ELEMENT # 3: Submerged Aquatic Vegetation (SAV)

A. CONTRIBUTORS/Element Team

Brooke Landry, CBP SAV Workgroup Chair
Becky Golden, CBP SAV Workgroup Vice-Chair
Marc Hensel, Virginia Institute of Marine Science
Chris Patrick, Virginia Institute of Marine Science
Dick Zimmerman, Old Dominion University
Rhianne Cofer, Old Dominion University
Bob Murphy, TetraTech

AT-A-GLANCE

· The three primary symptoms of climate change that will directly affect Chesapeake Bay SAV: rising water temperatures, increased CO_2 concentrations, and sea level rise.

· Temperature impacts to eelgrass are well understood. Without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay. The Bay's most economically significant fishery – blue crabs (*Callinectus sapidus*) – is directly dependent on eelgrass.

· Temperature impacts to other Chesapeake Bay SAV species are not as well studied but appear to be less dramatic than those to eelgrass. Increasing temperatures negatively impact all Chesapeake Bay SAV communities to some extent.

· The CO_2 fertilization effect may counterbalance some of the impacts from warming, but unknowns associated with invasive species, pathogens, cyanobacteria, etc. may set that balance awry.

· Management efforts (ie. the Chesapeake Bay TMDL) that have reduced N and P in the Chesapeake have facilitated recovery of SAV, and SAV are more resilient to all climate stressors if water clarity is maximized. The single most effective action to protect Chesapeake Bay SAV is to sustain and accelerate improvements in water quality and clarity through N, P, and TSS load reductions.

· The currently funded climate and SAV modeling project will be instrumental in answering many questions.

· SAV restoration efforts for diverse species may mitigate some of the loss of SAV from areas unable to recover without a seed source.

B. RESOURCES

Chesapeake Bay Submerged Aquatic Vegetation (SAV): A Third Technical Synthesis:
This technical synthesis (TS III) for Chesapeake Bay SAV was a multi-institutional effort to synthesize the state of the science completed in December 2016 and includes a detailed chapter on the known effects of climate change, including increasing temperatures. The chapter on climate is called *21ˢᵗ Century Climate Change and Submerged Aquatic Vegetation in the Chesapeake Bay*, and was written by Tom Arnold, Dick Zimmerman, Katia Engelhardt, and Court Stevenson. Because information about temperature impacts to Chesapeake Bay SAV was already synthesized in TS III, much of the information was copied directly into the synthesis below for ease of translation.

Virginia Institute of Marine Science (VIMS) Bay-wide Aerial Survey data This dataset provides annual information on the distribution and density of SAV throughout the Chesapeake Bay and its tributaries for all years since 1984 and allows for analysis of SAV trends in relation to water quality, clarity, and climate change related stressors, including increasing temperatures.

VIMS Ground-truthing observations and transect data: VIMS has collected ad-hoc SAV data from reliable sources since the beginning of the survey. Data collection has been sporadic and non-standardized, but the data collected has contributed to our understanding of the distribution of various species of SAV throughout the Bay. VIMS also conducts SAV surveys at long-term permanent transects. These transects are used to confirm SAV density and bed edge delineated in the aerial survey, and are standardized and reliable.

Chesapeake Bay SAV Watcher data: Though only recently developed and implemented, the SAV Watcher program data collected by Riverkeepers and watershed groups throughout the Bay have been helpful in identifying restoration sites and donor beds, and will be invaluable in the coming years for tracking climate impacts to specific species.

Chesapeake Bay SAV Sentinel Site Program: This nascent program is still in the development stage, but was initially conceptualized in order to track the impacts of climate change on SAV at a more detailed scale than either the Bay-wide aerial survey or the CB SAV Watcher program can provide. Though collection of data at "new" sites will begin in 2022, several existing long-term transects will be adopted as sentinel sites, so historical data will be available in some areas.

Chesapeake Bay SAV Fact Sheets: The Chesapeake Bay SAV Synthesis Project brought together experts from the CBP partnership specializing in SAV, water quality, and land-use research and management. The goal of the project was to conduct a synthesis of multiple long-term datasets to determine what role the growing human population in the Chesapeake Bay watershed has played in influencing SAV distribution and abundance and if the sustained efforts and management actions implemented by the CBP partnership have benefited SAV habitat. Additionally, the SAV Synthesis Project team conducted segment-specific reviews of SAV trends and progress towards restoration targets and created SAV fact-sheets for each

segment. This local-scale segment review of SAV in each tributary aims to provide a summary of information that may guide local planning and implementation of best management practices (BMPs) to encourage SAV recovery throughout the Bay. Although information from the fact sheets was not specifically referenced in the chapter following, they are mentioned here because SAV loss is often attributed to heat events, and these events are discussed in many of the fact sheets.

Published Papers: See Bibliography

C. APPROACH

No new analyses were conducted solely for the purposes of this chapter. Rather, the authors pulled heavily from the recently synthesized information in the TS III chapter on climate and SAV as well as on more recently published research. Additionally, authors included information regarding currently funded, on-going, and Chesapeake Bay-specific studies to learn more about rising temperature impacts on SAV. Preliminary results are included where available.

D. SYNTHESIS

INTRODUCTION
Submerged aquatic vegetation (SAV) in Chesapeake Bay and globally provides vitally important ecosystem services. These include the provision of food, habitat, refuge, and nursery grounds for commercially, recreationally, and ecologically important fish, shellfish, and a variety of invertebrates. Even waterfowl use SAV beds extensively. The submerged plants also take in and process excess CO_2 and nutrients, which helps mitigate impacts from climate change by sequestering carbon and decreasing the opportunity for macroalgae and phytoplankton blooms, including harmful algal blooms (HABS), by removing their fuel source. As they take up CO_2 and release O_2, SAV beds buffer the impacts of coastal acidification on the vulnerably shelled organism either living within the beds or nearby. Their physical presence in the water column baffles current and wave energy, reducing shoreline erosion.

Because of its importance, the Chesapeake Bay Program (CBP) and its partners have committed to achieving and sustaining 185,000 acres of SAV in Chesapeake Bay. This 185,000-acre target is the cumulative sum of 92 individual segment targets which state and local governments are attempting to achieve primarily by improving water quality and clarity conditions. In 2010, the Chesapeake Bay Total Maximum Daily Load (TMDL) was implemented. This "pollution diet" had the effect that two and a half decades of insufficient regulatory policies did not. Between 1984, when an annual Bay-wide aerial SAV survey was initiated and 2010 when the TMDL was implemented, SAV acreage went from just under 40,000 acres to just under 80,000 acres, essentially doubling. That represents slow but steady progress but was not impactful enough to entertain the idea of reaching the ultimate or interim SAV restoration targets (2017: 90,000 acres; 2025: 130,000 acres) on time or possibly

ever. Between 2010 and 2018, however, following implementation of the TMDL, SAV expanded from 80,000 acres to 108,000 acres, showing that significant management actions and consequent improvements in water quality can in fact facilitate the recovery of the Bay's SAV (Lefcheck et al., 2018).

Unfortunately, it has become apparent that current efforts to reduce nutrient and sediment loads to the Bay may be insufficient to ensure the long-term sustainability of SAV recovery in Chesapeake Bay. In 2020, just over 62,000 acres of SAV were mapped in the Bay, representing a loss of more than a third of the Bay's grasses in a two-year time frame. The loss was largely a result of rapidly degraded water quality from increased precipitation and the consequent run-off and elevated nutrient and sediment loads entering the Bay, broad fluctuations in salinity, and elevated water temperatures. Increased and more intense periods of precipitation are predicted symptoms of climate change which will inflate the current long-term reductions in water clarity and regional decreases in salinity observed in the Bay. These symptoms as well as others, such as rising water temperatures, will likely impact our ability to meet our SAV restoration targets and the impacts will vary among the Bay's salinity regimes and SAV communities.

WHAT WE KNOW ABOUT TEMPERATURE EFFECTS ON CHESAPEAKE BAY SAV

In 2016, members of the Chesapeake Bay Program's SAV Workgroup completed *Chesapeake Bay Submerged Aquatic Vegetation: A Third Technical Synthesis (TS III)* (Landry et al. 2016). The synthesis, conveniently for this purpose, includes a chapter on "21ˢᵗ Century Climate Change and SAV in Chesapeake Bay." The authors (Arnold, Zimmerman, Engelhardt, and Stevenson) scoured, evaluated, and synthesized the available literature to determine what impacts, if any, climate change and its associated stressors will have on the various SAV communities and species in the Chesapeake. Explained in more detail below, Arnold et al. found both reasons for concern and hope. The "CO_2 fertilization effect" caused by increased atmospheric CO_2 concentrations may counterbalance some of the known detrimental stressors that SAV will face, including rising water temperatures. On the other hand, a litany of unknowns may set that balance awry.

The following text is largely copied directly from TS III. Bracketed [text] indicates that this chapter's authors have added text for clarification or updated information and citations that were published after TS III was completed and either support or refute Arnold et al. In short, Arnold et al. concluded "that [SAV] restoration efforts will be complicated by new stressors associated with accelerating climate change. In the Chesapeake Bay these are: a mean temperature increase of 2-6°C, a 50-160% increase in CO_2 concentrations, and sea-level rise of 0.7-1.6m. Warming alone has the potential to eliminate eelgrass (*Zostera marina)*, the once dominant seagrass, from the Chesapeake. Already high summer temperatures cause mass die-offs of this cool-water species, which lives near its thermal limits [in the Chesapeake]. During this century, warming will continue and the Chesapeake will begin to exhibit characteristics of a subtropical estuary, with summer heat waves

becoming more severe. This will favor native heat-tolerant species such as widgeon grass (*Ruppia maritima*) and certain ecotypes of freshwater SAV, and may facilitate colonization by subtropical seagrasses. Intensifying human activities will also fuel biological processes, such as eutrophication, that drive coastal zone acidification. The resulting high CO_2 / low pH conditions, shaped by diurnal, tidal, and seasonal cycles, may benefit SAV. The *"CO_2 fertilization effect"* has the potential to stimulate photosynthesis and growth in at least some species of SAV and this may offset the effects of thermal stress, facilitating the continued survival of eelgrass at some locations. This equipoise between two forces - thermal stress and acidification - may ultimately determine the fate of cool-water plants in warming estuaries such as the Chesapeake Bay. Finally, sea level rise will reshape the shorelines of estuaries, especially the Chesapeake Bay where land subsidence is significant. Where waters are permitted to migrate landward, suitable habitat may persist; however, where shorelines are hardened SAV may be lost. Our understanding of SAV responses to these three stressors have greatly improved in recent years and allow us to make basic, testable predictions regarding the future of SAV in estuaries. The indirect effects of climate change on associated organisms, however, including fouling organisms, grazers, and microbes, are poorly understood. These indirect effects are likely to prevent smooth transitions, triggering abrupt phase changes in estuarine and freshwater SAV communities subjected to a changing climate."

Regarding temperature impacts, specifically, "Chesapeake Bay waters are predicted to warm by 2 to 6° C, on average, during this century. This is similar to global forecasts for surface air temperatures and ocean surface temperatures, which are predicted to increase 1.1 to 6.4° C and 3 to 4 ° C, respectively (Levitus et al. 2001; Meehl et al. 2007; Intergovernmental Panel on Climate Change [IPCC] 2007, 2014, 2021). These increases in temperature would be in addition to the 0.8 °C increase in mean global surface temperatures that has already occurred, as a result of atmospheric CO_2 exceeding 400 ppm. There are direct, first-order relationships between atmospheric carbon dioxide levels, air temperatures, and Chesapeake Bay water temperatures (Wood et al. 2002). In some areas of the Bay, such as the main stem of the Bay and the Potomac estuary, water temperatures are increasing faster than air temperatures (Ding and Elmore 2015). Unless there is a drastic change in the prevailing "business-as-usual" scenario whereby CO_2 levels continue to rise, exceeding 1000 ppm in the atmosphere over the next century, observed warming of Chesapeake Bay waters will continue in the future. In this case the Chesapeake Bay is likely to develop characteristics of a subtropical estuary by the next century.

Although average temperature projections represent a useful window into climate change, they provide an incomplete picture of the thermal environment, particularly in the near-term when the most devastating temperature effects may result from an increase in the frequency, duration, and amplitude of periodic summer heat waves (IPCC 2014). Furthermore, warming of the Chesapeake Bay will not occur uniformly. Local water temperatures will continue to depend upon circulation patterns that affect ocean mixing, precipitation, and other factors, all of which are impacted by climate change. The greatest and most inconsistent warming will almost certainly occur in shallow waters, the habitats of submerged vegetation, as well as in areas affected by urbanization, such as the Patapsco

River in Baltimore (Ding and Elmore 2015).

For Chesapeake Bay SAV, which can live close to their thermal limits, even moderate warming is problematic (Somero 2002; Hughes et al. 2003). Most Bay species are considered to be "temperate" species, with an optimal growth temperature of 11.5° C to 26° C. In general, increasing temperatures alter rates of photosynthesis and respiration, interfere with life-cycles, trigger disease outbreaks and algal blooms, and cause increased seagrass mortality e.g., (Campbell et al. 2006). The ability of SAV to tolerate warming will however be species-specific (McMahon 2005; Campbell et al. 2006; Walker et al. 2006).

Eelgrass. [Although the CO_2 fertilization effect may counter the negative impact of climate warming on eelgrass growth (Zimmerman et al. 2017), light intensities must be sufficient for photosynthesis to take advantage of the more abundant CO_2 substrate (Zimmerman 2021). Consequently,] general consensus supports the prediction that increased temperatures will adversely impact eelgrass populations in Chesapeake Bay during this century (Najjar et al. 2010). *Zostera marina* is a temperate species with an optimal water temperature of approximately 10-20° C, with 16-17° C being an optimal range for seedling growth (Niu et al. 2012). Colder temperatures are tolerated and plants remain healthy at 5° C. At these colder temperatures growth is slowed (Nejrup and Pedersen, 2008) but photosynthesis:respiration ratios are maximized (Marsh et al. 1986; Zimmerman et al. 1989). Eelgrass growth rates increase linearly from 5 to 25° C (Kaldy 2014). Beyond this temperature, however, deleterious effects emerge. High temperatures of 25-30° C depress rates of photosynthesis and growth (Zimmerman et al. 1989; Niu et al. 2012) and dramatically increase mortality. Marsh et al. (1986) determined that above 30°C, *Zostera marina* has a negative net carbon balance, photosynthesis becomes overwhelmed by increasing rates of respiration, and plants decline rapidly. [Hammer et al. (2018) found that high temperatures (30°C) negatively affect eelgrass growth, tissue integrity, nitrogen metabolism and protein/enzyme synthesis.] The impact of elevated temperatures can be worse in low light. Kaldy (2014) showed the temperature-induced increase in eelgrass respiration can be problematic even at temperatures between 10-20° C when light is limiting photosynthesis (also see Ewers 2013; Jarvis et al. 2014). In theory, eelgrass could escape deleterious temperatures by retreating to deeper, cooler waters (McKee et al. 2002; York et al. 2013). Increasing colonization depth, however, is not likely to be a successful strategy for adapting to future climate change, as the lower depth of eelgrass is restricted by light penetration and climate change is likely to cause further deterioration of water clarity in the Chesapeake (Thayer et al. 1984; McKee et al. 2002; York et al. 2013). The poor tolerance of elevated temperatures suggests a bleak future for eelgrass in the Chesapeake Bay.

The impacts of thermal stress have already been observed in the Chesapeake and neighboring coastal bays in Delaware, Maryland and Virginia. Extended warm periods, such as those occurring in the 1980s and 1990s, have been linked to population declines of eelgrass in the eastern Atlantic (Glmarec 1997). Acute warming from summertime heat waves has triggered shoot mortality and population declines. Eelgrass diebacks in the Goodwin Islands and York River Chesapeake Bay National Estuarine Research Reserve in

Virginia during 2005 were attributed to a greater frequency and duration of water temperatures above 30°C (Moore and Jarvis 2008; Moore et al. 2014). These authors noted a tipping point at 23° C; changing eelgrass cover from 2004 to 2011 was linked with temperatures below and above 23° C, respectively. Although a variety of other factors influence the thermal tolerance of *Z. marina*, it is clear that temperatures above 25°C or, more generally, increases of 1-5°C above normal summertime temperatures, can trigger large-scale die-off of eelgrass in the Chesapeake Bay (Jarvis et al. 2012; Moore et al. 2012, 2014; Jarvis et al. 2014). For example, these authors predicted that: (1) short-term exposures to summer temperatures 4-5° C above normal will *"result in widespread diebacks that may lead to Z. marina extirpation from historically vegetated areas, with the potential replacement by other species"* (Moore et al. 2014); (2) longer-term average temperature increases of 1-4° C are predicted to "severely reduce or eliminate" *Zostera marina* from the Chesapeake Bay (Moore et al. 2012, 2014); and "an increase in the frequency of days when summer water temperature exceeds 30°C will cause more frequent summer die-offs" and is likely to trigger a phase change from which "recovery is not possible" (Carr et al. 2012).

Similar losses have been predicted in neighboring regions, e.g. for the Bogue Sound-Back Sound in North Carolina (Micheli et al., 2008). Restored eelgrass meadows are also vulnerable as higher temperatures (at or above 30° C) are associated with summer die-offs and failures of these new meadows (Tanner et al. 2010; Carr et al. 2012). Similarly, successful SAV restoration in the neighboring coastal bays has been attributed to cooler temperatures (Orth et al. 2010, 2012; Moore et al. 2012) and more favorable water quality resulting in a better light environment (Zimmerman et al. 2015).

Widgeongrass. *Ruppia maritima* tolerates a wider range of temperature and salinity conditions than does eelgrass (Stevenson 1988). It ranges along the eastern coastline of North America from Florida to Nova Scotia and is distributed within meso- and polyhaline portions of the Chesapeake Bay, though populations are patchy and ephemeral (Stevenson et al. 1993). Although biomass does not approach that of eelgrass in the lower polyhaline region of the Bay, it can be the dominant SAV species in the meso- and polyhaline regions of the central Bay, even in intertidal flats when temperatures are moderate in spring and fall (Staver et al. 1996). Unlike eelgrass, *Ruppia* tolerates a wide range of water temperatures ranging from 7 to 40° C. Ideal growth conditions have been reported to range from 20 to 25° C or even 18 to 30° (see Pulich 1985; Lazzar and Dawes 1991; Moore et al. 2014). Anderson (1969) sampled SAV from a thermal plume at the Chalk Point Power Plant on the Patuxent River and found that the lethal temperature was 45°C. Although *Ruppia* tolerates these conditions, higher temperatures have a negative influence on photosynthesis beyond 25°C. For instance, Evans et al. (1986) observed that the maximum photosynthetic rate (P_{max}) increased with temperatures up to 23°C before becoming inhibited (compared to 19°C for *Z. marina* in the same study).

Ruppia sp. reproduction is also impacted by temperature. Optimal seed germination occurs at 15-20°C. In Europe, seed germination was observed to occur at temperatures beginning at 16°C but only after a period of cold stratification at 2-4°C (Van Vierson et al. 1984). If the Chesapeake becomes more subtropical, it may eventually not be cold enough for presently

adapted *Ruppia* plants to reproduce by seed, reducing overall population resilience. Temperature changes may have other subtle effects on future population cycles; for example, plants germinated at low temperatures reproduce much more quickly than plants germinated at higher temperatures.

Ruppia's very wide temperature tolerance may make it a "winner" in a warmer climate, replacing eelgrass in much of the lower Bay. This has already been observed [in several locations (Stevenson et al. 1993), including the York River (Moore et al., 2014; Shields et al. 2018, 2019), when unusually high summer temperatures caused die-offs of eelgrass which facilitated a shift from eelgrass to widgeon grass. Outside of the Chesapeake], *Zostera*-to-*Ruppia* transitions occurred in San Diego Bay following the 1997-8 El Niño Southern Oscillation (ENSO), leading Johnson et al. (2003) to predict that a warming of 1.5 to 2.5° C would result in *"a permanent shift in the local seagrass vegetation from eelgrass to widgeongrass"* in this bay.

Freshwater species. Lower salinity regions of the Chesapeake and its tributaries are also experiencing significant warming (Seekell and Pace 2011; Ding and Elmore 2015; Rice and Jastram 2015). Warming may decrease photosynthesis and increase respiration (Ryan 1991), thereby impacting the distribution, modes of reproduction, germination, growth, and dormancy of freshwater SAV (Welch 1952; Barko and Smart 1981; Lacoul and Freedman 2006).

The response of freshwater aquatic plants to climate warming is often species-specific, and may vary even for locally-adapted "biotypes" of a single species (Haller et al. 1976; Haag and Gorham 1977; Madsen and Adams 1988; Barko and Smart 1981; Pip 1989; Svensson and Wigren-Svensson 1992; Spencer and Ksander 1992; Santamaria and Van Vierssen 1997; Rooney and Kalff 2000; Sala et al. 2000; Lacoul and Freedman 2006; Amano et al. 2012). Some species exhibit earlier germination and increased productivity, while others do not (McKee et al. 2002; Lacoul and Freedman 2006). Most submerged freshwater plants require temperatures above 10°C during the growing season, exhibit optimal growth between 10° and 20° C, but do not survive temperatures above 45°C (Anderson 1969; Lacoul and Freedman 2006).

Myriophyllum spicatum, a non-native species, also has a broad temperature range with optimal photosynthesis between 30 to 35°C (Barko and Smart 1981; Nichols and Shaw 1986). Similarly, net photosynthesis of *Potamogeton crispus*, another non-native species, is also highest around 30°C (Nichols and Shaw 1986). *Stuckenia pectinata* prefers 23 to 30°C for early growth (Spencer 1986) and can tolerate 35°C (Anderson 1969). [Wittyngham et al. (2019) found that higher temperatures tended to have positive effects on *S. pectinata* traits and that high salinity treatments had few negative effects except when temperature was coolest. This could explain the recent migration of *S. pectinata* in the Bay from oligohaline to mesohaline waters. As the Bay warms, it is moving into higher saline environments.] Perhaps the most temperate sensitive species that occurs in freshwater areas of the Bay is *Elodea canadensis* with a reported range of 27 to 35°C (Santamaria and van Vierssen 1997; Olesen and Madsen 2000). In complementary growth chamber experiments, *Elodea canadensis* from the Chesapeake Bay

performed best at 28°C but were stressed at higher temperatures that are commonly experienced in the thermal plume (32°C) of C. P. Crane Power Station (Beser 2007). However, populations of the same species may vary widely in their adaptation to warm temperatures. For example, *Vallisneria americana*, the most dominant freshwater SAV species in the Chesapeake Bay, is reported to grow best between 33 and 36°C (Korschgen and Green 1988). However, Beser (2007) observed that *Vallisneria* from the Chesapeake Bay were able to survive 36°C over a six-week period whereas plants from Wisconsin could not, suggesting that conspecific plants are acclimated or are adapted to different temperatures through phenotypic plasticity and genetic diversity.

Warming may also impact the reproduction of freshwater SAV. Germination for many species requires cold stratification. However, warmer conditions and an extended growing season, now increasing at a rate of over 1 day per year (Kari Plough et al. in prep.), cause species such as *Potamogeton* spp., *Stuckenia pectinata* and *Vallisneria americana* to germinate more quickly, grow deeper, become more productive, and yield more biomass (Hay et al. 2008; Jarvis and Moore 2008; Yin et al. 2013; Bartleson et al. 2014). Cao et al. (2014) observed that temperature also increases growth of periphyton on aquatic macrophytes (an effect that was dependent upon the presence or absence of periphyton grazers). Periphyton overgrowth is a major problem for the survival of *Potamogeton perfoliatus* in the upper portion of Chesapeake Bay where grazers are not effective in cleaning leaves, leading to a decline of light availability (Kemp et al. 1983; Staver 1984).

Unlike marine seagrass beds that are often monotypic, freshwater beds often consist of a diversity of SAV species (Crow 1993) with different niche requirements. These differences provide some insurance against changes in the environment - as one species declines due to unfavorable conditions, another may compensate and increase in abundance. Thus, it has been suggested that increasing temperatures may have neutral effects on communities or even enhance species diversity within temperate freshwater aquatic plant communities (Grace and Tilley 1976; Haag 1983; Rooney and Kalff 2000; Heino 2002; Lacoul and Freedman 2006). However, warming may eventually compromise and weaken diversity. For example, observations of the SAV community within and outside the thermal effluent of the power generating station C. P. Crane located along Dundee and Saltpeter Creeks of the Gunpowder River, MD, (Beser 2007) show that SAV cover and diversity are both generally lower inside the thermal plume and that temperature is an important environmental gradient. SAV diversity is also impacted when warming boosts the productivity of non-native species such as *Hydrilla verticillata*, which colonized the tidal freshwater regions of the Chesapeake Bay from further south in the 1980s. This species possesses a variety of physiological adaptations that allow it to thrive in conditions that exclude native species (e.g. *Vallisneria americana*) in freshwater (Haller and Sutton 1975; Staver and Stevenson 1995).

It is worth noting that freshwater SAV habitats have been among the most highly-altered ecosystems, altered by human activity and non-native species, motivating new insights and approaches to resource management in the 21st century. Restoring freshwater SAV communities to *"an earlier condition or stable state"* is often no longer possible (Moyle 2014). This realization spawned the new field of "reconciliation ecology", described by Rosenzweig

(2003) as the *"science of inventing, establishing, and maintaining new habitats to conserve species diversity in places where people live, work, and play"* and by Moyle (2014) as *"a practical approach to living with the new reality"* where resource managers take *"an active approach to guiding ecosystem change to favor desired species"* (see Hershner and Havens, 2008). Within the context of climate change, our poor understanding of how warming impacts freshwater SAV limits this type of "active management". To manage the impacts of climate warming on freshwater aquatic plants, we require not only a better understanding of thermal tolerance of dominant plant species, but also their interactions with grazers and microbiota, which can be symbiotic or pathogenic (e.g. fungi, bacteria, archaea, viruses, phages and etc.)

Comparison to other regions. Thermal stress impacts seagrasses inhibiting other coastal ecosystems beyond the Chesapeake. For example, it is well-established that changing climate conditions have impacted populations of *Posidonia oceanica* in the Mediterranean (between 1967 and 1992; Marba and Duarte 1997). More recently, Olsen et al. (2012) documented reduced growth rates, leaf formation rates and leaf biomass per shoot in response to warming from 25-32°C on *Posidonia oceanica* and *Cymodocea nodosa* from the Mediterranean Sea. Climate-induced thermal stress is a concern for Australian seagrasses as well, where *Zostera muelleri* was deemed *"sensitive to temperatures predicted under future climate change scenarios"* (York et al. 2013). *Z. muelleri* from southeast Australia has a thermal tolerance similar to *Z. marina* in the Chesapeake: it "grows optimally at 27° C, shows signs of thermal stress at 30°C, and exhibits shoot mortality at 32° C" (York et al. 2013). A modest warming of 2° C is believed to be responsible for a loss of *Z. muelleri* and a transition to the smaller, more tolerant *Halophila ovalis*, a shift that has persisted at one site for 33 years. Thomson et al. (2015) reported the >90% die-back of the temperate seagrass, *Amphibolis antarctica*, in Shark Bay, Australia, following an extreme heat event in 2010-11. These, and other studies, strongly suggest that climate warming could lead to the local extinction of seagrasses with low thermal tolerance in regions beyond the Chesapeake (Short and Neckles 1999).

Complication Factors. Climate warming will alter the diversity, composition, and functioning of SAV, grazers, fouling organisms, and pathogens (Blake and Duffy 2010; Blake et al. 2012). Some of the community-level changes that are likely to be triggered by warming include: increased eutrophication and poorer light penetration; proliferation of epiphytes that grow on the leaves of SAV; increases in harmful sediment sulfide levels (Goodman et al. 1995; Garcia et al. 2013); and increases in outbreaks of the seagrass wasting disease caused by the microbial pathogen *Labyrinthula* spp. (Kaldy 2014, but see Olsen and Duarte 2015 and Olsen et al. 2015). These interacting forces are likely to trigger episodic events, pass ecological thresholds, trigger tipping points, and induce phase changes so as to make it more difficult to predict the future of SAV communities. Wood et al. (2002) surmised that *"While it is likely that a prolonged warming will lead to a shift in the ecosystem favoring subtropical species over temperature species, physical or ecological factors other than temperature may preclude a smooth transition to a balanced <subtropical> ecosystem."*

Conclusion. Logically, nutrients and light have received the majority of attention for influencing SAV growth rates and survival in the Chesapeake Bay. However, long-term observations and research have also shown that temperature is an important environmental

factor that controls the germination, growth, reproduction and mortality of SAV. These effects will become even more important in the future with global climate change and the continued development and urbanization of coastal zones. The direct impacts of warming on most marine seagrasses are relatively well-understood. An abundance of evidence suggests that the outlook is poor for eelgrass (*Z. marina*), a cool-water species, in a steadily warming Chesapeake. The indirect impacts of warming on SAV species are more complex and difficult to predict and are likely to trigger relatively sudden, unpredictable changes, including increased abundances of thermo-tolerant species and the introduction of subtropical species, particularly *Halodule wrightii*, which currently persists in Back Sound, North Carolina (Kenworthy 1981). In contrast, it is difficult to accurately forecast the impacts of climate warming on SAV in the freshwater regions of the Chesapeake Bay, where temperature effects on plant metabolism may significantly interact with other environmental changes such as salinity and eutrophication (Ryan 1991)."

CURRENTLY FUNDED STUDIES ASSESSING CLIMATE-RELATED IMPACTS TO SAV IN CHESAPEAKE BAY

1. SAV and Climate Change Modeling Project
Following the development and completion of TS III, the CBP supported a multi-institutional effort that synthesized over 30 years of SAV, water quality, and land-use data. Results of the study empirically demonstrated that management efforts to reduce nutrient pollution were responsible for the recovery of tens of thousands of acres of SAV in the Bay. While the validation of environmental policy is rewarding and provides necessary incentive to stay the course to ensure additional future recovery, the role of emerging climate stressors was not included or accounted for in this study, and the question of these threats to the Chesapeake Bay ecosystem, and to SAV specifically, still lingers.

As such, the SAV Workgroup recently collaborated with CBP's Scientific, Technical Assessment, and Reporting (STAR) team and Climate Resiliency Workgroup (CRWG) to obtain Goal Team Implementation (GIT) funding for a project to address the role of climate stressors on Chesapeake Bay SAV, including warming temperatures, rising sea levels, chronic low oxygen concentrations, and increased runoff driven by greater precipitation and more frequent, intense storm activity. This project was awarded to Dr. Chris Patrick and his team at VIMS with a sub-award granted to Dr. Jon Lefcheck at the Smithsonian Environmental Research Center (SERC). Balancing nutrient management strategies with emerging stressors will be a significant challenge for the Chesapeake Bay management community. Complicating this task will be the variety of SAV species in the Bay and their potentially contrasting responses, as was demonstrated during the 2019 Bay-wide SAV survey. The excessive precipitation in 2018 and 2019 increased nutrient loading to the Bay and also affected salinities. This had a dramatic and negative impact on SAV in the mid to southern, saltier portion of the Bay in 2019 where thousands of acres of SAV were lost, but SAV in the upper portion of the Bay and tributaries continued to expand in most areas. This does not suggest that freshwater SAV communities are impervious to poor water quality; there is some anecdotal evidence that species diversity has decreased in recent years in some of the

Bay's freshwater areas suggesting that water quality changes have in fact affected these communities. It also highlights the necessity to identify the ecological tipping points or levels of stress these communities can endure before they collapse. Furthermore, it suggests that it may be beneficial to tailor future management strategies to the various SAV communities present in the Bay.

Specifically, the objective of this project is to model interactions between nutrient loading and emerging climate stressors, including warming temperatures, oxygen minimum zones, sea-level rise, greater precipitation, and reduced water clarity in determining future SAV abundance and recovery potential, and to determine species and community-level tipping points.

Final project products will include a detailed report of model outcomes and potential SAV recovery trajectories under various climate change scenarios. Additionally, a software application will be developed for use by the Chesapeake Bay research and management community that will allow users to explore and determine the relative impact of various stressors on future community-specific SAV abundance. The software application will be developed with the flexibility to determine site-specific SAV restoration potential in future versions. [Text copied directly from project RFP.]

Although only approximately six months into their study, the team working on the SAV and Climate Modeling project has already yielded important results. Those results are included here with the caveat that this information is preliminary and not yet peer-reviewed, and that on-going analyses may yield results that complicate present interpretation of model outputs. Regardless, internal discussions suggested that the results to date were worth including as they may illuminate additional research needs and management responses. To our benefit, the VIMS team is also simultaneously working on a widgeon grass specific project that complements the SAV and Climate project. Together, these two studies have begun to answer questions related to the impact of rising water temperatures on Chesapeake Bay SAV. A series of these questions were posed to the team; the questions and responses are summarized here, with some additional commentary included for clarity provided by the chapter authors.

Q1: What do preliminary analyses suggest about the impacts of temperature on the various SAV communities in the Bay? Do the communities respond differently?

R1: For this study, the Bay's SAV communities were clumped into four main groups. These include Eelgrass monoculture, Widgeon grass monoculture, Mixed Mesohaline, and Oligohaline/Tidal Fresh. Our Structural Equation Model (SEM) results suggest that temperature affects multiple SAV communities in the Chesapeake, but the strength of the effect varies over space and time. SAV communities respond differently to temperature in the sense that temperature at different times of the year and previous year affects SAV in different ways. Regardless, temperature always has a negative effect, and the strength varies across the bay.

Community	Is there a temperature effect on annual change?	Is there a temperature effect on large meadows?	Are nutrient effects on SAV stronger than temperature effects?	Are salinity/ water clarity effects on SAV stronger than temperature effects?	Notes:
Eelgrass monoculture	Yes, Summer temps(last year) & spring temps (this year)	Yes, Summer temps (last year)	No, but chl-a_{spring} is important also	Possibly, summer salinity and secchi are equivalent to temp effects	$Temp_{sum\,y1}$ can swamp out other effects
Widgeon grass monoculture	No	Yes, Spring temps have tiny effect	Yes, TN has direct negative effect	Yes, high summer salinity promotes regrowth	$Temp_{spring}$ does contribute to elevated chl-a and lower water clarity (indirect effect)
Mixed Mesohaline	Yes, Summer temps (min, this year)	No	Possibly, TP has similar negative effect	Yes, last year's salinity maximum has strongest negative effect	Only community where temp is in change model but not area model
Oligohaline/ Tidal Fresh	Yes, Summer temps (last year)	Yes, Summer temps(last year)	No, but TP_{summer} does have strong negative effect	No, but Summer chl-a has a negative effect	Temp effects may be via effects on the cyanobacteria!

To simplify communication of the results, model outcomes are further displayed in the following graph. Temperature is on the x-axis, but note that the variable changes for each community assemblage; significant temperature predictors were used for each.

- Widgeon grass monoculture: Spring mean temp
- Eelgrass monoculture: Summer last year median temp
- Mixed mesohaline: Summer min temp
- Fresh/oligohaline: Summer last year mean temp

The y-axis value is the mean change in vegetation area per station, in hectares. Communicating the difference in community assemblage by slope clarifies the ultimate message that eelgrass monocultures and tidal fresh/oligohaline communities clearly have a stronger (negative) response to temperature than widgeon grass monocultures or mixed mesohaline communities. While extensive research has shown that eelgrass is a cold water plant physiologically susceptible to high temperature extremes, it is not immediately clear why the tidal fresh/oligohaline community is also showing a significant negative response to increased temperatures. The majority of the plants in the freshwater regions of Chesapeake Bay (there are over a dozen freshwater SAV species in the Bay) are found throughout freshwater systems of the southeastern United States, suggesting they should be tolerant to heat extremes. One possible explanation, therefore, and as noted in the table above, is that the negative response in the tidal fresh/oligohaline community may be a result of cyanobacteria expansion in increasingly warm freshwaters of the Chesapeake. If this is the case, the effect is likely indirect and a result of shading rather than a physiological response and is in line with what Arnold et al. suggested in TS III regarding the plethora of unknown stressors that Chesapeake Bay SAV has in store as the climate warms. The impact of cyanobacteria on freshwater SAV are discussed later in this chapter.
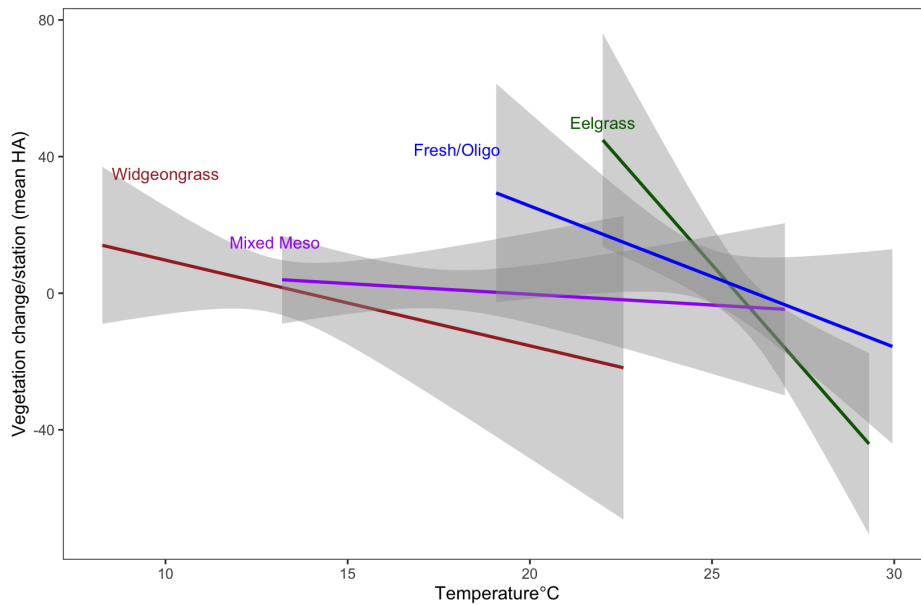
Q2: Do other stressors have a synergistic effect with temperature on Chesapeake Bay SAV, or does temperature stand alone in its impact?

R2: Actual synergistic effects (i.e., temp * light effects) have not been evaluated, but that is a potential analytical option that has been discussed. Other stressors have been evaluated in the models, however, as indicated in the table above. Temperature is never the sole predictor of annual vegetation change across the Bay's SAV communities. When using the area-change

model developed for this project (this model is more responsive to change in large meadows), temperature is overwhelmingly the strongest predictor of negative change in eelgrass monocultures and in the tidal fresh/oligohaline community, but a comparison of the magnitude of the effect size provides information on the relative importance of other variables as well. These are included in the table above and show that nutrients and clarity do, at times, have an equal or greater effect than temperature.

Temperature also has indirect effects on SAV in some of the models used. Specifically, high spring temperatures contribute to elevated chl-*a* and decreased water clarity (Secchi) in the widgeon grass monoculture analyses. Nutrient levels are more important than temperature in this case, but temperature does play a role in the biggest predictor of widgeon grass loss, which is high chl-a levels. Temperature similarly contributes to chl-a in the tidal fresh/oligohaline zone, but chl-a is less important in this model than in the widgeon grass monoculture model.

Q3: Is there sufficient certainty in the summarized research findings to support asking for further nutrient and sediment reductions for increased water clarity to offset the impacts of rising tidal water temperatures?

R3: Yes, there is sufficient certainty to support asking for further nutrient and sediment reductions not just to offset the temperature impacts for eelgrass monocultures and tidal fresh/oligohaline SAV communities, but to reduce the general impacts from above-average rain years like 2018-2019. Unmanaged nutrient inputs will surely exacerbate the effects of temperature extremes. The evidence for this lies within our SEMs that show, in each of the SAV communities where temperature is a significant predictor, that it is never the *only* significant predictor of change. Specifically, nutrient levels and/or water clarity variables frequently have either equivalent or greater effects on annual SAV change.

Outside of the direct comparison to temperature effects and more to the general importance of continued nutrient reductions, the baywide widgeon grass research also being conducted by VIMS nearly shows this on its own. Widgeon grass currently makes up approximately 40% of baywide SAV and is extremely sensitive to poor springtime water clarity. A significant proportion of recent SAV "recovery" over the last two decades is clearly correlated with nutrient reductions. Specifically, the two largest SAV acreage peaks that have occurred since the baywide aerial survey began in 1984 (2002-2003 & 2014-2016) are predominantly widgeon grass driven and widgeon grass clearly responds to both N and P (non-point source N, point-source P from the watershed) and chl-*a* (phytoplankton blooms) reductions. Widgeon grass recovery occurs almost exclusively in high salinity conditions (wherein low river flow/rainfall facilitates high water clarity).

Q4: How do Nitrogen, Phosphorus, and Total Suspended Solids impacts differ across the Bay and between SAV communities?

R4: Analyses indicate that the importance of each varies across the bay. Nitrogen appears to be most important in the lower bay. It affects both eelgrass and widgeon grass *via* chl-*a* and also affects widgeongrass directly, likely from epiphyte loading (epiphytes grow in response to high N) early in the growing season. Phosphorus does contribute to chl-*a* in the widgeongrass and eelgrass models even though it seems to be more important in the fresh and mesohaline regions, where summer TP actually has direct interactive effects on last year's grass coverage to negatively affect SAV acreage. TSS did not play a significant role in our models, but that doesn't necessarily mean it's not important. Rather it may reflect a lack of data.

Q5: Do you envision a set of circumstances in which we can keep a viable population of eelgrass in Chesapeake Bay in the coming decade(s) given increasing temperatures above survival thresholds for this species?

R5: The combined effect size of temperature variables and water clarity variables are nearly equivalent in the eelgrass model in terms of year to year change. However, when the eelgrass area change model (which is driven more by large meadows) is employed, the previous summer median temperature is the only significant predictor of area change and the effect is quite strong. In fact, the negative effect size is larger than the positive effect of the grass that was there the year before. This indicates that temperature extremes have the ability to completely outweigh any water clarity effects when we look at change over large areas as opposed to proportional change across all areas, even areas with sparse SAV.

With that in mind, the answer may still be yes. Temperature extremes would need to occur practically every year to completely extirpate what we have now, theoretically, if temperature were the only stressor. Eelgrass in the Bay continues to respond positively to nutrient reductions/water clarity improvements, so management of those is absolutely essential moving forward to maintain eelgrass populations.

2. Cyanobacteria Study
Another issue of emerging concern regarding increasing water temperatures and the Chesapeake's SAV is the recent proliferation of benthic cyanobacteria in the Bay's freshwater regions. Benthic cyanobacteria, originally identified in the Bay as *Lyngbya* and *Oscillatoria,* became prevalent on the Susquehanna Flats beginning in 2004, and reports of their presence in the SAV beds of other tidal fresh and oligohaline tributaries of the upper and mid-Bay are becoming more frequent as well. The expansion of benthic cyanobacteria is thought to be facilitated in part by increasing water temperatures. Because these cyanobacteria fix atmospheric nitrogen into a biologically useful form of N, they could be altering the role of SAV beds where they co-occur as net nitrogen sinks, seasonally turning them into nitrogen sources instead. If so, this may exacerbate the complexity of management actions needed to support SAV productivity in the Bay.

Additionally, the overgrowth of benthic cyanobacteria atop SAV leads to reduced light availability and inhibition of gas exchange, which may decrease SAV photosynthetic rates and

increase sediment anoxia and nutrient fluxes (Watkinson et al. 2005; O'Neil et al. 2012; Tiling & Proffitt 2017). As mentioned in the discussion of the SAV and Climate Modeling study above, this may explain the negative effect of increasing temperatures on freshwater SAV. Interestingly though, cyanobacteria blooms are far more prevalent on the Susquehanna Flats SAV bed than anywhere else in the Bay, and the bed has continued to expand in acreage and density regardless of their presence.

Aside from serving as a possible explanatory variable in the SAV and Climate Modeling study, these co-occurring cyanobacteria have not been taken into consideration in previous studies of ecological and biogeochemical dynamics on the Susquehanna Flats or other regions of Chesapeake Bay. Furthermore, it is unclear whether these cyanobacteria produce harmful toxins, as documented in other geographic regions.

As such, researchers and managers from the University of Maryland Center for Environmental Science, St. Mary's College of Maryland, and the Maryland Department of Natural Resources were recently funded by Maryland Sea Grant to conduct a study that aims to better understand the causes and effects of increasing benthic cyanobacteria abundance in Chesapeake Bay with an emphasis on their impact on SAV and nutrient dynamics. The team will address the following questions: 1) what factors are driving benthic cyanobacteria proliferation on the Susquehanna Flats and other regions of Chesapeake Bay (ie. increasing water temperature?), 2) what effect do benthic cyanobacteria have on ecosystem processes, including SAV and nutrient dynamics, and 3) are benthic cyanobacteria producing toxins known to cause adverse reactions in humans or animals?

It is anticipated that the results of this study will generate important scientific insights about the role of benthic cyanobacteria in shallow, tidal fresh and oligohaline ecosystem recovery dynamics and will inform management efforts aimed at protecting human and ecological health in Chesapeake Bay. [Much of this text was copied directly from the project proposal but information was added in for clarity and comparison to the SAV and Climate Modeling study by the chapter authors.]

WHAT IS BEING DONE TO DIRECTLY RESTORE CHESAPEAKE BAY SAV?
While there are multiple stressors acting against the sustained recovery of SAV in Chesapeake Bay, including rising water temperatures, SAV restoration practitioners have seen increasing success rates in small-scale, direct SAV restoration efforts. Historically, direct restoration in Chesapeake Bay has proven costly and largely ineffective because most efforts centered on the restoration of a single species: eelgrass. As discussed previously, eelgrass is a cool water species near its southern limit in the Chesapeake Bay. Although it can tolerate some turbidity and some heat stress, it doesn't tolerate both simultaneously. As Lefcheck et al. (2017) described in recent research, "declining clarity has gradually reduced eelgrass cover the past two decades, primarily in deeper beds where light is already limiting. In shallow beds, however, reduced visibility exacerbates the physiological stress of acute warming, leading to recent instances of decline approaching 80%. While degraded water quality has long been

known to influence underwater grasses worldwide, they demonstrated a clear and rapidly emerging interaction with climate change (increasing temperatures)."

In 2011, CBP's STAC conducted a review of Chesapeake Bay SAV restoration efforts. In line with what Lefcheck et al. later found in 2017, the review team, led by Mark Luckenbach at VIMS, had the following to say: "Our review generally supports the techniques used for planting and monitoring SAV. Evidence from the York and James rivers and from Virginia's Coastal Bays supports the premise that SAV beds can be successfully restored using these techniques where water quality is sufficient. The majority of direct SAV restoration efforts were undertaken with eelgrass *Zostera marina*. The rationale for focusing most of the effort on this species—its wide distribution, established restoration techniques and historic low levels—was sound. However, if more resources had been available to develop techniques, direct restoration with other species would have been desirable.

The primary means of selecting restoration sites was a GIS-based decision tool, which incorporated information on water quality, water depth, current and historical SAV distribution, important fisheries habitat, and potential disturbance from clam fisheries. Though this site selection model was arguably state-of-the-art at the time it was developed, it fell short in meeting its intended use. A review of the model's effectiveness revealed that it was adequate for predicting sites where germination of SAV seeds would occur, but not for predicting persistence of beds beyond one year. Shortcomings of the model include (*i*) limitations on the data available to parameterize it, (*ii*) failure to include temperature as a stressor, and (*iii*) perhaps most importantly, reliance on multi-year average water quality, rather than variances and even extremes. This latter limitation was evident in numerous instances when data used to select restoration sites were collected in dry or average rainfall years and restoration was then followed by high rainfall (and thus poor water quality) years. The need to incorporate longer-term data sets, multiple stressors and environmental extremes into the site selection model is now apparent."

With the recent success of small-scale restoration efforts in tidal fresh, oligohaline, and mesohaline environments (facilitated in part by research conducted at Anne Arundel Community College and Maryland Department of Natural Resources) and insights from Lefcheck et al. (2017) and Luckenbach et al. (2011), the SAV Workgroup proposed in 2020 the development of a small-scale SAV restoration protocol and technical guidance manual (and associated outreach materials) and obtained Goal Implementation Team funding to do so. The project was contracted to Green Fin Studios with a sub-contract awarded to SAV expert Cassie Gurbisz, St. Mary's College of Maryland and was completed in November, 2021.

The intended audience for *Small-scale SAV Restoration in Chesapeake Bay: A Protocol and Technical Guidance Manual* is federal and state agencies, local jurisdictions, and non-government organizations, such as Riverkeeper and other watershed organizations. The ultimate purpose of the effort is to accelerate SAV recovery in Chesapeake Bay and its tidal tributaries, to the extent feasible, by supplementing natural recovery with direct restoration efforts in which seeds or mature plants are planted in areas where water quality is deemed

sufficient for growth and expansion, but where a seed bank or persistent population is not currently present.

In the manual, guidance is provided for multiple species to facilitate plantings in all salinity regimes. Wild celery is recommended for tidal fresh and oligohaline restoration projects. Mesohaline species include widgeon grass, sago pondweed, and redhead grass. Polyhaline species includes widgeon grass and eelgrass. Although restoration efforts with eelgrass have been largely unsuccessful in Chesapeake Bay, restoration in the nearby coastal bays of Virginia have done astonishingly well because of the higher water quality in those Bays, indicating that with improved water quality/clarity conditions, all is not lost for eelgrass in the Chesapeake. With proper management and sustained efforts to improve water clarity, eelgrass will be able to more effectively withstand heat stress during extreme events. This is also evidenced by the thriving populations of eelgrass further south in North Carolina. The water there is warmer than in the Chesapeake, but clearer, and consequently the eelgrass can maintain its populations.

E. EVALUATION

Key Findings:
- There are three primary symptoms of climate change that will directly affect Chesapeake Bay SAV: rising water temperatures, increased CO_2 concentrations, and sea level rise.

- Temperature impacts to eelgrass are well understood and without drastic improvements in water clarity or a reversal of warming trends, viable populations of eelgrass will likely be extirpated from Chesapeake Bay.

- Temperature impacts to other Chesapeake Bay SAV species are not as well studied but based on available data, appear to be less dramatic than those to eelgrass. With that said, current research and preliminary results suggests that increasing temperatures do negatively impact all Chesapeake Bay SAV communities to some extent.

- The CO_2 fertilization effect may counterbalance some of the impacts from warming, but unknowns associated with invasive species, pathogens, cyanobacteria, etc. may set that balance awry.

- Management efforts (ie. the Chesapeake Bay TMDL) that have reduced N and P in the Chesapeake have facilitated the (partial) recovery of SAV.

- The currently funded climate and SAV modeling project will be instrumental in answering many of our questions.

- The benthic cyanobacteria project will (hopefully) confirm if temperature increases are facilitating the spread of benthic cyanobacteria throughout the freshwater regions of the Bay, and if that spread is affecting SAV.

- SAV restoration efforts for diverse species may mitigate some of the loss of SAV from areas unable to recover without a seed source.

Management Implications:

As discussed, SAV provides multiple ecosystem services and co-benefits. These include the provision of food, habitat, refuge, and nursery grounds for commercially, recreationally, and ecologically important fish, shellfish, and a variety of invertebrates. Even waterfowl use SAV beds extensively. The submerged plants also take in and process excess CO_2 and nutrients, which helps mitigate impacts from climate change by sequestering carbon and decreasing the opportunity for macroalgae and phytoplankton blooms, including HABS, by removing their fuel source. As they take up CO_2 and release O_2, SAV beds not only oxygenate the water column; they also buffer the impacts of coastal acidification on the vulnerably shelled organism either living within the beds or nearby. Their physical presence in the water column baffles current and wave energy, reducing shoreline erosion. These are all ecosystem services – services provided to the growing human population in the watershed and beyond by the Bay's SAV - that could be lost with the continued degradation of water quality and impacts of climate stressors, including rising temperatures.

The continued loss of the Bay's SAV and ecosystem services that it provides could have significant management implications and profound economic consequences (Lefcheck et al. 2017), particularly regarding fisheries. The Bay's most economically significant fishery – blue crabs (*Callinectus sapidus*) – is directly dependent on eelgrass. In the spring, planktonic blue crab larvae migrate into the Bay assisted by winds and tides from offshore. The larvae rely heavily on the physical structure of eelgrass as a cue to settle. Juvenile blue crabs then proceed to shelter in the eelgrass beds and use the protection of the SAV for habitat and forage. In areas where eelgrass is lost and not replaced by widgeon grass, juvenile blue crabs will be significantly more susceptible to predation. In areas where widgeon grass does replace eelgrass, there remains the question of timing. Eelgrass begins to emerge from the sediment in December/January and reaches peak biomass in May. Widgeon grass, on the other hand, does not start to emerge until later in the spring, generally in April, and reaches peak biomass in July/August. Even in areas where widgeon grass does replace eelgrass, this shift in timing of available habitat when juvenile blue crabs are entering the Bay in the spring could have significant implications for population level survival. It could also force larvae to travel farther into the Bay in search of widgeon grass before settling; the more time in the water column, the bigger the odds of predation.

Of course, blue crabs do use widgeongrass and other mesohaline SAV species when available. Widgeon grass is the most abundant and widespread SAV species in the Bay. Unfortunately, it is susceptible to water quality degradation, like other SAV, but tends to

respond more dramatically, leaving juvenile and adult blue crabs alike vulnerable to limited habitat availability when it crashes. Following the ~42,000-acre loss of SAV from 2018 to 2019, and the additional ~4,000-acre loss from 2019 to 2020, the [2020 and 2021 Blue crab winter dredge surveys](#) both yielded significantly reduced numbers of juvenile blue crabs. The expansive loss of Chesapeake Bay SAV in 2019 and 2020 was likely a factor in that reduction.

Likewise, fisheries throughout the Bay would be impacted by a loss of SAV associated with increasing temperatures. While eelgrass is clearly the most vulnerable Chesapeake Bay SAV species, the information provided in TS III and the preliminary results of the SAV and Climate Modeling study suggest that all of the Bay's SAV communities are at least somewhat susceptible to increasing water temperatures. Where direct impacts are less severe, indirect impacts may prove equally damaging. Indirect impacts associated with increasing temperatures include unknowns like

- changes in rainfall and the frequency and intensity of storms,
- increased eutrophication,
- proliferation of epiphytes,
- increased shoreline armoring,
- higher sediment sulfide levels,
- changes in microbiota that support SAV productivity
- invasive species,
- expanding *Lyngbya* and other filamentous cyanobacteria
- changes in grazer types and abundance
- pathogens (ie. *Labyrinthula spp.*)

All of these could impact SAV productivity and consequently the animals that rely on it for forage and habitat, from the smallest of forage fish to larger recreationally important species like Largemouth bass. The bass-fishing industry in the upper Bay (Susquehanna Flats) and on the Potomac River are reliant on SAV health and productivity, for example.

Aside from the ecologically and commercially significant consequences of fisheries declines associated with SAV loss, there is also the practical concern of not being able to reach Bay-wide or segment-specific SAV goals. SAV recovery goals were established, of course, to ensure that the ecological benefits of SAV were maintained. To ensure that segment-specific goals are met and based on differences in SAV community responses to increasing temperatures, it may be necessary to consider more regionally-focused management actions or to concentrate BMP implementation and restoration efforts in areas where SAV is most impaired.

To manage the impacts of increasing temperatures on freshwater plants, we require not only a better understanding of individual freshwater species' heat tolerances, but also how those species will be affected by grazers and other microbiota that may become established as a result of increasing temperatures. That, and how the timing differential between eelgrass and

widgeon grass will affect blue crab productivity are two research needs identified by the SAV Workgroup associated with the issue of rising Bay water temperatures.

While questions remain regarding the impact of rising temperatures on SAV and the effects of climate change in general, it is clear that the single most effective action that can be taken to protect Chesapeake Bay SAV is to sustain and accelerate improvements in water quality and clarity through N, P, and TSS load reductions and appropriate BMP implementation. Chesapeake Bay SAV will be substantially more resilient to all climate stressors if water clarity is maximized.

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