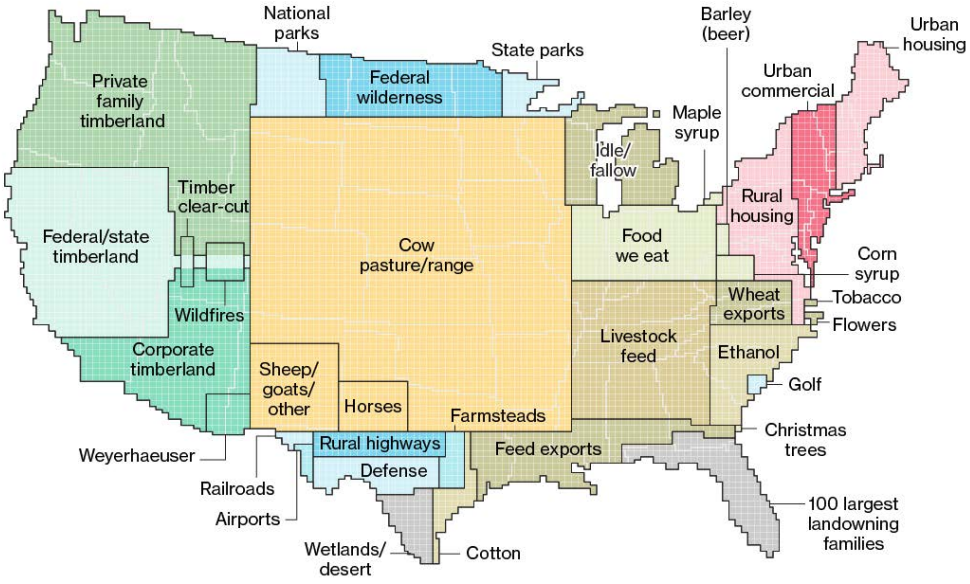


Figure 1. Land use in the United States, where golf courses take up roughly the combined area of Rhode Island and Delaware. Figure from Merrill and Leatherby (2018).[2]

Golf has a long-standing legacy, beginning in the green hills of Scotland, and has spread around the world.[4] In addition to opportunities for professional and recreational play, golf promotes tourism,[5] health benefits,[6] and social connections.[7] Golf courses also provide many environmental and economic benefits, including species conservation;[8] potential access to green, open spaces in urban communities;[9] and support of local economies.[10]

To maintain the services that golf courses provide to golfers and the larger community, course managers and industry leaders will need to consider how infrastructure and player participation will be vulnerable to changing climate conditions, then plan for how they will prepare for and respond to those changes to enhance resilience to climate change. Climate change adaptation will, ultimately, save money and ensure that golf course conditions and access are maintained to allow safe and enjoyable play. Golf courses can also play a role in supporting climate change resilience within the larger community where they are embedded, by providing wildlife habitat and movement corridors for native species impacted by climate change, flood protection, air and water filtration, and a host of other environmental functions that benefit both native species and adjacent human communities.[11–13]

Adaptation Basics

What is Adaptation?

Climate change adaptation is focused on preparing for or responding to the climate changes that are already occurring or will occur in the future, like warmer temperatures, shifts in precipitation patterns, more heat waves and droughts, increased storm intensity, and sea level rise, among others. Along with **climate change mitigation**, which focuses on preventing even more extreme changes by reducing greenhouse gas emissions, climate change adaptation plays a critical role in minimizing damage, ensuring natural systems remain functioning, and keeping communities safe.

Key Terms

1. **Adaptation** focuses on preparing for, responding to, or recovering from climate changes that we are already experiencing or expect to experience in the future. This is accomplished through adjustments in natural or human systems in response to changing climate conditions, which can occur at individual, community, and societal scales.

2. **Adaptation actions** are concrete steps taken by humans to cope with or respond to current and future climate changes. Examples of adaptation actions include planting heat- and drought-tolerant turfgrasses in zones where currently used varieties are not well-suited for expected future conditions, or shifting hours of operation on a golf course to limit the risk of heat-related illness during heat waves, among many other actions.

3. **Mitigation** focuses on reducing the magnitude and rate of climate change through measures that reduce greenhouse gas emissions or increase carbon sequestration and storage. Although mitigation is not a focus of this report, some adaptation actions can also support mitigation, and it is a highly valued co-benefit.

4. **Vulnerability** refers to the degree to which natural, built, and human systems are susceptible to harm from climate change. Vulnerability considers the magnitude and likelihood that a change will occur in a given location (e.g., whether extreme heat is expected to increase and by how much) and characteristics that may result in a greater or lesser chance that a harmful impact will occur (e.g., golf is largely played outdoors, which means golfers can be at risk of heat-related illness during heat waves).

5. **Confidence** refers to the level of certainty that scientists currently have about a given climate change. In this document, confidence is assigned a ranking of ***low***, ***moderate***, or ***high***, based on factors such as the amount and quality of available evidence, the methods used to detect and attribute trends to climate change, and the amount of agreement amongst the available information sources.[14] Scientists are certain that climate change is occurring, even where there is not high confidence about the parameters (e.g., magnitude, timing) of every single specific change.[15] Understanding confidence can help support decisions around adaptation, but note that low levels of confidence in a high-impact event should not be construed as encouragement not to act. We all make decisions in the face of uncertainty every day, using the best information available to weigh the risk of inaction against the potential level of impact that we might experience (e.g., we purchase home insurance even though house fires are statistically uncommon).

This report represents an effort to collect information about how climate change is already affecting golf, aspects of the sport that are vulnerable to future changes, and opportunities for adaptation that will support the industry under future conditions. The key elements of this report include a literature review that details existing research on the vulnerabilities of golf courses to climate change and strategies that other people have implemented to reduce climate hazards, the results of a survey of members of the golf community, and interviews with representatives of several golf courses to gauge the concerns of people within the golf industry about climate change and how some courses have begun to develop plans to respond to climate change. The goal of this report is to not only share information, but also to inform and inspire climate adaptation actions in golf courses across the country.



Credit: Jura on Unsplash.



Credit: Welcome on Unsplash.

This report is not intended to predict climate changes that will occur in any particular location or provide a step-by-step guide for what to do to address climate change risks. This report should be used to help people understand the broader context of how climate change will impact various aspects of the golf industry. Each individual must consider how the information provided here applies to their situation based on site-specific factors and seek out additional expertise and resources where more personalized guidance is needed.

Methods

This effort gathered information about climate change vulnerabilities and opportunities for adaptation in golf through three primary channels: 1) a literature review, 2) a survey of members of the golf community, and 3) interviews with golf course representatives that are already dealing with the impacts of climate change.

Literature Review

We reviewed the scientific and gray literature (e.g., white papers, reports) to identify publications that discuss how climate change will affect golf courses and possible solutions to minimize those impacts. We used combinations of predefined search terms related to potential impacts of climate change on golf, golf courses, and turfgrass, as well as possible adaptation solutions (Table 1). The search focused on five topic areas under which the keywords were categorized: sea level rise; warmer temperatures and more heat waves; changes in precipitation patterns and flooding/drought; climate-driven increases in disease, insect pests, and weeds; and golf course management and use.

From the initial pool of potentially relevant articles identified through keyword searches, 364 were selected for in-depth review based on their alignment with the objectives of the report. During our review, we identified additional relevant papers based on citation connections to the initial set, and many of these were included in the in-depth review as well. Across all papers reviewed, the keyword combination "turfgrass and flooding/drought" yielded the highest number of results, with 100 articles identified, followed by "turfgrass and heat" (n=59) and "golf courses and heat stress" (n=27) (Table 1).

The 364 studies selected for in-depth review span more than five decades, with publication dates ranging from 1970 to 2025 (Figure 2). Despite the climate change focus of the keywords, 72% of the studies reviewed did not mention climate change, although this improved in later years of the search range with 48% of the

Table 1. List of pre-defined keyword combinations used in the literature search. Parentheses denote the number of publications reviewed that were identified by each combination.

CLIMATE CATEGORY	KEYWORD COMBINATIONS (NUMBER OF PUBLICATIONS REVIEWED)
General	• Golf and climate change (14) • Golf courses and climate change (19) • Golf course maintenance and climate change (3) • Turfgrass and climate change (17) • Golf and weather (9)
Sea level rise	• Golf courses and sea level rise (12) • Golf course and saltwater intrusion (7) • Golf course and erosion (10) • Turfgrass and sea level rise (7) • Turfgrass and saltwater intrusion (10)
Warmer temperatures and more heat waves	• Golf and heat (2) • Golf course and heat stress (27) • Turfgrass and heat (59) • Golf and allergies and climate change (1)
Changes in precipitation patterns and flooding/drought	• Golf course and flooding/drought (11) • Golf course and water availability and climate change (7) • Turfgrass and flooding/drought (100) • Turfgrass and water quality (12) • Turfgrass and extreme weather events (4) • Turfgrass and hurricane (1)
Climate-driven increases in disease, insect pests, weeds, etc.	• Turfgrass pests and climate change (5) • Turfgrass disease and climate change (3) • Golf course weeds and climate change (1) • Golf course invasive species and climate change (1)

articles published between 2020 and 2025 mentioning climate change at least once within their text. However, less than 16% of the publications reviewed had incorporated climate change into their study design or explicitly discussed climate change impacts or adaptation within their introduction or discussion.

Among all of the studies, heat and drought stress emerged as the most prevalent themes. Numerous studies have investigated the effects of these climatic stressors on turfgrasses, with many identifying varieties that exhibit greater resilience under such conditions. At least one of the papers we reviewed commented on the lack of evidence on climate impacts as they relate to golf, as well as to a dearth of knowledge on adaptation options in the literature.[16]

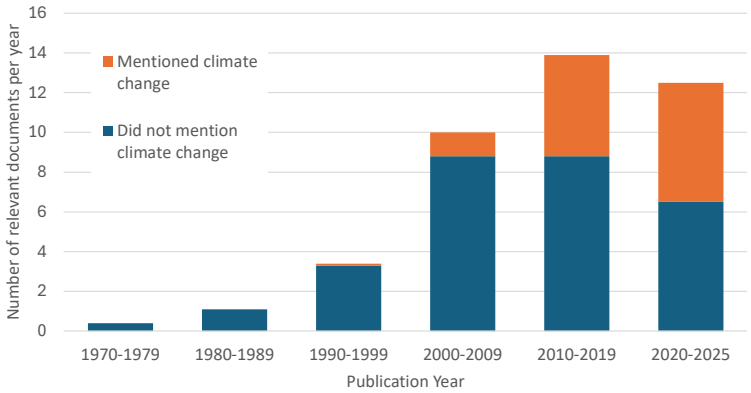


Figure 2. Distribution of the publishing date of all papers within the literature review.

Survey

To gain insight into how the golf industry is experiencing and preparing for climate change, we conducted an online survey geared toward golf course owners, superintendents and staff, people involved in supporting golf-related industries and associations, and golfers. The survey consisted of 32 questions, with a mix of multiple choice and short answer formats designed to elicit personal observations related to experiences with climate changes (e.g., sea level rise, heat waves, flooding) as well as existing issues that might intersect with climate change (e.g., water availability and quality, invasive plants, pests and diseases, pollution). The questions also asked about formal and informal adaptation efforts attempting to reduce those impacts, barriers, or challenges that might limit adaptation within the golf industry, and factors that might support greater adoption of adaptation initiatives. The survey was distributed through social media, newsletters, and direct email outreach by the U.S. Golf Association (USGA) and EcoAdapt, with an emphasis on reaching out to national audiences that would represent diverse perspectives. Survey responses were collected through SurveyMonkey, a web-based survey company, between April and June 2024, and 59 unique responses were received.



Credit: USGA.

Survey respondents represented 29 U.S. states as well as Canada. Washington was the most frequently reported state (12%), followed by Pennsylvania (9%) and Virginia (9%) (Table 2).

The vast majority of survey respondents reported that they play golf recreationally (95%) or professionally (2%), with only two respondents (3%) selecting that they did not play golf.

Most survey respondents did not work in the golf industry (59%). Among those who did, the most frequently reported position was golf course superintendents or directors of agronomy (10%). Respondents also held positions as golf administrators (8%), university scientists (5%), course maintenance staff (3%), and maintenance industry representatives (3%), among others (Table 3).

Table 2. Survey respondent location of residence (n=59).

LOCATION	RESPONSES (%)	LOCATION	RESPONSES (%)	LOCATION	RESPONSES (%)
Washington	7 (12%)	**Massachusetts**	2 (3%)	**Michigan**	1 (2%)
Pennsylvania	5 (9%)	**New Jersey**	2 (3%)	**Montana**	1 (2%)
Virginia	5 (9%)	**Wisconsin**	2 (3%)	**Nebraska**	1 (2%)
Minnesota	4 (7%)	**Alabama**	1 (2%)	**New Hampshire**	1 (2%)
Florida	3 (5%)	**Arizona**	1 (2%)	**North Carolina**	1 (2%)
New York	3 (5%)	**Colorado**	1 (2%)	**Oklahoma**	1 (2%)
California	2 (3%)	**Iowa**	1 (2%)	**Rhode Island**	1 (2%)
Georgia	2 (3%)	**Kansas**	1 (2%)	**South Carolina**	1 (2%)
Illinois	2 (3%)	**Kentucky**	1 (2%)	**Texas**	1 (2%)
Maine	2 (3%)	**Maryland**	1 (2%)	**Canada**	1 (2%)

Table 3. Survey respondent role within the golf industry (n=59).

ROLE WITHIN THE GOLF INDUSTRY	RESPONSES
Does not work in the Golf Industry	35 (59%)
Golf course superintendent/director of agronomy	6 (10%)
Golf administrator	5 (8%)
University scientist	3 (5%)
Golf course maintenance staff	2 (3%)
Golf course maintenance industry representative (e.g., technical services, sales)	2 (3%)
Golf course ranger/starter	2 (3%)
General manager	1 (2%)
Other golf course management role (e.g., assistant superintendent)	1 (2%)
Elected official with golf course in jurisdiction	1 (2%)
Retired director of agronomy / general manager	1 (2%)



Credit: Dan Congdon on Unsplash.

Respondents who either managed or were employed by a golf course reported a range of ownership structures, with the largest proportion being member-owned golf facilities (33%) followed by city- or county-owned facilities (27%) (Figure 3). Most of the courses where these individuals worked were 18-hole (69%) or 27-hole (15%) courses (Figure 4).

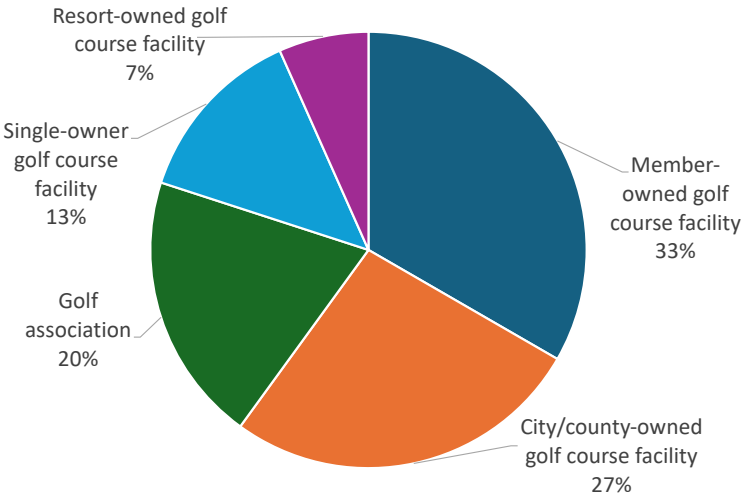


Figure 3. Course ownership structure for survey respondents managing or employed by a golf course.

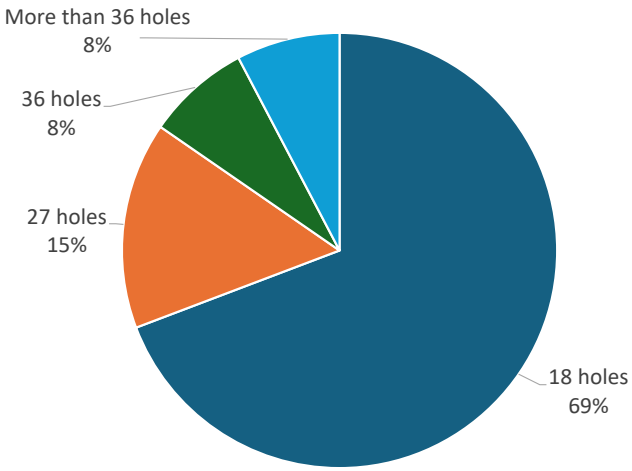


Figure 4. Course size for survey respondents managing or employed by a golf course.

Survey Demographics

Thirty-four percent of survey respondents were between the ages of 45 and 64 (Figure 5)

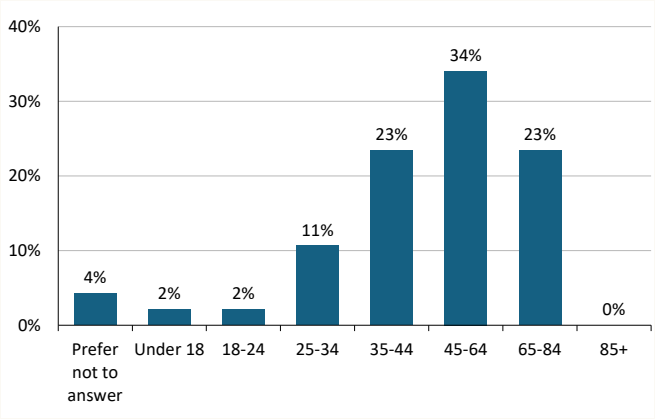


Figure 5. Age range of survey respondents.

Eighty-nine percent of respondents described their race as white, and the remaining 11% declined to answer (Figure 7)

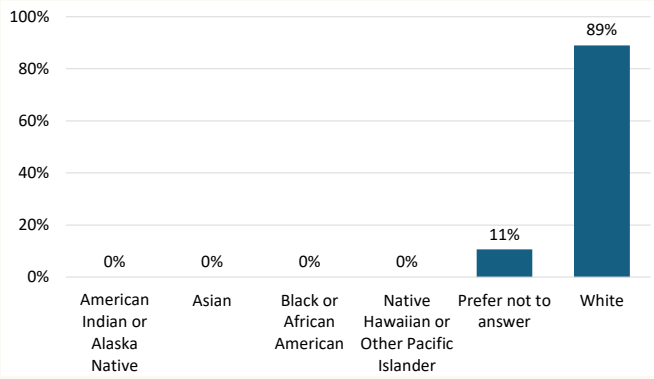
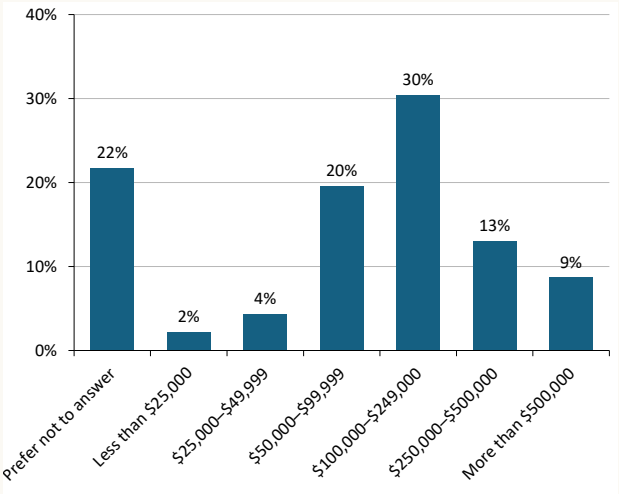


Figure 7. Race and ethnicity reported by survey respondents.



Eighty-seven percent of respondents were not of Hispanic, Latino, or Spanish origin (Figure 6)

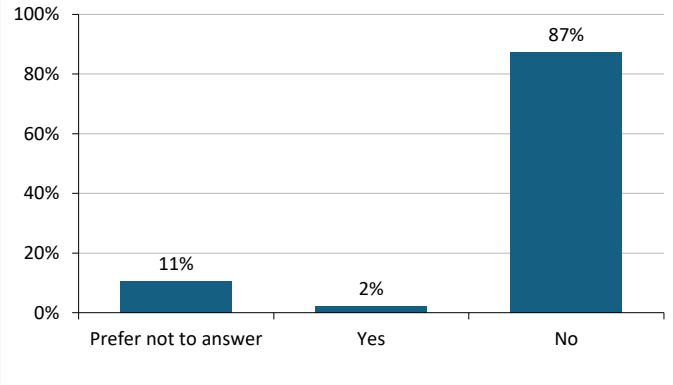


Figure 6. Percentage of survey respondents who reported being of Hispanic, Latino, or Spanish origin.

Fifty percent of respondents reported a bachelor's degree as their highest level of education (Figure 8)

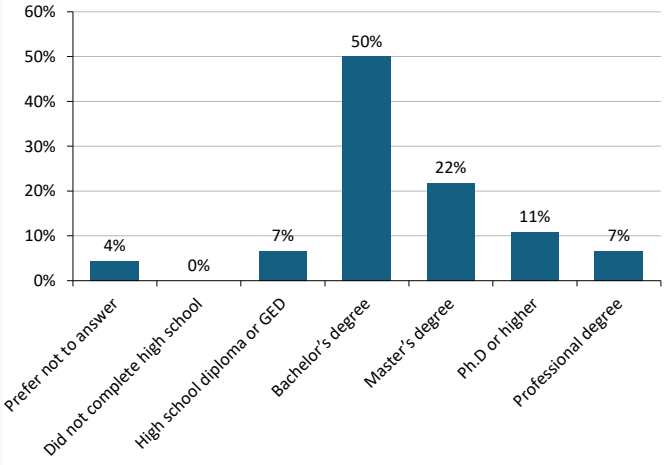


Figure 8. Highest level of education completed by survey respondents.

Thirty percent of respondents had an annual household income between $100k and $249k (Figure 9)

Figure 9. Total annual household income reported by survey respondents.



Credit: Richard Brutyo on Unsplash.

Interviews and Case Studies

The final component of this effort was a series of interviews conducted with golf course managers and stakeholders to understand the climate hazards they are seeing and what, if any, actions they are taking to reduce those impacts. We identified several golf courses to reach out to, based on recommendations from contacts at USGA, and emailed them to request an interview. These efforts resulted in four interviews, carried out between winter 2025 and summer 2025 with staff of golf courses in California, Iowa, Massachusetts, and Washington, D.C.

Interview questions explored key issues around climate change awareness, action, and adaptation within the context of golf course management. Specifically, we sought to understand:

- **Observed impacts and concerns:** What climate-related changes have managers and staff observed on their courses? What aspects of climate change are they most concerned about?
- **Experience with climate action:** Have they undertaken any climate-related initiatives or adaptation efforts to date? If so, what strategies were implemented, how were they received, and what outcomes or lessons emerged?
- **Barriers to action:** What challenges have they encountered in addressing climate change, either in initiating conversations or implementing adaptation measures?
- **Enabling factors:** What factors have supported or facilitated climate action on their courses (e.g., public support, available funding, institutional backing)?
- **Future adaptation goals:** What plans or aspirations do they have for future climate adaptation efforts? Are any projects currently underway?

Each case study showcases the distinct climate-related challenges facing these golf courses, highlights the innovative strategies their managers and superintendents employ to address and anticipate these challenges, and demonstrates how they integrate climate considerations into their long-term planning and daily operations. Notes from the interviews were written up into case studies, which are included with this report, and notable findings informed our review and synthesis of the literature.

The interviews were used to inform the report, particularly the adaptation section, and are also presented as case studies in ***Appendix A***.

Vulnerability of the Golf Industry to Climate Change

Climate changes are already being felt across the U.S., including increasing temperatures, altered precipitation patterns, and rising seas.[15,17–19] As global temperatures continue to rise, particularly in the absence of immediate and significant reductions in greenhouse gas emissions, these impacts will become increasingly extreme.[20–23] However, exposure to climate changes is not evenly distributed, with some regions of the country experiencing more frequent storms and flooding[21,24] while others are more likely to experience drought and fire.[25,26] Generally speaking, existing stressors are likely to become even more extreme (e.g., areas prone to floods, drought, or heat waves will see the same types of events that are even more frequent or severe), but many areas will also see new challenges arise. For instance, dangerously high temperatures have recently become a significant issue in the Pacific Northwest, which has historically enjoyed relatively moderate summer temperatures and so lacks the infrastructure typically found in the southern U.S. (e.g., widespread use of air conditioning in residences).[27]

Table 4. Example climate impacts in the golf industry by region.

REGION	EXAMPLES OF CLIMATE IMPACTS
Northeast	• Increased risk of flooding due to wetter winters and more extreme precipitation, with corresponding impacts on turfgrass, course infrastructure (e.g., buildings), and staff and player safety • Sea level rise, resulting in coastal erosion and likely course damage • More extreme heat, impacting staff and player comfort and safety as well as turfgrass health
Midwest	• Increased risk of flooding due to wetter winters and more extreme precipitation, with corresponding impacts on turfgrass, course infrastructure (e.g., buildings), and staff and player safety • Increased drought, with reduced water availability/quality combined with increased water demand, creating challenges for turfgrass irrigation and course management • Warmer temperatures, potentially increasing the length of the golf season although in some areas play may be reduced during the hottest summer months • Increased risk of wildfire and associated impacts on air quality
South	• Inland and coastal flooding as a result of sea level rise and storms, which are likely to impact turfgrass, course infrastructure (e.g., buildings, greens), and player safety • More extreme heat, impacting staff and player comfort and safety as well as turfgrass health • Increased drought, with reduced water availability/quality combined with increased water demand, creating challenges for turfgrass irrigation and course management
West (including Hawai‘i and Alaska)	• Drier conditions and increased drought (particularly in the Southwest), with impacts on turfgrass, course condition, and water quality and availability • More extreme heat, impacting staff and player comfort and safety as well as turfgrass health • Increased risk of wildfire and associated impacts on air quality • Inland and coastal flooding as a result of sea level rise and storms, which are likely to impact turfgrass, course infrastructure (e.g., buildings, greens), and player safety

Table 4 outlines a few of the most significant concerns for each region of the U.S., together with some of the ways that these changes may impact golf for management, players, and spectators.

Regional summaries, which can be found in ***Appendix B***, outline in more detail the primary vulnerabilities for each of the four regions.

Survey Respondent Views on Climate Change Impacts

The survey undertaken as part of this project explored respondent concerns about the impacts of climate change on golf, including changes that have already been observed and aspects of the golf industry that people believe may be most impacted.

Three-quarters of survey respondents were at least slightly concerned about the impacts of climate change generally and as they relate to golf (Figure 10).

At least two survey respondents of the 14 who were not at all concerned about climate change clarified within the comments that they do not believe climate change exists, or that they believe any changes observed are natural and unrelated to anthropogenic increases in greenhouse gas emissions.

The biggest climate concerns for survey respondents are changes in the amount or seasonality of rain and snow (a concern for 49% of respondents), followed by more frequent and/or severe droughts (46% of respondents) (Figure 11).

Twenty-seven percent of survey respondents reported that they are not concerned about the impact of any of the listed climate changes on golf.

Seventy-eight percent of survey respondents think that course maintenance will be negatively impacted by climate change (Figure 12). Specifically, survey respondents noted maintenance concerns such as new/changing insect pests and fungal issues requiring treatment, changes in irrigation and drainage needs, and the impacts of erosion and possible loss of course areas adjacent to the coast.

Fifty-six percent of respondents believe that costs will increase as a result of climate change. In particular, they noted the potential for increased costs of clean-up and repair following extreme events as well as higher costs for routine maintenance.

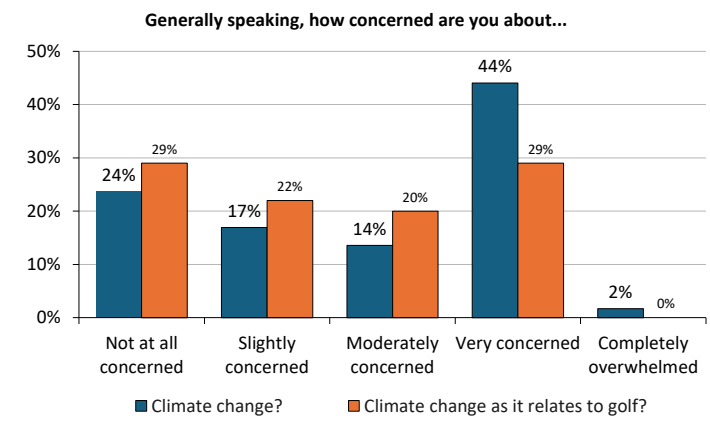


Figure 10. Percent of survey respondents concerned about climate change generally, and as it relates to golf.

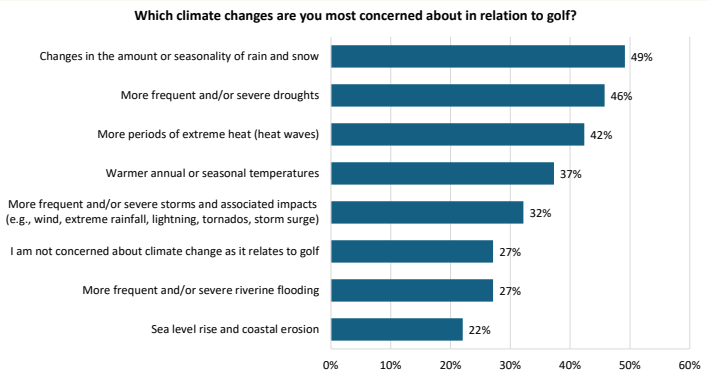


Figure 11. Percent of total survey respondents that expressed concern about specific climate changes in relation to golf (note that respondents could select more than one concern).

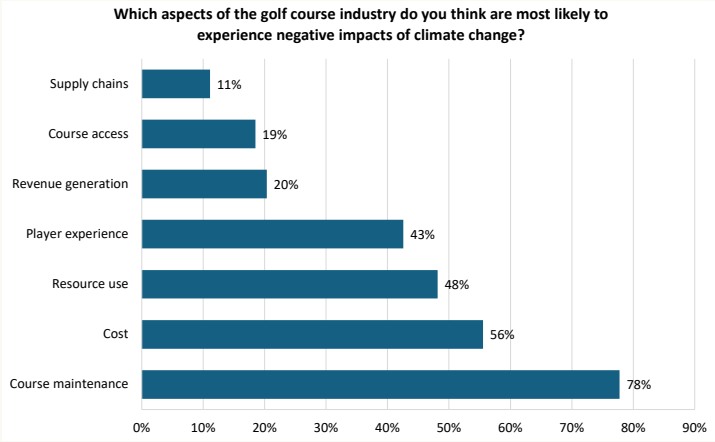


Figure 12. Percent of total survey respondents that expressed concern about the negative impacts of climate change on different aspects of the golf industry (note that respondents could select more than one aspect).

Climate changes are already affecting communities, and impacts are expected to accelerate over the coming decades. Changes such as temperature increases, altered precipitation patterns, sea levels rise, and extreme weather events are already becoming more apparent, and it is critical to understand how these changes might impact different aspects of our lives. Understanding how the golf industry is vulnerable to climate change will allow golf course owners, managers, and staff, as well as other industry leaders (e.g., the USGA), stakeholders, and players, to proactively prepare for those changes and maintain course safety and player enjoyment, in addition to the valuable services that golf courses provide to the larger community (e.g., through their role as wildlife habitat and open space).

The following sections provide an overview of how climate change may alter conditions on golf courses, as well as some of the other aspects of the game that may be affected.

Warmer Temperatures and Increased Extreme Heat

One of the most widespread impacts of climate change will be warmer temperatures, with every region expected to see higher average seasonal and annual temperatures (high confidence).[15] Climate data suggests that the U.S. is warming faster than the global average (i.e., a global increase of 1.7°F has resulted in a temperature increase of 2.5°F in the U.S. since 1970), particularly at higher latitudes (e.g., Alaska has warmed by 4.2°F over the same period).[15] In most of the U.S., average nighttime and winter temperatures have increased more than daytime and summer temperatures.

Extreme heat and heat wave frequency, intensity, and duration have also increased across all regions, and this trend is expected to accelerate (high confidence).[15,28-30] These changes are associated with significant impacts on golf, including changes in the timing and length of the playing season,[31] threats to the health and safety of players and staff spending time outdoors during periods of extreme heat,[32] increased water consumption (and corresponding reductions in water availability),[33,34] and damage and mortality in turfgrass and other course vegetation as a result of heat stress,[35,36] particularly in combination with drought. Warmer temperatures and extreme heat also exacerbate the impacts of other stressors.[15] For instance, hotter temperatures increase evaporation and plant transpiration, resulting in drier vegetation and loss of surface water (e.g., through evaporation)[37] as well as declines in water quality[38] and increased fire risk.[26]

Within the survey associated with this project, 42% of respondents were concerned about more periods of extreme heat in the future, and 37% were concerned about warmer annual or seasonal temperatures. Many respondents also noted that they are already observing the impacts of warmer temperatures and extreme heat within the golf courses where they work and play. The most common observation that people mentioned was an extension of the golf season as a result of mild winters and warmer spring and autumn seasons, noted primarily by respondents in the mid-Atlantic, Northeast, and Midwest regions.

Other impacts were more negative – specifically, respondents noted patterns of increased heat stress in turfgrass during hotter summers, which included damage to greens in Virginia that could not be repaired, as well as more extreme temperature swings and freeze-thaw cycles that increase the severity of winter turfgrass mortality. A respondent in Georgia mentioned multiple instances of health impacts to staff because of extreme heat, while in the Northeast periods of high heat and little rain have resulted in stagnant water and necessitated maintenance adjustments. These survey results align closely with a survey conducted by the British Association for Sustainable Sport,[39] which found that 66% of respondents expressed concern about the impacts of extreme heat on golf, and 30% felt that it was already having an impact. Additionally, 36% felt that their club was not prepared to deal with those impacts.

Changes in timing and length of the playing season

Warmer temperatures and increased frequency of heat waves are already shifting the timing and length of the golf season, and this pattern is expected to accelerate as climate-driven changes have even greater impacts on player comfort and enjoyment in the coming decades.[31,40] In regions with historically shorter golf seasons, warmer temperatures in the



Credit: Edwin Compton on Unsplash.

winter and shoulder seasons (e.g., spring and fall) are likely to increase the length of the playing season,[31,40,41] as is already being observed by seven of our survey participants (primarily those in the Northeast and Upper Midwest). Studies have shown that higher temperatures are associated with greater numbers of rounds played per day in Michigan,[40] and that the golf season is projected to lengthen in the colder regions but not in the areas where golf courses already operate year round.[31] These shifts are highly dependent on historical temperatures, however. For instance, in Michigan where warmer temperatures have increased the number of rounds played, historical temperatures are not high enough for those increases to cross the tipping point where temperatures cause participation to decline.[40] This would not be the case in areas where temperatures are closer to that threshold; in areas farther south, the season may extend into the cooler months but activity may also decline in the hot summer months.

Seasonal shifts in temperature are already affecting pollen production and the flowering time of plants and are expected to continue to do so, with impacts on people with pollen allergies.[34,42,43] While changes in plant phenology (i.e., timing of events such as flowering) are species-specific, multiple studies have suggested that allergy season is likely to become longer and more severe,[42-45] with the potential for increases in pollen emission of up to 200% by the end of the century.[43] Exposure to new types of pollen as plants expand their range could also make spending time outdoors less pleasant for many.[34]

Human health and safety

Higher summer temperatures and more frequent and intense heat waves are already occurring across the U.S., and these trends are expected to become even more extreme over the coming century.[15] The U.S. National Weather Service defines "dangerous" heat as occurring when the heat index (a measure of what the heat feels like to the human body, combining air temperature and relative humidity) is above 104ºF, when muscle cramps and heat exhaustion are likely to occur.[46] A recent study suggests that large portions of the U.S. will experience between 15 and 90 days per year of dangerous heat, and that, specifically, Chicago may experience a 16-fold increase in 4-day heat waves by the end of the century, going from a historical average of two heat waves per year up to 32.[30] Increases such as these will have serious implications for outdoor activities such as golf,[47] both for players and for staff.

Players and maintenance staff spending time outdoors in the heat are vulnerable to heat exhaustion and heat stroke, as are spectators,

Diminished air quality

Hot summer air temperatures are frequently associated with diminished air quality. This can occur when high levels of ozone are generated during periods of high temperatures and/or drought[45,53] increases flammability of drying vegetation that acts as fuel[26] for wildfires that result in smoke and particulate matter in the air.[45] Both of these factors are associated with recommendations for reduced outdoor physical activity, particularly in the elderly and people with pre-existing respiratory problems, and are likely to be further exacerbated by climate-driven increases in summer high temperatures and periods of extreme heat.[47] Within our survey, one respondent from Minnesota mentioned that they are already observing increased air particulate matter, which negatively impacts the golfer experience.

vendors, and other participants at events.[32] People who are less acclimated to heat and humidity are particularly at risk,[48] along with those who are older or who have pre-existing health conditions.[47] For competitive golfers, unusually warm weather conditions and extreme heat may also affect performance.[32,48] While very few studies discuss this in the context of golf and none of them specifically tie in climate change, it is reasonable to conclude that the quality of competition may decline as extreme heat becomes more problematic, at least when competitive events are not shifted.[32] Schedule shifts and cancellations are likely to become more frequent as air temperatures more frequently cross safety thresholds set by venues or organizing bodies.[32,49]

Reduced water availability and quality

Warmer temperatures are directly associated with increased rates of plant transpiration, which helps them reduce the impacts of heat stress but, together with increased evaporation rates at higher temperatures, also reduces water availability in the environment.[37,50] Warmer temperatures as a result of climate change are also expected to require greater water use for irrigation, although modeling suggests that temperature is less important than other factors such as amount of precipitation received, site-specific factors (e.g., area, number of fairways, type of turfgrass), and management decisions (e.g., frequency and extent of irrigation).[33]

Warmer temperatures are also associated with reductions in water quality, potentially affecting water bodies on golf courses by creating conditions suitable for harmful algal blooms.[38] These are likely to be particularly problematic where fertilizer contributes to nutrient runoff that interacts with climate-driven increases in water temperature, thus driving more frequent and more intense toxic cyanobacteria blooms.[51] This is most likely to occur where best management practices (BMPs) are not being followed to limit the impacts of nonpoint source pollution, though other site-specific factors such as soil type and the amount of impervious surfaces in surrounding areas can also contribute.[52]

*See **Increased Drought** section for details on the impacts of reduced water availability.*

Heat stress in turfgrass

Significant research has been conducted on turfgrass response to heat stress, but in our literature review 90% of studies on this topic did not explicitly consider climate change within the study design or interpretation of results. These can offer important information and insights on topics such as the ideal temperature range of different species and cultivars,[54] physical changes that occur as a result of heat stress,[55] and factors associated with increases or decreases in heat impacts.[56] However, it is important to consider that future changes in temperature may not occur as steady, consistent warming across all seasons. For instance, a simulation study in Sweden investigated biomass production and loss in three turfgrass species to understand how warming impacted growth under current and future climate conditions.[57] They found that stress and mortality as a result of cold winter temperatures increased under future conditions despite higher winter temperatures because warmer autumns limited hardening (i.e., gradual acclimation to colder temperatures), while warm spells in winter and early spring that accelerated the process of dehardening.

Generally speaking, heat stress acts as a limiting factor for summer growth in turfgrasses, particularly for cool-season grasses.[35,36,58] High air and soil temperatures affect key plant processes that impact turfgrass growth and development,[35,36,55,57–63] which can result in injury or mortality[64,65] as well as reduced aesthetic quality.[56,64–68] Turfgrasses experiencing heat stress can also be more vulnerable to impacts from additional stressors (e.g., drought, subsequent heat waves),[59,69] particularly in turfgrasses that take longer to recover from periods of heat stress.[59] This suggests that slower-recovering species and cultivars may be more vulnerable to climate change, as many stressors are projected to become more frequent and overlapping stressors (often called compound stressors) are almost certain to happen, even if the types of events themselves may be vary across different regions of the United States.[23,70,71] Heat stress and drought stress are particularly likely to co-occur,[70] particularly in the southwest U.S.,[23] and can be more damaging for turfgrass compared to either heat or drought stress alone.[72]

Variations in heat sensitivity and tolerance exist even among species and cultivars.[36,56,59,62] For example, tall fescue (*Schedonorus arundinaceus*) is more heat tolerant than many other cool-season species, and significant variation exists within genotypes as well.[59,73] Warm-season turfgrasses, which are better-adapted to heat, are already widely used in areas of the U.S. where summer high temperatures routinely exceed the tolerance range of cool-season grasses. For these species, warmer springs may lead to earlier establishment favoring turfgrass maturation before winter.[74] However, maximum high temperatures in these areas are projected to continue increasing, and for many regions, increases in the number of summer days with high temperatures above 90° or 100° F may still lead to heat stress even in warm-season turfgrasses.[59]

The timing of changes in temperature may also determine the degree of stress, as both heat and cold impacts on plants are dependent on the degree of acclimation that occurs during gradual increases (or decreases) in temperature over the shoulder seasons.[75] As a result, unusually high spring temperatures may be detrimental to turfgrasses that have not yet acclimated to heat, while warmer fall temperatures may prevent full cold acclimation, thus reducing winter survival.[36,76] More frequent winter temperature swings may also result in deacclimation to cold temperatures during thaw events, which increases the risk of subsequent mortality when temperatures dip below freezing again.[36,76]

Increased atmospheric carbon dioxide (CO2) can provide some benefit to plants experiencing heat stress by improving metabolic processes and promoting above- and belowground growth.[63] However, in most cases this potential benefit of climate change will not be realized, because factors other than CO2 are usually limiting growth.

Economic impacts of increased temperatures and extreme heat

Warmer temperatures and periods of extreme heat are likely to result in economic impacts for golf courses. Uncomfortably warm playing conditions, particularly in more southern regions, may result in summer revenue loss as player participation declines.[31] Research suggests this is particularly likely for golf courses whose revenue largely comes from local or regional clientele rather than tourists, as they are more likely to change or cancel their plans based on weather conditions compared to tourists who have invested time and money into a trip.[40] By contrast, golf courses in more northern regions, where not only do summer conditions remain relatively favorable but warmer temperatures extend the golf season earlier in the spring and/or later into the fall, may see increased revenue along with greater wear on golf courses as a result of a longer playing season.[31,40]

During extreme heat events, player participation may drop off significantly, and very hot temperatures may also necessitate the cancellation of events and competitions in the interest of public safety.[77] These cancellations can result in significant revenue loss for golf facilities as well as merchants, vendors, and community businesses where tourist income declines.[78] The cost of continuing events as usual in hotter summers may be expensive as well, due to increased costs of cooling and other measures required to maintain player comfort and safety.

Changes in the Amount and/or Seasonality of Precipitation

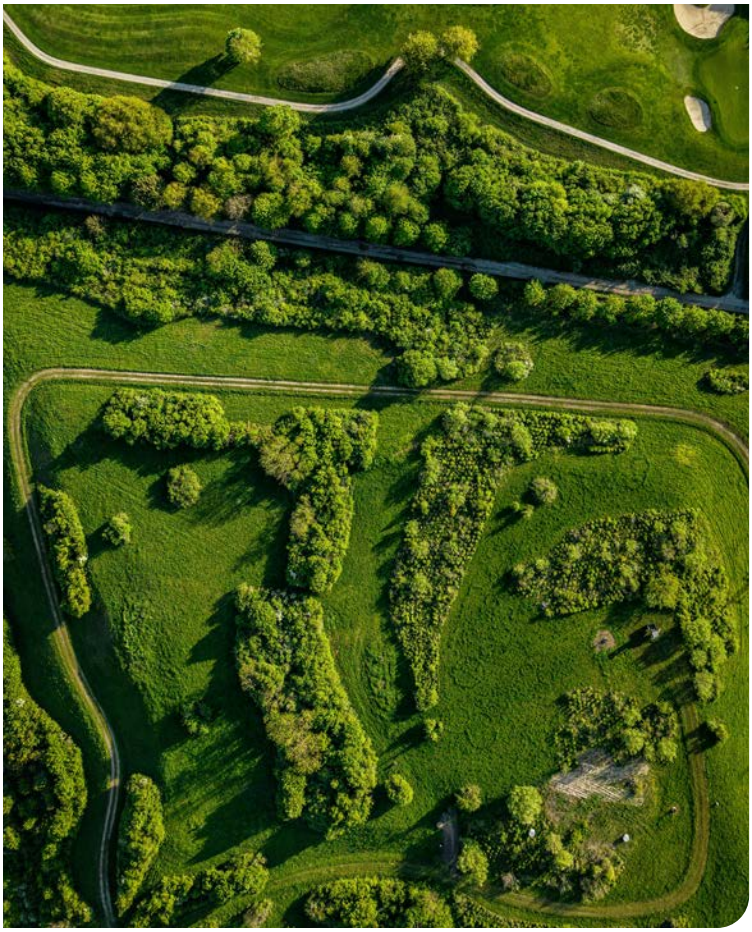
The timing and amount of precipitation has already shifted, both in terms of annual rain and snow totals as well as seasonal patterns, and these trends are expected to accelerate in the future.[15,79] Broadly speaking, much of the central and eastern U.S. has gotten wetter, with the most extreme changes observed in the Northeast and Midwest regions, where average annual precipitation from 2002 to 2021 was as much as 15% higher than historical averages for the first half of the 1900s (1901–1960).[15] By contrast, the western U.S. and Hawai'i have generally gotten drier, particularly in the Southwest region and Hawai'i, where significant and widespread declines in summer precipitation (over 15%) along with more moderate declines in winter precipitation for many areas have led to large reductions in annual precipitation. In the Pacific Northwest, summers are drier and winters are wetter, resulting in more inconsistencies in overall trends across the region. These trends are expected to continue, with Alaska and the northern and eastern regions of the U.S. getting wetter while the southwestern regions, Hawai'i, and Caribbean getting overall drier (*moderate confidence*).[79]

Interannual variability has increased as well, with larger swings between very dry years and very wet years, even in areas where the overall trend is heading in one direction.[79] For instance, a survey respondent in New York observed long dry periods interspersed with more intense storms. Across the country, more precipitation is falling as rain rather than snow, resulting in decreased snowpack[80] followed by warmer spring temperatures that cause earlier snowmelt.[22] This contributes to reduced groundwater recharge and summer streamflow that diminish water supplies, particularly in the western U.S.,[79] as was noted by a survey respondent in Washington who observed water restrictions being placed earlier in the summer. These trends are also expected to continue, with heavier rainstorms and greater variability alongside significant decreases in snowpack and earlier snowmelt (*high confidence*).[79]

Within the survey associated with this project, 49% of respondents were concerned about changes in the amount or seasonality of rain and snow, making it the climate stressor of concern to the greatest number of people. Only two of those named specific impacts that they had observed related to those changes (greater swings between wet and dry periods, and earlier water restrictions, both mentioned above), likely reflecting greater difficulty in identifying more gradual shifts in comparison to extreme events such as flooding or drought. However, these changes are likely to have significant impacts on turfgrass health and quality,[35] playing conditions,[81] and associated maintenance needs and costs/revenue.[82]

Changes in precipitation amount, timing, and intensity impact surface water and soil moisture availability.[79] Water requirements for turfgrasses vary widely across species and cultivars,[83] suggesting that the impacts of changing precipitation on turfgrasses will be highly dependent on the direction and type of change in addition to site-specific factors (e.g., soil type and texture) and species characteristics (e.g., rooting depth).[35] However, general trends towards more extreme wet or dry conditions and increased variability, or swings, between the two increase the likelihood that a larger proportion of the growing season will have moisture conditions that are not ideal for turfgrass growth.[35] It is likely that existing management activities may no longer be suitable or well-timed to address soil conditions that are drier or more saturated than they historically have been.[35] This will require shifts such as increased irrigation in areas where rainfall alone has typically been sufficient[16] or additional closures to limit compaction of saturated soils,[81] resulting in increased staff time and costs and/or reduced revenue.

Overall, wetter conditions are likely to result in soft surfaces that are more easily compacted, particularly if warmer autumn and winter temperatures increase foot traffic by extending the playing season.[81] Increased spring precipitation, which is projected to occur across the eastern U.S. as well as the Midwest and Northern Great Plains regions,[15] is particularly likely to lead to more saturated soils given that cool temperatures result in low evaporative demand and plants are not yet growing and taking up significant amounts of soil moisture.[83] Heavy precipitation can



Credit: Bernd Dittrich on Unsplash.

also increase runoff volume and velocity, causing flooding in streams and waterways as well as issues with water quality.[16] These changes could result in more frequent closures, especially in areas with reduced drainage rates,[81] which would decrease golf course revenue. Because golf is entirely outdoors, more frequent episodes of rainy weather or stormy conditions are likely to be associated with reduced play.[31,40,82] In fact, one report mentioned a 2020 study by the National Golf Foundation that found for every extra inch of rain per year there was a 2.2% decrease in on-course play.[82]

*See **Increased Flooding** section for details on the impacts of extreme precipitation. Drier conditions are also a concern and are covered more thoroughly in the Increased Drought section.*

Increased Drought

Drought is generally defined as a period when water availability is below average as a result of warmer temperatures, changes in precipitation, soil moisture, streamflow, and groundwater.[84] Drought conditions are strongly associated with periods of low rainfall and/or snowfall and snowpack, often combined with high rates of evaporation and plant transpiration that occur because of warming temperatures.[15,84,85] Together, these factors result in reduced availability of soil moisture and surface water that impacts plants, wildlife, and humans.[84–86] The southwestern U.S. recently experienced a decadal-scale megadrought thought to be more severe than any that has occurred over the last 1,200 years,[19,87] and drought frequency and severity is also occurring across other parts of the western U.S..[15] Over the coming decades, drought risk is expected to increase significantly in the southwestern U.S., as well as more broadly across the western U.S. (*high confidence*).[25,84] Due to the impact of warming temperatures, drought may occur even in areas where annual precipitation increases,[84,86] and swings between very wet and very dry conditions mean that areas that receive ample precipitation, such as the Northeast, are likely to experience more frequent and intense periods of drought (*moderate confidence*).[88]

Within the survey associated with this project, 46% of respondents were concerned about the impacts of drought on golf, making it second only to the level of concern about changes in precipitation. Respondents mentioned concerns about turfgrass stress, reduced water availability and increased irrigation needs, and stagnant water during periods with high heat and no rain. The scientific literature confirms these responses, with the most significant impacts of drought being reduced water availability, along with increased water requirements, and drought stress in turfgrass.

Reduced water availability and increased water use

Climate-driven increases in drought will exacerbate existing issues with water scarcity in drier regions[89,90] and has the potential to create new problems in areas that historically have not had to worry about competition for or access to water.[86] Rapidly growing populations are an additional concern, and together with climate change will further amplify the scarcity of freshwater.[91] Golf courses, in particular, may experience significant challenges given that they can

be quite water intensive, with some 18-hole golf courses consuming 250,000 to 1,000,000 gallons of water per day during summer months.[92] During periods of drought that result in competition for water, intensive water use by golf courses is likely to be painted in a negative light,[90,93,94] even as water conservation efforts or self-supported water supplies (e.g., through wastewater recycling or desalination) can be overlooked[93] and the actual rate of water use ranges widely based on factors such as turfgrass type and management practices.[95] Competing societal demands for water use, such as agricultural irrigation, drinking water supplies, and ecological use for species conservation,[36,96] are likely to result in turfgrass irrigation being a lower priority as climate change continues to exacerbate existing drought impacts.[34] In many areas, groundwater overdraft (e.g., extracting water from an aquifer at a greater rate than it is recharged) is likely to become a more significant issue, as wells that access local groundwater are the primary irrigation source for U.S. golf courses.[1]

Where golf course irrigation does increase in response to drier conditions and periods of drought, costs are likely to increase.[34] A 2015 survey of European turfgrass managers found that an increased need for irrigation, along with other climate-related changes in required maintenance, had resulted in an average increase of more than five working hours a month for over half of the respondents, suggesting that necessary staffing may increase as well.[34]

Drought stress in turfgrass

Along with temperature, the impact of drought stress on turfgrass is frequently studied and was addressed in 113 of the articles identified through our literature review, although only three of those (2.7%) explicitly considered climate change within their study design or interpretation of results.

Decreased soil water availability associated with periods of drought alters the plant water balance, impacting cellular functioning and plant processes.[66,97-99] These impacts severely limit growth and reproduction and, under more prolonged or severe periods of drought, result in injury or mortality[36,72,83,100,101] as well as potentially increased vulnerability to disease[102] and weed pressure.[103] Like heat tolerance, turfgrass drought resistance varies both among and within species, with cool-season turfgrasses generally less tolerant compared to warm-season grasses.[36,68,104] Turfgrasses can possess a wide range of traits that can help them avoid or tolerate drought, including deeper root growth during dry periods in order to access moisture farther underground (e.g., tall fescue [*Lolium arundinacea*]), leaf rolling or stomatal closure to limit water loss (e.g., Kentucky bluegrass [*Poa pratensis*]), or reduced rates of water use (e.g., hard fescue [*Festuca brevilipa*]), among many others.[36,56,104,105] In some cases, mild water deficits can prime plants, including turfgrasses, thus improving their tolerance of future drought periods.[106] However, studies in turfgrass and other taxa have also found that prolonged or repeated periods of more severe drought stress may result in more significant impacts,[107,108] and these types of drought events are likely to increase, particularly in areas of the U.S. that are already prone to drought (e.g., much of the Southwest).[108]

As climate change increases drought frequency, length, and severity,[15,25,84,86] it is likely to be difficult for golf course managers to maintain turfgrass aesthetics and performance during drought periods,[34,35,68] particularly when combined with high summer temperatures.[68] Across the U.S., increased drought is expected to further limit water supplies and necessitate use restrictions within the golf industry as well as many other sectors (e.g., municipal and agricultural use),[34] which will potentially limit the ability to significantly increase turfgrass irrigation.

Increased Flooding and Storms

Extreme precipitation has increased significantly across the U.S. over the past several decades,[15,109,110] where the number of days with extreme precipitation has increased by 60% in the Northeast and 45% in the Midwest since the 1950s.[15] These changes are closely tied to corresponding increases in the frequency and intensity of flooding,[111,112] which, along with extreme precipitation events, is expected to continue increasing across all regions of the country but particularly in the eastern U.S. [15,21,113,114] (*high confidence in river flooding as a result of extreme precipitation, but moderate confidence for flooding more generally due to the number of other factors that contribute, including development policies and land surface processes*).[115]

Changes in the pattern of severe weather events such as thunderstorms and tornadoes are much more difficult to identify and attribute to large-scale climate changes, but there is some evidence that tornadoes have become more powerful[116] and that tornado activity has shifted eastward[117] and farther into the autumn.[118] In the central U.S., the frequency and duration of heavy rainfall associated with thunderstorm systems has increased since 1997,[119] and large hail has become more frequent in the central and eastern U.S. since 1979.[120] Hurricanes have shifted more clearly, with increases noted in hurricane activity in the North Atlantic[24] as well as increased rates of intensification[121] and slower movement[122] that results in greater flooding and associated damage.[17] Research suggests that some of these trends may be occurring for tropical cyclones as well, including heavier rainfall.[123] Taken together, these studies suggest that there may be overall trends toward more frequent and/or more severe storms, even as it is more difficult for scientists to track and accurately predict those changes (*low confidence for specific changes in different locations, but higher confidence in an overall trend towards more frequent and intense severe weather*).[15]

Within the survey associated with this project, 32% of respondents were concerned about changes in the frequency and severity of storms and their related impacts (e.g., wind, lightning, heavy rain, tornadoes, storm surge), and 27% of respondents were concerned about more frequent or severe flooding. In their comments, survey respondents mentioned observing reduced playability in low areas near water hazards and the need to close and repair holes due to flooding and erosion. A review of the literature did not reveal any studies in the peer-reviewed literature that specifically address the impact of climate-driven increases in extreme precipitation and flooding on golf course playing conditions or access, a gap that was also noted in the broader context of sporting events by Orr et al.[32] Regardless, the impact of more frequent and severe flooding and storms on golf courses is likely to cause significant impacts, which may include stress in turfgrass,[66,74] damage to course facilities, erosion and/or loss of access to portions of a course, and the need for shifts in events to ensure player safety.[32,77]

Stress and damage in turfgrass

Turfgrasses are vulnerable to flooding stress,[66,74,124] which is likely to increase in extent, severity, and duration under future climate conditions.[15,21,114] Flooding and associated sediment deposition reduces oxygen availability to the plants and causes a variety of physiological and morphological changes in turfgrasses (e.g., damage to cell membranes, decreased photosynthesis, changes in root surface area and volume), resulting in injury or mortality.[66,74,125,126] High water velocity during flood events can also cause direct damage to turfgrasses and increase soil erosion and debris.[127] As with other stressors, the impacts of flooding vary across species and cultivars, with some (e.g., seashore paspalum [*Paspalum vaginatum*], bermudagrass [*Cynodon dactylon*]) exhibiting considerable tolerance to flooding.[124–126,128] Flooding impacts can vary based on site-specific factors as well, such as soil type and temperature or topography.

Where climate change results in increased seasonal precipitation (e.g., springs become much wetter) or increases in extreme precipitation events, the impacts may become more apparent even for flood-tolerant species.[74] For example, areas of standing water or waterlogged soils that persist over unusually long periods of time can result in hypoxia and, eventually, mortality in most turfgrass species.[74] The impacts of flooding may also be more severe where they intersect with changes in other factors. For instance, studies have demonstrated that rapid increases in water temperature within shallow standing pools of water results in greater turfgrass injury and mortality.[127,129] Climate projections show significant temperature increases across the U.S.[15] as well as more severe heat waves.[28] This suggests that future flood events may be more likely to coincide with periods of warmer air temperatures, increasing the likelihood of turfgrass damage above what might occur under historically typical conditions.

Damage to course infrastructure and safety concerns

More frequent and severe storm events and associated impacts such as flooding and erosion can damage or destroy golf course facilities and

greenways,[77] which in turn forces closures to ensure player safety and allow time for repairs. A report published by the British Association for Sustainable Sport found that increased rainfall, together with a general trend towards more extreme weather, had caused course closures to become longer and more frequent.[39] Event delays and cancellations are also likely to become more frequent, and together these impacts can significantly lower course revenues.[77]

Sea Level Rise and Coastal Erosion

Golf courses are very common in tourist destinations along coastlines, which increases their exposure to sea level rise and associated impacts such as storm surge, coastal erosion, and saltwater intrusion.[11] Although the occurrence of sea level rise is a certainty, the rate at which sea levels will rise is uncertain. Current projections show average sea level rise across all U.S. coastlines will be in the range of 9 to 13 inches by 2050 (compared to 2020 levels), and that rates will accelerate in the second half of the century to over 2 feet by 2100 (*high confidence*).[18,130] However, sea level rise rates vary geographically and are expected to be higher on the Atlantic Coast compared to the Pacific, with the greatest amount of change likely occurring along the Gulf Coast.[18] Modeling of sea level rise rates for Hawai'i and the Caribbean is complex but tend to be somewhat lower than those along the Atlantic Coast.[18]

During hurricanes or other storm events, higher water levels as a result of sea level rise result in even higher storm surge and corresponding erosion of coastlines, and this trend is projected to continue to increase (*high confidence*).[18,131,132] When storm events coincide with high tides, or even seasonal king tides, water levels are even more extreme.[18] These impacts are a significant threat to coastal golf courses, leading to damage and loss to golf courses and access routes, as well as stress to turfgrass experiencing flooding and increased salinity.[132] While rising sea levels are occurring on a global scale, local and regional factors such as coastal land subsidence or uplift and surrounding land use can affect the amount of sea level rise and erosion that any given site experiences.

Within the survey associated with this report, 22% of respondents reported being concerned about the impacts of sea level rise and coastal erosion on golf, less than any other climate stressor in the list presented to them. This likely reflects the reality that many respondents are not located in coastal areas. One survey respondent Pennsylvania noted that they had already observed erosion of the coastlines on golf courses and were specifically concerned that holes would be lost in the future within those areas.

Course damage and loss

Coastal flooding and associated erosion can damage golf courses severely, requiring holes to be closed during recovery or even, in some cases, resulting in the permanent loss of holes in affected areas.[133] While relatively few peer-reviewed studies address this topic, many examples of affected golf courses are mentioned in online articles from various sources.[131–133] Several of these discuss sea level rise impacts that are already being felt by golf courses in low-lying coastal areas such as Charleston, South Carolina. Golf courses in Charleston are experiencing frequent flooding during high tides and storms, resulting in waterlogged soils and standing water that impacts play and can necessitate closing holes.[131,133] These observations are backed up by a 2020 study that found the frequency of nuisance tidal flooding on the Charleston peninsula increased 1,200% from 1950 to 2014 (from 2 days per year to 25 days). The tidal flooding is projected to more than double again by 2050, to 60 days per year, with the flooding also expected to increase in duration and extent.[134] Another example comes from New Orleans, where buildings and turfgrass in City Park golf courses were damaged following inundation by storm surge during Hurricane Katrina.[132]

The fixed layout of greens, tees, and fairways on golf courses creates a landscape that is incompatible with erosion and sand deposition,[11,133] which is challenging given the naturally dynamic nature of coastal landscapes. Under changing climate conditions, the pace and degree of change occurring in coastal environments is accelerating further.[11] Additionally, the placement of hard structures (e.g., levees, seawalls) meant to protect high-value areas from sea level rise tend to accelerate shoreline loss in adjacent areas, or result in more extreme impacts if they fail.[11] Similarly, the loss of protective coastal features (e.g.,

intact sand dunes) to sea level rise – or to development – can leave adjacent golf courses more vulnerable to flooding and erosion.[135]

Salinity stress in turfgrass

As sea level rise pushes saltwater farther inland, it seeps into freshwater aquifers where higher salinity can cause issues for turfgrasses on golf courses that rely on groundwater for irrigation.[136] Turfgrass can also experience salinity stress where storm surge inundates golf courses, such as after hurricanes.[132] In many areas, brackish water is already used for irrigation.[137] As drought impacts and population increases further stress freshwater supplies, golf course irrigation may make greater use of non-potable recycled or reclaimed water with even higher salt content, potentially resulting in salinity stress on turfgrasses.[136,138,139]

High salinity impacts both cool-season and warm-season turfgrasses by causing osmotic stress that results in limited water and nutrient uptake[36,139,140] and through ion toxicity.[139-142] These impacts impede turfgrass growth,[140,142,143] quality, and playability[144,145] and can cause tissue damage or mortality.[132,146] However, the degree of impact can vary depending on species, salt concentration, and length of exposure.[36,139,140] Impacts tend to be more extreme when combined with other stressors, such as heat or drought stress.[60,139]

Secondarily, high salinity can affect soil conditions, reducing soil structure, which results in more compaction-prone soils that impact plant growth and survival,[138,143,147] in addition to making surfaces firmer and less suitable for playing.[81]

Changes in Insects, Diseases, and Invasive Weeds

Climate changes such as warmer temperatures and shifts in precipitation patterns have strong impacts on the growth and development, reproduction, and survival of problematic organisms such as insect pests, pathogens/diseases, and non-native plants that function as invasive weeds within golf courses.[16,148] While impacts are species-specific, some overall trends include:

- Expansion in the range of problematic species due to factors such as milder winters, along with increased potential for the introduction and establishment of invasive insects, pathogens, and weeds[16,148];
- Increased prevalence of insect pests due to warmer temperatures that allow more reproductive cycles within a year and/or increased overwintering[35,149];
- Increased susceptibility of turfgrass to insects and disease as a result of heat or drought stress that weakens the plants[35,150-152];
- Increased problems with fungal diseases where warmer, wetter autumns and winters support spread[35,81]; and
- Potential increases in disease vectors such as ticks and mosquitoes, impacting player safety and enjoyment.[34,47]



Credit: USGA.

The first step to supporting the golf industry through climate change adaptation (i.e., preparing for or responding to the impacts of climate change) is carefully considering which climate changes are most likely to impact a particular area or topic of interest, whether this is a specific aspect of the industry or one or more golf courses in a specific location. The information in the previous section about vulnerabilities provides a foundation for that part of the process, which can be guided by an understanding of the changes that might occur in a particular region along with observations of changes that are already occurring or challenges that already exist and are likely to be exacerbated by future shifts in climate (e.g., areas with poor drainage are likely to be heavily impacted by even small increases in heavy precipitation). It is important to also consider areas where combinations of stressors may be more likely to co-occur than they have in recent history, as well as shifts in the zone where a particular type of event or range of conditions can be expected.

The next step, which is addressed in this section about adaptation, involves thinking through actions that might address those vulnerabilities, whether they are already occurring or expected to become more likely to occur in the future. The actions taken to reduce the impact of climate vulnerabilities or increase the ability of the site or site users to withstand the impacts of climate change are called **adaptation actions**. These generally fall into one of the following categories:

- Actions that people are already undertaking (e.g., BMPs that are routinely implemented on a golf course), but that will become even more critical to continue under future climate changes.
- Actions that people are already undertaking, but that may need to be shifted or altered (e.g., changing the timing, intensity, or location of a particular management action) to better address future climate conditions.
- Actions that have not historically been necessary, or were not a priority, but that will become important tools under future conditions. These can include larger efforts such as transitions in turfgrass varieties to better match changing conditions or relocating infrastructure away from areas that are becoming flooded more frequently.

The actions that will fall into each of these categories varies from course to course or topic to topic, and the process by which people undertaking adaptation identify the best actions to prioritize is an individual one. A wide range of factors must be considered including whether climate changes are already being felt and whether existing challenges unrelated to climate change may be exacerbated by future changes, along with issues of capacity, funding, political will, and public opinion, among others.

Ideally, undertaking climate change adaptation should become part of standard practice for a golf course. Operationalizing adaptation requires data, resources, monitoring techniques, and of course the organizational will to make it happen, which are described below:

- **Data** are needed to assess local climate vulnerabilities, including data about current conditions as well as relevant climate projections to understand how near- and long-term conditions are likely to change. This will allow managers to understand what changes need to be addressed through adaptation.
- **Monitoring** will be needed to assess the effectiveness of adaptation actions undertaken to lessen climate impacts, as well as monitor conditions that have not been addressed through adaptation actions. This will allow for adjustment of strategies as conditions change over time.

- **Resources** (e.g., funding, technical assistance) are often necessary to implement adaptation, although they do not have to be immense. Ensuring that existing resources are not being used for efforts that will result in unsuccessful outcomes is key.
- **Organizational will** should not be undervalued. Being committed to considering climate change as part of standard operational approach allows for more complete integration of adaptation across all aspects of golf management. Undertaking adaptation in a piecemeal manner is less likely to lead to successful outcomes.

Survey Respondent Views on Climate Change Adaptation

The current level of organizational willingness to undertake adaptation for the golf industry can be explored in the responses to the survey undertaken as part of this project. Survey results indicate that overall, there is a need to increase awareness, understanding, and action in addressing the impacts of climate change on golf. In the survey we learned that:

Adaptation is not being widely discussed. Only 32% of respondents indicated that adaptation was being discussed moderately or widely (Figure 13).

Adaptation strategies are not being widely implemented, formally or informally. Only 20% of respondents have observed or engaged in informal adaptation, such as going to earlier tee times or seeking out air conditioning. Only 13% have observed or engaged in formal adaptation, such as "Late Mow May", use of different turfgrass strains, irrigation and stormwater infrastructure modification, extended hours (open earlier, closing later), or adding temporary greens (Figure 14).

More than 60% of respondents have not observed or engaged in adaptation informal strategies, and more than 70% have not observed or engaged in formal adaptation strategies.

There are many perceived potential barriers to adaptation in golf. These barriers include perceived lack of funds (53%), conflicting user expectations (49%), lack of staff time or capacity (40%), lack of public support for climate adaptation mandates (35%), lack of public support or concern in general (33%), more pressing concerns (27%), lack of access

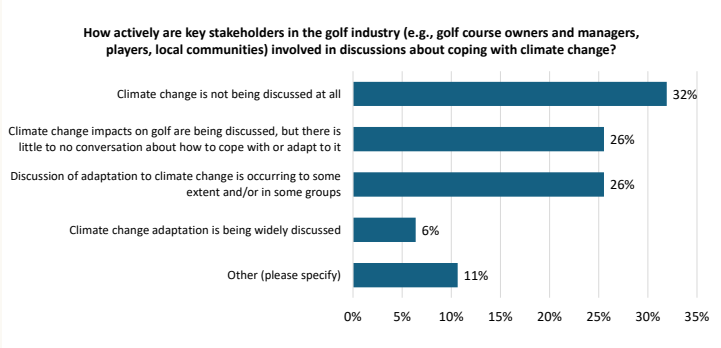


Figure 13. Extent to which climate adaptation is being discussed by key stakeholders within the golf industry.

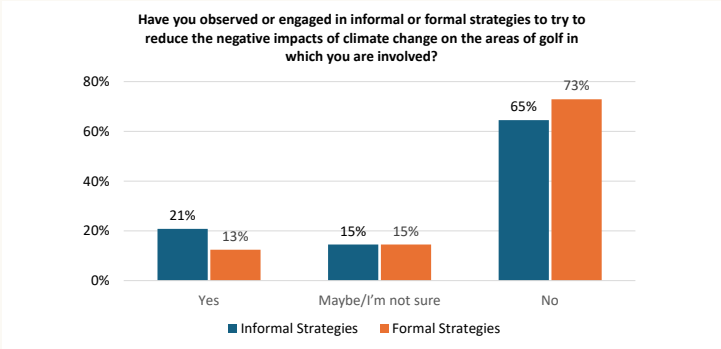


Figure 14. Observations of informal or format strategies to adapt to the impacts of climate change on golf.

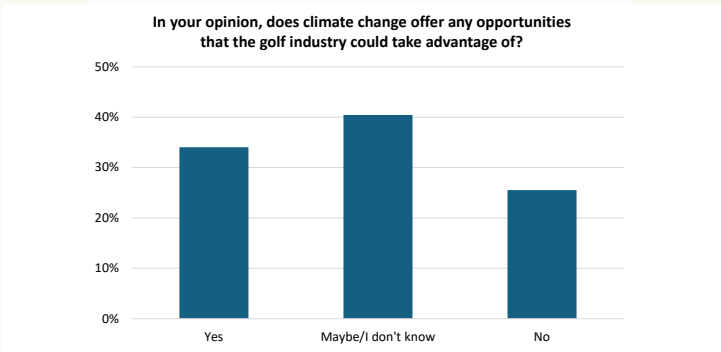


Figure 15. Survey respondent opinions about whether climate changes could offer opportunities that the golf industry could take advantage of.

to data or technical knowledge (27%), and existing state or local policies (16%). Finally, 18% of respondents indicated that there were no barriers. Some specific concerns mentioned included funding, such as the need for additional maintenance funds. This especially applies to courses that already have inadequate funds. Other concerns are that funding adaptation will reduce funds for staff and result in fewer staff or lower pay; the potential that if an adaptation action is not effective, funds will have been wasted; and that players be asked to adapt or courses close periodically to accommodate adaptation.

There was also concern that too many people ignore or deny climate change. Evidence to support this point is found in some of the respondent survey comments stating that they do not think climate change is happening, and perhaps the 24% of respondents that indicated they were "not at all concerned" about climate change (broadly speaking, not just in relation to golf).

It is not clear to respondents if climate change will offer any opportunities for golf. Respondents were fairly well split between feeling that there are not opportunities (25%), there are opportunities (34%), or they are not certain if there are opportunities (40%) (Figure 15).

Those that did think there were opportunities saw regional benefits (e.g., longer playing season in the northeastern U.S.), reductions in expectations around maintaining playing surface conditions in rough areas that allow mixed use of courses (e.g., walking trails, wildlife habitat), addition of splash areas for cooling that would attract more family players, transfer of turfgrass management innovations to other lawn applications (e.g., homeowners, parks), promotion of historic "heathland" style courses with seasonal browning, reductions in water and chemical use, promotion of golf as an alternative to lost skiing seasons, and the potential for golf courses to be seen as part of the solution to climate change (e.g., reduction of heat islands, wildlife habitat). Respondents did remark that some adaptation actions may be easier to implement, such as turfgrass and irrigation regime changes.

The survey also shared some insight about the perception of resource availability for undertaking climate adaptation within golf. **Respondents did identify existing structures in golf to support adaptation**. Although 38% of respondents did not believe there were factors to support adaptation in golf, many factors were identified by others. Counter to identified barriers, some respondents see sufficient funds (18%), sufficient staff capacity (20%), and sufficient data and technical knowledge (24%). Twenty-four percent thought engaged communities who were aware and supportive of action could benefit the effort to adapt golf courses, along with the existence of supportive businesses and other local organizations (24%). State and local policies (18%) and local elected officials (11%) were also seen as enabling factors. Specific ideas shared by respondents to leverage existing structures included integrating climate change into water quality improvement projects in planned capital investments, highlighting the health benefits of being outdoors in greenspace that is reducing heat islands, golf's ability to support lifelong multi-generational engagement, the potential for early adaptation action to increase future affordability and playability as a business case, engaging professional tours in conversation about the need for adaptation, and that communication and awareness raising in the golf community increases acceptance of the need for action.

Reducing Golf's Vulnerabilities to Climate Change

A wide range of adaptation strategies are needed to address climate change, and successful adaptation will require implementation at different levels.

Site-level adaptation are actions that will be implemented by course managers either within the scope of existing operations or in conjunction with adjacent jurisdictions (e.g., a municipality or water management district) that oversee resources or infrastructure upon which the course relies. Site adaptation includes everything from course maintenance (e.g., vegetation, irrigation) to visitor infrastructure (e.g., clubhouse, carts, trails, power sources) and governance (e.g., capital investment, board).

Individual or user adaptation are largely behavioral shifts for both local course visitors and tourists. These can include shifts in course use timing, on-course behavior and equipment needs, and possible geographic preference changes. This may require efforts to educate users, including tourists, by providing guidance on shifting climatic conditions (e.g., earlier tee times, increased hydration, ideal vacation timing to avoid extreme weather events).[153]

Landscape-level adaptation includes actions that are needed to support continued golf course function but require action at a larger scale or in another location. For example, actions to address flooding often require regional efforts to slow water flow, increase water retention, or optimize recharge in appropriate off-site locations. It is unlikely that limiting actions to the course alone will achieve the scale of effect required, particularly in addressing issues related to course access via potentially vulnerable roads. Therefore, golf course managers may benefit from collaborating with neighbors, surrounding jurisdictions, and other resource managers to participate in regional plans.

The following information complements the previous section on climate change vulnerabilities relevant for golf by briefly illustrating some of the types of adaptation actions that could be implemented to reduce those vulnerabilities. Many of the actions mentioned below are already being undertaken, at least in some areas, and the examples presented here are not meant to imply that these are novel ideas. Rather, they are intended to prompt consideration of (a) which current management actions might play an even more important role under future climate conditions; (b) whether some of those might need to be shifted in terms of timing, location, etc. to better respond to conditions that do not match those of the recent past; and (c) whether there are new actions that have not previously been necessary in a particular area but may become so in the future. The examples presented here are focused primarily on management actions that are specifically being used within the context of climate change adaptation in at least some areas. They represent a small subset of the myriad possibilities for adaptation that exist within the golf industry and should be used as a starting point for deeper discussion and exploration.

Warmer Temperatures and Increased Extreme Heat

Projected increases in average temperatures and the frequency, intensity, and duration of extreme heat events are expected to affect golf courses by influencing turfgrass performance, water demand, player health and safety, and the timing and safety of play.[15,28,30–33,35,36] Warmer temperatures and extreme heat can also intensify other climate stressors by increasing evapotranspiration, reducing soil moisture, and contributing to broader landscape-level risks (e.g., water scarcity and wildfire).[15,26,37] Rising average temperatures and the earlier onset of extreme heat in spring may reduce germination success in cool-season turfgrasses[154] and lengthen the growing season, which would require more frequent mowing into autumn and winter.[16] Required additional maintenance traffic may contribute to soil compaction, which can create drainage issues and damage turf quality.[16] Rising temperatures are likely to make cool-season grasses less viable in some areas, potentially prompting a transition toward warm-season or more heat-tolerant species, especially in warmer regions.[35] Higher temperatures and water stress will increase abiotic (heat, drought) and biotic (pests, diseases) pressures, meaning turf systems will require more adaptive, responsive management approaches.[35]

Site-level adaptation for heat

The selection and management of turfgrass species and cultivars for stress tolerance is a highly covered topic in the literature, with much focus on heat stress. Researchers have used a range of testing and monitoring methods to identify turfgrasses that better withstand increasing heat stress (e.g., identifying genetic markers associated with heat tolerance traits, experimenting with new varieties).[155–158] It will be important for golf course managers to consider the temperature range that is expected in the future when selecting turfgrass varieties, including periods of extreme heat in the summer and warmer winter temperatures that can cause grasses to de-harden. Managers should also consider how warmer temperatures might interact with other stressors that may occur, such as changes in pest distribution or more frequent flooding, and prioritize species or cultivars more likely to be tolerant to those combined stressors. In some areas, changes in temperature may make a transition from cool-season to warm-season turfgrass appropriate, potentially also reducing maintenance requirements and water usage.[68,159] In locations experiencing periods of unusually warm winter temperatures, it may become increasingly necessary to monitor conditions and protect turfgrass from winter injury.[160] Other management practices that may become tools for heat adaptation include shifts in irrigation timing or frequency to help maintain turf health and quality,[161] or the use of exogenous treatments (spraying or foliar application) to support turfgrass heat tolerance.[58,61,65,66,162–167] Course managers may also consider creating or expanding cooling infrastructure for players such as rehydration facilities, shaded rest stations and air-conditioned clubhouses, as well as heat-response medical areas during tournaments or on extreme heat days.[168,169]

A range of planning and decision support tools are available to help course managers prepare for extreme heat events and better understand their potential impacts. Managers may benefit from resources that help them anticipate when heat risk will rise, identify where people and turf are most exposed, and translate those insights into operational adjustments or recommendations. Planning and educational tools, such as the National Oceanic and Atmospheric Administration (NOAA) Climate Explorer (https://crt-climate-explorer.nemac.org), can help managers explore historical conditions and extreme heat projections. Tools such as Heat.gov can support preparedness, communication, and decision-making around dangerous heat conditions, including heat-related health risks that may affect course operations, staff, and users.

Individual and user behavior adaptation for heat

Extreme heat events may pose health and safety risks for both course staff and users and reduce player activity. Adjusting tee times to provide more options for early morning or evening play, limiting play during peak heat periods, and encouraging flexible scheduling for maintenance could reduce heat exposure for players and golf course staff.[31,32,169] Players may increase use of carts rather than walking, and fans could be added to golf carts for cooling. Course managers can also modify staffing practices by shifting work that requires staff to be outside during the cooler parts of the day and adapting seasonal employment periods to reflect changing temperature and use patterns. Staff breaks could be increased or modified during extreme heat events.[169] These measures can help maintain safe play and working conditions while allowing courses to continue operating under increasingly hot periods.

Courses that usually employ fewer staff during the winter due to course closures or limited player demand may need to increase staffing during this time to support operations as temperatures warm and demand for course use increases.[31]

Landscape-level adaptation for heat

Large vegetated areas within golf courses (e.g., greens, fairways, roughs, clusters of trees) may help reduce land surface temperatures and provide a cooling effect for surrounding areas.[12,170–173] Large green spaces such as golf courses can support biodiversity, provide habitat for wildlife, enhance habitat connectivity, and contribute to additional ecosystem services.[8,174] There are also opportunities for golf courses within a larger municipal landscape to align with local adaptation efforts. Proactive engagement with local government officials may position public courses to have access to funding, regulatory support, and collaborative

opportunities for larger-scale design that maximize the potential cooling benefits of courses as well as ecosystem services they may be able to provide, within and beyond course boundaries.[12,175,176]

Changes in the Amount and/or Seasonality of Precipitation

Changes in precipitation, including changes in the amount and seasonal distribution of rain and snow, pose challenges for golf course water management, turf health, course operations, and playing conditions.[35,81] Increasing variability between excessively wet and dry periods may result in soil moisture conditions less favorable to turfgrass growth and could require adjustments to existing management practices, including irrigation, drainage, and course maintenance, which could increase staffing needs and operational costs.[82] These changes may also cause reduced play due to green closures, which would impact course revenue.[81]

Adaptation strategies related to shifts in precipitation amount, timing, and seasonality are relevant to addressing both water scarcity and excess water management and are discussed in subsequent sections on **Increased Drought** and **Increased Flooding and Storms**.

Increased Drought

Projected increases in drought frequency, severity, and duration will impact golf courses by reducing water availability, increasing irrigation demand, elevating maintenance costs, and placing constraints on the ability to maintain turfgrass quality.[15,25,34,84,86] Drought conditions can intensify existing water scarcity challenges, particularly where golf course irrigation competes with surrounding municipalities and agricultural land during periods of limited supply.[34,36,96] Reduced soil moisture associated with drought can impair turfgrass growth, appearance, and survival and contribute to wilting, discoloration, and loss of quality.[68,104,105,160,177,178] These impacts are likely to be amplified when drought occurs alongside high temperatures, thus placing additional stress on turfgrass and course operability and making management practices focused on water conservation[179] even more critical.[34,68]

Site-level adaptation for drought

Site-level adaptation for golf courses can include a wide range of strategies designed to reduce water use or increase water availability. In some areas, it may become increasingly desirable to replace high-water-demand or drought-sensitive turfgrasses with those better suited to drier conditions,[97,180] which would reduce irrigation requirements.[170,181] Species selection should consider combined heat-drought stress, as hotter dry seasons are expected to increase irrigation demand in many regions.[137,182] Cross-breeding turfgrass species has already improved drought tolerance and could continue to do so, along with resistance to other stressors such as pests or diseases.[183–186]

Site-specific, response-based irrigation using soil moisture, evapotranspiration, and spatial variability data can help to manage water use[187–189], particularly as climate conditions diverge from historical patterns. Spatial mapping with handheld sensors, in-ground sensors, drone imagery, or remote sensing can help identify management zones, although some studies indicate that these areas may require reassessment and data collection that can be time-consuming, potentially straining staff capacity.[187,189,190] Further diversifying water supplies by expanding to additional sources not already in use on a given course, such as recycled water, harvested water, storage ponds, and reuse systems, may also help support course adaptation to drought conditions.[94,97] Alternative water supplies, however, may have tradeoffs that have to be weighed against the potential benefits (e.g., higher salinity)[97,191].

Non-play areas present an opportunity to replace existing plants with native, drought-tolerant vegetation that can reduce irrigation demand and support wildlife habitat.[97,192] A case example in Scottsdale, Arizona, found that in a dry desert environment, a course with 64% naturalized landscape saved 40 to 50 million gallons of water per year.[97] On urban golf courses, boundary and remnant habitats exhibit higher species presence and diversity compared to frequently played areas.[193]

Tools such as NOAA's National Integrated Drought Information System (www.drought.gov) can help golf course managers understand drought risk and

severity to inform irrigation scheduling, drought contingency planning, and decision-making about when to reduce water use.

Individual and user behavior adaptation for drought

Managing golfer expectations can be considered an adaptation strategy. For example, promoting public acceptance of areas where turf quality is reduced but playability is maintained can allow more limited irrigation while preserving player experience. In some areas, outreach campaigns are being used to educate golfers about water conservation, shift expectations, and increase buy-in for adaptation initiatives that support turf survival and playability.[181] Private courses can at times face additional pressure to maintain particular standards due to higher membership fees that increase expectations about course appearance and quality.[181,194]

Managing course access during periods of drought is another tool that can be used to adapt to increased drought. For instance, thresholds at which golf cart use and/or play is limited or redirected away from vulnerable areas may need to be shifted as severe drought becomes more frequent. Temporary restrictions have the potential to reduce stress on turfgrass, which supports survival and recovery.

Landscape-level adaptation for drought

Golf courses can account for a meaningful share of local water demand[92], and their water needs tend to rise under hotter and drier conditions[34]. This makes them relevant to broader regional drought planning and water allocation decisions.[176,194] Integrating courses into municipal drought planning and water governance, rather than treating them as isolated entities, may support water conservation and course management under changing climate conditions.

Increased Flooding and Storms

Increased flooding and more extreme weather events can result in course inundation, soil erosion, and blanketing sedimentation. All of this can stress turfgrasses, which can be further exacerbated by co-occurring higher temperatures.[127] Additionally, flooding and storms can damage course infrastructure (e.g., buildings, paths, fairways, greens) and threaten player safety, necessitating closures and cancellations.[40]

Site-level adaptation for flooding

Course managers can use flood maps, such as the Federal Emergency Management Administration (FEMA) Flood Maps (https://msc.fema.gov/portal/home), and seasonal flood forecasts to identify at-risk areas, both on the course and in adjacent areas that may include vital infrastructure that support the course or access to it. Although FEMA flood maps are based on historical data and do not utilize projections of future flooding, tools such as NOAA's Climate Resilience Information System (https://cris.climate.gov/) can provide this information as it relates to future changes in precipitation patterns, including the type of heavy precipitation that leads to flooding.

Site-level management actions that are also being used as flooding adaptation tools often focus on designing courses for both infiltration (into soils and groundwater) and surface drainage to prevent damage to turfgrass and course infrastructure. Overall, ensuring good drainage within the "everyday" functioning of a golf course will become an even more critical consideration in the future, and these standardized practices serve as adaptation actions that will help courses withstand increasingly frequent and severe flood events. It is likely to become increasingly necessary to design drainage systems to withstand storms with a return interval of 100 years or greater (i.e., a 100-year storm), which is significantly more than the 25- to 50-year storm return interval that many golf courses currently use as a benchmark.[195] Floodwater storage can also be enhanced (e.g., by creating swales or through existing waterbodies[195]) to better accommodate the expected increases in floodwater volume throughout much of the U.S., while also filtering runoff1[96-198] and providing wildlife habitat.[82,170,199] Management practices to reduce erosion are likely to become more critical in the context of climate change and may need to be expanded or supplemented in some locations.

In regions of the U.S. where flooding is likely to become much more frequent, golf course managers could consider whether it makes sense to shift towards more flood-tolerant turfgrass varieties.[35] Trees or shrubs can also be strategically planted to

slow and take up stormwater[171,183] and can contribute to a reduction in soil erosion, especially in riparian buffers.[81,200,201] In frequently flooded areas, it may become necessary, now or in the future, to reengineer a grade or move a hole or other course infrastructure (e.g., trails, buildings). In some extreme cases where a course or course access is in a floodplain, the course may eventually need to operate seasonally or be entirely relocated.

Individual and user behavior adaptation for flooding

Increased weather unpredictability as the climate changes is likely to affect player participation. Local golfers may need to adjust when and where they play to avoid more frequent bad weather days and courses or access roads that have been damaged by flooding or storm events. Patterns in golf tourism may shift as well, with tourists increasingly avoiding locations and seasons with a greater risk of climate-driven storm events.[40] Risk reduction measures such as offering travel insurance or flexible reservations might help ameliorate some of the impacts on revenue. The creation of systems that communicate extreme weather and seasonal climate forecasts could also help better inform golfers planning a trip.[153]

Unpredictable weather will also affect participation in golf tournaments and other golf course events, which could require cancellations, rescheduling, or relocation.

Landscape-level adaptation for flooding

Significant flooding events will be more than a course-level concern, as they are likely to affect the broader region. As a result, golf courses should be included in regional stormwater and water management planning efforts. This will ensure course interests are represented and also provide the opportunity to consider how the course can contribute to solving a regional problem (e.g., by providing water retention space), given the many regional assets (e.g., transportation, water and wastewater systems, housing) needed to support a golf course and its staff.

Sea Level Rise and Coastal Erosion

Given the certainty associated with the processes related to sea level rise, it is not a question of whether it will happen but rather how quickly and to what extent. Adaptation actions to address the impacts of sea level rise include those focused on storm surge and coastal flooding, erosion, and saltwater intrusion.

Site-level adaptation for sea level rise

The first step in developing an adaptation strategy for sea level rise is understanding the anticipated extent of sea level rise for a given location. Climate Central's Surging Seas Risk Finder (https://riskfinder.climatecentral.org/) provides local assessments of expected sea level rise, assessment of risk, and map visualizations. Tools such as these allow users to understand how an asset such as a golf course and the resources upon which it relies (e.g., transportation, utilities, services) will be affected by sea level rise. Some areas that have not historically been concerned with saltwater intrusion may need to begin monitoring and addressing that impact as well, particularly where factors such as drought or aquifer overdraft are accelerating the process.

Sea walls and levees are sometimes considered early in the process of addressing sea level rise. However, sea walls and other coastal armoring structures accelerate shoreline erosion on neighboring properties and risk critical failures that cause flooding if they are overtopped by storm surge or trap rainwater behind them. Additionally, most sea walls will eventually fail as sea levels continue to rise, erosion undermines them, or saltwater intrusion through soils bypasses them.

Adaptation actions that may be more appropriate for coastal golf courses include creating or expanding wetlands that can divert rising sea water and stormwater from heavy rain events to prevent harm to other areas on the course and in the surrounding landscape.[202] Coastlines on or adjacent to golf courses can also be redesigned as living shoreline, where coastal vegetation (e.g., salt marsh grasses) and/or offshore elements (e.g., oyster beds) are used to reduce wave action. Ideally, living shorelines have the potential to shift inland over time, resulting in a slow loss of upland areas but continued protection from storm surge that causes significant flooding and erosion. In some high-risk areas, it may become increasingly necessary, or even desirable, to modify or relocate vulnerable elements of golf courses (e.g.,

holes, buildings, roadways) to avoid areas that are frequently inundated. Temporary closures may also be required, particularly where these modifications are not possible, and permanent closures of holes, buildings, or even entire courses might become necessary over longer time scales. However, planning for the impacts of sea level rise now will help to minimize permanent losses.

For golf courses that have already experienced repeated flooding, managers should consider transition to flood- and salinity-tolerant turfgrasses.

Intentional overwatering with freshwater has the potential shown to help protect courses from saltwater intrusion by recharging the underlying aquifer.[203] The increased soil permeability of golf courses compared to other development allows for greater aquifer recharge rates,[204] which makes overwatering on golf courses a potential benefit for those beyond the course perimeter who rely on that same aquifer. This method has been proposed and modeled for many golf courses across the country,[13,203] though it may become more complicated by more severe declines in the availability of fresh water under changing climate conditions.

Individual and user behavior adaptation for sea level rise

Sea level rise occurs gradually, making it less of a sudden event (with the exception of a king tide or storm surge that extends much farther than expected as a result of the added effect of sea level rise). Over time, golfers will likely begin to recognize that a favorite course is frequently compromised or a different route is often required to access the course. Long-term changes in player behavior will most likely involve finding new courses where access is more predictable.

Landscape-level adaptation for sea level rise

As mentioned above, overwatering golf courses can help to slow or ameliorate saltwater intrusion into aquifers,[203] benefitting the water supplies of the larger community that is also being impacted. Wetlands and other water features on golf courses can also hold or divert floodwaters, which will reduce flood damage in adjacent or inland areas.[202]

Insects, Diseases, and Invasive Weeds

The major climate driver of disease, pests, and invasive weeds is a milder winter, which is not something course managers can address directly. However, the effects of other climate stressors (heat, drought, waterlogging) that exacerbate the prevalence of these problematic species can be reduced (see previous sections) as an adaptation measure.[205] Another approach, building on theories of natural ecosystem management of golf courses, focuses on supporting more native vegetation in rough areas to yield a more diverse system that can reduce disease spread, harbor fewer pests (or host their predators),[206] and allow fewer invasive weeds to establish.

An increased prevalence of ticks and mosquitoes may require modifications to player clothing and/or playing time.

The contribution of golf courses to community and regional adaptation

The value of golf courses as part of the adaptation solution set for communities and nature should not be overlooked, as they have the potential to help reduce the impacts of climate change for those around them.[16] Many of their potential adaptation benefits are already well-known from previous explorations of the environmental benefits of golf courses[207]: For example:

- As significantly-sized green spaces in or adjacent to urban and suburban communities,[13] golf courses can **reduce local warming**[208] and have the potential to improve air quality.[209]
- Courses can play a role in community **flood management** by providing space for water to be held and filtered during and after flood events.[210,211]
- Some course elements can be part of a **water storage** plan for use during periods of drought.[211]
- Golf courses can play an important role in **improving habitat connectivity** for plants and animals moving across the landscape in response to climate stressors.

Golf courses are well-positioned to engage in elements of regional adaptation planning[202] related to open space, ecosystem services, habitat conservation for native species, and development of broad consortiums of partners (as described below).

Open Space. Golf courses are generally large green spaces nested within more developed areas and can play a role in protecting open space across the landscape by being more resistant to development pressure than other types of green space.[212] Vegetated oases such as these provide connectivity corridors that link habitat patches for native species (e.g., birds, insects, amphibians, mammals), acting as migratory stepping stones that serve a purpose similar to hummingbird feeders. An unexpected potential benefit of golf courses is that they may serve as fire breaks and reduce fire risk for neighboring infrastructure.[171] Perhaps most importantly, golf courses already have passionate advocates who can be allies in protecting these locations for the long term.

Ecosystem Services. Open space from golf courses can support many ecosystem services, including but not limited to the following:

- *Groundwater recharge*. In urban settings where impermeable surfaces are prevalent, increased soil permeability associated with turfgrasses can help recharge groundwater tables[204] and can protect coastal aquifers from saltwater intrusion,[203] which enhances water security under future climate scenarios.
- *Riparian protection*. While golf course development can cause erosion and sedimentation, once established they can reduce streambank erosion and sedimentation.[213] Course landscaping that promotes riparian vegetation can further benefit stream and river systems.
- *Water holding capacity (storage, flood diversion)*. Turfgrasses hold water during storm events,[214] reducing surface runoff.[171] Given the size of golf courses, they have the potential to hold significant amounts of water. Additionally, trees and other golf course vegetation can add to this absorption.
- *Water filtration (where BMPs are used)*. Turfgrasses can filter surface water and enhance groundwater quality.[215]

- *Temperature regulation (shade, evaporation).* Golf courses, especially in urban or agricultural locations, can act as microclimate oases due to shade and evaporation provided by vegetation that can reduce regional temperatures. Maintaining or adding shade trees and water features on golf courses can increase this effect.
- *Air filtration.* Golf courses, especially where they are vegetated oases, can play an important role in filtering pollutants and particulates from the air, which improves air quality.[209]
- *Pollination support.* Golf courses can provide habitat to support regional pollinator populations for neighboring landscaping and agriculture,[206,216] particularly where native plants are emphasized.

The potential for golf courses to support ecosystem services is exemplified in the "triple play" approach of water management (filtration, holding, infiltration), species support (habitat and food sources), and natural aesthetics at the Palmer Hills Golf Course in Bettendorf, Iowa (Appendix A). At Palmer Hills, a stormwater pond and the riparian zone along Stafford Creek, which runs through the course, are managed to capture, slow, and filter runoff from nearby roads, parking lots, and neighborhoods. These features help reduce flooding on the course and minimize pooling on fairways and greens after heavy precipitation events, which would impact the accessibility and playability of certain holes on the course. Management prioritizes planting native species in the shoreline and riparian buffer zones to enhance water quality while supporting habitat and food sources for the herons and aquatic species frequently observed there.

Habitat conservation. The potential for golf courses to be part of habitat conservation (terrestrial and aquatic) should not be overlooked. Habitat loss has been a longstanding challenge, but climate change is exacerbating the impacts further. Climate stressors (e.g., drought, flooding, wildfire, sea level rise) and human responses to the changes (such as the construction of sea walls or increases in water demand) are further degrading habitat. Golf courses have the potential to provide consistent habitat for native species in a changing landscape.[8] For example, courses can be designed to support amphibians such as frogs and salamanders by ensuring consistent water supplies and including trees that provide refuge from high temperatures (Figure 16).[217]

Prioritizing connection of course water elements with natural aquatic systems (e.g., streams, estuaries) can further support use by native species.[218] Ensuring very limited application of chemical fertilizers, herbicides, and pesticides through the use of BMPs further increase the value of golf courses as habitat for native plants, birds, and insects.[219,220] For some species, golf courses have the potential to provide benefits similar to protected areas,[221] and, given their high degree of management (e.g., irrigation and other maintenance of vegetation and water elements), they could serve as local refugia in locations where surrounding areas experience more extreme impacts of climate change. In many areas, there is considerable interest in using golf courses for conservation goals,[222,223] and there is also opportunity to use them for planning regional adaptation.[224]

Expanded partner base. There are opportunities within the golf community to increase interest and action around climate change adaptation, and golfers are passionate advocates to maintain the activity. Where golf course management can be recruited as adaptation partners within a community or region, there is the potential for long-term, enthusiastic cooperation. Solutions that support the persistence of golf courses and also enhance ecosystem services and species conservation under changing climate conditions are particularly good opportunities to explore collaboration. Approaches that can develop such a partnership also expand the political base for successful climate action.

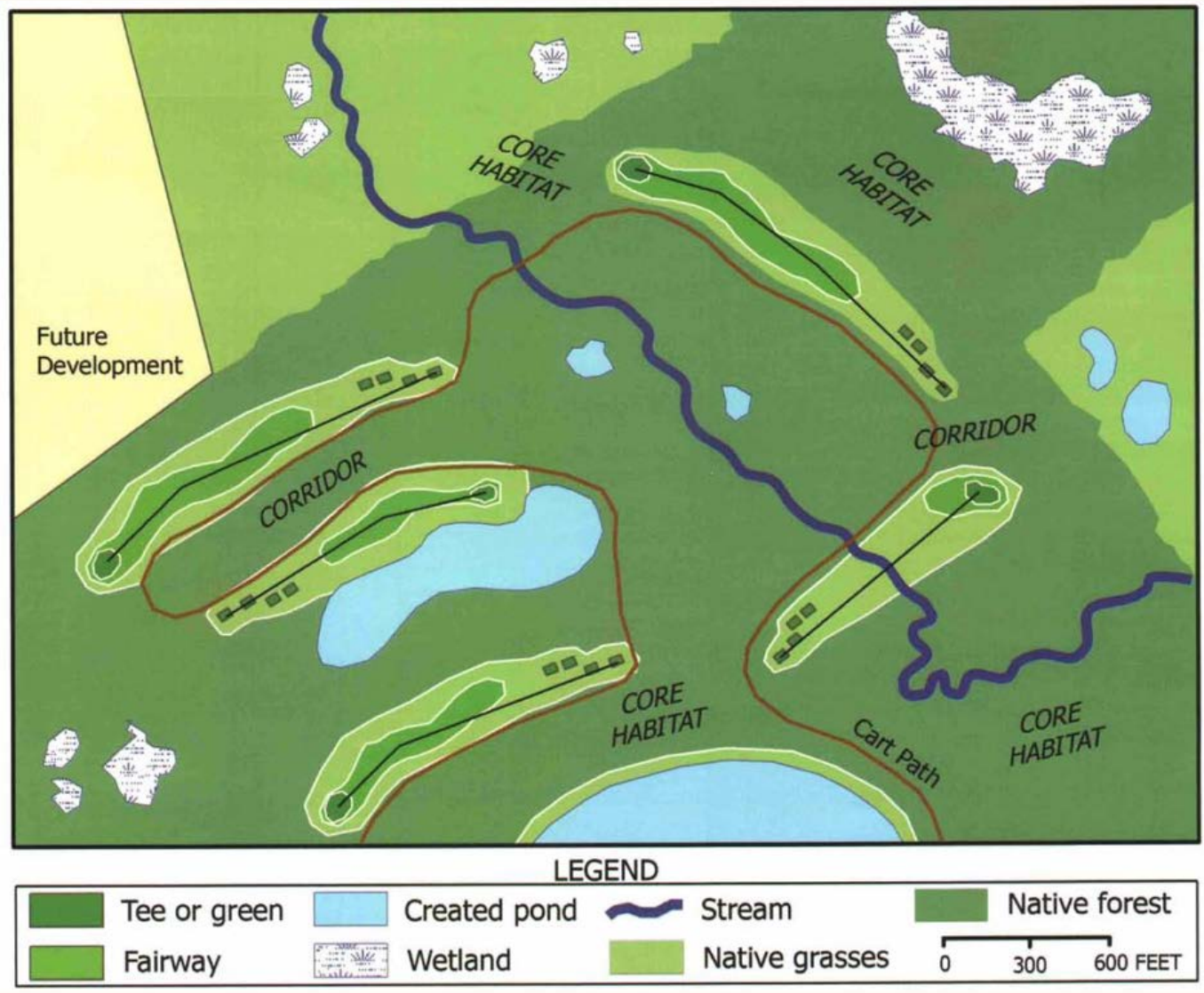


Figure 16. Example course design to support amphibian populations. Figure from Semlitsch et al. 2007.[217]

Adaptation Challenges

Climate change adaptation within the golf industry can be impeded by institutional capacity and staffing constraints; funding and cost justification; aesthetic expectations; and engineering, permitting, and operational feasibility.

One of the most common challenges is institutional capacity, as many courses operate with limited staff time and the planning and implementation of adaptation efforts must compete with routine maintenance demands and other operational priorities. Staff turnover; the need for coordination amongst managers, boards, and other stakeholders; and the time required for project design and approval can also slow action. Even when a course recognizes the need to adapt, limited workforce capacity can make it difficult to plan, implement, and sustain new initiatives over time. This has been the case for National Links Trust in Washington, D.C., an organization working to advance resilience on three area golf courses. The Trust has found staff capacity to be one of the major constraints to their work, as people are already managing extensive day-to-day responsibilities, and it is difficult to add the implementation of adaptation strategies on top of their existing workload. To help address the issue, they are trying to make sure that new initiatives are designed to improve efficiency, save resources, or create operational capacity (Appendix A).

Financial constraints can also hinder progress toward adaptation. Adaptation strategies such as irrigation upgrades, drainage improvements, turfgrass conversion, alternative water sources, and expanded monitoring systems can be costly.[34,225] Superintendents and managers will need to justify these costs to boards, membership, or owners, particularly when results or benefits will take a long time to be fully realized. Ongoing expenses, including maintenance, equipment replacement, staff training, and consultant support, can add additional costs to already constrained budgets.

Golf course users often expect green turf, predictable playing conditions, and a consistent course experience. As a result, adaptation efforts that visibly alter turf conditions, change course features, affect scheduling and playability, or require temporary or permanent closures may face resistance. Public perceptions also play a large role in shaping support for management decisions and interventions related to nature and conservation.[222,226] Golfers' preexisting attitudes toward nature and the environment may influence the extent to which adaptation measures are implemented, layering additional challenges on top of factors such as finances, capacity, and technical feasibility. However, strategic communication that explains the rationale for these actions, as well as the benefits and trade-offs (short- and long-term), may help build support for adaptation.[97] At the La Rinconada County Club in La Gatos, California, course leadership launched a six-month outreach campaign to increase support for their climate adaptation interventions, which include transition to drought-tolerant turfgrass. Their strategic communication about the benefits of the plans together with their efforts to address member concerns about the changes enabled them to gain the votes of 73% of the membership in favor of their comprehensive renovation plan. As a result, they were able to use membership fees to fund turfgrass conversion and upgrades to maintenance facilities (Appendix A).

Ultimately, the feasibility of any adaptation strategy is context dependent. Golf courses contain various landscape elements (tees, greens, water features, roughs, and natural areas) that serve different functions and require different management approaches. Engineering limitations, permitting requirements, site design, and competing objectives across the course can all restrict what is realistically achievable. This has been a challenge faced by the Kittansett Club in Marion, Massachusetts, where efforts to address sea level rise have required collaborating with the town Conservation Commission, finding and partnering with local experts, accessing the necessary technology, and ensuring staff capacity for the required planning and coordination (Appendix A). Over time, increased research on the impacts of climate change in the golf industry, and on the adaptation strategies that effectively address those impacts, will be an important tool to support action.[16]



Credit: Bryce Wendler on Unplash.

Future Opportunities for Adaptation

The effects of climate change are already being experienced by golf courses across the U.S. and additional impacts are projected in the coming decades; and as a result, climate change is not something that can be ignored. However, there are opportunities for golf courses to prepare themselves for the impacts of climate change as well as to be part of regional adaptation planning efforts relating to drought, flooding, extreme weather, sea level rise, and increasing temperatures.

While there are many approaches that can be taken to respond to and prepare for climate change, it can be daunting to start for those who have never undertaken such an effort previously. The following are a few entry points to begin the process of identifying and planning for adaptation.

Conduct your own course vulnerability assessment

This report provides overviews of the types of vulnerabilities that a golf course may experience due to climate change, but it cannot tell anyone which ones will be relevant for their location. While it is useful to start with the general introduction provided here and begin to apply that knowledge to course decision-making, there could be added value in undertaking a vulnerability assessment focused on a specific course to ensure that all of the relevant climate hazards are being considered and understand the magnitude of change projected for the site. Such an effort can be undertaken using the data tools highlighted in each of the sections above (e.g., FEMA Flood Maps, NOAA's Climate Explorer or Climate Resilience Information System, Heat.gov, NOAA's National Integrated Drought Information System, Climate Central's Surging Seas Risk Finder), along with a vulnerability assessment process such as the Rapid Vulnerability and Adaptation Tool (RVAT) or the Climate Change Adaptation Certification Tool. A vulnerability assessment is an important step for understanding the full range of potential climate impacts that may affect a particular course prior to the development of an adaptation plan.

Create and implement climate-informed plans

The findings of your vulnerability assessment help with the development of an adaptation plan, which can remain independent or be integrated into a course management or capital investment plans. Effective adaptation plans contain specific actions that map to one or more climate vulnerabilities, monitoring to evaluate the impact of your actions to improve outcomes, and checkpoints to allow actions to be altered if needed. As discussed at the beginning of the adaptation section, it can be beneficial to consider which management actions you are already undertaking that might become even more important under future climate conditions, as well as those that might need to be tweaked to better address them. Importantly, it is also useful to consider whether there are actions to address future climate stressors that are not already in place, or that need to be implemented as larger projects not currently being considered. Finally, it is most effective to develop actions that address the range of climate stressors your vulnerability assessment has identified, including those that are expected to co-occur as compound events. Failing to do so could result in undertaking

adaptation actions that fail to address the ways that these stressors can exacerbate one another. For example, building a sea wall to address sea level rise and storm surge could make a course vulnerable to flooding as extreme precipitation events also become more frequent and intense. In order to avoid unintended and maladaptive consequences such as these, as well as to enable innovative plan development, it is advisable to invite people with a variety of perspectives and experience to be part of your adaptation planning process.

Join regional planning efforts

In many regions, city- and county-level jurisdictions are undertaking climate-informed regional planning initiatives. In some states this is required as part of land use planning (e.g., California, Washington, Massachusetts, New York), and in others local jurisdictions are developing or updating climate action plans that include adaptation plans. In both cases, these efforts often include responding to or preparing for changing availability of water, damage to infrastructure (e.g., transportation, housing, utilities), risks to public health, and adverse impacts to ecosystems—all of which can also impact golf course management and enjoyment. These processes generally involve a regional vulnerability assessment that could be used to inform course decisions, especially in relation to how changes in the region may impact course management and use. Participation in regional processes also affords the opportunity to collaborate with others in developing a regional plan that may provide greater potential benefits over the longer term.

Collaborate with other golf courses

Knowing which adaptation actions will be the most effective at reducing the impacts of climate change on your golf course is not always obvious, in part because the field of adaptation is relatively young and scientists are just beginning to understand whether strategies that have been implemented are reducing impacts on the ground. We have included four case studies in Appendix A of this report to illustrate adaptation efforts underway on golf courses in Massachusetts, Washington D.C., Iowa, and California, as much can be learned from the experience of peers. Consider using your existing networks and resources, including the USGA, to exchange knowledge with one another to improve course management in light of climate change.



Credit: Noah Rosenfield on Unsplash

Communicate

The golf industry will need to be part of developing and implementing an adaptation plan. This will require that players, staff, board members, and other course personnel have a common understanding of the climate challenges being faced so they are ready to support the planning and implementation of adaptation strategies that suit your site's needs. Use common spaces such as clubhouses and existing outreach such as newsletters and websites to share examples, post relevant data, and publicize opportunities to join planning teams.

Share what you learn

Whether it is through a professional network, regional partners, or an adaptation learning exchange, everyone will benefit if you share what you implement, monitor how it works, and share when it succeeds or even if it fails. There is much to learn as we all endeavor to undertake our regular responsibilities in a changing climate.

Share this report and the online materials https://sites.google.com/ecoadapt.org/teeingupforclimatechange that accompany it to expand the conversation and innovation about golf course adapting to climate change.

Literature Cited

1. Shaddox TW et al. Land-use and energy practices on US golf courses. HortTechnology. 2023;33(3):296–304. https://doi.org/10.21273/horttech05207-23
2. Merrill D, Leatherby L. Here's how America uses its land. Bloomberg. 2018 [accessed 2026 June 3]. https://www.bloomberg.com/graphics/2018-us-land-use/
3. Winters-Michaud C, Haro A, Callahan S, Bigelow DP. Major uses of land in the United States, 2017. U.S. Department of Agriculture, Economic Research Service; 2024. https://doi.org/10113/8633522,%2010.32747/2024.8633522.ers
4. Browning R. A history of golf: the royal and ancient game. Papamoa Press; 2018.
5. García-Mestanza J, García PM. Golf tourism. In: Jafari J, Xiao H, editors. Encyclopedia of tourism. Springer International Publishing; 2024. p 447–448. https://doi.org/10.1007/978-3-030-74923-1_336. https://doi.org/10.1007/978-3-030-74923-1_336
6. Murray AD et al. The relationships between golf and health: a scoping review. British Journal of Sports Medicine. 2017;51(1):12–19. https://doi.org/10.1136/bjsports-2016-096625
7. Greyling RMM. The role of social networks formed on the golf course [Master's thesis]. University of Pretoria; 2010. http://hdl.handle.net/2263/23304
8. Petrosillo I et al. Can a golf course support biodiversity and ecosystem services? The landscape context matter. Landscape Ecology. 2019;34:2213–2228.
9. Ryan JC. Do urban golf courses provide barriers to equitable greenspace access in the United States? Annals of the American Association of Geographers. 2023;113(5):1057–1070. https://doi.org/10.1080/24694452.2023.2166011
10. Haydu JJ, Hodges AW, Hall CR. Estimating the economic impact of the U.S. golf course industry: challenges and solutions. HortScience. 2008;43(3):759–763. https://doi.org/10.21273/hortsci.43.3.759
11. Doody JP. Sand dune conservation, management and restoration. Springer Netherlands; 2013. http://link.springer.com/10.1007/978-94-007-4731-9. https://doi.org/10.1007/978-94-007-4731-9
12. Lonsdorf EV, Nootenboom C, Janke B, Horgan BP. Assessing urban ecosystem services provided by green infrastructure: Golf courses in the Minneapolis-St. Paul metro area. Landscape and Urban Planning. 2021;208:104022. https://doi.org/10.1016/j.landurbplan.2020.104022
13. Quach J. A resilient ecological development of Ala Wai golf course: symbiosis between buildings, communities and urban waterways [Doctoral dissertation]. University of Hawaii; 2021. http://hdl.handle.net/10125/75893
14. Avery CW et al. Front matter. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
15. Marvel K et al. Chapter 2. Climate trends. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
16. Strandberg M, Blombäck K, Jensen AMD, Knox JW. Priorities for sustainable turfgrass management: a research and industry perspective. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science. 2012;62(sup1):3–9. https://doi.org/10.1080/09064710.2012.682163
17. Hall TM, Kossin JP. Hurricane stalling along the North American coast and implications for rainfall. npj Climate and Atmospheric Science. 2019;2(1):17. https://doi.org/10.1038/s41612-019-0074-8
18. May CL et al. Chapter 9. Coastal effects. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
19. Williams AP, Cook BI, Smerdon JE. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nature Climate Change. 2022;12(3):232–234. https://doi.org/10.1038/s41558-022-01290-z
20. Jay AJ et al. Chapter 1. Overview: Understanding risks, impacts, and responses. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
21. Kim H, Villarini G. Higher emissions scenarios lead to more extreme flooding in the United States. Nature Communications. 2024;15(1):237. https://doi.org/10.1038/s41467-023-44415-4
22. Musselman KN, Addor N, Vano JA, Molotch NP. Winter melt trends portend widespread declines in snow water resources. Nature Climate Change. 2021;11(5):418–424. https://doi.org/10.1038/s41558-021-01014-9
23. Tripathy KP et al. Climate change will accelerate the high-end risk of compound drought and heatwave events. Proceedings of the National Academy of Sciences. 2023;120(28):e2219825120. https://doi.org/10.1073/pnas.2219825120
24. Vecchi GA et al. Changes in Atlantic major hurricane frequency since the late-19th century. Nature Communications. 2021;12(1):4054. https://doi.org/10.1038/s41467-021-24268-5
25. Cook BI et al. Twenty-first century drought projections in the CMIP6 forcing scenarios. Earth's Future. 2020;8(6):e2019EF001461. https://doi.org/10.1029/2019EF001461
26. Williams AP, Abatzoglou JT. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. Current Climate Change Reports. 2016;2(1):1–14. https://doi.org/10.1007/s40641-016-0031-0
27. White RH et al. The unprecedented Pacific Northwest heatwave of June 2021. Nature Communications. 2023;14(1):727. https://doi.org/10.1038/s41467-023-36289-3
28. Lyon B, Barnston AG, Coffel E, Horton RM. Projected increase in the spatial extent of contiguous US summer heat waves and associated attributes. Environmental Research Letters. 2019;14(11):114029. https://doi.org/10.1088/1748-9326/ab4b41
29. Sheridan SC, Lee CC. Temporal trends in absolute and relative extreme temperature events across North America. Journal of Geophysical Research: Atmospheres. 2018;123(21):11,889-11,898. https://doi.org/10.1029/2018JD029150
30. Vargas Zeppetello LR, Raftery AE, Battisti DS. Probabilistic projections of increased heat stress driven by climate change. Communications Earth & Environment. 2022;3(1):183. https://doi.org/10.1038/s43247-022-00524-4
31. Scott D, Jones B. A regional comparison of the implications of climate change for the golf industry in Canada. Canadian Geographies / Les Géographies Canadiennes. 2007;51(2):219–232. https://doi.org/10.1111/j.1541-0064.2007.00175.x
32. Orr M, Inoue Y, Seymour R, Dingle G. Impacts of climate change on organized sport: a scoping review. WIREs Climate Change. 2022;13(3):e760. https://doi.org/10.1002/wcc.760
33. Berghammer A, Schmude J, Dingeldey A. Effects of different scenarios on water consumption by golf courses. In: Mauser W, Prasch M, editors. Regional assessment of global change impacts: the Project GLOWA-Danube. Springer International Publishing; 2016. p 553–559. https://doi.org/10.1007/978-3-319-16751-0_63
34. Pröbstl-Haider U, Hödl C, Ginner K, Borgwardt F. Climate change: impacts on outdoor activities in the summer and shoulder seasons. Journal of Outdoor

Recreation and Tourism. 2021;34:100344. https://doi.org/10.1016/j.jort.2020.100344

35. Hatfield J. Turfgrass and climate change. Agronomy Journal. 2017;109(4):1708–1718. https://doi.org/10.2134/agronj2016.10.0626
36. Huang B, DaCosta M, Jiang Y. Research advances in mechanisms of turfgrass tolerance to abiotic stresses: from physiology to molecular biology. Critical Reviews in Plant Sciences. 2014;33(2–3):141–189. https://doi.org/10.1080/07352689.2014.870411
37. Hall AE. Crop responses to environment: adapting to global climate change. 2nd ed. CRC Press; 2018. https://doi.org/10.1201/9781315147130
38. Chapra SC et al. Climate change impacts on harmful algal blooms in U.S. freshwaters: a screening-level assessment. Environmental Science & Technology. 2017;51(16):8933–8943. https://doi.org/10.1021/acs.est.7b01498
39. BASIS. Game changer II: the impact of climate change on sports in the UK. British Association for Sustainable Sport; 2023. https://basis.org.uk/2023/11/23/game-changer-ii/
40. Nicholls S, Holecek DF, Noh J. Impact of weather variability on golfing activity and implications of climate change. Tourism Analysis. 2008;13(2):117–130. https://doi.org/10.3727/108354208785664256
41. Scott D, Jones B. The impact of climate change on golf participation in the Greater Toronto Area (GTA): a case study. Journal of Leisure Research. 2006;38(3):363–380. https://doi.org/10.1080/00222216.2006.11950083
42. Anderegg WRL et al. Anthropogenic climate change is worsening North American pollen seasons. Proceedings of the National Academy of Sciences. 2021;118(7):e2013284118. https://doi.org/10.1073/pnas.2013284118
43. Marvel K et al. Projected changes to hydroclimate seasonality in the continental United States. Earth's Future. 2021;9(9):e2021EF002019. https://doi.org/10.1029/2021EF002019
44. Damialis A, Traidl-Hoffmann C, Treudler R. Climate change and pollen allergies. In: Marselle MR et al., editors. Biodiversity and health in the face of climate change. Springer International Publishing; 2019. p 47–66. https://doi.org/10.1007/978-3-030-02318-8_3
45. D'Amato G et al. The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. Allergy. 2020;75(9):2219–2228. https://doi.org/10.1111/all.14476
46. NOAA. What is the heat index? National Weather Service. [accessed 2026 July 1]. https://www.weather.gov/ama/heatindex
47. Bernard P et al. Climate change, physical activity and sport: a systematic review. Sports Medicine. 2021;51(5):1041–1059. https://doi.org/10.1007/s40279-021-01439-4
48. Zoffer M. Competitive golf: how longer courses are changing athletes and their approach to the game. Nutrients. 2022;14(9):1732. https://doi.org/10.3390/nu14091732
49. Grundstein A, Elguindi N, Cooper E, Ferrara MS. Exceedance of wet bulb globe temperature safety thresholds in sports under a warming climate. Climate Research. 2013;58:183–191. https://doi.org/10.3354/cr01199
50. Huang B, Fry JD. Turfgrass evapotranspiration. Journal of Crop Production. 2000;2(2):317–333. https://doi.org/10.1300/J144v02n02_14
51. Havens KE, Paerl HW. Climate Change at a Crossroad for Control of Harmful Algal Blooms. Environmental Science & Technology. 2015;49(21):12605–12606. https://doi.org/10.1021/acs.est.5b03990
52. Bock EM, Easton ZM. Export of nitrogen and phosphorus from golf courses: a review. Journal of Environmental Management. 2020;255:109817. https://doi.org/10.1016/j.jenvman.2019.109817
53. Le Page Y et al. Global fire activity patterns (1996–2006) and climatic influence: an analysis using the World Fire Atlas. Atmospheric Chemistry and Physics. 2008;8(7):1911–1924. https://doi.org/10.5194/acp-8-1911-2008
54. Heckman NL, Horst GL, Gaussoin RE, Young LJ. Heat tolerance of kentucky bluegrass as affected by trinexapac-ethyl. HortScience. 2001;36(2):365–367. https://doi.org/10.21273/HORTSCI.36.2.365
55. He Y, Liu X, Huang B. Protein changes in response to heat stress in acclimated and nonacclimated creeping bentgrass. Journal of the American Society for Horticultural Science. 2004;130. https://doi.org/10.21273/JASHS.130.4.521
56. Cross JW, Bonos SA, Huang B, Meyer WA. Evaluation of heat and drought as components of summer stress on tall fescue genotypes. HortScience. 2013;48(12):1562–1567. https://doi.org/10.21273/hortsci.48.12.1562
57. Blombäck K, Eckersten H, Sindhøj E. Growth of golf turf as a function of light and temperature under Swedish conditions – a simulation study. International Turfgrass Society Research Journal. 2009;11:27–28.
58. DaCosta M, Huang B. Heat-stress physiology and management. In: Stier JC, Horgan BP, Bonos SA, editors. Turfgrass: biology, use, and management. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2013. p 249–278. https://doi.org/10.2134/agronmonogr56.c7
59. Breuillin-Sessoms F, Watkins E. Performance of multiple turfgrass species during prolonged heat stress and recovery in a controlled environment. Crop Science. 2020;60(6):3344–3361. https://doi.org/10.1002/csc2.20262
60. Drake AM et al. Effect of plant growth regulators on creeping bentgrass during heat, salt, and combined stress. HortScience. 2023;58(4):410–418. https://doi.org/10.21273/hortsci16978-22
61. Hu L, Zhang Z, Xiang Z, Yang Z. Exogenous application of citric acid ameliorates the adverse effect of heat stress in tall fescue. Frontiers in Plant Science. 2016;7. https://doi.org/10.3389/fpls.2016.00179
62. Wang JZ, Cui LJ, Wang Y, Li JL. Growth, lipid peroxidation and photosynthesis in two tall fescue cultivars differing in heat tolerance. Biologia Plantarum. 2009;53(2):237–242. https://doi.org/10.1007/s10535-009-0045-8
63. Yu J, Du H, Xu M, Huang B. Metabolic responses to heat stress under elevated atmospheric CO2 concentration in a cool-season grass species. Journal of the American Society for Horticultural Science. 2012;137(4):221–228. https://doi.org/10.21273/JASHS.137.4.221
64. Alam MN et al. Role of melatonin in inducing the physiological and biochemical processes associated with heat stress tolerance in tall fescue (Festuca arundinaceous). Journal of Plant Growth Regulation. 2022;41(7):2759–2768. https://doi.org/10.1007/s00344-021-10472-6
65. Jespersen D, Huang B. Effects of trinexapac-ethyl and daconil action (acibenzolar-S-methyl and chlorothalonil) on heat and drought tolerance of creeping bentgrass. Crop Science. 2017;57(S1). https://doi.org/10.2135/cropsci2016.05.0377
66. Fan J et al. Mechanisms of environmental stress tolerance in turfgrass. Agronomy. 2020;10(4):522. https://doi.org/10.3390/agronomy10040522
67. Severmutlu S et al. Establishment and turf qualities of warm-season turfgrasses in the Mediterranean region. HortTechnology. 2011;21(1):67–81. https://doi.org/10.21273/horttech.21.1.67
68. Tate TM et al. Inheritance of summer stress tolerance in tall fescue. Grass Research. 2023;3(1):0–0. https://doi.org/10.48130/GR-2023-0014
69. Liu J et al. Effects of simultaneous drought and heat stress on Kentucky bluegrass. Scientia Horticulturae. 2008;115(2):190–195. https://doi.org/10.1016/j.scienta.2007.08.003

70. Ridder NN, Ukkola AM, Pitman AJ, Perkins-Kirkpatrick SE. Increased occurrence of high impact compound events under climate change. npj Climate and Atmospheric Science. 2022;5(1):3. https://doi.org/10.1038/s41612-021-00224-4
71. Zscheischler J et al. Future climate risk from compound events. Nature Climate Change. 2018;8(6):469–477. https://doi.org/10.1038/s41558-018-0156-3
72. Wang Z, Huang B. Physiological recovery of Kentucky bluegrass from simultaneous drought and heat stress. Crop Science. 2004;44(5):1729–1736. https://doi.org/10.2135/cropsci2004.1729
73. Fry J, Huang B. Applied turfgrass science and physiology. John Wiley & Sons; 2004.
74. Giolo M. Germination, seedling growth and establishment of warm-season turfgrasses related to climate changes in the Mediterranean region. Università di Padova; 2019. https://www.research.unipd.it/retrieve/e14fb26f-a7ed-3de1-e053-1705fe0ac030/Giolo_tesi_def_nov_19.pdf
75. Levitt J. Responses of plants to environmental stress. 2nd Ed. Academic Press; 1980.
76. Bélanger G et al. Climate change and winter survival of perennial forage crops in eastern Canada. Agronomy Journal. 2002;94(5):1120–1130. https://doi.org/10.2134/agronj2002.1120
77. Orr M, Inoue Y. Sport versus climate: introducing the climate vulnerability of sport organizations framework. Sport Management Review. 2018;22(4):452–463. https://doi.org/10.1016/j.smr.2018.09.007
78. Orr M. Warming up: how climate change is changing sport. Bloomsbury Publishing; 2024.
79. Payton EA et al. Chapter 4. Water. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
80. Kluver D, Leathers D. Regionalization of snowfall frequency and trends over the contiguous United States. International Journal of Climatology. 2015;35(14):4348. https://doi.org/10.1002/joc.4292
81. Windows R. Climate change and Scottish golf courses. Scottish Golf Environment Group; 2004. https://www.sgeg.org.uk/documents/ClimateChangeandScottishGolfCourses.pdf
82. White O, College W. The opportunity for sustainability in golf. Williams College, Acer Sustainability, LLC; 2021.
83. Kopp KL, Jiang Y. Turfgrass water use and physiology. In: Stier JC, Horgan BP, Bonos SA, editors. Turfgrass: biology, use, and management. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2013. p 319–345. https://doi.org/10.2134/agronmonogr56.c9
84. Cook BI, Mankin JS, Anchukaitis KJ. Climate change and drought: from past to future. Current Climate Change Reports. 2018;4(2):164–179. https://doi.org/10.1007/s40641-018-0093-2
85. Siirila-Woodburn ER et al. A low-to-no snow future and its impacts on water resources in the western United States. Nature Reviews Earth & Environment. 2021;2(11):800–819. https://doi.org/10.1038/s43017-021-00219-y
86. Yao L et al. Emergent constraints on global soil moisture projections under climate change. Communications Earth & Environment. 2025;6(1):39. https://doi.org/10.1038/s43247-025-02024-7
87. Williams AP et al. Large contribution from anthropogenic warming to an emerging North American megadrought. Science. 2020;368(6488):314–318. https://doi.org/10.1126/science.aaz9600
88. Krakauer NY, Lakhankar T, Hudson D. Trends in drought over the Northeast United States. Water. 2019;11(9):1834. https://doi.org/10.3390/w11091834
89. Dawadi S, Ahmad S. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. Journal of Environmental Management. 2013;114:261–275. https://doi.org/10.1016/j.jenvman.2012.10.015
90. Klein J, Ekstedt K, Walter MT, Lyon SW. Modeling potential water resource impacts of Mediterranean tourism in a changing climate. Environmental Modeling & Assessment. 2015;20(2):117–128. https://doi.org/10.1007/s10666-014-9418-2
91. Liu J et al. Water scarcity assessments in the past, present, and future. Earth's Future. 2017;5(6):545–559. https://doi.org/10.1002/2016EF000518
92. Huck M, Carrow RN, Duncan RR. Effluent water: nightmare or dream come true? USGA Green Section Record. 2000;March/April.
93. Emmanuel K, Spence B. Climate change implications for water resource management in Caribbean tourism. Worldwide Hospitality and Tourism Themes. 2009;1(3):252–268. https://doi.org/10.1108/17554210910980594
94. Salgot M, Priestley GK, Folch M. Golf course irrigation with reclaimed water in the Mediterranean: a risk management matter. Water. 2012;4(2):389–429. https://doi.org/10.3390/w4020389
95. López-Bonilla LM, Reyes-Rodríguez MDC, López-Bonilla JM. Golf tourism and sustainability: content analysis and directions for future research. Sustainability. 2020;12(9):3616. https://doi.org/10.3390/su12093616
96. Rodriguez Diaz JA, Knox JW, Weatherhead EK. Competing demands for irrigation water: golf and agriculture in Spain. Irrigation and Drainage. 2007;56(5):541–549. https://doi.org/10.1002/ird.317
97. Serba DD et al. Pertinent water-saving management strategies for sustainable turfgrass in the desert U.S. Southwest. Sustainability. 2022;14(19):12722. https://doi.org/10.3390/su141912722
98. Yu J, Liu M, Yang Z, Huang B. Growth and physiological factors involved in interspecific variations in drought tolerance and postdrought recovery in warm- and cool-season turfgrass species. Journal of the American Society for Horticultural Science. 2015;140(5):459–465. https://doi.org/10.21273/JASHS.140.5.459
99. Zhang X et al. Drought-induced injury is associated with hormonal alteration in Kentucky bluegrass. Plant Signaling & Behavior. 2019;14(10):e1651607. https://doi.org/10.1080/15592324.2019.1651607
100. Hatamzadeh A, Molaahmad Nalousi A, Ghasemnezhad M, Biglouei MH. The potential of nitric oxide for reducing oxidative damage induced by drought stress in two turfgrass species, creeping bentgrass and tall fescue. Grass and Forage Science. 2015;70(3):538–548. https://doi.org/10.1111/gfs.12135
101. Yu S et al. Effect of antecedent drought stress on spring green-up in turf-type bermudagrasses. Agrosystems, Geosciences & Environment. 2023;6(2):e20353. https://doi.org/10.1002/agg2.20353
102. Youngner VB et al. Water use and turf quality of warm-season and cool-season turfgrasses. California Turfgrass Culture. 1981;31(3–4):1–7.
103. McElroy JS, Bhowmik PC. Turfgrass weed management. In: Stier JC, Horgan BP, Bonos SA, editors. Turfgrass: biology, use, and management. American Society of Agronomy, Soil Science Society of America, Crop Science Society of America; 2013. p 777–808. https://doi.org/10.2134/agronmonogr56.c23
104. Żurek G, Prokopiuk K, Rachwalska A. Effect of drought on the performance of three turf grass species. Plant Breeding and Seed Science. 2018;78:2–22. https://doi.org/10.1515/plass-2018-0010

105. Katuwal KB, Schwartz B, Jespersen D. Desiccation avoidance and drought tolerance strategies in bermudagrasses. Environmental and Experimental Botany. 2020;171:103947. https://doi.org/10.1016/j.envexpbot.2019.103947

106. Backhaus S et al. Recurrent mild drought events increase resistance toward extreme drought stress. Ecosystems. 2014;17(6):1068–1081. https://doi.org/10.1007/s10021-014-9781-5

107. Monje-Jiménez R, Egea G, Pérez-Urrestarazu L. Turfgrass recovery after an induced drought period on a golf course fairway: case study in southern Spain. Journal of Irrigation and Drainage Engineering. 2019;145(6):05019005. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001392

108. Müller LM, Bahn M. Drought legacies and ecosystem responses to subsequent drought. Global Change Biology. 2022;28(17):5086–5103. https://doi.org/10.1111/gcb.16270

109. Easterling DR et al. Precipitation change in the United States. In: Wuebbles DJ et al., editors. Fourth national climate assessment. U.S. Global Change Research Program; 2017. p 207–230. https://doi.org/10.7930/J0N29V45

110. Payne AE et al. Responses and impacts of atmospheric rivers to climate change. Nature Reviews Earth & Environment. 2020;1(3):143–157. https://doi.org/10.1038/s43017-020-0030-5

111. Davenport FV, Burke M, Diffenbaugh NS. Contribution of historical precipitation change to US flood damages. Proceedings of the National Academy of Sciences. 2021;118(4):e2017524118. https://doi.org/10.1073/pnas.2017524118

112. Mallakpour I, Villarini G. The changing nature of flooding across the central United States. Nature Climate Change. 2015;5(3):250–254. https://doi.org/10.1038/nclimate2516

113. Kim H, Villarini G. Floods across the eastern United States are projected to last longer. npj Natural Hazards. 2024;1(1):23. https://doi.org/10.1038/s44304-024-00021-y

114. Wing OEJ et al. Inequitable patterns of US flood risk in the Anthropocene. Nature Climate Change. 2022;12(2):156–162. https://doi.org/10.1038/s41558-021-01265-6

115. Leung LR et al. Chapter 3. Earth systems processes. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment

116. Elsner JB, Fricker T, Schroder Z. Increasingly powerful tornadoes in the United States. Geophysical Research Letters. 2019;46(1):392–398. https://doi.org/10.1029/2018GL080819

117. Gensini VA, Brooks HE. Spatial trends in United States tornado frequency. npj Climate and Atmospheric Science. 2018;1:38. https://doi.org/10.1038/s41612-018-0048-2

118. Moore TW. Annual and seasonal tornado trends in the contiguous United States and its regions. International Journal of Climatology. 2018;38(3):1582–1594. https://doi.org/10.1002/joc.5285

119. Hu H, Leung LR, Feng Z. Observed warm-season characteristics of MCS and non-MCS rainfall and their recent changes in the central United States. Geophysical Research Letters. 2020;47(6):e2019GL086783. https://doi.org/10.1029/2019GL086783

120. Tang BH, Gensini VA, Homeyer CR. Trends in United States large hail environments and observations. npj Climate and Atmospheric Science. 2019;2(1):45. https://doi.org/10.1038/s41612-019-0103-7

121. Bhatia KT et al. Recent increases in tropical cyclone intensification rates. Nature Communications. 2019;10(1):635. https://doi.org/10.1038/s41467-019-08471-z

122. Kossin JP. A global slowdown of tropical-cyclone translation speed. Nature. 2018;558(7708):104–107. https://doi.org/10.1038/s41586-018-0158-3

123. Utsumi N, Kim H. Observed influence of anthropogenic climate change on tropical cyclone heavy rainfall. Nature Climate Change. 2022;12(5):436–440. https://doi.org/10.1038/s41558-022-01344-2

124. Giolo M, Onofri A, Macolino S. Establishment of warm-season turfgrasses in a Mediterranean transition zone under simulated waterlogging. Agronomy Journal. 2023;115(5):2384–2394. https://doi.org/10.1002/agj2.21430

125. Wang K, Jiang Y. Waterlogging tolerance of Kentucky bluegrass cultivars. HortScience. 2007;42(2):386–390. https://doi.org/10.21273/hortsci.42.2.386

126. Xiao B, Jespersen D. Morphological and physiological responses of seashore paspalum and bermudagrass to waterlogging stress. Journal of the American Society for Horticultural Science. 2019;144(5):305–313. https://doi.org/10.21273/JASHS04737-19

127. Beard JB, Martin DP. Influence of water temperature on submersion tolerance of four grasses. Agronomy Journal. 1970;62(2):257–259. https://doi.org/10.2134/agronj1970.00021962006200020024x

128. Tan S, Zhu M, Zhang Q. Physiological responses of bermudagrass (Cynodon dactylon) to submergence. Acta Physiologiae Plantarum. 2010;32(1):133–140. https://doi.org/10.1007/s11738-009-0388-y

129. Fry JD. Submersion tolerance of warm-season turfgrasses. HortScience. 1991;26(7):927.

130. Sweet WV et al. Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. coastlines. National Oceanic and Atmospheric Administration, National Ocean Service; 2022. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf

131. Miller E, Stevens S. As rising seas flood Charleston's fairways, its municipal golf course leads in adapting. Climate Central. 2022 Nov 17 [accessed 2026 Jan 13]. https://www.climatecentral.org/partnership-journalism/as-rising-seas-flood-charlestons-fairways-its-municipal-golf-course-leads-in

132. Williams VJ. Identifying the economic effects of salt water intrusion after Hurricane Katrina. Journal of Sustainable Development. 2010;3(1):29–37. https://doi.org/10.5539/jsd.v3n1p29

133. DeSmith D. Game changer: what does climate change mean for golf? LINKS Magazine. 2019 Oct 1 [accessed 2026 Jan 13]. https://linksmagazine.com/game-changer-what-does-climate-change-mean-for-golf/

134. Morris JT, Renken KA. Past, present, and future nuisance flooding on the Charleston peninsula. PLOS ONE. 2020;15(9):e0238770. https://doi.org/10.1371/journal.pone.0238770

135. Keenan R. 'This is climate change': Scottish beach eroding by 7 metres a year. The Guardian. 2024 Aug 3 [accessed 2026 May 29]. https://www.theguardian.com/environment/article/2024/aug/03/scottish-beach-eroding-by-7-metres-a-year-montrose-climate-change

136. Marcum KB. Use of saline and non-potable water in the turfgrass industry: constraints and developments. Agricultural Water Management. 2006;80(1–3):132–146. https://doi.org/10.1016/j.agwat.2005.07.009

137. Shaddox TW et al. Water use and management practices on U.S. golf courses. Crop, Forage & Turfgrass Management. 2022;8(2):e20182. https://doi.org/10.1002/cft2.20182

138. Carrow RN, Duncan RR. Best management practices for saline and sodic turfgrass soils: assessment and reclamation. CRC Press; 2011.

139. Liu H, Todd JL, Luo H. Turfgrass salinity stress and tolerance—a review. Plants. 2023;12(4):925. https://doi.org/10.3390/plants12040925

140. Marcum KB, Murdoch CL. Growth responses, ion relations, and osmotic adaptations of eleven C4 turfgrasses to salinity. Agronomy Journal. 1990;82(5):892–896. https://doi.org/10.2134/agronj1990.00021962008200050009x

141. Alshammary SF, Qian YL, Wallner SJ. Growth response of four turfgrass species to salinity. Agricultural Water Management. 2004;66(2):97–111. https://doi.org/10.1016/j.agwat.2003.11.002

142. Uddin MK et al. Physiological and growth responses of six turfgrass species relative to salinity tolerance. The Scientific World Journal. 2012;2012:1–10. https://doi.org/10.1100/2012/905468

143. Marcum KB. Salinity tolerant turfgrasses for biosaline urban landscape agriculture. In: Khan MA et al., editors. Sabkha ecosystems: volume IV: cash crop halophyte and biodiversity conservation. Vol. 47. Springer Netherlands; 2014. p 223–232. http://link.springer.com/10.1007/978-94-007-7411-7_15

144. Rue K, Zhang Q. Kentucky bluegrass growth under saline, waterlogging, and saline-waterlogging conditions during germination and seedling growth. Crop, Forage & Turfgrass Management. 2020;6(1):e20002. https://doi.org/10.1002/cft2.20002

145. Chavarria M et al. Salinity tolerance and recovery attributes of warm-season turfgrass cultivars. HortScience. 2019;54(9):1625–1631. https://doi.org/10.21273/hortsci-19

146. Dudeck AE, Peacock CH, Wildmon JC. Physiological and growth responses of St. Augustinegrass cultivars to salinity. HortScience. 1993;28(1):46–48. https://doi.org/10.21273/hortsci.28.1.46

147. Harivandi MA, Marcum KB. A review of salt tolerance among sports field turfgrass. Acta Horticulturae. 2008;(783):159–162. https://doi.org/10.17660/ActaHortic.2008.783.14

148. Entwistle K et al. Biosecurity and emerging plant health problems in turf production and maintenance. European Journal of Horticultural Science. 2014;79(3):108–115.

149. Scott D, Jones B. Climate change and seasonality in Canadian outdoor recreation and tourism. Waterloo University; 2006. https://lib.icimod.org/records/2w15s-w7b13

150. Unruh B, Davis S. Diseases and heat besiege ultradwarf bermudagrasses. Golf Course Management. 2001;69(4):49–54.

151. Williamson RC, Held DW, Brandenburg R, Baxendale F. Turfgrass insect pests. In: Stier JC, Horgan BP, Bonos SA, editors. Turfgrass: biology, use, and management. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2013. p 809–890. https://doi.org/10.2134/agronmonogr56.c23

152. Young JR, Tomaso-Peterson M, Tredway LP, De La Cerda K. Occurrence and molecular identification of azoxystrobin-resistant isolates from golf course putting greens in the southern United States. Plant Disease. 2010;94(6):751–757. https://doi.org/10.1094/PDIS-94-6-0751

153. Scott DJ, Lemieux CJ, Malone L. Climate services to support sustainable tourism and adaptation to climate change. Climate Research. 2011;47(1–2):111–122. https://doi.org/10.3354/cr00952

154. Giolo M et al. High-temperature effects on seed germination of fourteen Kentucky bluegrass (Poa pratensis L.) cultivars. Agronomy Research. 2017;15(1):123–132.

155. Yu X et al. Detection of quantitative trait loci associated with drought tolerance in St. Augustinegrass. PLOS ONE. 2019;14(10):e0224620. https://doi.org/10.1371/journal.pone.0224620

156. Jespersen D et al. Quantitative trait loci associated with physiological traits for heat tolerance in creeping bentgrass. Crop Science. 2016;56(3):1314–1329. https://doi.org/10.2135/cropsci2015.07.0428

157. Marcum KB. Cell membrane thermostability and whole-plant heat tolerance of Kentucky bluegrass. Crop Science. 1998;38(5):1214–1218. https://doi.org/10.2135/cropsci1998.0011183X003800050017x

158. Yousfi S et al. Remote sensing devices as key methods in the advanced turfgrass phenotyping under different water regimes. Agricultural Water Management. 2022;266:107581. https://doi.org/10.1016/j.agwat.2022.107581

159. Minelli A et al. Transition from cool-season to warm-season grass: environmental effects in a golf course in the North of Italy. In: Proceedings of the Fourth European Turfgrass Society Conference, Osnabrueck, Germany. 2014. https://www.federgolf.it/wp-content/uploads/2015/07/ALLEGATO-B.pdf

160. Martínez-Espinoza AD, Burpee LL, Waltz C. Abiotic injuries and disorders of turfgrasses in Georgia. University of Georgia Cooperative Extension; 2009. p 3–16. https://openscholar.uga.edu/record/24543

161. Fu J, Dernoeden PH. Creeping bentgrass putting green turf responses to two summer irrigation practices: rooting and soil temperature. Crop Science. 2009;49(3):1063–1070. https://doi.org/10.2135/cropsci2008.06.0312

162. Liu S, Vargas J, Merewitz E. Jasmonic and salicylic acid effects on bacterial etiolation and decline disease of creeping bentgrass. Crop Protection. 2018;109:9–16. https://doi.org/10.1016/j.cropro.2018.02.023

163. Zhang X, Ervin EH, Schmidt RE. Plant growth regulators can enhance the recovery of Kentucky bluegrass sod from heat injury. Crop Science. 2003;43(3):952–956. https://doi.org/10.2135/cropsci2003.9520

164. Wang Z, Sun J, Li J, Zhu Y. Heat resistance enhanced by trinexapac-ethyl and benzyladenine combination in creeping bentgrass. HortScience. 2006;41(7):1711–1714. https://doi.org/10.21273/hortsci.41.7.1711

165. Li Z et al. The transcriptional and post-transcriptional regulation in perennial creeping bentgrass in response to -aminobutyric acid (GABA) and heat stress. Environmental and Experimental Botany. 2019;162:515–524. https://doi.org/10.1016/j.envexpbot.2019.03.026

166. Merewitz EB, Liu S. Improvement in heat tolerance of creeping bentgrass with melatonin, rutin, and silicon. Journal of the American Society for Horticultural Science. 2019;144(2):141–148. https://doi.org/10.21273/JASHS04643-19

167. Katuwal KB, Rowe S, Jespersen D. The use of 5-aminolevulinic acid to reduce heat-stress-related damages in tall fescue. Crop Science. 2021;61(5):3206–3218. https://doi.org/10.1002/csc2.20294

168. Racinais S et al. Consensus recommendations on training and competing in the heat. British Journal of Sports Medicine. 2015;49(18):1164–1173. https://doi.org/10.1136/bjsports-2015-094915

169. Habibi P et al. Climate change and heat stress resilient outdoor workers: findings from systematic literature review. BMC Public Health. 2024;24(1):1711. https://doi.org/10.1186/s12889-024-19212-3

170. Nguyen TT. The ecological roles of golf courses in urban landscapes [Doctoral dissertation]. Murdoch University; 2022. https://researchportal.murdoch.edu.au/esploro/outputs/991005543433707891

171. Monteiro JA. Ecosystem services from turfgrass landscapes. Urban Forestry & Urban Greening. 2017;26:151–157. https://doi.org/10.1016/j.ufug.2017.04.001

172. Stier JC et al. Turfgrass benefits and issues. In: Stier JC, Horgan BP, Bonos SA, editors. Turfgrass: biology, use, and management. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2013. p 105–145. https://doi.org/10.2134/agronmonogr56.c23

173. Fung CKW, Jim CY. Influence of blue infrastructure on lawn thermal microclimate in a subtropical green

space. Sustainable Cities and Society. 2020;52:101858. https://doi.org/10.1016/j.scs.2019.101858

174. Bartlett MD, James IT. A model of greenhouse gas emissions from the management of turf on two golf courses. Science of The Total Environment. 2011;409(8):1357–1367. https://doi.org/10.1016/j.scitotenv.2010.12.041

175. Braun RC et al. Strategies for reducing inputs and emissions in turfgrass systems. Crop, Forage & Turfgrass Management. 2023;9(1):e20218. https://doi.org/10.1002/cft2.20218

176. Gilman J, Hill J, Wang X, Wu J. Re-envisioning par for the course: an assessment of desert golf sustainability from a landscape perspective. International Journal of Sustainable Development & World Ecology. 2025;32(1):80–95. https://doi.org/10.1080/13504509.2024.2405818

177. Jiang Y, Carrow RN. Assessment of narrow-band canopy spectral reflectance and turfgrass performance under drought stress. HortScience. 2005;40(1):242–245. https://doi.org/10.21273/hortsci.40.1.242

178. Jiang Y, Huang B. Osmotic adjustment and root growth associated with drought preconditioning-enhanced heat tolerance in Kentucky bluegrass. Crop Science. 2001;41(4):1168–1173. https://doi.org/10.2135/cropsci2001.4141168x

179. Bremer DJ et al. USGA Water Conservation Playbook. U.S. Golf Association; 2025. https://www.usga.org/content/usga/home-page/course-care/water-resource-center/usga-water-conservation-playbook.html

180. Katuwal KB et al. Multilocational screening identifies new drought-tolerant, warm-season turfgrasses. Crop Science. 2022;62(4):1614–1630. https://doi.org/10.1002/csc2.20726

181. Peister C. Water use on Ontario golf courses [Master's thesis]. University of Waterloo; 2014. http://hdl.handle.net/10012/8472

182. Franco-Navarro JD et al. Advancements in water-saving strategies and crop adaptation to drought: a comprehensive review. Physiologia Plantarum. 2025;177(4):e70332. https://doi.org/10.1111/ppl.70332

183. Jiuxin L, Liebao H. Progress and challenges in China turfgrass abiotic stress resistance research. Frontiers in Plant Science. 2022;13:922175. https://doi.org/10.3389/fpls.2022.922175

184. Bonos SA, Clarke BB, Meyer WA. Breeding for disease resistance in the major cool-season turfgrasses. Annual Review of Phytopathology. 2006;44(1):213–234. https://doi.org/10.1146/annurev.phyto.44.070505.143338

185. Abraham EM, Meyer WA, Bonos SA, Huang B. Differential responses of hybrid bluegrass and Kentucky bluegrass to drought and heat stress. HortScience. 2008;43(7):2191–2195. https://doi.org/10.21273/hortsci.43.7.2191

186. Abraham EM, Huang B, Bonos SA, Meyer WA. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Science. 2004;44(5):1746–1753. https://doi.org/10.2135/cropsci2004.1746

187. Meza K et al. Relating spatial turfgrass quality to actual evapotranspiration for precision golf course irrigation. Crop Science. 2025;65(1):e21446. https://doi.org/10.1002/csc2.21446

188. Powlen JS, Bigelow CA. Cool-season golf course fairway species irrigation requirements under limited irrigation. Crop, Forage & Turfgrass Management. 2023;9(1):e20205. https://doi.org/10.1002/cft2.20205

189. Straw C et al. Soil moisture variability on golf course fairways across the United States: an opportunity for water conservation with precision irrigation. Agrosystems, Geosciences & Environment. 2022;5(4):e20323. https://doi.org/10.1002/agg2.20323

190. Kerry R et al. Precision turfgrass irrigation: capturing spatial soil moisture patterns with ECa and drone data. Agronomy. 2024;14(6):1238. https://doi.org/10.3390/agronomy14061238

191. Zhu H, Li D. Using humus on golf course fairways to alleviate soil salinity problems. HortTechnology. 2018;28(3):284–288. https://doi.org/10.21273/horttech03989-18

192. Tapias JC, Salgot M. Management of soil-water resources in golf courses. Tourism and Hospitality Research. 2006;6(3):197–203. https://doi.org/10.1057/palgrave.thr.6050017

193. Nooten SS et al. What shapes plant and animal diversity on urban golf courses? Urban Ecosystems. 2018;21(3):565–576. https://doi.org/10.1007/s11252-017-0728-4

194. Scott D, Rutty M, Peister C. Climate variability and water use on golf courses: optimization opportunities for a warmer future. Journal of Sustainable Tourism. 2018;26(8):1453–1467. https://doi.org/10.1080/09669582.2018.1459629

195. McCoy E. Drainage systems for golf courses. Ohio State Institution; 2015. https://kb.osu.edu/server/api/core/bitstreams/6aae3a3c-4eec-5646-aa39-3038a32db938/content

196. Soldat DJ, Petrovic AM. The fate and transport of phosphorus in turfgrass ecosystems. Crop Science. 2008;48(6):2051–2065. https://doi.org/10.2135/cropsci2008.03.0134

197. Kohler EA, Poole VL, Reicher ZJ, Turco RF. Nutrient, metal, and pesticide removal during storm and nonstorm events by a constructed wetland on an urban golf course. Ecological Engineering. 2004;23(4–5):285–298. https://doi.org/10.1016/j.ecoleng.2004.11.002

198. Schwecke M, Simmons B, Maheshwari B. Sustainable use of stormwater for irrigation case study: manly golf course. The Environmentalist. 2007;27(1):51–61. https://doi.org/10.1007/s10669-007-9013-z

199. Guzmán CAP, Fernández DJM. Environmental impacts by golf courses and strategies to minimize them: state of the art. International Journal of Arts & Sciences. 2014;7(3):403–417.

200. Dai Z, Puyang X, Han L. Using assessment of net ecosystem services to promote sustainability of golf course in China. Ecological Indicators. 2016;63:165–171. https://doi.org/10.1016/j.ecolind.2015.11.056

201. Winter JG, Dillon PJ. Effects of golf course construction and operation on water chemistry of headwater streams on the Precambrian Shield. Environmental Pollution. 2005;133(2):243–253. https://doi.org/10.1016/j.envpol.2004.05.037

202. Rogers K et al. Impacts and adaptation options for estuarine vegetation in a large city. Landscape and Urban Planning. 2019;182:1–11. https://doi.org/10.1016/j.landurbplan.2018.09.022

203. Langevin CD, Zygnerski M. Effect of sea-level rise on salt water intrusion near a coastal well field in southeastern Florida. Groundwater. 2013;51(5):781–803. https://doi.org/10.1111/j.1745-6584.2012.01008.x

204. Dogan A, Fares A. Effects of land-use changes and groundwater pumping on saltwater intrusion in coastal watersheds. In: Fares A, El-Kadi AI, editors. WIT Transactions on State of the Art in Science and Engineering. 1st ed. WIT Press; 2008. p 219–249. https://doi.org/10.2495/978-1-84564-091-0/08

205. Hansen LJ, Hoffman JR. Climate savvy: adapting conservation and resource management to a changing world. Island Press; 2011.

206. Dale AG, Perry RL, Cope GC, Benda N. Floral abundance and richness drive beneficial arthropod conservation and biological control on golf courses. Urban Ecosystems. 2020;23(1):55–66. https://doi.org/10.1007/s11252-019-00907-0

207. Merrick B, Thompson C. The environmental benefits of golf courses. USGA Green Section Record. 2024 [accessed 2026 June 30];62(6). https://www.usga.org/content/usga/home-

page/course-care/green-section-record/62/issue-06/the-environmental-benefits-of-golf-courses.html

208. Li Y et al. Landscape patterns and diurnal thermal effects of golf courses in urban and suburban settings. Urban Climate. 2026;65:102763. https://doi.org/10.1016/j.uclim.2025.102763
209. Ahn MH, Jeon SW, Lim NO. Rethinking land use in cities: the ecological role of urban golf courses in forest and air quality management. Urban Ecosystems. 2025;28(5):197. https://doi.org/10.1007/s11252-025-01822-3
210. Waters G. Golf, Communities and Stormwater. United States Golf Association. 2017 Oct 17 [accessed 2026 June 30]. https://www.usga.org/content/usga/home-page/articles/2017/10/golf--communities-and-stormwater.html
211. American Society of Golf Course Architects. Golf and water: case studies in water stewardship. American Society of Golf Course Architects Foundation; 2016. https://asgca.org/wp-content/uploads/2021/03/ASGCA_Water_Golf_Spreads_lores_FINAL2.pdf
212. Nguyen TT et al. Vegetation trends associated with urban development: the role of golf courses. PLOS ONE. 2020;15(2):e0228090. https://doi.org/10.1371/journal.pone.0228090
213. Bruneau AH et al. Water quality and golf course superintendents. North Carolina Cooperative Extension Service; 1995.
214. Beard JB, Green RL. The role of turfgrasses in environmental protection and their benefits to humans. Journal of Environmental Quality. 1994;23(3):452–460. https://doi.org/10.2134/jeq1994.00472425002300030007x
215. Petrovic A, Easton Z. The role of turfgrass management in the water quality of urban environment. International Turfgrass Society Research Journal. 2005;10:55–69.
216. Colding J, Folke C. The role of golf courses in biodiversity conservation and ecosystem management. Ecosystems. 2009;12(2):191–206. https://doi.org/10.1007/s10021-008-9217-1
217. Semlitsch RD, Boone MD, Bodie JR. Using golf courses to bolster amphibian communities. USGA Green Section Record. 2007;45(4):7–11.
218. Holland R. Why wetlands are more than a water hazard on the golf course. Geo Foundation for Sustainable Golf. 2022 [accessed 2026 June 30]. https://sustainable.golf/news/articles/news/articles/why-wetlands-more-than-water-hazard-golf-course
219. LaVardera F, editor. A guide to environmental stewardship on the golf courses. 3rd ed. Audubon International; 2020.
220. USFWS. Bird-friendly golf courses. United States Fish & Wildlife Service. 2024 June 24 [accessed 2026 June 30]. https://www.fws.gov/story/bird-friendly-golf-courses
221. Winchell KM, Gibbs JP. Golf courses as habitat for aquatic turtles in urbanized landscapes. Landscape and Urban Planning. 2016;147:59–70. https://doi.org/10.1016/j.landurbplan.2015.11.001
222. Fouillouze A, Lacoeuilhe A, Truong M-XA. A step towards a greener green? Investigating golfers' relationships with nature and attitudes about biodiversity conservation in golf courses. Journal of Outdoor Recreation and Tourism. 2023;43:100659. https://doi.org/10.1016/j.jort.2023.100659
223. Green J. Ace idea: transforming defunct golf courses into parks. American Society of Landscape Architects. 2019 June 4 [accessed 2026 July 3]. https://www.asla.org/news-insights/dirt/ace-idea-transforming-golf-courses-into-public-parks
224. McCullough A. Tee change: restoring golf courses for climate resilience. Trust for Public Land. 2024 [accessed 2026 June 30]. https://www.tpl.org/blog/restoring-golf-courses-for-climate-resilience
225. Wang R et al. Molecular mechanism of exogenous magnesium in regulating cation homeostasis in roots of peanut seedlings under salt stress. Agronomy. 2024;14(4):724. https://doi.org/10.3390/agronomy14040724
226. Bennett NJ. Using perceptions as evidence to improve conservation and environmental management. Conservation Biology. 2016;30(3):582–592. https://doi.org/10.1111/cobi.12681
227. Whitehead JC et al. Chapter 21. Northeast. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
228. USGCRP. Fifth national climate assessment. Crimmins AR et al., editors. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
229. West JJ et al. Chapter 14. Air quality. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
230. Hayden MH et al. Chapter 15. Human health. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
231. Wilson AB et al. Chapter 24. Midwest. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
232. Domke GM et al. Chapter 7. Forests. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
233. McPherson RA et al. Chapter 26. Southern Great Plains. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
234. Hoffman JS et al. Chapter 22. Southeast. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
235. Thornton PE et al. Chapter 6. Land cover and land-use change. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
236. Chang M et al. Chapter 27. Northwest. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
237. Huntington HP et al. Chapter 29. Alaska. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
238. Knapp CN et al. Chapter 25. Northern Great Plains. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
239. White DD et al. Chapter 28. Southwest. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment
240. Frazier AG et al. Chapter 30. Hawai'i and US-Affiliated Pacific Islands. In: Crimmins AR et al., editors. Fifth national climate assessment. U.S. Global Change Research Program; 2023. https://www.cakex.org/documents/fifth-national-climate-assessment

Appendix A: Adaptation Implementation Case Studies

EcoAdapt conducted interviews with representatives from four golf courses (in Massachusetts, Iowa, California, and Washington, D.C.) between winter 2024 and summer 2025. Each course is pursuing climate change adaptation in response to its own site-specific conditions, climate impacts and vulnerabilities, and management priorities. The courses also vary in where they are in the adaptation process, ranging from planning and assessment to on-the-ground implementation. This appendix presents the interviews as case studies, highlighting each course's adaptation efforts, barriers, opportunities, and next steps.

The following case studies are meant to illustrate the real-world process that golf courses are engaged in to address the impacts of climate change, and they represent the best understanding that course representatives have of the climate stressors they are facing and the adaptation strategies that they are trying to implement. They are based on interview content only and should not be interpreted as broader recommendations.

The Kittansett Club's Response to Sea Level Rise in Buzzards Bay, MA

The Kittansett Club, a century-old private golf course situated on a low-lying peninsula in Buzzards Bay, Massachusetts, is proactively addressing the accelerating threat of sea level rise through a data-driven, phased adaptation framework. Leveraging high-resolution topographic mapping, probabilistic sea level rise projections, and site-specific inundation modeling, the Club has developed a strategic plan to elevate critical course infrastructure while minimizing disruption to operations.

STRESSOR	SEVERITY
Sea Level Rise	High

STRATEGY	DIFFICULTY	COST
Phase Elevation	High	High
Model-Driven Planning	Moderate	Moderate

COURSE FACTS
• Location: Marion, MA
• Private club, member-owned
• Established in 1922
• ~186.5 acres
• Approximately 300 golfing members

Climate Impacts and Course Vulnerabilities

Over the past decade, members and staff at Kittansett have observed increasing impacts from sea level rise, storm surge, and extreme tidal flooding. Twice-daily tidal encroachment in some areas of the course has become more pronounced, and major storm events have caused significant flooding and infrastructure damage. The club likely faces significant sea level rise by mid-century, with the risk of flooding on the course also increasing. Based on prediction models generated by Woods Hole Group and Forth Engineering for 2030, 2050, and 2070, there is a potential for sea level rise to impact nine holes on the course through flooding.

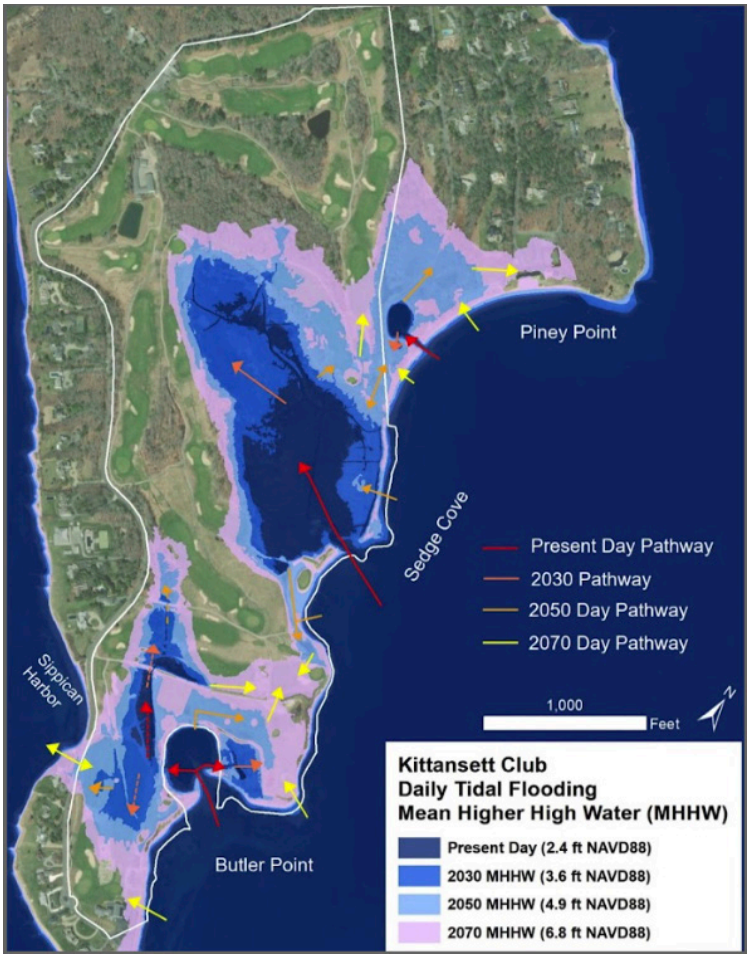


King tide plus storm surge flooding on the iconic 3rd hole of the Kittansett Club golf course. Credit: John Kelly and the Kittansett Club.

With the flooding of some holes during king tides, the impacts of sea level rise is evident on the course today and can influence when and where golfers play. Although some members initially viewed climate change with skepticism, the narrative began to shift around 2018 when Don Anderson, a club member and scientist at the Woods Hole Oceanographic Institution, began presenting data and future projections to the Club's Greens Committee and the Board of Governors.

On-the-Ground Adaptation Action[1]

Don's efforts, which included the use of NOAA's Sea Level Rise Viewer and other spatial modeling tools, made the risks tangible. Over several years, this work culminated in the formation of the Kittansett Club's Sea Level Rise Task Force in 2021. The task force's mission was to assess the club's vulnerabilities to future sea level conditions and guide long-term adaptation planning. As a starting point, the club commissioned a high-resolution elevation survey using drone-mounted lidar, which produced detailed altimetry data of the course's terrain, including greens, fairways, and topographic features. These elevation data were essential not only for modeling flood risk but also for preserving the architectural integrity of the course during potential redesign efforts.



Flooding inundation risk analysis for Kittansett Club. Colored arrows show the inundation pathways for 2030, 2050, and 2070 sea level rise estimates. Credit: The Kittansett Club.

To assess future risk scenarios, the Club teamed with a Massachusetts-based coastal modeling firm specializing in localized sea level rise projections. Using the 2022 NOAA Sea Level Rise Technical Report[130], the team analyzed region-specific scenarios for 2050 and 2070. For Buzzards Bay, projections indicate a likely (50th percentile) rise of 1.3 feet by 2050, but when planning for more conservative, high-confidence scenarios (e.g., 99th percentile), the club used a projection of 2.6 feet of sea level rise by mid-century. With these data, the task force mapped out inundation pathways, identifying which sections of the course are most vulnerable under these future sea level scenarios. This included modeling not just flooding, but also how saltwater could interact with stormwater drainage and further complicate course management.

The Club launched a complementary drainage assessment to evaluate how rainfall runoff will be affected by rising base water levels and design integrated stormwater management systems. Having an irrigation system with individually controlled sprinkler heads allows the Club to apply water where it is most needed, making every drop count. During an in-season saltwater flooding event, a well-designed irrigation system allows the Club to leach the areas most vulnerable to salt damage.

Throughout this time and going forward, the Club is working closely with its local engineering consultant and with the town Conservation Commission. This strategy comes with moderate difficulty and cost, as it requires finding and partnering with local experts, access to the necessary technology, and ensuring staff capacity for the required planning and coordination.

The Club's adaptation strategy is structured as a two-phase implementation plan. The first phase, already underway, is described as a "hold the line" approach. It targets areas above the U.S. Army Corps of Engineers (USACE) jurisdictional high tide line, allowing the Club to proceed without requiring federal wetland or coastal modification permits. In the first

1 This section presents the actions that a specific course is undertaking to build resilience and address the impacts of climate change. The case studies are derived directly from conversations with course management. At the time this case study was written, the authors were not aware of monitoring or evaluation efforts for the implemented strategies. The strategies and projects described do not represent adaptation recommendations by the authors of the report. Courses should always consult the most recent and locally relevant research before implementing a strategy.

phase, small berms are being added, and cart paths are being raised to reduce nuisance flooding. These modifications are relatively low-disruption and have helped build confidence among the membership. The second phase will be more ambitious and costly, and the Club is proceeding cautiously. If implemented, it will involve significant course alterations, including raising some fairways, bunkers, and greens by 2 to 3 feet to ensure course viability as water levels rise.

In addition to elevating course features, the Club has launched initiatives to prepare for extreme weather and adapt to changing conditions. A committee focused on storm preparedness has developed contingency plans for infrastructure protection, such as relocating critical gear from the pro shop to elevated areas and identifying roads that remain passable during severe events.

The Club has installed a reverse osmosis system to address saltwater intrusion in irrigation water and is experimenting with topdressing to gradually raise course elevation and improve drainage. As most of the Club's irrigation is from wells that are brackish in nature, a likely impact of sea level rise for the Club is the salinization of water supplies. If irrigation sources become too salty, it can stress turfgrass, thereby reducing performance and survival and threatening the course's playability. The reverse osmosis system will help minimize this impact, as will the proactive seeding of areas of the course with grasses that have increased disease resistance and drought and salt tolerance.

Opportunities and Barriers

While support among members has grown, financial and cultural barriers persist. Some members are hesitant to fund large-scale, long-term improvements whose benefits may not be realized within their tenure. Others are not convinced that the sea level rise estimates are accurate. Fundraising will certainly be an issue if the decision is made to move to the second phase of the plan, as will coordinating course closures to complete the proposed raising of fairways, bunkers, and greens while maintaining member play. A key constraint is the seasonal mismatch between golf's off-season (winter) and turf's optimal growing period (spring and fall), which limits the temporal window for successfully implementing strategies such as raising fairways.

Looking Ahead

The Club will continue the first phase of its climate adaptation strategy while engaging with members and the broader community to expand support for more extensive implementation. To foster buy-in, the task force is emphasizing that the "hold the line" policy gives the club time to examine new sea level rise data over the next few years while ensuring that the USACE jurisdictional line does not shift and prevent future interventions.

The task force is highlighting current "nuisance flooding" from once-yearly king tides as a glimpse of the potential for twice-daily high tide conditions expected several decades from now without action. Ongoing outreach, including meetings with members to communicate planned and in-progress climate interventions, aims to strengthen understanding, transparency, and collective commitment to the Club's long-term resilience.

The Kittansett Club, one of the nation's most historic and highly ranked courses, is emerging as a leader in coastal climate adaptation. Its approach to its sea level rise issues can be viewed as forward-looking, data-driven, and appropriately cautious. By leveraging high-resolution elevation data, regional sea level rise models, and in-house scientific expertise, the Club is taking a logical and methodical approach to safeguarding its landscape and legacy.

Acknowledgments
Don Anderson (Senior Scientist, Biology Department and Director, Cooperative Institute for the North Atlantic Region (CINAR) and Director, US National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution)

Photo Credit
All images were provided for use in this case study courtesy of Don Anderson and the Kittansett Club.

Related Resources
- Responding to the rise at The Kittansett Club, GCM
- Kittansett Club Targets Rising Seas, John Steinbreder
- NOAA Sea Level Rise Viewer
- 2022 SLR Technical Report, Sweet et al. 2022
- Kittansett Club Website

Palmer Hills' Strategy for a Climate-Resilient Course

Palmer Hills Golf Course is implementing habitat restoration, turf management updates, and community programming to build a course that is more resilient to the impacts of climate change. Located within city boundaries and surrounded by homes and businesses, Palmer Hills is becoming an important part of the community's efforts toward adaptation. The course's adaptation interventions aim to support water conservation, flood mitigation, and the conservation of habitats and biodiversity, as well as education.

STRESSOR	SEVERITY
Flooding	High
Drought	Moderate-to-high
Erosion	Moderate

STRATEGY	DIFFICULTY	COST
Turf Management	Moderate	Moderate
Restoration	Moderate	Moderate-to-high

COURSE FACTS
• Location: Bettendorf, IA
• Public course, municipal facility
• Established in 1974
• 150 acres
• 41,700 rounds in 2024



Flooding along Stafford Creek, which runs through much of Palmer Hills Golf Course. Credit: Brian Hickey and Palmer Hills Golf Course.

Climate Impacts and Course Vulnerabilities

Palmer Hills Golf Course is facing worsening drought conditions that have resulted in water scarcity and increased irrigation demand. These impacts have led course management to seek expanded water allocations from the State of Iowa Department of Natural Resources. Simultaneously, rainfall has become less frequent but more intense, with sudden deluges causing flash flooding along Stafford Creek, a waterway that drains a significant portion of the city and courses directly through Palmer Hills. Flooding across Iowa is projected to worsen and become more unpredictable. This will increase flooding risks for Palmer Hills, which already experiences flooding and is near the Mississippi River, with several creeks running through the course. Increased extreme heat events and late-summer drought will also affect the course by impacting turfgrass health and causing health and safety concerns for staff and golfers. Erosion in the creeks running through the course is already evident, and future erosion severity will be tied to heavier rainfall and more frequent flooding.

On-the-Ground Adaptation Action[2]

Palmer Hills has taken a proactive, multifaceted approach to ecological and operational adaptation, with a strong emphasis on turfgrass resilience. Recognizing the unsuitability of legacy grass varieties under current climatic conditions, Palmer Hills is working to transition to drought- and heat-tolerant turfgrass species on greens and fairways. On tees, fairways, and roughs, they have introduced a turf-type tall fescue developed at Iowa State University that has been tested for drought and heat tolerance. This turf has required minimal maintenance and has proven durable, which is important because 85% of the golf rounds at Palmer Hills are played with a golf cart, which often causes significant wear and tear on the turf. They have also built a 1.5-acre putting green using T1 bentgrass, a variety that has drought and heat tolerance.

[2] *This section presents the actions that a specific course is undertaking to build resilience and address the impacts of climate change. The case studies are derived directly from conversations with course management. At the time this case study was written, the authors were not aware of monitoring or evaluation efforts for the implemented strategies. The strategies and projects described do not represent adaptation recommendations by the authors of the report. Courses should always consult the most recent and locally relevant research before implementing a strategy.*



Derecho wind event caused the loss of 25 full-size trees, including 250-year-old oak trees on the Palmer Hills Golf Course. Credit: Brian Hickey and Palmer Hills Golf Course.

As with many courses, during the golf season, soil moisture meters are used daily to help managers assess whether the irrigation system is delivering the appropriate amount of water to the greens and collars. These readings provide site-specific insight into which areas require irrigation and which do not, thus allowing staff to fine tune watering practices and reduce unnecessary water use. Rather than relying on visual estimates, managers can use moisture data to make informed decisions. At Palmer Hills, the use of moisture meters has helped improve consistency in course playability by supporting turf health through identifying where and when water is needed.

Palmer Hills completed a restoration project to help manage course flooding and mitigate drainage from neighboring residential and commercial areas into the creeks that run through the course. They made a $200,000 investment to repair severe erosion in a small creek by hole 10 and to build a pond to slow water flow and reduce downstream damage. Course management is also planning restoration efforts for Stafford Creek, which runs through the course property. Its banks are steep, with some approaching 90 degrees, which has led to significant erosion over time. Building on the success of the previous creek restoration, course leadership has proposed a phased approach over the next decade to reshape the banks of Stafford Creek with more gradual slopes. The cost of this effort is projected to exceed $1 million. Restoration of the creek would help stabilize the channel, reduce erosion, improve the site's ecological integrity, increase the creek's capacity to manage heavier rainfall, and reduce sediment runoff. Restoration costs can be high, and course management is actively working to secure funding to advance these projects.

Palmer Hills has also converted over 25 acres of non-play areas to native Iowa prairie, which has enabled management to focus labor and turf maintenance on areas actively in play on the course and on those areas potentially more sensitive to drought or flooding. This transition has helped reduce watering needs on the course and the resources used to maintain the area (e.g., mowing, fertilizer, and water).



A group of students visiting Palmer Hills Golf Course conducts water quality testing in the creek near Hole 10 to learn more about local water conditions. Credit: Brian Hickey and Palmer Hills Golf Course.

Community Engagement Co-Benefits

Palmer Hills is actively involved in environmentally related community engagement and outreach initiatives. This has not only brought residents together to engage in course activities but also has the co-benefit of increasing community awareness of climate impacts and the strategies course management is using to address these impacts. Palmer Hills participates in the Audubon Cooperative Sanctuary Program, which has supported the course toward developing an environmental management plan. Additionally, Palmer Hills has become a local leader in environmental education. Through a partnership with the Bettendorf School District and First Green initiative, the course hosts over 300



A clear, sunny day at Palmer Hills Golf Course. Credit: Brian Hickey and Palmer Hills Golf Course.

students annually for environmental science lessons that use the course as a "living laboratory." These programs introduce participants to water conservation, habitat restoration, and sustainable land management, and provide an opportunity to discuss how climate change may impact the course and how these practices may relate to climate change adaptation efforts planned or implemented on the course.

Opportunities and Barriers

While many of these efforts stem from local initiative rather than regulatory mandate, they are enabled by a supportive municipal structure. When Brian Hickey, the current Golf Maintenance Manager, assumed the role, the city administrator encouraged him to think innovatively and adapt the course to better serve its users and the environment. In response, Hickey introduced strategic changes, including new tee boxes and forward tees in a neutral gray color, to make the course more inclusive for seniors and younger players. He also proposed converting 25 acres of underused, intensively maintained turf into native Iowa prairie, a suggestion that the city embraced, resulting in significant reductions in mowing, irrigation, and fertilizer use. These actions reshaped public perception of course modifications, including those related to ecological restoration. This enhanced public perception and favorable response to course modifications resulted in an increase in the number of rounds played annually from 26,000 to 41,000. This earned Hickey and Palmer Hills the trust needed from the municipality to pursue further sustainability and resilience efforts.

Challenges persist as seasonal staffing shortages strain the course's ability to meet rising maintenance demands, especially with longer golf seasons driven by warming temperatures. Large-scale infrastructure projects, such as creek restoration and renewable energy installations, face funding hurdles and depend on external grants. These obstacles are balanced by notable opportunities. The environmental initiatives at Palmer Hills follow the guidelines established by the Audubon Cooperative Sanctuary Program, enhancing the property's environmental quality through operational efficiency, education, and stewardship. The course also has strong municipal backing that has granted the manager operational autonomy. Also, public engagement has built goodwill between the course and the community and increased local interest in and knowledge of resilience-building strategies to address the impacts of climate change.

Looking Ahead

Palmer Hills is exploring future initiatives such as installing bat and birdhouses to expand wildlife habitat, adopting solar energy, and eventually implementing a water recycling system to reduce reliance on potable and irrigation water. Plans also include broadening public programming on sustainable land use and climate resilience, supported by a proposed committee to guide ongoing sustainability efforts. Palmer Hills is a model for how a city-owned course can lead the way in local adaptation efforts.

Acknowledgments
Brian Hickey (Golf Maintenance Manager, Palmer Hills Golf Course)

Photo Credit
All images were provided for use in this case study courtesy of Brian Hickey and Palmer Hills Golf Course.

Related Resources
- The First Green program
- Audubon Sanctuary Program
- Championing Sustainable Turf Management at Palmer Hills Golf Course, SoilTech
- Palmer Hills Best Management Practices
- Palmer Hills Golf Course Website

Drought Adaptation and Landscape Transformation at La Rinconada Country Club

La Rinconada Country Club is implementing adaptation strategies, including turfgrass conversion and phased landscape transformation, to address increasing drought, extreme heat, and water scarcity. The Club is also investing in technology and infrastructure to support the long-term resilience of the course.

STRESSOR	SEVERITY
Drought	High
Extreme Heat	Moderate-to-high

STRATEGY	DIFFICULTY	COST
Landscaping and Turf Management	Moderate	Moderate

COURSE FACTS
• Location: Los Gatos, CA
• Private course
• Established in 1929
• 446 equity members and ~1,000 social members
• 125 acres

Climate Impacts and Course Vulnerabilities

Drought is projected to become more severe and prolonged as higher temperatures increase soil drying and water demand. Extreme heat events are also expected to become more frequent and intense, which will incresae stress on turfgrass, irrigation supplies, and worker safety. These impacts, in addition to regulatory mandates and resource cutbacks, have created operational uncertainty and prompted the La Rinconada Country Club to reevaluate its water-use practices and turfgrass strategy.

While not as persistent as drought, extreme weather events, including atmospheric rivers, wildfires, and winter storms, also impact the course. For example, one atmospheric river event caused the uprooting and loss of 40 mature trees in La Rinconada.

On-the-Ground Adaptation Action[3]

La Rinconada has taken a phased approach to climate adaptation over the past decade. One of the most significant interventions to date is the transition to more drought-tolerant turfgrass. Club management has introduced bermudagrass to the course, replacing previously used perennial ryegrass. The goal of introducing drought-tolerant turfgrasses was to reduce irrigation demand, cut maintenance costs, and support the health and survival of the course's turf under changing climate conditions. The Club has observed that bermudagrass requires fewer resources and less frequent watering, which ultimately is expected to be a financial benefit for the Club. However, replacing the grass can require a significant amount of resources upfront, both financially and in terms of staff capacity, with a course-wide redesign requiring substantially more time, funding, and coordination than replacing turfgrass in only select areas on the course. While the bermudagrass has provided superior summer playability for La Rinconada compared to less heat- and drought-tolerant grasses, its dormant appearance in the winter has made it necessary for the Club leadership to manage member expectations about what a course "should" look like and reaffirm the Club's commitment to year-round resilience and playability.

The Club is also removing non-native and high-water-use tree species and replacing them with native species, prioritizing drought-tolerant species when possible. This change is supported by local municipal authorities and has encouraged Club management to focus more on restoration and preservation activities. Advanced monitoring tools, including drones, soil

[3] *This section presents the actions that a specific course is undertaking to build resilience and address the impacts of climate change. The case studies are derived directly from conversations with course management. At the time this case study was written, the authors were not aware of monitoring or evaluation efforts for the implemented strategies. The strategies and projects described do not represent adaptation recommendations by the authors of the report. Courses should always consult the most recent and locally relevant research before implementing a strategy.*

sensors, and robotic mowers, have also been integrated into daily operations to support precision irrigation and reduce resource consumption.

Opportunities and Barriers

One of the biggest challenges for La Rinconada has been the visible change in the course's appearance as drought-tolerant turfgrass and other landscape modifications have been implemented. Members have compared La Rinconada with nearby facilities that still use traditional turf and some have expressed concern about the differences in color and texture. Still, Club leadership views these changes as an opportunity to improve long-term course performance and reduce resource use. Although the transition may require adjustments in member expectations, managers believe the Club's willingness to adopt new practices will strengthen its resilience to climate change.

A factor supporting the Club's adaptation efforts has been its sustained leadership and perseverance. Securing member support for climate adaptation interventions required careful, consistent communication and a clear demonstration by Club management of the benefits of resilience-building initiatives to members. Member concerns about course renovations, particularly those requiring temporary closures, have been addressed through small group meetings and direct conversations with Club leadership. Early wins for management from the turfgrass transition, such as water-use reductions during mandated cutbacks, helped build trust with members. The Club has built momentum toward its resilience goals, but management recognizes that maintaining that progress will require continued communication, transparency, and engagement with staff and members.

Looking Ahead

La Rinconada leadership is focused on ensuring that adaptation becomes embedded in the Club's culture and operations and plans to continue investing in innovative technology and infrastructure improvements. The Club also sees potential in sharing its model more broadly to demonstrate how legacy institutions can take meaningful steps to address climate challenges while enhancing the member experience.

Acknowledgements
Kevin Breen (Project Manager, Superintendent, La Rinconada Country Club)
Andy Kimball (General Manager, La Rinconada Country Club)

Related Resources

- Taking a Bird's Eye View
- Course Website
- Managing microclimates on golf courses
- Planning with climate and weather data

Advancing Climate Resilience Across Public Golf Courses in Washington, D.C.

National Links Trust (NLT) is advancing resilience at three public golf facilities in Washington, D.C.: Langston Golf Course, Rock Creek Park Golf, and East Potomac Golf Links. Each course is closely connected to waterways and exposed to flooding and stormwater runoff. Through stormwater management and restoration projects, NLT is working to improve water quality, biodiversity, and community resilience. Their efforts demonstrate how urban public golf courses can serve as recreational assets and important components of broader resilience strategies.

STRESSOR	SEVERITY
Flooding	High
Precipitation	High
Sea level rise	Moderate-to-high

STRATEGY	DIFFICULTY	COST
Habitat Restoration	Moderate	Moderate-to-high
Stormwater Management	High	Moderate-to-high

COURSE FACTS
• Location: Washington, D.C.
• Public courses
• Part of the National Park System
• **Langston Golf Course**
• Established in 1939
• 145 acres
• Home to the oldest African American men's and women's golf clubs in the United States
• **Rock Creek Park Golf**
• Established in 1923
• 100 acres
• The first public golf course in Washington, D.C.
• **East Potomac Golf Links**
• Established in 1923
• ~395 acres
• Has the oldest continuously operating miniature golf course in the country

Climate Impacts and Course Vulnerabilities

At **East Potomac Golf Links**, heavy rainfall contributes to flooding along the main access route to the course. Stormwater from heavy rain events accumulates across the golf course from poor grading and drainage, which creates areas of standing water throughout the property. This impacts the golf course agronomy department's ability to effectively maintain the course and negatively affects customer experience and satisfaction resulting from poor turfgrass and soil conditions, as well as erosion-created ruts throughout the maintained areas of the golf course and the cart paths.

At **Rock Creek Park Golf**, stormwater runoff and erosion are priority concerns. Heavy rainfall puts pressure on stormwater infrastructure, particularly in areas of D.C. served by combined sewer systems. During intense rain events, these systems can become overwhelmed, increasing the risk of untreated discharges into local waterways. At the course level, runoff and erosion can contribute to sediment loss and degrade both playing conditions and nearby ecosystems. Rock Creek Park Golf must also manage invasive species. Prior to restoration efforts, many out-of-play areas were heavily overrun by invasive species, including amur honeysuckle (lonicera maackii), porcelain berry vine (Ampelopsis glandulosa), oriental bittersweet vine (Celastrus orbiculatus Thunb), and linden viburnum (Viburnum dilatatum). Overcrowded and unmanaged forested areas have also affected turfgrass performance by limiting sunlight, restricting airflow, increasing root competition, and reducing turf's ability to recover during warm periods. Poor turf conditions negatively affect customer satisfaction and course playability.

Langston Golf Course faces many of the same stormwater, drainage, and habitat-related issues as East Potomac Golf Links and Rock Creek Park Golf, but its site conditions add further complexity. Langston Golf Course is in northeast D.C. along the Anacostia River and Kingman Lake and just south of the National Arboretum. Kingman Lake is a tidal impoundment established when the Anacostia River was dredged as part of a USACE project over 100 years ago. Portions of the golf course were built on dredged soil from the USACE project, and much of the

remaining portion is on a former landfill. These conditions complicate habitat restoration and turfgrass management due to the potentially degraded soils that may restrict plant growth. Standing water in fairways, sediment loss around buried irrigation infrastructure, poor soil conditions, limited turfgrass coverage, and overgrown canopy areas all contribute to maintenance and playability challenges. In addition, trash and debris that enters the course through stormwater flows and tidal movement from Kingman Lake and the Anacostia River creates ongoing management challenges along stream corridors.

On-the-Ground Adaptation Action[4]

NLT is pursuing a range of strategies focused on stormwater management, erosion control, habitat restoration, and operational resilience. These efforts are guided by the organization's mission to support affordable and accessible municipal golf while increasing the value that golf courses provide to surrounding communities.

At **East Potomac Park Golf**, NLT completed a total restoration and renovation of the historic miniature golf course associated with the site in August 2024. Before the project, even moderate rainfall could make the course unplayable for 24 to 48 hours. As part of this effort, rain gardens were installed to improve stormwater retention, and while on-site drainage improvements are ongoing, the project has already improved the miniature golf course's ability to reopen much sooner after even the heaviest of rainfalls. At a small scale, rain gardens can be a lower-cost, lower-difficulty intervention for capturing water. Performance may be limited, however, by large storms or inappropriate siting, making rain gardens complementary to broader drainage or flood mitigation efforts rather than a stand-alone effort.

Native rain gardens were a necessary addition to the newly restored East Potomac Miniature Golf Links to alleviate flooding and standing water after heavy rain.

At **Rock Creek Park Golf**, NLT is designing a 600,000-gallon rainwater cistern to be constructed beneath the new clubhouse and portions of the nine-hole regulation course. The cistern is intended to reduce reliance on municipal water for irrigation while also capturing and storing stormwater during heavy rain events. This approach supports both operational efficiency and watershed protection by reducing runoff and helping limit erosion and sediment loss. Maintenance, sizing, and siting approvals may affect implementation difficulty or the cistern's success.



East Potomac Golf Links Miniature Golf Course. Native rain gardens were a necessary addition to the newly restored East Potomac Miniature Golf Links to alleviate flooding and standing water after heavy rain. Credit: Andrew Szunyog and the National Links Trust.

At **Langston Golf Course**, NLT is advancing a large-scale stream daylighting and wetland restoration project, which will restore more than 4,600 linear feet of stream and establish approximately 10 to 13 acres of wetland habitat. These improvements are intended to reduce stormwater impacts, limit sediment loss, improve water quality, and support biodiversity. Project completion is expected by 2030. Daylighting and restoration may be costly and challenging for a course due to technical requirements, staff capacity for planning and sustained maintenance, and physical site constraints. NLT is also partnering with the Anacostia Watershed Society on habitat restoration efforts connected to the golf course,

[4] *This section presents the actions that a specific course is undertaking to build resilience and address the impacts of climate change. The case studies are derived directly from conversations with course management. At the time this case study was written, the authors were not aware of monitoring or evaluation efforts for the implemented strategies. The strategies and projects described do not represent adaptation recommendations by the authors of the report. Courses should always consult the most recent and locally relevant research before implementing a strategy.*



Langston Golf Course stream daylighting. An Environmental Protection Agency Clean Water Construction Grant will help restore approximately 4,600 linear feet of stream to improve on-course resilience, restore native ecosystems, and mitigate the impacts of stormwater runoff. Credit: Andrew Szunyog and the National Links Trust.

Kingman Lake, and the Anacostia River. Regional restoration efforts have already contributed to visible conservation benefits, including the presence of wildlife such as beavers, ospreys, and bald eagles in the area.

Across all three courses, adaptation options have been shaped through discussions with external stakeholders around BMPs for stormwater management as well as guidance from organizations such as the Golf Course Superintendents Association of America. Project development across the courses has relied on strong relationships with stakeholders, an understanding of stormwater management requirements, collaboration with qualified vendors, and securing approvals from the National Park Service.

Opportunities and Barriers

Funding is one of the most significant barriers to implementing adaptation projects. Many of the NLT's planned or ongoing projects would be difficult to fund without grants and external support. Staff capacity is another constraint. Course departments already manage extensive day-to-day responsibilities, so new initiatives must be designed to improve efficiency, save resources, or create operational capacity rather than adding to already heavy workloads. Staff turnover and loss of institutional knowledge can also affect long-term project success. NLT recognizes the importance of creating strong program foundations so that adaptation efforts can continue even as staffing changes occur. Time and prioritization are additional challenges, particularly given the number and complexity of vulnerabilities across the three facilities. Rather than attempting to solve every issue at once, the organization is focusing on incremental progress, risk prioritization, and steady improvements.

The acquisition of grant dollars to address priority issues such as stormwater management and the expansion of staff to address areas of concern have facilitated adaptation actions across the three courses. Partnerships with organizations such as the Anacostia Watershed Society and engagement with D.C. agencies have helped NLT better understand local priorities and align golf course projects with broader watershed goals. NLT has also expanded staff capacity by hiring a Habitat Restoration Specialist, a role designed to bridge habitat restoration and golf course maintenance by monitoring out-of-play areas, managing invasive species, supporting restored habitats, and training operations staff.

Stakeholder support has also been important. Internally, NLT has emphasized the need for buy-in from leadership and staff. Externally, public reception to sustainability initiatives has generally been positive. However, communicating the purpose and value of these efforts to course users remains an ongoing challenge. Many people visit golf courses for recreation and to relax, so outreach must inform and engage users without overwhelming them. Effective outreach strategies will help golfers and visitors understand how golf courses contribute to

community resilience and why that matters to them. This benefits the courses' sustainability and adaptation efforts by building user buy-in.

Looking Ahead

The NLT will continue working with internal stakeholders (staff and leadership) and external stakeholders (community partners, non-profits, and environmental organizations) to understand how climate vulnerabilities are changing over time and to refine priorities for action. A major goal is to establish vulnerability baselines and track climate-related impacts and frequencies across the courses in order to answer these questions when making adaptation strategy decisions: What information do we need? How should we interpret data? What is the feasibility of this? How will it impact daily operations? And who are the partners we need?

The NLT's work demonstrates how public golf facilities can address climate risks while also contributing to stormwater management, habitat restoration, biodiversity, and broader community resilience. The NLT sees an opportunity to apply lessons from its projects to develop best practices and storytelling tools to support other golf organizations.

Acknowledgements
Andrew Szunyog (Director of Sustainability, National Links Trust)

Photo Credit
All images were provided for use in this case study courtesy of Andrew Szunyog and the National Links Trust.

Related Resources
National Links Trust 2024 Sustainability Report

Appendix B. Regional Summaries

The following tables summarize historic trends and projected future changes for climate hazards within the Northeast, Midwest, South, and West regions of the U.S. The information in these tables is adapted from the 5th National Climate Assessment, published by the U.S. Global Change Research Program in 2023.

NORTHEAST U.S.

The Northeast region includes New England and northern Middle Atlantic states (Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont), where climate conditions are expected to shift towards wetter winters and more extreme precipitation, more extreme heat, higher sea levels, and increased coastal erosion.[227] These conditions can be particularly impactful in urban areas, where impervious surfaces (e.g., roads, sidewalks, parking lots) create areas of significantly higher heat and increase runoff that contributes to additional flooding and erosion.[227]

Table 5 presents climate trends and projections specific to the Northeast U.S., along with a confidence ranking based on the amount and accuracy of data that supports the projected outcome.

Table 5. Summary of historic trends and projected changes for climate hazards relevant for the Northeast U.S., based on climate information available in the 5th National Climate Assessment.[228]

CLIMATE HAZARDS AND FUTURE DIRECTION OF CHANGE	PAST AND FUTURE CHANGES IN THE NORTHEAST U.S.
Temperature ↑ High confidence	• Annual average temperatures have already increased by more than 2°F since the first half of the 20th century[15] • High ozone levels and smoke particulate concentrations are both expected to increase significantly as a result of heat waves and wildfire[229]
Extreme Heat ↑ High confidence	• Heat waves in the region have increased in frequency and length[15] • Days with a heat index over 100°F are expected to triple in the Northeast by mid-century[227] • Humid heat waves are much more likely to occur, which pose greater risk to human health because they limit the ability of the body to cool down through sweating[15]
Precipitation ↑ Moderate confidence	• Average annual precipitation has increased by 5–15% across the region,[15] and average precipitation has also increased in every season[15] • Projected increase of 2–5 inches of annual precipitation by 2065[227]
Drought ↑ Low confidence	• Drought occurrence has decreased slightly since 1901, though less than would be expected given precipitation increases[227]
Extreme Precipitation, Storms, and Flooding ↑ High confidence	• Extreme precipitation events (i.e., events with the top 1% of daily precipitation accumulation) have increased by 60% in the Northeast since 1958, which is a larger increase than for any other region of the U.S. and has resulted in increased flooding[15] • The frequency of extreme precipitation events and associated flooding are highly likely to continue to increase[227]

Sea level rise ↑ Moderate confidence	• Sea levels are rising faster than the global average along the Northeast Atlantic coastline, with 6 inches of sea level rise occurring between 1990 and 2020[18] • Under an Intermediate sea level rise scenario, 12 inches of sea level rise is projected to occur by 2050[18] • Coastal flooding has become more frequent over the last 30 years, as sea levels have risen, and will become about 8 times more frequent than it is today by 2050[18] • Coastal groundwater supplies are likely to be affected by saltwater intrusion[227]
Insects and Diseases ↑ Moderate confidence (variable, species-specific)	• Increased tick populations are expected as a result of warmer winter temperatures and reduced snow depth • West Nile virus is projected to expand further into the Northeast the next 50 years as a result of climate-related spread of mosquito populations[230]

MIDWEST U.S.

The Midwest region includes states in the northern central U.S. (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin), where climate impacts including warmer temperatures, large swings between wet and dry conditions, and riverine flooding are expected.[231] Climate variability is expected to continue increasing, exacerbating existing challenges managing water supply and quality, particularly in areas with significant agricultural land use.[231]

Table 6 presents climate trends and projections specific to the Midwest U.S., along with a confidence ranking based on the amount and accuracy of data that supports the projected outcome.

Table 6. Summary of historic trends and projected changes for climate hazards relevant for the Midwest U.S., based on climate information available in the 5th National Climate Assessment.[228]

CLIMATE HAZARDS AND FUTURE DIRECTION OF CHANGE	PAST AND FUTURE CHANGES IN THE MIDWEST U.S.
Temperature ↑ Moderate confidence	• Daily minimum temperatures have increased in the region, but daily maximum temperatures have cooled slightly in some areas due to high levels of plant transpiration as cropland has expanded. This trend is unique to the area, and introduces uncertainty about how agricultural land use will interact with future climate change[231] • Periods of cold have shortened and snow cover has decreased[231] • High ozone levels and smoke particulate concentrations are both expected to increase significantly as a result of heat waves and wildfire[229] • Pollen counts have increased and this trend is expected to continue as a result of warmer spring and fall temperatures[231]
Extreme Heat ↑ Moderate confidence	• Heat waves are projected to increase, along with heat-related illness and death[231]
Wildfire ↑ Moderate confidence	• Increased wildfire risk over the coming decades, along with increased exposure to wildfire smoke and associated illness[232] • 600% increase in the annual number of days conducive to very large fires in forested areas of Michigan, Minnesota, and Wisconsin[232]
Precipitation ↑ Moderate confidence	• Average annual precipitation has increased by 5–15% across most of the region and across seasons, although some areas have seen drier summers[15,231] • Annual precipitation is likely to increase by 0.3% to 1.5% per decade in the eastern portion of the region, and by 0.3% to 0.5% in western areas, depending on the climate scenario used[231] • Shift in future patterns of seasonal precipitation, with wetter conditions in the winter and spring, and drier or more variable conditions in the summer and autumn[115,231] • Increased precipitation variability, including rapid swings between very dry and very wet conditions, is highly likely by the end of the century[231] • By the end of the century, winter conditions are expected to result in reduced snow frequency and amounts, as well as shorter snow seasons and fewer intense snow events[231]

Drought ↑ Low confidence	• Overall decline in drought since 1895, although flash droughts (i.e., a rapid and intense drop in soil moisture) have become more frequent since 1980[231] • Future drought impacts on water availability will depend on the water source (surface water vs. groundwater), with surface water sources much more sensitive to flash droughts caused by warmer temperatures and drier or more variable summer runoff[231]
Extreme Precipitation, Storms, and Flooding ↑ High confidence	• Extreme precipitation events (i.e., events with the top 1% of daily precipitation accumulation) have increased by 45% in the Midwest since 1958, which has resulted in increased flooding[15] • Under global warming of 3.6°F (2°C, almost certain to occur), the intensity of extreme precipitation events is expected to increase by 10–15%, and up to 20% in some areas[15,231] • Increased riverine flooding is projected, particularly for the Ohio, upper Mississippi, and parts of the Missouri River basins[231] • Severe thunderstorms are likely to become more frequent, particularly in the spring and fall, resulting in a longer thunderstorm season[15]
Insects and Diseases ↑ Moderate confidence (variable, species-specific)	• Increased tick populations are expected as a result of warmer winter temperatures and reduced snow depth[232] • Northward expansion of insect pests into the region are expected as temperatures continue to warm[231]

SOUTHERN U.S.

This region includes of the southeast, south central, and south Atlantic U.S., including Alabama, Arkansas, Delaware, District of Columbia, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, and West Virginia. Climate changes in the region are expected to range from hotter conditions and more heat waves to drought, higher sea levels, coastal erosion, and more severe hurricanes and other storms, among other changes.[233,234] Across parts of the region, rapid population growth has led to sprawling development that increases vulnerability to climate change. As a result of development, large areas of impervious surfaces create heat islands and increase runoff and subsequent flooding, while development along the coastline is extremely vulnerable to sea level rise and storm surge, particularly during hurricanes and other storm events.[233,234] Other areas of this large region are much more rural, often dominated by uses such as agriculture and energy production.[233,234]

Table 7 presents climate trends and projections specific to the Southern U.S., along with a confidence ranking based on the amount and accuracy of data that supports the projected outcome.

Table 7. Summary of historic trends and projected changes for climate hazards relevant for the Southern U.S., based on climate information available in the 5th National Climate Assessment.[228]

CLIMATE HAZARDS AND FUTURE DIRECTION OF CHANGE	PAST AND FUTURE CHANGES IN THE SOUTHERN U.S.
Temperature ↑ Moderate confidence	• Average annual temperatures have increased in Oklahoma and Texas[233] but warming trends are much slower in the southeast states as a result of forest increases as agricultural areas were abandoned between 1920 and 1990[235] • High ozone levels, particulate concentrations, and pollen counts are expected to increase significantly as a result of warmer temperatures[233,234]
Extreme Heat ↑ High confidence	• Heat waves in the region have increased in frequency and length, and the season is starting earlier and lasting longer[233,234] • Days with a heat index over 95∞F are expected to increase significantly, with the greatest changes in Florida, southern Louisiana, and southwestern Texas (up to an additional 50 days per year)[233,234] • Humid heat waves are much more likely to occur, which pose greater risk to human health because they limit the ability of the body to cool down through sweating[15]
Precipitation ↑ Moderate confidence	• Precipitation in the southeastern states has increased in the fall, but drier conditions are occurring in the spring and summer[15] • Annual precipitation is expected to increase across most of the region by midcentury, though overall drier conditions are projected for southern Florida, most of Texas, and western Oklahoma[79,233]
Drought ↑ Low confidence	• Summer soil moisture is expected to decline across the region by midcentury[79] • Drought risk is projected to increase significantly in Texas and Oklahoma, and more moderately in most other areas of the region[79]

Extreme Precipitation, Storms, and Flooding ↑ High confidence	• Extreme precipitation events (i.e., events with more than 2 or 3 inches in 24 hours) have increased, and are expected to continue to do so[233,234] • Severe thunderstorms are likely to increase in frequency, particularly in the spring and fall, resulting in a longer thunderstorm season[15] • Hurricanes are intensifying more rapidly and have exhibited a trend towards moving more slowly or stalling, which has resulted in greater likelihood of very high rain totals, and these trends may continue[234] • Over the coming decades, hurricanes are expected to strengthen to Category 4 intensity and make landfall more frequently, resulting in greater flooding as a result of increased storm-related rainfall and higher storm surges driven by sea level rise[234]
Sea level rise ↑ Moderate confidence	• Sea levels are rising faster than the global average along the southeast Atlantic and eastern Gulf Coast coastlines, with an average of 6 inches of sea level rise occurring between 1990 and 2020. The greatest rise in the U.S. is occurring along the western Gulf Coast, where land subsidence due to tectonic plate shifts and groundwater pumping has resulted in 9 inches of sea level rise[18] • Under an Intermediate sea level rise scenario, 9 inches of sea level rise is projected to occur in the eastern Gulf Coast by 2050, with 10 inches in the southeast Atlantic and 15 inches in the western Gulf Coast[18]. • Coastal flooding has become more frequent over the last 30 years, as sea levels have risen. It will become about 5 times more frequent than it is today by 2050, with the exception of the western Gulf Coast where it may become up to 10 times more frequent[18] • Coastal groundwater supplies are likely to be affected by saltwater intrusion, particularly where land subsidence is occurring[233,234]
Insects and Diseases ↑ Moderate confidence (variable, species-specific)	• Expected increase in mosquito-borne diseases, along with tick populations that carry Lyme disease, Rocky Mountain spotted fever, and other diseases[234]

WESTERN U.S. (INCLUDING HAWAI'I AND ALASKA)

The Western region of the U.S. includes Alaska, Arizona, California, Colorado, Hawai'i, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. The region is characterized by climate extremes and high levels of variability and is experiencing significant climate changes that impact wildfire regimes and water supplies.[236-240] These trends are likely to continue, likely including warmer temperatures and more extreme heat, shifts in precipitation patterns, increased drought, and wildfire, among others.[236-240]

Table 8 presents climate trends and projections specific to the Western U.S., along with a confidence ranking based on the amount and accuracy of data that supports the projected outcome.

Table 8. Summary of historic trends and projected changes for climate hazards relevant for the Western U.S., based on climate information available in the 5th National Climate Assessment.[228]

CLIMATE HAZARDS AND FUTURE DIRECTION OF CHANGE	PAST AND FUTURE CHANGES IN THE WESTERN U.S.
Temperature ↑ High confidence	• Average annual temperatures are significantly increasing across the region,[15] particularly in Alaska where temperatures are rising up to three times the global average[237] • Temperatures will continue to warm, with more extremely hot days and fewer extremely cold days[236-240] • High ozone levels, dust, and smoke particulate concentrations are expected to increase significantly as a result of heat waves and wildfire[229]
Extreme Heat ↑ High confidence	• Heat waves in the region have increased in frequency and severity since the 1980s[15] • In June 2021, a deadly heat wave in the Pacific Northwest was 2–4° F hotter than it would have been in the absence of climate change[15] • Heat waves are expected to continue to increase in frequency and intensity[15,115]
Wildfire ↑ Moderate confidence	• Wildfire frequency, size, and area burned at high severity has significantly increased across the region, particularly in the southwest[232] • Wildfire is expected to increase, including fire severity, size, and the frequency of extreme fire conditions[232] • Wildfire increases are particularly likely where invasive grasses occur, leading to high fuel loads[232]
Precipitation ↑ Moderate confidence	• Average annual precipitation has decreased by 10–15% across Hawai'i and the southwest, as well as much of the Northwest and parts of Alaska[15] • Annual precipitation is expected to increase in Alaska and decrease in the Southwest under an Intermediate scenario, with smaller changes occurring in other areas of the region[79] • In many areas of the region, summer precipitation is expected to decline while winter precipitation will increase[236,239] • Precipitation variability is expected to increase, with larger swings between wet and dry periods[238,239] • Significant snowpack declines are expected to occur by mid-century across the region, except for northern Alaska where temperatures will stay cold enough to sustain snowfall[79] • Changes in precipitation and the proportions of rain and snow are likely to result in continued changes in surface water availability[79]

Drought ↑ High confidence	• Drought frequency and intensity has significantly increased over the past century,15 particularly in the Southwest[239] • Between 2000 and 2021, drought conditions in the southwestern U.S. were calculated to be more severe than any other drought event over the last 1,200 years[15] • Severe and prolonged periods of drought are expected to increase significantly, resulting in large impacts to groundwater and surface water supplies across the region[15,79,239]
Extreme Precipitation, Storms, and Flooding ↑ High confidence	• The frequency of extreme precipitation events and associated flooding are highly likely to increase in most areas[15,236,239] • Atmospheric rivers (i.e., narrow bands of concentrated water vapor in the atmosphere that bring large amounts of moisture from the tropics towards the poles) are expected to become larger and stronger, increasing flood risks[15,236]
Sea Level Rise ↑ Moderate confidence	• Sea levels have risen 2 inches along the northwest Pacific coastline, 3 inches along the southwest Pacific coastline, and 4 inches along the Hawaiian coastline between 1990 and 2020. Sea level rise along the Pacific and Alaskan coastlines is highly variable due to a combination of land subsidence and tectonic uplift occurring in different areas[18] • Under an Intermediate sea level rise scenario, an average of 5 inches of sea level rise is projected to occur in the coastal northwest Pacific by 2050, with 6 inches in the southwest Pacific and 8 inches in Hawai‘i[18] • Coastal flooding has become more frequent over the last 30 years, as sea levels have risen, and will continue to increase significantly by mid-century[18]
Insects and Diseases ↑ Moderate confidence (variable, species-specific)	• Expansion of mosquito- and tick-borne diseases such as West Nile virus and Rocky Mountain spotted fever[230] • Warmer temperatures and shifts in seasonal precipitation patterns are expected to accelerate the establishment and spread of invasive plants, including non-native grasses that exacerbate the impacts of wildfire and drought[238]