SUBMERGED AQUATIC VEGETATION AND HABITAT: SURVEY AND MAPPING METHODOLOGIES REVIEW

FINAL REPORT

Scientific Advisory Board - Ecological Processes Standing-Committee (EPSC)

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Mr. Dan Cooke; CDM Smith
Dr. Elizabeth Burke Watson; Drexel University
Dr. Jonathan Kennen; U.S. Geological Survey
Dr. Meiyin Wu, Montclair State University
Dr. Ildiko C. Pechmann, Meadowlands Environmental Research Institute

A Report to the Scientific Advisory Board (SAB)
New Jersey Department of Environmental Protection

July 2021

ECOLOGICAL PROCESSES SUBCOMMITTEE CONTACT INFORMATION

Charles R. Harman, S.P.W.S. (Chair)
Wood Environment & Infrastructure Solutions
Somerset, NJ 08873
charles.harman@woodplc.com

Paul Bovitz, P.W.S.
Kleinfelder
321 Wall Street
Princeton, NJ 08405
bovitzpl@comcast.net

Catherine Nellie Tsipoura, Ph.D.
New Jersey Audubon Society
11 Hardscrabble Road
Bernardsville, NJ 07924
nellie.tsipoura@njaudubon.org

Meiyin Wu, Ph.D.
Director, New Jersey Center for Water Science and Technology
Professor, Department of Biology
Montclair State University
1 Normal Ave
Montclair, NJ 07043
wum@mail.montclair.edu

Ildiko C. Pechmann, Ph.D.
Meadowlands Environmental Research Institute
DEES, Rutgers-Newark
1 DeKorte Park Place
Lyndhurst, NJ 07072
ildiko.pechmann@rutgers.edu

Dan Cooke
CDM Smith
110 Fieldcrest Avenue, 6th Floor
Edison, NJ 08837
cookedw@cdmsmith.com

Elizabeth Ravit, Ph.D.
Rutgers University
93 Lipman Drive
New Brunswick, NJ 08901
bravit@scarletmail.rutgers.edu

Elizabeth Burke Watson, Ph.D.
Drexel University
1900 Benjamin Franklin Parkway
Philadelphia, PA 19103
elizabeth.b.watson@drexel.edu

Jonathan G. Kennen, Ph.D.
US. Geological Survey
810 Bear Tavern Road, Suite 206
West Trenton, New Jersey 08628
jgkennen@usgs.gov

ACKNOWLEDGEMENTS

The members of the Ecological Processes Standing Committee (EPSC) would like to thank the NJDEP staff for their support and assistance in the preparation of this report.

<u>Sections of this Report were Prepared by</u> Dan Cooke, Elizabeth Ravit, Meiyin Wu, and Elizabeth Watson; <u>Editorial Review Provided by</u>: Joseph Bilinski, Dan Millemann, Nick Procopio, and Chuck Harman

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EXECUTIVE SUMMARY

Submerged aquatic vegetation (SAV), consisting of approximately 60 species worldwide (Green & Short 2007), is found in marine, estuarine, and freshwater ecosystems. SAV populations are composed of rooted, vascular, flowering plants that live and grow primarily below the water surface and include seagrass species found globally in shallow marine and estuarine environments. These submerged communities contribute to one of the most productive ecosystems in the world (Havel 2018), supporting biogeochemical cycling, physical stabilization of sediments, and life cycle habitat needs of multiple aquatic species (Green & Short 2007). SAV provides a nutrient source, nursery area, and critical habitat for commercially and recreationally important fish, benthic, and marine mammal populations (de Boer 2007), including threatened and endangered species.

The New Jersey Department of Environmental Protection (NJDEP), Land Resource Protection (formerly the Division of Land Use Regulation) and Bureau of Shellfisheries programs have asked for a summary of methods for surveying and mapping the SAV resources in New Jersey. The areas to be surveyed include areas where SAV has historically been observed. Specifically, the NJDEP has asked:

1. The NJDEP is looking for a detailed summary of the existing remote sensing technologies that are accepted by the professional community of seagrass ecologists. Details of the summary must include, but are not limited to, identification of commercially available products and their utility at various scales, effectiveness under differing water quality conditions and depths, and relative costs of each technology.

2. Additionally, the NJDEP would value a summary of the SAV survey programs executed elsewhere in the country with respect to their chosen methods of surveying and survey timing intervals (annually, every 5 years, etc.).

3. Finally, the NJDEP would like a summary of the mapping technologies (software and methods) that can interpret the raw data into a fluid, GIS-based surface layer map.

A dedicated monitoring program, performed on an annual or semi-annual basis, is necessary to assess the health of SAV meadows and to avoid missing significant changes. Monitoring should include both remote sensing and *in situ* sampling. The recent advances in the technologies and capabilities available for unmanned aerial vehicles (UAVs), stabilized high-resolution imaging cameras, GIS technology, flight planning software, barometric altimeters, long-range transmitters, Structure from Motion (SfM) photogrammetry, Object-Based Image Analysis (OBIA), multi-spectral imaging, and other imaging software provide investigators with inexpensive tools to produce high-resolution orthomosaics to perform rapid, cost-effective remote monitoring of SAV.

Using remote sensing to focus the more labor-intensive *in situ* sampling and measurement of SAV health (e.g., above- and below-ground biomass, blade lengths, shoot densities) will allow for the most robust evaluation of SAV extent and health, though some recommendations for *in situ* in-water sampling methods have been included.

1.0 INTRODUCTION

Submerged aquatic vegetation (SAV) is a term used to describe rooted, vascular plants that grow completely underwater except for periods of brief exposure at low tides. The term SAV is generally used for marine, estuarine, and riverine angiosperms, and macrophytes. Most of these plants have leaves and stems with an extensive system of lacunal air spaces for buoyancy; thin cellulose walls for diffusion of gases, and high concentrations of chloroplasts in the epidermal layer for light absorption (Thayer and Fonseca, 1984).

Under NJDEP regulations, a submerged vegetation habitat special area consists of water areas supporting or documented as previously supporting rooted, submerged vascular plants such as widgeon grass (*Ruppia maritima*), sago pondweed (*Potamogeton pectinatus*), horned pondweed (*Zannichellia palustris*), and eelgrass (*Zostera marina*). In New Jersey, submerged vegetation is most prevalent in the shallow portions of the Navesink, Shrewsbury, Manasquan, and Metedeconk Rivers, and in Barnegat, Manahawkin, and Little Egg Harbor Bays. Other submerged vegetation species in lesser quantities include, but are not limited to, the following: water weed (*Elodea nuttalli*), *Eriocaulon parkeri*, *Liaeopsis chinesis*, *Naja flexilis*, *Nuphar variegatum*, *Potamogeton crispus*, *Potamogeton epihydrus*, *Potamogeton perfoliatus*, *Potamogeton pusillus*, *Scirpus subterminalis*, and *Vallisneria americana*. Development in areas inhabited by SAV is expressly prohibited, except in limited situations. Any construction activity proposed for a marine or estuarine setting can only be implemented upon authorization by the NJDEP pursuant to the Coastal Zone Management Rules (N.J.A.C. 7:7).

Charge

The NJDEP, Land Resource Protection and Bureau of Shellfisheries programs have asked, "what are the best methods for surveying and mapping the SAV resources in New Jersey?" The areas to be surveyed include all Atlantic coastal estuaries, Delaware Bay tributaries, and portions of the Delaware River. Specifically, the NJDEP has asked:

1. The NJDEP is looking for a detailed summary of the existing remote sensing technologies that are accepted by the professional community of seagrass ecologists.

2. Additionally, the NJDEP would value a summary of the SAV survey programs executed elsewhere in the country with respect to their chosen methods of surveying and survey timing intervals (annually, every 5 years, etc.).

3. Finally, the NJDEP would like a summary of the mapping technologies (software and methods) that can interpret the raw data into a fluid, GIS-based surface layer map.

The Scientific Advisory Board, Ecological Processes Standing Committee (EPSC) was tasked with responding to these charge elements. Following are the findings of the EPSC with respect to the charge.

2.0 OVERVIEW OF SUBMERGED AQUATIC VEGETATION

Submerged aquatic vegetation (SAV), consisting of approximately 60 species worldwide (Green & Short 2007), is found in marine, estuarine, and freshwater ecosystems. SAV populations are composed of rooted, vascular, flowering plants that live and grow primarily below the water surface and include seagrass species found globally in shallow marine and estuarine environments. SAV habitats are designated as Essential Fish Habitats by the National Marine Fisheries Service (NMFS) (Orth et al., 2002). These submerged communities contribute to one of the most productive ecosystems in the world (Havel 2018), supporting biogeochemical cycling, physical stabilization of sediments, and life cycle habitat needs of multiple aquatic species (Green & Short 2007). SAV provides a nutrient source, nursery area, and critical habitat for commercially and recreationally important fish, benthic, and marine mammal populations (de Boer 2007), including threatened and endangered species. Multiple SAV habitat protections are provided under federal regulations (Section 404 of the Clean Water Act, Section 10 of the Rivers and Harbors Act) (Orth et al., 2002 and references therein). Federal permit applications that may impact SAV habitat require review by U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA). The Fish and Wildlife Coordination Act and the National Environmental Policy Act (NEPA) require federal agencies consult on environmental impacts of Federal projects (Orth et al., 2002). The Atlantic States Marine Fisheries Commission (ASMFC), responsible for conserving and enhancing Atlantic coast fisheries in the 15 Atlantic States, adopted an SAV Policy in1997, which supports state, federal, local, and cooperative initiatives that influence and regulate fish habitat (Orth et al., 2002).

Biotic and abiotic environmental factors affect the distribution, species composition, and productivity of these submersed macrophyte communities (Barko et al., 1986). Natural habitat disturbances include bioturbation, over grazing, storm, wave or ice scour, coastal uplift or subsidence, disease, epiphytic loads, and macroalgae smothering (Thayer et al., 1997; Spaulding et al., 2007). Human caused disturbances occur on multiple scales, and include dredging, filling, land reclamation, dock and infrastructure construction, trawling, hydrologic alterations, and aquaculture (Short et al., 2007; Spaulding et al., 2007). Cultural eutrophication is a major cause of seagrass disappearance (Burkholder et al., 2007) and can be compounded with stresses associated with a changing climate including sea level rise, increasing temperatures, radiation exposure, and increased storm activity (Short et al., 2007).

Seagrasses are susceptible to anthropogenic impacts, and declines have occurred globally because of adverse effects caused by activities that negatively impact coastal zones (Stephan and Bigford 1997; Thayer et al., 1997; Green & Short 2007). SAV declines are often related to reduced light availability associated with excessive inputs of macronutrients in shallow coastal waters that stimulate competing primary producers (i.e., micro-, and macro-algae, phytoplankton) (Kemp et al., 2004; Burkholder et al., 2007). Declines have also been associated with brown tide (*Aeurococcus*) blooms (Bologna et al., 2000).

Worldwide, SAV habitat is experiencing stress related to degraded water quality, a changing climate, and physical destruction of the submerged beds because of human activities (Short et al., 2006). Catastrophic losses have been observed in poorly flushed estuaries and coastal embayments with reduced tidal flushing where nutrient loads concentrate (Burkholder et al., 2007). SAV loss in most Atlantic coastal states is due to degraded water quality (Havel 2018). New Jersey SAV losses of 62% over a 25-year period have been documented in Little Egg Harbor, primarily as loss of eelgrass; although widgeon grass loss has been less significant, respectively (Bologna et al., 2000). Eelgrass (*Zostera marina*), the dominant NJ seagrass species, is also subject to wasting disease infections caused by *Labyrinthula zosterae* which can be an added stressor on this resource (Spaulding et al., 2007).

2.1 Identification of Common Species

Along the New Jersey coastline two seagrass species, eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*), are found in salt waters (greater than 10 parts per thousand salinity [>10 ppt]) west of the barrier islands (Orth and Moore 1982 and references therein; Koch and Orth 2007). The dominant New Jersey saltwater SAV species is eelgrass, a species widely distributed along the Atlantic coast from Nova Scotia, Canada to North Carolina (Orth and Moore 1982). New Jersey is at the interface of northern and southern populations of eelgrass (Bologna and Sinnema 2012). Widgeon grass is a more cosmopolitan species able to tolerate greater temperature and salinity ranges (Short et al., 2007; Thayer et al., 1997), and so can extend farther into lower salinity portions of the estuary (Koch and Orth 2007). Estimated seagrass coverage in Barnegat Bay has ranged from 8,799 hectares (ha.) in the 1980s to 6083 ha. in the 1990s (Lathrop et al., 2001 and references therein). Less is known about the potential presence of seagrass populations in Delaware and Raritan Bays, although widgeon grass was documented in the Shrewsbury Estuary in 2015 (Dacanay 2015; Smith et al., 2018). Portions of the lower Delaware River were recently surveyed by the US EPA, and seagrass (wild celery) has been documented prior to this survey (EPA 2020; report in progress). Lee et al. (2007) found that the optimal Chesapeake Bay temperature range for eelgrass photosynthesis was 19 – 22 degrees centigrade (° C), and 23 - 28 ° C for widgeon grass. However, optimal growth temperatures (15 – 20 ° C for eelgrass) may be lower than optimal photosynthetic temperatures, causing spring or fall seasonal growth to be greater than summer productivity (Lee et al., 2007). Though high summer temperatures may cause plants to shed their leaves in response to heat stress.

Genome sequencing of eelgrass, the most widespread species in the temperate northern Atlantic, highlights unique genetic adaptations to life under the continually fluctuating conditions encountered in a shallow marine environment (Olsen et al., 2016). These adaptations include the ability to osmoregulate under high salinities, expanded light-harvesting complexes to enhance performance in low light, and specialized cell wall structural adaptations to resist desiccation and osmotic stress at low tide. Eelgrass can exist as either a perennial or an annual (Thayer et al., 1997). Sexual reproduction occurs underwater with male and female flowers employing a completely submerged pollination process (Olsen et al., 2016). Eelgrass exhibits a strong seasonal signal in shoot abundance and plant biomass, peaking in August (Bologna et al., 2000). Widgeon grass can also exhibit a perennial or annual growth pattern (Malea et al., 2004), reproducing asexually through extensive rhizome production or sexually through seeds that can remain viable in the sediments for up to three years (Kantrud 1991). Plants subject to exposure to air in intertidal habitats produce fewer shoots and lower seed production than plants remaining submersed during the growing season (Kantrud 1991).

2.2 Description of habitats

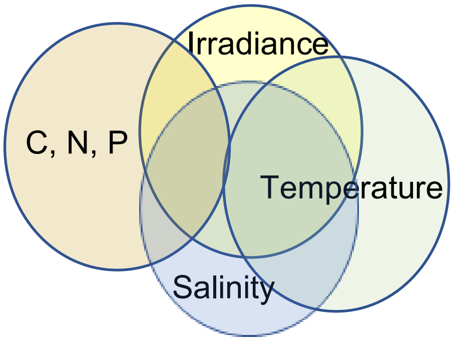

Figure 1. Submerged aquatic vegetation (SAV) species distribution and abundance is controlled by interactions between water column irradiance, water temperature, salinity range, and sediment/water column concentrations of inorganic macronutrients carbon, nitrogen, and phosphorus.

SAV species abundance and distribution are determined by inter-related factors, including the availability of light at the leaf surfaces, water salinity and temperature ranges, and inorganic macronutrient availability (de Boer 2007; Lee et al., 2007) (see Figure 1). Limiting factors can change seasonally (e.g., light limitation in winter and nitrogen limitation in summer) (de Boer 2007). Salinity determines the location and species composition of SAV populations; saltwater communities exhibit lower diversity than freshwater communities (Havel 2018).

Water column light levels are directly affected by the concentration of total suspended solids (TSS) and indirectly affected by concentrations of macronutrients (carbon, nitrogen, and phosphorus), which control the growth of micro- and macro algae, planktonic chlorophyll-a, and the density of epiphytes on leaf blades (Kemp et al., 2004). Photosynthesis supporting SAV productivity is controlled by water column irradiance, which ranges from 15% to 37% of surface irradiance, and temperature (Lee et al., 2007; Thayer et al., 2007). Bicarbonate (HCO_3^-) dissolved in seawater can be utilized by eelgrass as a major source of photosynthetic inorganic carbon (Lee et al., 2007).

Seagrasses can reproduce sexually (flowering) which occurs above ground, and asexually (rhizome budding) which occurs below ground (Thayer et al., 1997). Sea grass habitat is characterized by the presence of aboveground leaves and belowground reproductive structures, rhizomes, and roots, which can exceed 50% of total plant biomass (Lee et al., 2007). Seagrasses have a relatively low nutrient requirement, although nitrogen limitation is associated with sandy sediments; excess nutrient loadings can change seagrass species composition or favor algal and phytoplankton populations that increase TSS and organic matter (OM) (de Boer, 2007). Sediment nutrients produced by remineralization and decomposition processes have rapid turnover rates (0.3 to 6 days) (Lee et al., 2007). Sediment nitrogen and phosphorus concentrations may be orders of magnitude greater than water column concentrations (Lee et al., 2007).

High inter-annual variability in seagrass abundance and productivity depends on meteorological and hydrographic conditions (Burkholder et al., 2007). SAV growth is seasonal, and leaf blades may not be present in winter. Beds may be present, but ephemeral or too small to map (Koch and Orth 2007).

Within species-specific tolerance ranges, environmental factors promote seagrass productivity; outside the tolerance range these factors become negative. Seagrass habitats and their limiting factors are highly dynamic for several physical and chemical variables; these limiting factors are species specific and fluctuate both seasonally and regionally (de Boer 2007). Seagrasses occur in protected habitats, sheltered from wave energies (Koch and Orth 2007), forming a mosaic of vegetated and unvegetated areas. The physical setting produces different vegetation cover patterns (Short et al., 2007). Seagrass beds are continually changing (Short et al., 2007), shifting over time to produce cover patterns which range from patchy to continuous that can change on a scale of days to decades (Thayer et al., 1997). Defining the extent and the physical arrangement of SAV patches is essential when mapping habitat (Bologna et al., 2000). Therefore, the accuracy of surveys to identify SAV habitat is enhanced when conducted during peak growing season (Havel 2018).

Marine sea grass beds are limited to shallow coastal areas (Kemp et al., 2004), typically in low energy areas (de Boer 2007). Seagrass depth distribution is directly linked to irradiance (Lee et al., 2007), and has been reported to occur at the maximum Mid-Atlantic depth is 0.5 to 1.0 meters (Koch and Orth 2007); however, shellfish surveys conducted by NJDEP (Bureau of Shellfisheries and others) have found eelgrass down to 1.8 meters (K. Dacanay, personal communication). Shallow seagrass beds are exposed to environmental extremes including high solar radiation and wide temperature fluctuations (Lee et al., 2007).

In addition to salinity, temperature, nutrient, and OM concentrations, current velocity is a critical habitat factor. The upper water depth of seagrass is determined by wave energy and the maximum tidal amplitude; if excessive, desiccation or freezing will cause seagrass beds to disappear (de Boer 2007). Current velocity above an upper maximum (180 centimeters per second [cm/s] tolerated by seagrass) causes erosion of seagrass beds; low current velocity (less than 0.25 cm/s) reduces carbon availability by limiting carbon dioxide (CO_2) diffusion (de Boer 2007 and references therein). Sediment resuspension is frequent in shallow water where the water column depth is one-third of the wavelength. The balance between sediment erosion and deposition fixes the depth of seagrass meadows. Trapping of sediment by seagrass meadows may cause meadows to decrease over time due to sedimentation (de Boer 2007).

Seagrasses may create positive feedback loops, changing the environment due to their capacity to trap sediment and OM (de Boer 2007). An example of a beneficial positive feedback occurs when SAV traps sediment, thus reducing turbidity, which increases water column light availability. The increased irradiance increases SAV photosynthesis. Conversely, a negative feedback loop can occur when high nutrient loadings cause algal blooms followed by high rates of OM decomposition, producing low oxygen conditions within seagrass meadows leading to the production of sulfides and organic acids toxic to SAV in high concentrations. These conditions can cause increased SAV die off, increasing the amount of decomposing organic material and stimulating additional die off (Barko et al., 1986; de Boer 2007). High salinity, high temperatures, and decreased irradiance can exacerbate the effects of excess nutrient inputs (Burkholder et al., 2007).

Seagrasses provide one of the most important shallow marine ecosystems, which plays a significant role in supporting commercial and recreational fisheries, stabilizing sediments, and providing some protection from coastal erosion. Shallow marine and estuarine environments provide complex physical structure, and their high productivity, relative to other marine vegetation, supports high biomass and diversity of associated species of endangered sea turtles, waterfowl, fish, and invertebrates (Green and Short 2007). Mesograzers, small detritivores and amphipod, isopod crustaceans, crab, and mollusk invertebrates, are common within seagrass beds (Burkholder et al., 2007). Hughes et al. (2004) found grazers had a positive effect on SAV shoot density, but conversely, increased epiphyte biomass caused by water column nutrient enrichment was correlated with strong negative effects on seagrass biomass.

Protection and conservation of SAV habitat is more assured and cost effective than restoration or mitigation after SAV loss (Havel 2018). Water quality standards must be met before restoration can be attempted; restoration failures have been documented due to predators, human impacts, and planted shoots that uproot easily (Havel 2018). SAV habitat recolonization can be important in maintaining populations (Bologna et al., 2000).

2.3 SAV and Blue Carbon

The designation "Blue Carbon" was first used in 2009 by Nelleman et al. to characterize the proportion of biological carbon (55%) captured by marine living organisms. Blue Carbon components currently include organic and inorganic C that is sequestered by the coastal ecosystems of mangrove forests, salt marshes, and seagrass beds (McLeod et al. 2011).

Seagrass production not consumed by herbivores, estimated by Duarte et al. (2010) as 81.4% on average, decomposes slowly, and is therefore relatively recalcitrant. Short-term carbon (C) sequestration (decennial time scales) occurs in seagrass aboveground biomass; long-term sequestration (potentially millennial time scales) occurs in belowground biomass and sediments (Duarte et al., 2010). The majority (67%) of seagrass biomass can be found belowground in roots and rhizomes, although the ratio of above-to below-ground biomass varies by species (Fourqurean et al., 2012) and C biologic storage measurements are lacking for most individual seagrass species (Macreadie et al., 2014).

Seagrass meadows can bury C at a rate 35 times faster than a tropical rainforest (McLeod et al., 2011). Organic sediment fractions include detritus, bacteria, micro- and macro algae; inorganic fractions include carbonates (Macreadie et al., 2014). Inorganic C may also be sequestered in sediments due to seagrass water filtration capacities followed by sedimentation of particles carried in the water column (Fourqurean et al., 2012). Because sediments accrete vertically, they do not become C saturated as the size of this C-sink increases over time (McLeod et al., 2011; Macreadie et al., 2014).

Because of the Blue Carbon storage capacities of seagrass beds, they are now considered an important component in mitigating the increasing CO_2 concentrations driving a globally changing climate. Research is showing that increases in ocean CO_2 can enhance seagrass productivity and heat tolerance, creating a negative feedback to climate change (Zayas-Santiago et al., 2020).

However, responses to higher CO_2 differ between seagrass species, as do ratios of above versus belowground biomass. Palacios & Zimmerman (2007) demonstrated CO_2 enrichment did not alter growth rates of *Zostera marina* aboveground shoots, but did lead to significantly higher reproduction, belowground biomass, and vegetative reproduction under high irradiance (33% of surface irradiance) conditions. Under light limited conditions (< 11% surface irradiance) growth did not increase. Zayas-Santiago et al. (2020) found metabolome responses to increased CO_2 in *Zostera marina* populations from Chesapeake Bay and Puget Sound. Prolonged (1 year) exposure to elevated CO_2 produced enhanced leaf photosynthesis, increased shoot survival, growth, and flowering; these effects coincided with increased metabolic markers for thermal tolerance.

Die-off or impairment of a seagrass bed, and the associated loss of root and rhizome sediment stabilization, can result in erosion that potentially releases sequestered C, turning former seagrass beds into marine C-sources (McLeod et al., 2011; Lovelock & Duarte 2019).

2.4 Environmental and Economic Benefits

Ecological functions of SAV include chemical cycling and beneficial physical modifications of the water column and sediments that dampen surge and wave energies and reduce suspension and resuspension of water column sediments (Havel 2018). Aquatic communities use SAV for refuge, attachment, spawning, food, and prey capture for various parts of their life cycles (Havel 2018). SAV habitat provides refugia and trophic transfer functions. Predator-prey relationships are influenced by SAV biomass, shoot density and surface area (Thayer et al., 1997). Therefore, seagrass health and abundance impact important fisheries.

Sea grass beds provide shelter for commercial, recreational, and ecologically important invertebrate, finfish species, and marine mammals, which is especially critical for juveniles (Havel 2018). Commercially important species (e.g., scallops, blue crabs, shrimp, fish) use seagrass habitat for early development or as vital nursey grounds. SAV are primary producers, a direct food source for grazers and an indirect food source for secondary consumers (Bologna et al., 2000). Seasonal reproduction and development of many temperate species coincides with seasonal abundances of seagrasses (Thayer et al., 2007). SAV is associated with the attachment or protection of bay scallops (*Argopecten irradians*), hard clam (*Mercenaria mercenaria*), blue crab (*Callinectes sapidus*), shrimp (*Penaeus* spp.), and lobster (*Homarus americanus*) (Thayer et al., 1997).

Seagrass roots and rhizomes bind sediments; leaf blades trap water column materials and retard sediment resuspension (Thayer et al., 1997). SAV loss reduces sediment stability, increasing resuspension, water column turbidity, and shoreline erosion (Thayer et al., 1997). Seagrass loss, which is extremely difficult to reverse, leads to loss of these ecological functions and values.

Costanza et al. (2014) estimated the annual global value of "Seagrass/algal beds" at $28,900 (Hectares/yr) based on the ecosystems services these ecosystems provide. In a separate report Costanza et al. (2006) estimated, New Jersey's estuaries and tidal bays provided over $5 billion of ecosystem services in 2004 dollars, the second highest for any ecosystem category.

2.5 Distribution in New Jersey

Globally, SAV beds are declining at an alarming rate due to both natural and anthropogenic sources (Orth et al., 2006). In New Jersey, similar patterns have been observed. Bologna and Lathrop (2000) investigated SAV distributions in Little Egg Harbor and concluded that about 62% of SAV was lost during the last quarter of the 20th century. There is a lack of sufficient information on the current extent and condition of viable SAV habitats in New Jersey. Barnegat Bay was reported to house approximately 75% of New Jersey's SAV beds (Lathrop et al. 2001). Within Barnegat Bay, eelgrass was reported to dominate SAV beds south of Toms River and widgeon grass dominated in the central and northern portions of the Bay (Barnegat Bay Partnership 2019). Eelgrass was reported to be the dominant species at Little Egg Harbor (Bologna and Lathrop 2000).

3.0 REVIEW OF CURRENT SAV MAPPING TECHNIQUES

The techniques utilized for mapping SAV in New Jersey have included boat-based visual surveys, in-water observations, aerial photography, GIS-based mapping from imagery, and computerized image interpretation.

3.1 Desktop Techniques Currently used in New Jersey

Desktop techniques currently used in New Jersey include computerized image interpretation of aerial photos. Image interpretation is discussed in Section 3.3.

3.2 Field Techniques Currently used in New Jersey

In-field techniques currently used in New Jersey include aerial photography and boat-based visual surveys confirmed by in-water visual observations. In water observations include identification of SAV species present, along with estimates of bottom coverage.

Lathrop et al. (2014) did a comparison of remote sensing versus *in situ* plot-based monitoring of seagrass meadows in Barnegat Bay-Little Egg Harbor (BB-LEH), NJ, and found that a combination of the two methods provided the most robust approach to fully characterize the spatial extent, health, and density across the entire estuary.

Lathrop et al. (2014) found that the dominant species of seagrass in BB-LEH is eelgrass (*Zostera marina*), while widgeon grass (*Ruppia maritima*) is common in the lower salinity areas. Aerial imagery collected in 2003 and 2009 from manned aircraft was processed and the results were compared to survey results from boat-based *in situ* plot-based monitoring conducted from 2004 through 2009. While there were broad similarities between the two methods, and both methods showed overall declines in seagrass meadows, investigators found that remote sensing surveys provided a "big picture" evaluation, but that the *in situ* sampling was necessary to determine the health status of the meadows (above versus below-ground biomass, blade length, shoot density, etc.). The combination of remote sensing and focused *in situ* sampling provided the data to evaluate the health of the seagrass meadows in BB-LEH.

The figure below is from Lathrop et al. (2014) and shows a color-coded comparison between remotely-sensed seagrass meadows from 2003 to 2009, with dark green shading indicating major increase in seagrass grading down to red shading that indicates major decrease. The figure shows an overall decrease in the aerial extent of the meadows throughout the estuary.

To understand the factors impacting seagrass health and distribution, it is necessary to have a dedicated monitoring program, performed on an annual or semi-annual basis to avoid missing significant changes. However, for most estuary programs, annual remote sensing surveys by manned aircraft are cost-prohibitive, and there are often not resources for annual *in situ* monitoring that includes multiple visits over the growing season over multiple years. For the BB-LEH system, Lathrop et al. (2014) reports mapping surveys conducted from 2004 through 2009.

3.3 Existing New Jersey SAV Mapping

The NJDEP's Division of Land Resource Protection provides historical maps of SAV in 31 New Jersey coastal bays (https://www.nj.gov/dep/landuse/sav.html). The map for Little Egg Harbor Bay was updated in 1987, 2001, and 2011. The NJDEP does have data from Barnegat Bay from 2012, and from Shrewsbury/Navesink from 2015 (Dacanay 2015). The USEPA has unpublished survey data from the lower Delaware River. The resource includes 27 low-resolution, black-and-white jpg format maps from 1979, with broad areas outlined in each bay, an estimate of aerial coverage, and a listing of SAV species (interspersed with macroalgae species) expected to be within the outlined areas. There are three low-resolution, black-and-white pdf format maps from 1986, with broad areas outlined in each bay and a legend indicating areas of eelgrass or no eelgrass; no other SAV species are noted. The 2001 and 2011 maps of Little Egg Harbor Bay are low-resolution nautical charts with broad areas shaded in green to indicate a mixture of eelgrass and widgeon grass, but no indication of percent coverage or which species is dominant.

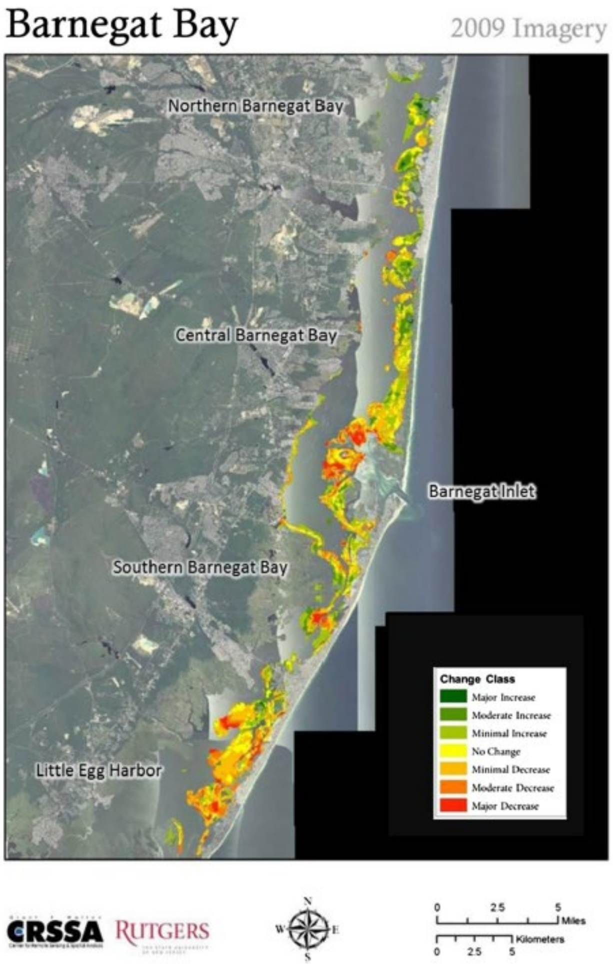

Figure 2: Barnegat Bay map from CRSSA

Rutgers University's Center for Remote Sensing and Spatial Analysis (CRSSA) provides a more expansive database of coastal SAV mapping (https://crssa.rutgers.edu/projects/sav/). The CRSSA resource contains data from the 1960s through 2009, using various methodologies (Figure 2).

- The 1960s and 1970s mapping information for Barnegat Bay and Little Egg Harbor were derived through boat-based surveys and several pilot-studies to determine whether aerial photography could be used to map SAV. Earth Satellite Corporation mapped NJ's entire Atlantic coast to produce a 1:24,000 scale map series based on interpretation of black-and-white photos taken from low-altitude sea plane reconnaissance and then ground-checked in the field during the summer of 1979. The map series included eelgrass, widgeon grass, and sea lettuce (actually a macroalga; *Ulva lactuca*). The US Fish and Wildlife Service also incorporated the aerial photo data into the National Wetland Inventory. The CRSSA digitized the maps, using existing shoreline geographical information system (GIS) data as the base map. The

NJDEP is redigitizing the CRSSA maps for use in Waterfront Development Permit application review.

- During 1985 through 1987, eelgrass distribution was measured in conjunction with a shellfish inventory of Barnegat and Little Egg Harbor bays spanning 489 stations in spring, summer, and fall. Eelgrass distribution was extrapolated for the areas in between sampling stations, and for shallow areas where the boats could not operate (though visual observations were made for as far as investigators could see. The CRSSA digitized photocopies of the maps, using existing land-based GIS, and determined that there were 896 ha. of SAV. These maps are available on the NJDEP's website.
- Field surveys of Barnegat Bay were conducted during the summers of 1996, 1997, 1998, and 1999. The middle portion was mapped in 1996, the northern portion in 1997, and the southern portion in 1998. The dominant species (eelgrass and widgeon grass) were identified. The surveys were boat-based, marking SAV meadow boundaries on a 1:40,000 scale National Oceanic and Atmospheric Administration (NOAA) nautical chart. The southern portion was re-mapped in 1999 using a global positioning system (GPS). The CRSSA digitized the maps, integrated with the GPS data.
- As part of the ongoing Barnegat Bay National Estuary Program, the CRSSA mapped the aerial extent of SAV in a 73,000 ha. area of Barnegat Bay and Little Egg Harbor in 2003. The survey utilized remote sensing that allowed for determination of seagrass at four levels of density, rather than simple presence/absence. The aerial digital camera used had flexible acquisition, suitable image scale, fast processing return times, and comparatively low cost, but it had inconsistent radiometric response across images. The remote sensing method was field-checked to 68% accuracy for the four density levels and 83% accurate for presence/absence. The multi-scale image segmentation approached had the potential to be more replicable than boat-based surveys or visual image interpretations, to allow for a more robust conclusions regarding potential changes in location, extent, and spatial pattern of SAV over time. The CRSSA mapped 5,184 ha. of SAV, which was less than the 6,083 ha. documented during the 1996-1999 boat surveys, but investigators believe the difference was more an artifact of the different mapping techniques than a significant change in SAV.
- In 2009, the CRSSA conducted aerial photography during June, July, and August, followed by field site visits to collect reference information to enable interpretation of the imagery and to assess the accuracy of the resulting maps. The team used eCognition software, similar to that used for the 2003 survey to perform multi-scale image segmentation/object-orient image classification, and showed an overall mapping accuracy of 87%, while the four density classes (absent, sparse, moderate, dense cover) had an overall accuracy of 70%. There were again differences in the total SAV cover (approximately 140 ha. increase over 2003), but the differences were attributed to the 2009 imagery being collected later in the growing season. A full description of the methods utilized and the comparisons between the 2003 and 2009 surveys are in Lathrop and Haag, 2011.

The Rutgers CRSSA has published numerous papers on the monitoring of SAV in NJ, focusing on Barnegat Bay and Little Egg Harbor estuary, each changing the survey methods as progress in remote imaging, and more specifically in digital image processing have evolved.

Stockton University's Coastal Research Center (https://stockton.edu/coastal-research-center/habitat-mapping.html) website currently states that they are working with NJDEP to identify habitat preference for shellfish and SAV, using a GIS-based approach. While no results or maps are yet available on their website, several reports have been published on the Barnegat Bay Partnership website (https://www.barnegatbaypartnership.org/report/).

NOAA, in cooperation with the University of New Hampshire (UNH) used remote sensing to assess the distribution and relative percent cover of seagrass in Barnegat Bay using aerial reconnaissance and topographic-bathymetric lidar (TBL) systems. Flights were made in October 2012 (before Superstorm Sandy hit NJ on October 29, 2012), and post-storm, between November 1, 2012 and January 10, 2013. The data collected was used to quantify the seafloor changes from sediment movement caused by the storm, and to show differences in SAV density. The UNH Center for Coastal and Ocean Mapping (Calder and Mayer, 2015) also used imagery from the Landsat 8 satellite to visualize differences in SAV density between June and August 2013 and June and August 2014 (http://sandy.ccom.unh.edu/publications/library/2015-12-29_FinalReport.pdf).

The Barnegat Bay Partnership (https://www.barnegatbaypartnership.org/report/) also lists studies, including SAV monitoring, that have been performed in and around Barnegat Bay.

4.0 IDENTIFICATION AND SUMMARY OF NEW SAV MAPPING TECHNIQUES

Older techniques for mapping SAV ranged from in-water snorkel/SCUBA transects of SAV meadows with a survey tape and a compass, to boat-based visual surveys, to GPS-aided visual surveys, to aerial imagery, to satellite imagery. Advances over the years have reduced the manual labor involved, and therefore, the time and expense required to monitor SAV resources. Surveys of SAV have historically been hampered by funding and by the time required both to collect the data and to interpret the data, and that has contributed to a paucity of SAV maps, and often many years in between monitoring surveys.

Table 4-1. SAV Mapping Technique Pros and Cons

Method	Pro	Con
Snorkel/SCUBA transects with survey tape and compass	-Inexpensive, low-technology -Precise marking of SAV bed edges -High confidence in species ID -Easily survey to maximum SAV depth -Can sample biomass -Can collect water quality data -Can collect SAV health metrics -Useful in limited visibility -Can be performed frequently	-Labor intensive -Time consuming -Useful only for small areas
Boat-based visual surveys	-Larger areas than snorkeling surveys -Less labor intensive than snorkeling -Can be performed frequently	-Imprecise marking of bed edges -Requires boat/operator -Lower confidence in species ID -Requires clear, calm water -Max depth SAV may not be visible -Require in-water ground-truthing
GPS-aided visual survey	-Added precision to all surveys	-None
Aerial imagery – plane	-Precise surveys -Can use multi-spectral imaging -Useful for large areas	-Expensive -Requires airport/planes/pilots -May requires FAA permits -Some airspace is restricted -Requires clear weather -Altitude limits image resolution -Require in-water ground-truthing
Aerial imagery – drone	-Precise surveys -Low altitude high resolution images -Can use multi-spectral imaging -Very small takeoff/landing area -Useful for large areas -Much cheaper than manned aircraft	-Some airspace is restricted -Requires licensed operator -Requires clear weather -Requires in-water ground-truthing

Method	Pro	Con
	-Can be performed frequently	
Satellite imagery	-Useful for very large areas -Precise surveys -Can use multi-spectral imaging	-Access to satellites restricted -Altitude limits image resolution

4.1 New Desktop Techniques

Computerized interpretation of aerial photos, Light Detection and Ranging (LiDAR) images, and multispectral remote sensing technology can be considered desktop techniques and are discussed in the following section. The United States Geological Survey (USGS) provides some LiDAR data and satellite imagery on the National Map Downloader web page (https://apps.nationalmap.gov/downloader/#/), but data usability for SAV mapping would have to be assessed on a site-specific basis. Data interpretation is the necessary follow-up to field data collection, and while interpretation software is commercially available, training and expertise are required. Computerization has greatly increased the efficiency of data interpretation, from investigators viewing individual aerial photos and estimating the SAV coverage, to being able to interpret large areas of potential SAV habitat incorporating GIS data in days rather than weeks.

4.2 New Field Techniques

The United States Geological Survey (USGS) has done a preliminary assessment of using hyperspectral remote sensing technology (from satellite imagery) to map SAV in the Upper Delaware River National Parks (Slonecker et al. 2018). Hyperspectral imaging uses the entire electromagnetic spectrum, using the spectra in each image pixel to identify the object. The National Park Service (NPS) requested assessments of SAV to manage water quality degradation and eutrophication, and to document the presence of invasive aquatic plants.

Hyperspectral sensors can image in hundreds of discrete spectral wavelengths and can be used to identify individual SAV species because each species has a unique spectral signature (as determined through the use of field or laboratory spectrometers). Using remote sensing, larger areas can be monitored for SAV, algal blooms, and invasive species (Slonecker et al. 2018).

Historically, the use of aerial photography has been shown to be limited because it lacks the spectral range necessary to identify SAV species. Multispectral satellite sensors (e.g., Landsat) do not have the spatial resolution to map riverine environments. Because advances in sensor technology have become available in recent years, it is now possible to provide the detailed spatial and spectral resolution required to map SAV (Slonecker et al. 2018). Combined with advanced bathymetric LiDAR to map depth, bottom contours, and physical habitat, these will allow investigators to monitor entire aquatic systems remotely.

The USGS study addressed some of the technical difficulties associated with remote imaging (many of these are problems with any aerial photography over water). Among the difficulties encountered are the impacts to the optical properties of the water body; these impacts can be caused by weather conditions, sun and view angle, sunglint (specular reflectance), water clarity, water depth, the flow rate (e.g., still water versus turbulent flow), and the bottom substrate (Slonecker et al. 2018). Other sources of interference include turbid water containing chlorophyll and floating algae (which have spectral wavelengths similar to SAV), epiphyte colonization of SAV, and sediment coating of SAV leaves. Clear-flowing, relatively shallow water is best suited to the optimal use of remote sensing technologies.

Hyperspectral remote sensing (HRS; also known as imaging spectroscopy) has allowed investigators to bring spectroscopic measurements from the lab into remote sensing from aerial or satellite platforms. The measure of the reflected energy in numerous bandwidths is used to plot energy reflectance versus bandwidth (spectra), which can then be analyzed to identify certain compounds, materials, and plant species based on the interaction of photons with the molecular structure of the target (Slonecker, et al. 2018).

Identification of SAV species presents a technical challenge because of the spatial and spectral resolution required. The spatial resolution requires determination of the optimal pixel size to detect SAV. The spectral resolution requires the determination of which spectral bands are key not just to identify plants, but to identify differences between plants to the point of species identification. In a Great Lakes study, Becker et al. (2005) reported that spatial resolution with pixel dimensions below 5 square meters (m^2) were required for accuracy in their study area because it reduced the frequency of mixed pixels (the pixel is the smallest addressable image element, and a mixed pixel occurs when areas with different features are smaller than that resolution). The study also identified eight spectral bands in the red edge and near infrared range that allowed for enhanced spectral differentiation of individual coastal wetland SAV species. The bands are centered at 514.9, 560.1, 685.5, 731.5, 812.3, 823.9, 835.5, and 939.9 nanometers (nm), with the 812.3 and 823.9 nm bands being most important for identification of the unique spectral reflectance patterns of SAV species in the study area. The infrared spectrum is best used for intertidal and emergent vegetation, as there is rapid absorption of the red wavelengths by the water, and it is not reflected from depth (depending on a number of variables).

Imaging spectrometers are limited because utilizing a large number of spectral bands reduces the spatial resolution during image acquisition. Being able to focus on a smaller number of spectral bands allows investigators to acquire spectroscopic imagery with finer spatial resolution, which improves the accuracy of mapping and identifying SAV to individual species (Slonecker et al. 2018).

The USGS study included aerial photography from 800-meter (m) altitude, at 100-knot speed, that resulted in imagery with 1-m spatial resolution. The plane flew transects using an integrated geo-positioning and inertial navigation unit capable of correcting data in real-time, precisely geo-registering all collected imagery. The imagery consisted of two simultaneously collected segments, one high spatial resolution (0.5-m) panchromatic image and one 52-band hyperspectral image. The imagery was processed using GeoRegARCHER software (developed by Space Computer Corporation, Los Angeles, California) that incorporated location data and corrected for atmospheric effects.

Figure 3 is from Slonecker et al. (2018), and it shows a segment of the Delaware River with (Figure 3A) and without (Figure 3B) upland vegetation. The upland vegetation reflectance overwhelms the weaker SAV reflectance, showing almost no in-stream results (the river is black), but when the software masks the upland reflectance, the in-stream classification is visible (right).

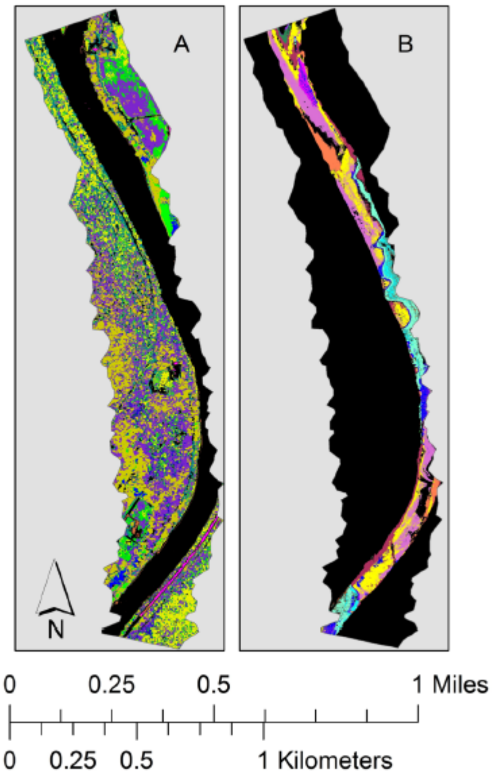

Figure 3. Delaware River SAV mapping (From Slonecker et al. 2018)

The USGS study was conducted as a preliminary assessment of the technology, with the goal to overcome some of the technical and physical difficulties noted above. Field ground-truthing by the authors to assess the presence or absence of SAV in the Delaware River showed an accuracy of approximately 45%. The study identified a number of technical issues that need to be remedied (e.g., the spectra collected above the water's surface may differ from those collected underwater, and an accurate relationship between the spectra is necessary).

While aerial imagery has historically been obtained using manned aircraft or satellites, recent research into the use of unmanned aerial vehicles (UAVs, sometimes called drones) has shown promise. UAVs are more economical than manned aircraft and can fly at lower altitudes to obtain greater resolution. Also, UAV technology is rapidly improving their utility and ease of operation.

Duffy et al. (2018) performed a spatial assessment of intertidal seagrass meadows near Wales, United Kingdom, using a consumer-grade camera mounted on a light-weight UAV to provide very high spatial resolution (less than 4 millimeters per pixel). The UAV/camera unit was also equipped with flight planning software to determine the ideal time intervals between photos, based on the field of view, altitude, and flight speed for optimal image overlap. The UAV was also run using an autopilot system to allow for waypoint-guided flight, controlling UAV position (in three dimensions) to perform a structured survey. The flights were made at an altitude of 15-m, with a ground speed of approximately 2 knots. The study was ground-truthed using standard field methods (the Seagrass-Watch protocols from Mckenzie et al. 2003), with a series of 0.5 m^2 quadrats (0.5 m x 0.5 m) randomly placed in the seagrass meadow to measure percent cover, shoot length, and densities. UAV images were processed using Agisoft Photoscan software (Agisoft LLC) to generate georeferenced orthomosaic models (orthomosaic refers to a geometrically correct composition of multiple still aerial images), from which the known sampling distances with the counts of pixels in each data set allowed for aerial seagrass coverage estimates. The estimated coverage from the imagery was statistically derived and compared favorably to the ground-truthed values, though at higher densities the remote sensor showed higher percent cover (positive bias) than the manual counts. This was likely due to investigator bias and uncertainty in both remote and manual field counts (e.g., estimates of percent cover should consider that seagrasses stand vertically when under water and lay flat when the tide recedes, whereas a remote sensor simply counts the fraction of pixels covered by seagrass).

Aerial imagery allows investigators to characterize the entire SAV meadow, while manual methods (e.g., swimming transects or counting quadrats) do not capture fragmentation within the SAV meadow. This can inform resource managers whether an SAV meadow is degrading or recovering. Aerial imagery allows access to some shallow intertidal areas that are not accessible to investigators because of deep mud or concerns about damaging the SAV. Another advantage is that UAVs can be deployed quickly and cover a much larger area within the time constraints of the low tide interval than is possible using observers on the ground (Konar and Iken, 2018).

There has been rapid advancement of UAV technology and capabilities in recent years. The use of UAVs, combined with stabilized high-resolution imaging, GIS technology, flight planning software, barometric altimeters accurate to 1-m, long-range transmitters, structure from motion (SfM) photogrammetry (software that estimates a three dimensional structure using two dimensional images), multispectral imaging that can “see” into the water and identify SAV species, and other advanced imaging software provides investigators with inexpensive tools to produce high-resolution orthomosaics to perform rapid, cost-effective monitoring of SAV.

Over the past decade, UAVs have become one of the most employed methods to assess landscape changes and map large areas, remote or inaccessible areas, agricultural fields, contaminated sites, forest dynamics, and for monitoring wildlife. UAVs that can survive an accidental dunking in water, and even take off from the water have expanded their utility to lakes, rivers, and coastal areas. As opposed to manned aircraft which require an airport, UAVs can be deployed from a vehicle, a boat, or from a small clearing on the ground. Because of the low cost, reliability, ready availability, and ease of use, UAVs can be used for routine assessment and monitoring.

A marine habitat mapping project in Italy (Ventura et al. 2018) used UAVs to survey a seagrass meadow, a fish nursery area, and a polychaete worm biogenic reef. The seagrass meadow (*Posidonia oceanica*) was mapped with commercially available, consumer-grade components, including a rotary-wing quadcopter UAV with vertical takeoff and landing (VTOL) capability and a gimbal-mounted GoPro camera, with a resolution of 2.76 centimeters per pixel. Using Object-Based Image Analysis (OBIA), which groups pixels into objects based on spectral similarity or other variables such as spectra or shape, can reduce the uncertainty of spectral analysis between live and dead seagrass leaves. The study was able to separate out isolated seagrass patches, dead seagrass matte, and sandy areas to identify the damaged parts of the seagrass meadow. Figure 4, from Ventura et al. (2018), shows habitat segmentation of a *P. oceanica* meadow using OBIA to demonstrate the different image objects correctly classified into eight cover classes including: beach; dead matte; dead *P. oceanica* leaves; emergent rock, live *P. oceanica*; sand, submerged rock, and terrestrial vegetation.

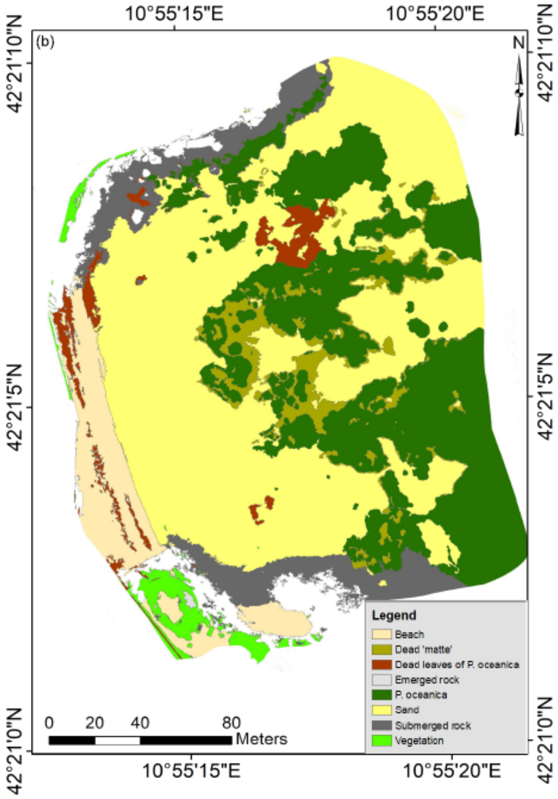

Figure 4. Seagrass habitat map from Ventura et al. 2018.

Multispectral imaging has also been advanced through the use of "fluid lensing", which uses water-transmitting wavelengths to gather high-resolution images of underwater objects by exploiting time-varying optical lensing events caused by surface waves (Chirayath and Earle, 2016). Fluid lensing data are used to derive multispectral imagery and bathymetry models on a centimeter-scale over large areas. The technology is limited to clear water at depths of less than 10-m. The fluid lensing technology is being developed for large-scale three-dimensional surveys of shallow habitats.

While UAVs are relatively inexpensive and readily available, there are national, state, and local constraints on their use (some like the use of manned aerial vehicles). Some examples of constraints that should be considered include: Federal Aviation Administration (FAA) pilot licensing; no-fly zones (e.g., near airports and military bases); and clear take-off and landing areas.

Other in-water remote sensing technologies that may be utilized include sidescan and multibeam sonars which bounce sound off the bottom to determine bathymetry and to classify the substrate (e.g., sand, rock, vegetation). Computer software is used to analyze the hydroacoustic data to evaluate the presence of SAV. Acoustic data is useful for determining the location of the SAV bed, its approximate density, and the height off the bottom of the SAV canopy. The Massachusetts Division of Marine Fisheries has found that eelgrass has a characteristic sonar pattern that can be used to delineate the extent of SAV beds, in concert with aerial imagery and submersible cameras for ground-truthing (Carr and Ford, 2017). Sidescan sonar data is generally collected by towing the sonar device behind a boat through a grid pattern over the area of concern and using computer software to stitch the resultant track images together. The use of sonar technology may be an additional line of evidence, but aerial imagery appears to be less limited.

5.0 REVIEW OF OTHER SAV PROGRAMS IN THE NORTHEAST, MID-ATLANTIC, AND FLORIDA

The following section reviews the SAV programs in other pertinent states.

MASSACHUSETTS

The Massachusetts Department of Environmental Protection (MassDEP) Eelgrass Mapping Project ranks among the longest sustained seagrass monitoring programs (utilizing the same methods) in the world (Massachusetts Document Repository). The program uses remote sensing to acquire data on SAV to monitor statewide status and trends. This approach is comparable to other large scale seagrass monitoring programs in Chesapeake Bay and Indian River Lagoon in Florida.

The dominant SAV in Massachusetts is *Zostera marina,* and *Ruppia maritima* is present in areas of lower salinity. Widgeon grass has a thread-like morphology that makes it difficult to identify using remotely sensed data and can only be identified and located by on-site survey. The (MassDEP) program to map SAV resources began in the early 1990s, and since 1995 has produced multiple surveys of SAV along the Massachusetts coastline.

This program utilizes "state of the art" methods to ensure scientific credibility and practical application of SAV mapping and monitoring data. Unlike monitoring and research programs that depend on "in water" sampling for data acquisition, MassDEP relies almost exclusively on remote sensing of aerial imagery as the principal source of information. During1995-2000, the program utilized high resolution aerial photography with strict requirements for the source data layer. Color photos were viewed using 10x magnification and the eelgrass polygon data were drafted to pin-registered acetate overlays. The overlays were then scanned at a high resolution and geo-registered to the Massachusetts orthophoto map series for digital distribution. Later years have utilized high resolution digital imagery (0.25m pixel) as the source data with on-screen digitizing functions available in ESRI's ArcMap. The remote sensing data are supplemented by boat-based underwater video data acquisition to verify benthic habitat signatures.

In the Spring of 1997, the Atlantic States Marine Fisheries Commission adopted an SAV policy that calls on states to protect existing SAV beds, reduce pollution to promote SAV comeback, and set quantifiable SAV recovery goals. Member states are responsible for: monitoring programs at one to five-year intervals; evaluating current regulatory program effectiveness and recommending improvements; setting SAV restoration goals; educating the public; and supporting SAV research. Rhode Island, Connecticut, New York, Delaware, Maryland, and Virginia have produced websites dedicated to raising awareness of the importance of SAV habitat, and that include description of threats to SAV and reports/data that the state has collected describing increases of loss of SAV habitat.

RHODE ISLAND

The goal of the Rhode Island (RI) Coastal Resources Management Council (CRMC) is to preserve, protect, and where possible, restore SAV habitat. The following activities under CRMC jurisdiction are required to avoid and minimize impacts to SAV habitat under Section 300.18 of the RI Coastal Resources Management Program (RICRMP): Residential, Commercial, Industrial, and Public Recreational Structures, Recreational Boating Facilities, Sewage Treatment and Stormwater, Dredging and Dredged Materials Disposal, Filling in Tidal Waters, Aquaculture, and activities undertaken in accordance with municipal harbor regulations. Links to the regulations that pertain to these activities and SAV habitats are provided for public convenience on a state website (http://www.edc.uri.edu/eelgrass/policyandregs.html). Eelgrass maps and links to metadata are also available on this website, as well as links to government and non-profit organizations working to protect and restore SAV beds.

Statewide SAV surveys, predominately focusing on Narragansett Bay, were conducted in 2012 and 2016 (http://www.crmc.ri.gov/sav.html).

CONNECTICUT

SAV is broadly protected under the Connecticut (CT) Coastal Management Act. The Act also establishes policies to preserve and enhance coastal resources. Eelgrass in estuarine embayments is a resource protected by the Act. Adverse impacts to SAV are defined pursuant to C.G.S. Sec. 22a-93(15)(G) as those impacts "degrading or destroying essential wildlife, finfish or shellfish habitat through . . . significant alterations of the natural components of the habitat." The policy of this State is "to manage estuarine embayments so as to insure that coastal uses proceed in a manner that assures sustained biological productivity, the maintenance of healthy marine populations and the maintenance of essential patterns of circulation, drainage and basin configuration; to protect, enhance and allow natural restoration of eelgrass flats except in special limited cases most notably shellfish management, where the benefits accrued through alteration of the flat may outweigh the long-term benefits to marine biota, waterfowl, and commercial and recreational finfisheries" [C.G.S. Sec. 22a-92(c)(2)(A)].

Considerable efforts have been directed towards understanding the water quality requirements for SAV. Water quality data at restoration sites (successes and failures) have been used to refine these requirements. Similar, but more stringent, habitat parameters were identified for SAV in Long Island Sound. The more conservative values are based on the findings that regenerating eelgrass beds require better conditions than those needed for simply maintaining existing beds (Okubo and Slater, 1989). The Chesapeake studies have shown that if several of the water quality requirements are not met, eelgrass is usually not present (Orth et al., 2002).

The Long Island Sound Study (LISS) is being conducted through CT Coastal Resources (University of CT https://climate.uconn.edu/coastal-resources/sav/#). Along the CT coast, SAV beds occur from the Rhode Island border at Stonington west to Clinton. Mapping of these beds was completed in 1996 by a team of researchers from the University of CT (*C. Yarish, University of CT, pers. comm.*). There are no known eelgrass populations along the north shore of Long Island (*Black, pers. comm.; NYSDEC surveys*). Eelgrass beds are prioritized for restoration and the eelgrass off Plum Island, Southold, NY is designated as a Priority Habitat.

https://www.arcgis.com/apps/MapTour/index.html?appid=e0ee06bc69dd4f3da462425bdc19787d.

NEW YORK

The New York State Department of Environmental Conservation (NYSDEC) Hudson River Estuary Program, in collaboration with numerous partners, has supported the mapping of SAV habitats of the Hudson River Estuary. This data set contains polygons showing the distribution of SAV from Hastings-on-Hudson to Troy. Data are a combination of layers from the 1997, 2002, 2007, 2014, 2016, and 2018 SAV data sets, representing a culmination of all areas where SAV habitat has been documented. Metadata is available online at the Geographical Information Service (GIS) Clearinghouse: https://gis.ny.gov/gisdata/inventories/details.cfm?DSID=1209.

The maximum SAV coverage was determined to be from Kingston to Catskill, where SAV covers approximately 20% of the river. Maps of SAV from Hastings-on-Hudson to Troy have been made for the years 1997, 2002, 2007, and 2014, and the latter three inventories are available on the GIS Clearinghouse. To map areas that have the potential to support SAV growth, all four inventories have been combined into one "Hudson River Estuary Documented Submerged Aquatic Vegetation" map, also available on the GIS Clearinghouse.

Scientists have documented a return of native plant beds in recent years. This recovery will be quantified through the interpretation of 2016 aerial imagery. The resulting GIS maps, when completed, will provide important additional information on the status and trends of SAV. The SAV mapping project is funded by the Environmental Protection Fund. In addition to several regulations protecting SAV from disturbance, restoration planning efforts for the upper Hudson River estuary have focused on restoring lost SAV habitats. Current restoration planning efforts for the upper estuary are looking into opportunities to restore some of the shallows and SAV that have been lost (https://www.dec.ny.gov/lands/87648.html).

DELAWARE

In coordination with the Delaware Estuary National Estuary Program, the Partnership for the Delaware Estuary identified SAV as a critical component of their Comprehensive Conservation and Management Plan (CCMP). The CCMP is based on a scientific characterization of the estuary developed and approved by a broad coalition of stakeholders. This blueprint guides decisions and establishes priorities for activities, research, and funding to address environmental protection issues in the estuary. In 2017 and 2018, EPA Mid-Atlantic Region researchers conducted field surveys along the Delaware River and Bay shores (https://www.epa.gov/sciencematters/mapping-underwater-vegetation-delaware-estuary). Hydroacoustic monitoring devices, similar to the types of “fish finders” used by fishermen and other boaters, but more advanced and finely tuned to detect SAV beds instead of fish were used to collect information about the geographic range and density of the SAV beds. The device hangs over the side of the sampling vessel and emits a beam of soundwaves into the water, recapturing the sound as it reflects off objects. Based on the strength of the reflected sound, the device differentiates between a vegetation bed and the bottom substrate. The device also determines water depth and height of a seagrass bed based on the amount of time it takes to recapture the sound. Together, this information provides a comprehensive picture of vegetation distribution and density. Divers also collected raking samples to verify the hydroacoustic data with direct observation. The final results and data from this project will be used to create a comprehensive map of submerged aquatic vegetation throughout the Delaware Estuary. This map will be shared with Environmental Protection Agency (EPA) partners and stakeholders to assist with other aquatic habitat assessments, support restoration efforts, and inform regulatory decisions made throughout the Delaware River.

CHESAPEAKE BAY (BAY-WIDE INCLUDING MARYLAND AND VIRGINIA)

The Chesapeake Bay Program (CBP) defines 93 segments grouped into four salinity zones, that reflect communities of SAV species found in Chesapeake Bay: Tidal Fresh (less than 0.5 ppt), oligohaline (0.5-5 ppt), mesohaline (5-18 ppt), and polyhaline (18-25 ppt). Ground surveys are accomplished by cooperative efforts from a number of agencies and individuals. Ground surveys confirm the existence of some SAV beds mapped from the aerial imagery, as well as SAV beds that were too small to be visible on the imagery. Although not all areas of Chesapeake Bay are ground surveyed, the data collected provides valuable supplemental information. The surveys also provide species data for many of the SAV beds. Ground survey information supplied to Virginia Institute of Marine Science (VIMS) researchers is included in VIMS digital maps describing SAV distribution and abundance, and in the VIMS SAV GIS Database. All ground survey data supplied to VIMS are tabulated in the ground survey table. Standard operating procedures (SOPs) have been developed to facilitate orderly and efficient processing of SAV maps and SAV computer files, and to comply with the need for consistency, quality assurance, and quality control. SOPs include a detailed procedure for orthorectification, mosaicking, and photo-interpretation; tracking sheets which record the processing of flight lines and quadrangles; and weekly summary progress reports of all operations. Interactive Maps (by year) are available from a publicly accessible website: https://www.chesapeakeprogress.com/abundant-life/sav.

Annual reports of Chesapeake Bay SAV monitoring conducted since 2010 are available online. SAV in Chesapeake Bay and its tributaries was mapped from multispectral digital imagery. National Agricultural Imagery Program (NAIP) imagery was used to augment the multispectral imagery in a portion of the Potomac, James, and Pamunkey rivers; Pungoteague Creek; and Mobjack Bay (https://mobjack.vims.edu/sav/oldsite/sav16/exec_summary.html. Direct comparisons to previous years are restricted to only those regions that were mapped in successive years. Although the Chesapeake Bay and its tributaries were fully mapped for 2019, highly turbid water, weather conditions, and security restrictions in the District of Columbia area, over Patuxent Air Base and associated mid-Bay areas prevented acquisition of useable imagery in 2018 for a portion of the tidal fresh and mesohaline Potomac River, the Bohemia, Choptank, and Mattaponi rivers.

Maryland Sea Grant partners with VIMS to survey and restore SAV habitats in Chesapeake Bay. The Maryland Department of Natural Resources (MDNR) website includes information about seagrass habitats and protection, and has a hotline weblink where individuals can report threats to seagrass beds: https://dnr.maryland.gov/waters/bay/Pages/sav/Coverage-of-SAV.aspx.

FLORIDA

Although outside the Mid-Atlantic region, it may be helpful to consider steps taken by the State of Florida to protect seagrass habitat. Florida SAV communities differ from those found in NJ; the dominant species is turtle grass (*Thalassia testudinum*). After the first documented mass mortality event occurred in the shallow Florida Bay estuary in 1987, the system's slow recovery has been documented by the Fisheries Habitat Assessment Program (FHAP) since 1995 (Hall et al., 2016). Status and trends data are gathered in order to separate natural ecosystem fluctuations from changes occurring due to anthropogenic activities. The research provides baseline data to evaluate macrophyte community responses to management or restoration activities https://myfwc.com/research/habitat/seagrasses/projects/active/fhap/.

The FHAP program was begun by the Florida Fish and Wildlife Conservation Commission (FWC), which began systematically surveying seagrass species composition, distribution, and abundance in ten Florida Bay basins. Seagrass community recovery patterns have been documented for over 20 years, showing a near-full recovery by 2012, followed by a second major die-off event in 2015-2016 (Hall et al., 2016). The second die-off event was documented by visual surveys and areas of severe mortality were developed for the spatial data using ArcGIS (Hall et al., 2016). This program was funded by the South Florida Water Management District under the Restoration, Coordination, and Verification Program. The National Park Service provided logistical support. FWC research staff provides resource managers with data necessary to make effective decisions about the preservation, management and restoration of seagrass communities. Information available from the Florida Fish and Wildlife Conservation Commission website includes:

- Seagrass Information
  Articles providing general information about seagrasses, such as a glossary of terms, additional links, seagrass biology and ecology, and answers to your most frequently asked questions.
- Seagrass Projects
  To successfully protect Florida's seagrasses, FWRI staff members work on many different types of aquatic vegetation-related projects. Some of FWRI's current biological research, monitoring, and mapping projects are described.
- Seagrass Publications
  Selected seagrass-related documents available for download.

6.0 CONCLUSIONS

As noted in the introduction, SAV beds are designated as Essential Fish Habitat by the NMFS, contributing to one of the most productive ecosystems in the world (Havel 2018), supporting biogeochemical cycling, physical stabilization of sediments, and life cycle habitat needs of multiple aquatic species (Green & Short 2007). SAV provides a nutrient source, nursery area, and critical habitat for commercially and recreationally important fish, benthic, and marine mammal populations (de Boer 2007), including threatened and endangered species.

A dedicated monitoring program, performed on an annual or semi-annual basis, is necessary to assess the health of SAV meadows and to avoid missing significant changes. Monitoring should include both remote sensing and *in situ* sampling. The recent advances in the technologies and capabilities available for UAVs, stabilized high-resolution imaging cameras, GIS technology, flight planning software, barometric altimeters, long-range transmitters, SfM photogrammetry, OBIA, multi-spectral imaging, and other imaging software provide investigators with inexpensive tools to produce high-resolution orthomosaics to perform rapid, cost-effective remote monitoring of SAV.

Using remote sensing to focus the more labor-intensive *in situ* sampling and measurement of SAV health (e.g., above- and below-ground biomass, blade lengths, shoot densities) will allow for the most robust evaluation of SAV extent and health.

7.0 RECOMMENDATIONS

Periodic (optimally annually) *in situ* monitoring of SAV is recommended, in concert with the incorporation of UAVs and the advanced optical, OBIA, multi-spectral imaging cameras, and the commercially available imaging software.

The *in situ* monitoring should use standard field methods (e.g., the Seagrass-Watch protocols from Mckenzie et al. 2003, or the Seagrass Net monitoring protocols of Short et al. 2002), with a series of quadrats (0.25 m^2 to 0.5 m^2 in size) randomly placed in the seagrass meadow to measure percent cover, shoot length, and densities. Samples of biomass (both above- and below-ground), epiphytic loading, along with analysis of total organic carbon, grain size, nutrients, and contaminants (e.g., hydrocarbons, polychlorinated biphenyls (PCBs), pesticides, metals) are important to monitor the ongoing health of the SAV. Periodic water quality monitoring should include temperature, dissolved oxygen, salinity, total suspended solids, and turbidity.

An investment in the use of UAVs, along with the most up-to-date, state-of-the-science data processing software would allow the NJDEP to periodically evaluate coastal SAV in a cost-effective manner. Because of the rapid advances in UAV technology, the NJDEP should seek out an expert in the use of UAVs for technical advice. The ability to evaluate the commercially available and/or custom software programs against one another for cost, capabilities, or effectiveness is beyond the expertise of the SAB EPSC. However, the Rutgers CRSSA has the necessary expertise to give NJDEP the information to make programmatic decisions.

8.0 REFERENCES

Barko, J.W., Adams, M.S., Clesceri, N.L. 1986. Environmental factors and their consideration in the management of submerged aquatic vegetation: A. review. Journal of Aquatic Plant Management 24:1-10.

Becker, B.L, D.P. Lusch, and J. Qi. 2005. Identifying Optimal Spectral Bands from *in Situ* measurements of Great Lakes Coastal Wetlands using Second-Derivative Analysis. *Remote Sensing of Environment*, vol. 97, pp. 238-248.

Bologna, P.A.X., Lathrop, R., Bowers, P.D., Able, K.W. 2000. Assessment of the health and distribution of submerged aquatic vegetation from Little Egg Harbor, New Jersey. Technical Report #2000-11 of the Institute of Marine and Coastal Sciences. Rutgers, The State University of New Jersey. 71 Dudley Road, New Brunswick, New Jersey.

Bologna, P.A.X., Sinnema, M.S. 2012. Restoration of seagrass habitat in New Jersey, United States. Journal of Coastal Research 28. 1A:99-104.

Burkholder, J.M., Tomasko, D.A., Touchette, B.W. 2007. Seagrasses and eutrophication. Journal of Experimental Marine Biology and Ecology 350:46-72.

Carr, J. and K. Ford. 2017. Historic eelgrass trends in Salem Sound, Massachusetts, Final Report. Mass Division of Marine Fisheries, submitted to the Massachusetts Bays Program.

Chirayath, V., and S.A. Earle. 2016. Drones That See Through Waves – Preliminary Results from Airborne Fluid Lensing for Centimetre-scale Aquatic Conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 26, pp. 237-250.

Costanza, R., Wilson, M.A., Troy, A., Voinov, A., Liu, S. 2006. The value of New Jersey's ecosystem services and natural capital. New Jersey Department of Environmental Protection Division of Science, Research, and Technology. Trenton, NJ. Contract #SR04-075.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K. 2014. Changes in the global value of ecosystem services. Global Environmental Change 26:152-158.

Dacanay, K. (NJDEP – Bureau of Shellfisheries). 2020. Personal communication.

Dacanay, K. (NJDEP – Bureau of Shellfisheries). 2015. Inventory of New Jersey's Estuarine Shellfish Resources: Hard Clam Stock Assessment - Navesink and Shrewsbury Rivers (2015). https://www.nj.gov/dep/fgw/pdf/marine/shellfish_assessment_nr-sr15.pdf.

De Boer, W.F. 2007. Seagrass-sediment interactions, positive feedbacks and critical thresholds for occurrence: A review. Hydrobiologia 591:5-24.

Duffy, J.P., L. Pratt, K. Anderson, P.E. Land, J.D. Shutler. 2018. Spatial Assessment of Intertidal Seagrass Meadows Using Optical Imaging Systems and a Lightweight Drone. *Estuarine, Coastal and Shelf Science*, vol. 200, pp 169-180.

Duarte, C.M., Marbà, N., Garcia, E., Fourqurean, J.W., Beggins, J, Barrón, C., Apostolaki, E.T. 2010. Seagrass community metabolism: Assessing the carbon sink capacity of seagrass meadows. Global Biogeochemical Cycles 24:GB4032, doi10.1029/2016GB003793. Accessed 28 July, 2021.
EPA. 2020. Mapping Underwater Vegetation in the Delaware Estuary. Report in Progress: https://www.epa.gov/sciencematters/mapping-underwater-vegetation-delaware-estuary.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marba, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O. 2012. Seagrass ecosystems as a globally significant carbon stock. Nature Geoscience. Doi:10.1038/NGEO1477. Accessed 28 July, 2021.
Green, E., Short, F. 2007.World Atlas of Seagrasses. UNEP World Conservation Monitoring Centre. Cambridge, U.K.

Hall, M.O., Furman, B.T., Merello, M., Durako, M.J. 2016. Recurrence of Thalassia testudinum seagrass die-off in Florida Bay, USA: initial observations. Mar Ecol Prog Ser 560:243-249.

Havel, L.N., ASMFC Habitat Committee. 2018. Submerged Aquatic Vegetation Policy. ASMFC Habitat Management Series No. 15. Arlington, Va.

Hughes, A.R., Bando, K.J., Rodriquez, L.F., Williams, S.L. 1004. Relative effects of grazers and nutrients on seagrasses: a meta-analysis approach. Mar Ecol Prog Ser 282:87-99.

Kantrud, H.A. 1991. Wigeongrass (Ruppia maritima L.): A Literature Review. Fish Wildlife Research 10. U.S. Fish & Wildlife Service. 58 pp.

Kemp, W.M., Batiuk, R., Bartleson, R., Bergstrom, P., Carter, V., Gallegos, C.L., Hunley, W., Karrh, L., Koch, E.W., Landwehr, J.M., Moore, K.A., Murray, Naylor, M., Rybicki, N.B., Koch, E.W., Orth, R.J. 2007. The seagrasses of the Mid-Atlantic coast of the United States. *In* World Atlas of Seagrasses, Green, E., Short, F. (eds). UNEP World Conservation Monitoring Centre, Cambridge, U.K.

Konar, B. and K. Iken. 2018. The Use of Unmanned Aerial Vehicle Imagery in Intertidal Monitoring. *Deep-Sea Research Part II*, vol 147, pp 79-86.

Lathrop, R.G., Styles, R.M., Seitzinger, S.P., Bognar, J.A. 2001. Use of GIS mapping and modeling approaches to examine the spatial distribution of seagrasses in Barnegat Bay, New Jersey. Estuaries 24(6A): 904-916.

Lathrop, R.G. and S.M. Haag. 2011. Assessment of Seagrass Status in the Barnegat Bay – Little Egg Harbor Estuary System: 2003 and 2009. CRSSA Technical Report #2011-01. Rutgers University, Grant F. Walton Center for Remote Sensing and Spatial Analysis, New Brunswick, NJ.

Lathrop, R.G. Jr, S.M. Haag, D. Merchant, M.J. Kennish, and B. Fertig. 2014. Comparison of Remotely-sensed Surveys vs. in Situ Plot-based Assessments of Sea Grass Condition in Barnegat Bay-Little Egg Harbor, New Jersey USA. *Journal of Coastal Conservation*, May 2014.

Lee, K-S., Park, S.R., Kim, Y.K. 2007. Effects of irradiance, temperature, and nutrients on growth dynamics of seagrass: A review. Jour. Of Experimental Marine Biology and Ecology 350:144-175.

Lovelock, C.E., Duarte, C.M. 2019. Dimensions of Blue Carbon and emerging perspectives. Biology Letters 15:20180781.dx.doi.org/10.1098rsbl.2018.0781. Accessed 28 July, 2021.

Macreadie, P.I., Gaird, M.E., Trevathan-Tackett, S.M., Larkum, A.W.D., Ralph, P.J. 2014. Quantifying and modeling the carbon sequestration capacity of seagrass meadows: A critical assessment. Mar. Poll. Bull. 83:430-439.

Malea, P., Kevrekidis, T., Mogias, A. 2004. Annual versus perennial growth cycle in *Ruppia maritima* L: temporal variation in population characteristics in Mediterranean lagoons (Monolimni and Drana Lagoons, Northern Aegean Sea). Botanica Marina 24:357-366.

Mckenzie, L.J., S.J. Campbell, and C.A. Roder. 2003. Seagrass-Watch: Manual for Mapping and Monitoring Seagrass Resources by Community (Citizen) Volunteers. Produced by the Seagrass-Watch, Northern Fisheries Centre, Cairns, Queensland, AUS.

McLeod, E., Chomura, G.L., Bouillon, S., Salm, R., Bjork, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R. 2011. A blueprint for bule carbon: toward improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front. Ecol Environ 9(10):552-560.

Nelleman, C., Corcoran, E., Duarte, C., De Young, C., Fonseca, L.E., Grimsdith, G. 2010. “Blue Carbon”: The role of healthy oceans in binding carbon. Center for Coastal and Ocean Mapping. https://scholars.unh.edu/ccom/132. Accessed 29 July, 2021.

Olsen, J.L., Rouzé, Verhelst, B., Lin, Y-Ch., Bayer, T., Collen, J., Dattolo, E., De Paoli, E., Dittami, S., Maumus, F., Michel, G., Kersting, A., Lauritano, C., Lohaus, R., Töpel, M., Tonon, T., Vanneste, K., Amirebrahimi, M., Brakel, J., Böstrom, C., Chovatia, M., Grimwood, J., Jenkins, J.W., Jueterbock, A., Mraz, A., Stam, W.T., Tice, H., Bornberg-Bauer, E., Green, P.J., Pearson, G.A., Procaccini, G., Duarte, C.M., Schmutz, J., Reusch, T.B.H., Van de Peer, Y. 2016. The genome of the seagrass *Zostera marina* reveals angiosperm adaptation to the sea. Nature 530:331-334.

Orth, R.J., Moore, K.A. 1982. Distribution and abundance of submerged aquatic vegetation in the Chesapeake Bay: A Scientific Summary. Special Reports in Applied Marine Science and Ocean

Engineering (STAMSOE) No. 259. Virginia Institute of Marine Science, College of William and Mary. https:doi.org/10.21220/V58454.

Orth, R.J., Batiuk, R. A., Bergstrom, P.W., Moore, K. 2002. A perspective on two decades of policies and regulations influencing the protection and restoration of submerged aquatic vegetation in Chesapeake Bay, USA. Bulletin of Marine Science 71(3):1391-1403.

Palacios, S.L., Zimmerman, R.C. 2007. Response of eelgrass *Zostera marina* to CO_2 enrichment: possible impacts of climate change and potential for remediation of coastal habitats. Mar. Ecol.. Prog. Ser. 344:1-13.

Russell, B.D., Connell, S.D., Uthicke, S., Muehllehner, N., Fabricius, K.E., Hall-Spencer, J.M. 2013. Future seagrass beds: Can increased productivity lead to increased carbon storage? Mar. Poll. Bull. 10.1016/j.marpolbul.2013.01.031.

Short, F.T, McKenzie L.J, Coles, R.G., and Vidler, K.P. 2002. Seagrass Net manual for scientific monitoring of seagrass habitat. Queensland Department of Primary Industries – Marine Plant Ecology Group, Cairns.

Short, F.T., Koch, E.W., Creed, J.C., Magalhäes, K.M., Fernandez, F., Gaeckle, J.L. 2006. SeagrassNet monitoring across the Americas" case studies of seagrass decline. Marine Ecology 27:277-289.

Short, F., Carruthers, T., Dennison, W., Waycott, M. 2007. Global seagrass distribution and diversity: A bioregional model. Journ. of Experimental Marine Biology and Ecology 350:3-20.

Slonecker, T., S. Kalaly, J. Young, M.A Furedi, K. Maloney, D. Hamilton, R. Evans, E. Zinecker. 2018. A Preliminary Assessment of Hyperspectral Remote Sensing Technology for mapping Submerged Aquatic Vegetation in the Upper Delaware River National Parks (USA). *Advances in Remote Sensing*, vol. 7, pp 290-312.

Smith, B., McKenna, K., Pimpinelli, H. 2018. Establishing protocols for New Jersey shellfish and submerged aquatic vegetation (SAV) habitat mapping and sampling. New Jersey Department of Environmental Protection, Office of Coastal and Land Use Planning. Trenton, NJ.

Spalding, M., Taylor, M., Rarulious, C., Short, F., Green, E. 2007. The distribution and status of seagrasses. *In* World Atlas of Seagrasses, Green, E., Short, F. (eds). UNEP World Conservation Monitoring Centre, Cambridge, U.K.

Stephan, C.D., Bigford, T.E. 1997. Atlantic Coastal Submerged Aquatic Vegetation: A Review of its Ecological Role, Anthropogenic Impacts State Regulation, and Value to Atlantic Coastal Fish Stocks. ASMFC Habitat Management Series #1.

Stevenson, J.C., Wilcox, D.J. 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors. Estuaries 27(3):363-377.

Thayer, G.W., Fonseca, M.S., Kenworthy, J.W. 1997 Ecological Value of Seagrasses. A Brief Summary for the ASMFC Habitat Committee's SAV Subcommittee. NOAA/NMFS Southeast Fisheries Science Center. Beaufort Laboratory. Beaufort, NC.

Ventura, D., A. Bonifazi, M.F. Gravina, A. Belluscio, and G. Ardizzone. 2018. Mapping and Classification of Ecologically Sensitive Marine Habitats Using Unmanned Aerial Vehicle (UAV) Imagery and Object-Based Image Analysis (OBIA). *Remote Sensing*, vol. 10, 1331.

Zayas-Santiago, C.C., Rivas-Ubach, A., Kuo, L.-J., Ward, N.D., Zimmerman, R.C. 2020. Metabolic profiling reveals biochemical pathways responsible for eelgrass response to elevated CO2 and temperature. Nature Scientific Reports. Doi.org/10.1038/S41598-020-6184-X