Seagrass Depth Limits in Chincoteague Bay, Virginia

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Abstract

Knowledge of seagrass depth limits is essential in the understanding of seagrass distributions locally and at global scales. They also depend on sediment characteristics, nutrient levels, and other factors. Depth ranges vary with species depending on rhizome structures and complexity of seagrass species. Seagrass communities are a major part of marine ecosystems responsible for organic matter production and carbon sequestration. Ecosystems with abundant seagrass beds experience a clear water column which allows for abundant light penetration and the consequent establishment and survival of photosynthetic organisms, providing suitable habitat for a number of species that interact through complex food webs. For this reason seagrasses affect humans by favoring fish and shell production. Despite their importance, seagrasses are in decline globally due to climate change drivers and rapid rise of human populations on coastal regions. Conservation researchers strive to understand seagrass dynamics to help with preservation, restoration and other conservation strategies that are in place to help protect reduce and possibly stop seagrass declines.

In this thesis, I carried out an assessment of depth limits of seagrasses in the Chincoteague Bay, in the eastern shore of the United States. The results show seagrass in Chincoteague to occur at depth ranges of 0.2-1.2m, which are shallower than expected. The results also suggest that about 79 percent of the bay is suitable for seagrass restoration based on depth, though other factors are expected to play a role in determining the habitat suitability for seagrasses. These results could help future suitability studies that consider other factors affecting seagrass establishment and survival in shallow coastal bays.

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List of Abbreviations

SAV	Submerged Aquatic Vegetation
VCR-LTER	Virginia Coast Reserve-Long Term Ecological Research
VIMS	Virginia Institute of Marine Sciences
IUCN	International Union for Conservation of Nature
VMRC	Virginia Marine Resources Center
UNEP-WCMC	United Nations Environmental Program- World Conservation Monitoring Center
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
MSL	Mean sea level
DEM	Digital Elevation Model
NAVD88	The North American Vertical Datum of 1988
LiDAR	Light Detection and Ranging

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1. Introduction

Seagrasses are submerged, marine flowering plants known to habit tropical and temperate shallow waters (Heller, 1987). The seagrass functional type includes a variety of species (Table 1) ranging from *Zostera caulescens* with about 4 m long blade-like leaves in the Sea of Japan, to the small rounded (~3 cm) leaves of *Halophila decipiens* in tropical Brazil (Green and Short, 2003). Distribution of seagrass species in estuarine and marine environments depends on method of reproduction or growth, which are both influenced by dispersal and environmental conditions (Short, et al. 2007). Attempts to determine geographical distribution of seagrasses date back as far as 1871 by Ascherson, with improved maps and studies through time (de Hartog and Kuo, 2006; Green and Short, 2003). Relying on historical maps and studies on seagrass den Hartog and Kuo (2006), discussed the taxonomy and biogeography of seagrass, siting occurrences of seagrass genera along temperate and tropical coasts. Their investigation gives a different perspective in seagrass distributions and history by assessing "seagrass fossils" such as *Posidonia parisiensis* found in Basin of Paris from the Eocene, and *Thalassodendron auricula-leporis* also from the Eocene, found in the Avon Park formation in Florida. This study used both mapping and molecular DNA sequencing to understand seagrass now and infer previous distributions.

Maps of seagrass occurrence and species distributions have been developed (Short et al. 2007; Green and Short, 2003) using data from multiple sources (Fig 1 and Table 1). The Global Seagrass Atlas (Green and Short, 2003) recognizes almost sixty seagrass species found in shallow marine and estuary environments across the world with the exception of Antarctica. Generally seagrasses have a preference for soft sediment areas, but exceptions such as the *Phyllospadix* species, which grows on rock substrate, exist (Green and Short, 2003). The preferential occurrence of seagrass meadows in shallow areas is due to their elevated light requirements which, attenuates with depths, limiting growth to shallow areas (Duarte, 1991).

Seagrass species diversity is highest in tropical and temperate regions (with about 29 species in Australia, 23 in the United States and 16 in Japan), single climate countries (where the climate is almost constant) with high diversity are mostly in the tropics (for example, India and the

Philippines with 14 species each) (Green and Short, 2003). By growing completely submerged underwater, seagrasses have adaptations such as epidermal chloroplasts, internal gas transport, submarine pollination and seed dispersal (Orth et al. 2006b).

Due to taxonomic uncertainties, definition of threatened and restricted species (those that are found in one part of the world and nowhere else) of seagrasses is not clear (Green and Short, 2003), however, the International Union for Conservation of Nature (IUCN) lists *Halophila johnsonii* and *Phyllospadix serruletus* as threatened. The most notable of national endemics are thirteen species found in Australia and nowhere else in the world. Green and Short (2003) conclude that, although there has not been any ecological significance to this endemism, the knowledge is vital to conservation actions. Recent global distribution work (e.g. Short, et al. 2007) define seagrass occurrences based on species assemblages, species distributional ranges and tropical and temperate influences. Generally, this method depicts seagrass distributions in six bioregions (Table 1), four temperate and two tropical.

Table 1: Global distribution of seagrasses based on assemblages of taxonomic groups in temperate and tropical areas and the physical distribution of oceans (taken from Short et al., 2007).

Bioregion	Description	Species
1. *Temperate North Atlantic* (North Carolina, USA to Portugal)	Low diversity temperate seagrasses (5 species) primarily in estuaries and lagoons.	*Ruppia maritima*, *Zostera marina*, *Zostera noltii*, *Cymodocea nodosa*+, *Halodule wrightii*+
2. *Tropical Atlantic* (including the Caribbean Sea, Gulf of Mexico, Bermuda, the Bahamas, and both tropical coasts of the Atlantic)	High diversity tropical seagrasses(10 species) growing on back reefs and shallow banks in clear water.	*Halodule beaudettei*, *H. wrightii* (*H. bermudensis*, *H. emarginata*), *Halophila baillonii*, *Halophila decipiens*, *Halophila engelmanni*, *Halophila johnsonii*, *R. maritima*, *Syringodium filiforme*, *Thalassia testudinum*, *Halophila stipulacea*+
3. *Mediterranean* (including the Mediterranean Sea, the Black, Caspian and Aral Seas and northwest Africa)	Vast deep meadows of moderate diversity and a temperate/tropical mix of seagrasses (9 species) growing in clear water.	*C. nodosa*, *Posidonia oceanica*, *Ruppia cirrhosa*, *R. maritima*, *Z. marina*, *Z. noltii*, *H. wrightii*+, *H. decipiens*+, *H. stipulacea*+
4. *Temperate North Pacific* (Korea to Baja, Mexico)	High diversity of temperate seagrasses (15 species) in estuaries, lagoons and coastal surf zones.	*Phyllospadix iwatensis*, *Phyllospadix japonicus*, *Phyllospadix scouleri*, *Phyllospadix serrulatus*, *Phyllospadix torreyi*, *R. maritima*, *Zostera asiatica*, *Zostera caespitosa*, *Zostera caulescens*, *Zostera japonica*, *Z. marina*, *H. wrightii*+, *H. decipiens*+, *Halophila euphlebia*+, *Halophila ovalis*+
5. *Tropical Indo-Pacific* (East Africa, south Asia and tropical Australia to the eastern Pacific)	Largest and highest diversity bioregion; tropical seagrasses (24 species) predominantly on reef flats but also in deep waters, many commonly grazed by mega-herbivores.	*Cymodocea angustata*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Enhalus acoroides*, *Halodule pinifolia*, *Halodule uninervis*, *H. wrightii*, *Halophila beccarii*, *Halophila capricorni*, *H. decipiens*, *Halophila hawaiiana*, *Halophila minor*, *H. ovalis*, *Halophila ovata*, *Halophila spinulosa*, *H. stipulacea*, *Halophila tricostata*, *R. maritima*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Thalassodendron ciliatum*, *Zostera capensis*+, *Z. japonica*+, *Zostera muelleri*+ [*Zostera capricorni*]
6. *Temperate Southern Oceans* (New Zealand and temperate Australia, South America, and South Africa)	Extensive meadows of low-to-high diversity temperate seagrasses (18 species) often growing under extreme conditions.	*Amphibolis antarctica*, *Amphibolis griffithii*, *Halophila australis*, *Posidonia angustifolia*, *Posidonia australis*, *Posidonia ostenfeldii* complex, *Posidonia sinuosa*, *R. maritima*, *Ruppia megacarpa*, *Ruppia tuberosa*, *Thalassodendron pachyrhizum*, *Z. capensis*, *Z. muelleri* [*Z. capricorni*], *Zostera tasmanica* [*Heterozostera tasmanica*], *H. decipiens*+, *H. ovalis*+, *S. isoetifolium*+, *T. ciliatum*+

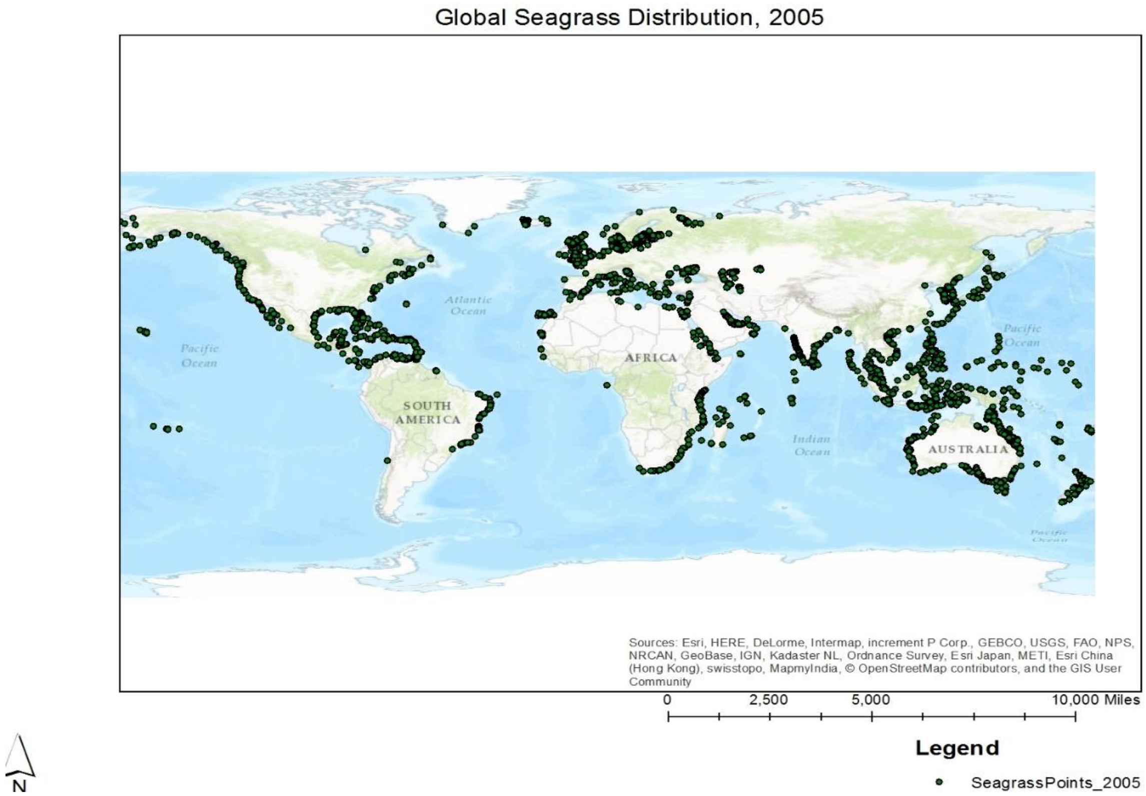

Figure 1: Global Seagrass Distribution (Based on data from UNEP World Conservation Monitoring Center). Location data was offered as shapefiles on UNE-WCMC datasets, and continent data from ArcGIS online.

2. Importance of seagrasses

Although they habit a small part of the world, seagrass have been found to play a major role in nearshore ecosystems (Orth et al. 2006b). Seagrasses are defined as a highly complex ecosystem because they do not grow in isolation. Primarily seagrasses are a food source to animals such as manatees, dugongs and green sea turtles (Green and Short, 2003) and can also enter various food chains in detrital form (Marba et al. 2007). The three dimensional structure of a seagrass meadow plays an important role in sheltering and stabilizing the sediment surface and altering wave energy and currents (Hansen and Reidenbach, 2012; Green and Short, 2003). A combination of the above factors determined the habitat for various organisms. Seagrasses are referred to as "ecosystem engineers" (e.g. Koch et al. 2007) because they modify their environment by affecting currents, turbulence and wave energy (Fonseca and Cahalan, 1992). Irlandi and Peterson (1991) demonstrated that *Mercenaria mercenaria* clams on unvegetated sand flats in Back Sound Carolina failed to grow as well and in abundance as those within seagrass beds. Organisms found in seagrass ecosystems may use the seagrass environment as a necessity (obligate organisms) (Green and Short, 2003) or just prefer the highly productive seagrass habitat during a part of their life cycle (nursery, breeding and spawning areas (Table 2)) (Global Seagrass Atlas, 2003). Seagrass beds in Chesapeake Bay are reported to be important nursery areas for the blue crab, *Callinectes sapidus*, whose commercial harvest can yield close to 45000 metric tons in a good year (Waycott et al. 2009). The bay scallop (*Argopecten irradians*) fishery is also closely tied to seagrass abundance because the larval stage attaches its byssal thread (a silky fibrous material used by most bivalves for attachment onto substrate) to seagrass leaves. Other important local fisheries sometimes associated with seagrasses include hard clams (*Mercenaria mercenaria*) and fish of commercial and recreational importance, e.g. striped bass (*Morone saxatalis*), spotted sea trout (*Cynoscion nebulosus),* spot (*Leiostomus xanthurus*) and gag grouper (*Mycteroperca microlepis*) (Koch and Orth, 2003).

Table 2: Major Taxonomic groups found in seagrass ecosystems (Taken from Green and Short, 2003)

Bacteria Fungi Diatoms (Bacillariophyta) Blue-green Algae (Cyanophyta) Red algae (Rodophyta) Brown algae (Phaeophyta) Green algae (Chlorophyta) Protozoa Sponges Cnidarians
Polychaetes Ribbon worms Sipunculid worms Flatworms Crustaceans Bivalve mollusks Gastropod mollusks Cephalod Mollusks Bryozoans Echinoderms
Tunicates Fish
Reptiles Birds Mammals

In comparison to terrestrial ecosystems seagrasses have a low biomass but exceed the oceanic plankton biomass (Table 3) (Short et al. 2007; Mateo et al. 2006). Published averages for seagrass biomass varies with the species: species such as *Amphibolis, Phyllospadix* and *Posidonia* have been found to reach high biomass densities, while *Halophila*, with its small leaves and very high turnover rates, is found at lower densities (Green and Short, 2003; Duarte and Chisano, 1999).

Differences in biomass estimates depend also on other factors, including grazing rates, which typically differ between tropical (high) and temperate (low) areas, and the relatively fast turnover of aboveground biomass (Duarte and Chisano, 1999).

Seagrasses play an important role in the global carbon cycle (Short et al. 2007) as they serve as important carbon sinks (Marba et al. 2007; Mateo et al. 2006). A combination of lack of fires under water and low decomposition rates due to low oxygen concentration in seagrass soils a suitable environment for carbon sequestration and biomass burial (Fourqurean et al. 2012). The carbon stored in coastal or marine ecosystems (including seagrasses, salt marshes, and Mangrove swamps) is also known as “blue carbon” and the sequestration of blue carbon can represent a major carbon sink in the global carbon budget. Seagrass meadows occupy less than 0.2% of the total world oceans area, but are estimated to contribute to about 10% of total yearly carbon burial in oceans (Fourqurean et al. 2012). By utilization of atmospheric carbon in the photosynthesis process and direct transfer to other nearshore and marine organisms as food, seagrasses are major primary producers in shallow water coastal environments (Bostrom et al. 2006). Above ground production may range between 0.1-18.7 grams of Carbon per square meter per day ($gCm^{-2}day^{-1}$) (Duarte and Chisano, 1999). Thus seagrasses are important primary producers comparable to other major aquatic and terrestrial ecosystems (Mateo et al., 2006). Belowground seagrass production (Duarte and Chisano, 1999) plays an important role in carbon storage and sediment-biogeochemical processes (Mateo et al, 2006). Belowground seagrass production is estimated at values ranging from 0.001 $gDW\ m^{-2}day^{-1}$to 20 $gDW\ m^{-2}day^{-1}$ (Duarte and Chisano, 1999). Table 3 gives a simplified comparison of Net Primary Production (NPP) between seagrass ecosystems, other aquatic and terrestrial ecosystems, and their areal coverage (Mateo et al, 2006).

Table 3: Average Net Primary Productivity (NPP) comparisons from past literature reviews, modified by Mateo et al. 2006.

System	Area covered (10^6 km^2)	NPP (gC m^{-2} year^{-1})	Total NPP (PgC year^{-1})
Marine phytoplankton			
Oceanic waters	332	130	43
Coastal waters	27	167	4.5
Coastal macrophytes			
Mangroves	1.1	1000	1.1
Seagrasses	0.6	817	0.49
Macroalgae	6.8	375	2.55
Microphytobenthos	6.8	50	0.34
Terrestrial ecosystems			
Forests	41	400	16.4
Crops	15	350	5.25
Deserts	40	50	2
Terrestrial ecosystems	148	200	29.6
Continental waters	1.9	100	0.19
Oceans	359	132	47.5

Due to insufficient studies in the African and South American seagrass meadows, the total areal cover of seagrass is estimated at a wide range of 300 000 km^2 to 600 000km^2, which corresponds to a carbon stock of 75.5-151TgC in the top meter of seagrass soils (Fourqurean et al. 2012). The above however increase to 4.2-8.4PgC when basing assumptions on core samples from the top meter of seagrass soils. This roughly equates to marsh and mangrove ecosystems carbon production (Fourqurean et al. 2012). It is apparent from such findings that, further research is needed to acquire more data to inform further estimates.

Fish and other marine organisms use seagrass meadows as nurseries, migration pathways and/or spawning areas (Short et al. 2007; Tuya et al. 2014), this interaction fraws the attention of predator species thus making seagrass meadows hotspots for biodiversity (Short et al. 2011; Bostrom et al. 2006; Orth et al 2006b). Organisms that hold cultural significance, such as manatees (Native American cultures), serenians and sea horses (Green and Short, 2003) have been found to use seagrass meadows as a habitat thus drawing the attention of scientists and environmental organizations committed to conservation and restoration efforts (Mumford et al 2007). For the services they provide, seagrass have been identified in the Puget Sound Nearshore Ecosystems Restoration Program (PSNERP, one of the major nearshore ecosystems restoration programs), in Washington state as one of few Valuable Ecosystem Components (VECs), which are those constituents of a nearshore ecosystem that can be used to evaluate the status of an ecosystem based on how they exist and fare in that particular regime (Mumford et al 2007). Seagrasses have a noticeable effect on many ecosystem components and their own environment. This is mainly due to seagrass effect on flow dynamics and thus sediment resuspension throughout the water column (Heller, 1987; Fonseca et al. 2007). A sediment bed without seagrass would experience scouring by waves and constant resuspension of sediment, leading to a turbid water column that strongly reduces light penetration to the bed, which in turn hinders growth and survival of sea grasses and other photosynthetic organisms (e.g. Garcia et al. 1999; Lefebvre et al. 2010). The trickle results of this can extend to fish and other nursing organisms that require presence of seagrass as food, nursery or habitat, thereby leading to the disappearance of these organisms and their predators. Dense seagrass canopies, on the other hand, reduce the rate of bed scouring and erosion thus reducing the amount of resuspension resulting in a clear water column which bears a biodiverse environment (Lefebvre et al. 2010; Garcia et al. 1999; Heller, 1987). The high presence of bivalve species in and around seagrass meadows in tropical areas has been attributed to the ability of seagrass meadows to shelter the sediment bed by reducing the drag force exerted by water flows on the sediment surface, while favoring fine sediment deposition (Green and Short, 2003; Short et al. 2007; Carr et al., 2010). Seagrass canopies increase trapping and deposition of suspended sediment by modifying flow(Koch et al, 2007; Heller, 1986) and also decreasing rate of resuspension of deposited sediments (Marba et al, 2007; Gacia and Duarte, 2001). Indirect reductions of suspended particles occurs when filter feeders, and epibionts that prefer seagrass beds to bare areas, consume particulate matter in the water column (Marba et al, 2007; Agawin and Duarte, 2002). Reduction of sediment suspension, like other seagrass functions, has been noted to be species specific, owing to species differences in canopy surface area, which limits area of colonization by macro suspension feeders and, life span of leaves, which affects the time window for successful sediment trapping by any means (Marba et al, 2007). Moore (2004) investigated the influence of seagrass on water quality seasonally across vegetated and formerly vegetated plots in the Chesapeake Bay and concluded that spring beds were sinks for nutrients, suspended inorganic particles and phytoplankton, whereas in summertime, as growth regressed and dieback progressed, the concentration of nutrients, suspended sediments and phytoplankton increased, thereby leading to a decline in water quality and light environment. The results and conclusion of this work suggests that dense seagrass beds are required for survival and progress of existing beds.

Owing to their ability to promote biodiversity, sustain fisheries, sequester carbon, and provide a host of other ecosystem services that directly and indirectly affect human societies, seagrass meadows have been frequently evaluated in economic terms with a monetary value as high as US$ 19002 per hectare per year (Tuya et al. 2014; Constanza et al, 1998; Constanza et al. 1997). Valuation of ecosystem services in these studies is a complex process that involves calculating marketable goods from ecosystems such as fish, but also placing a monetary value on those services that indirectly affect the lives of people by either increasing cost or benefits to human welfare. A good example is the effect of seagrass on wave attenuation, which retards bed erosion favoring more seagrass cover and a more complex ecosystem that favors multiple species of organisms, and giving humans a great variety of stocks to harvest from that same ecosystem. Putting monetary value to seagrasses is easier based solely on fisheries production that owes its abundance to seagrass beds that act as nursery grounds, migratory pathways and fishing hotspots for fishable fish stocks (Constanza et al, 1998). Valuation of services provided by seagrass has thus far been done for fish as it is easier to calculate amount of fish extracted from specific regions, however, services such as provision of recreational grounds or scenic beauty has not yet been established. In their assessment of value of seagrasses Tuya e al (2014) note that different studies in different regions calculated variable values for different species of seagrass, leading to an assumption once again that this might be a species specific function. Putting a monetary value to ecosystem components such as seagrass is believed to be successful in raising awareness that generates concern and conservation from different stakeholders (Constanza et al. 2014). In their valuation of global ecosystems Constanza et al. (2014) mention that between 1997 and 2011, global land use changes had resulted in a minimum loss of $4.3 trillion/year which could be avoided if people knew the value of land and how they could conserve it. The notion of putting a monetary value (almost a “price tag”) on natural capital, however, has been challenged by others, because it could lead to a commodification of nature and could favor an unsustainable use of its resources (e.g., Bakker et al., 2005).

3. Seagrass Habitat

Seagrasses require specific environmental conditions to exist and thrive. A clear water column that allows photosynthetically active radiation (PAR) to reach the seagrass canopy is essential for seagrass growth and survival (Green and Short, 2003). This explains why seagrasses are mostly found in clear water environments and shallow waters where sufficient sunlight can penetrate and reach their canopy. On the other hand, seagrasses modify the light environment by reducing sediment resuspension, thereby creating their own habitat. Known as ecosystem engineering (Jones at al., 1986), this phenomenon means that the reason why sea grasses are found in clear waters is also due to their own ability to improve the water quality (Carr et al., 2010; McGlathery et al., 2013). The ability of seagrasses to improve the light environment, however, is limited to a certain depth range because in deeper waters light penetration would be insufficient to sustain seagrass growth, regardless of the effect of sediment stabilization.

The growth and expansion of seagrass meadows is therefore constrained by their light requirements, which sets the depth limits at which seagrasses may thrive (Duarte, 1991). Early work (e.g. Duarte, 1991) held that seagrass beds could exist to maximum depths of 90 m (*Halophila engelmannii* in Dry Tortugas, USA). The water depths at which seagrasses can be found, however, vary among species and locations, for example, Zostera marina in Mexico, Japan and the Chesapeake Bay (USA) was found to colonize sediment surfaces at depths of 30 m, 5 m and 1.5 m, respectively (Duarte, 1991; Dennison and Moore, 1988). The depth range at which seagrasses are typically found depends also on their growth strategy. For instance, pioneer species (e.g. *Halodule spp*) grow in fringes above depths occupied by climax species (e.g. *Halophila spp*) (Duarte, 1991) and, species with smaller rhizomes (hence with lower respiratory demands) tend to occupy deeper waters as compared to species with a complex rhizome (Orth and Moore, 1988; Dennison, 1987). Work on seagrass depth limits has led to the development of a multispecies model for the prediction of depth limit (Duarte 1991; Duarte et al, 2007), which is the maximum depth at which a certain seagrass species can be found in a given environment. Even though the model overestimated the observed colonization depth in most cases (~89.2%), this approach could be improved if more measurements became available (Duarte et al, 2007). Orth and Moore (1988) noted that depth ranges can also depend on plant adaptations, giving as an example the case of *Ruppia maritima* in the Lower Chesapeake – a species with high light and high temperature preference – that tends to colonize shallower waters than *Z. marina* which is a low light, lower temperature adapted species and thus, is typically found at depths of 0.8-1.2 m in the Chesapeake Bay region (Orth and Moore, 1988). Despite differences in earlier and current models, the general agreement is that colonization depth declines as light attenuation increases.

Defining stability as the ability of a meadow to return to its reference state after a temporary disturbance or persistence through time of an ecological system Greve and Krause-Jensen (2005) set to compare stability of maximum depth limits for eelgrass in open coast with low nutrient conditions and the more nutrient rich inner bays. Their investigation shows that, inner bay populations are less stable (highly dynamic) because of multiple reasons associated with shallow water and the risk of anoxic conditions in such shallow areas due to high eutrophic conditions and ease of eelgrass burial during stormy events (Duarte 1995), low eelgrass cover leading to resuspension of sediment and (Koch 2001) and high wave energies in shallow water that lead to bed scouring and further vulnerability in seagrass stands (Greve and Krause-Jensen, 2005). Seagrass meadows are dynamic landscapes maintained by recruitment of new clones and growth of new shoots (Duarte et al. 2006), therefore the description of a stable meadow implies balance between reproduction and mortality within a seagrass patch, suggesting that unstable meadows in shallow, nutrient rich, inner bays to be at some imbalance of environmental conditions.

Greve and Krause-Jensen (2005) point to different determinants of light availability in shallow and deeper areas. Lawson et al (2007), suggest that light availability in shallow coastal areas is more dependent on suspended sediment while in deeper estuarine areas, phytoplankton has a more predominant influence on light attenuation. In a model-based investigation of the effect of light availability on seagrasses in Hog Island Bay (an inner coastal bay) in the Eastern Shore of

USA, Carr (2011) found that at depths shallower than 2.2m light was not a limiting factor for seagrass growth. For water depths between 2.2m and 3.6m the system was bistable, in the sense that it was stable both with no seagrass cover and turbid water and with seagrasses and clear water. In deeper waters there just isn't enough light to support seagrass growth bare sediment is the only stable state. Other process-based modeling studies (Carr et al., 2012) predict a similar pattern but at different depths (i.e., with a bistable range between 1.6 and 1.8 m). Experimental evidence of the depth range suitable for seagrass growth in the Eastern Shore of Virginia remains sparse, which limits our ability to develop a comprehensive seagrass restoration plan in the region.

Water quality and light penetration are affected by a variety of factors (Ralph et al. 2007) in addition to wave induced turbidity, namely, phytoplankton densities, dissolved organic matter and eutrophication caused by high levels of nutrients (Carr et al. 2010; McGlathery et al. 2007; Lawson et al. 2007). These factors where not accounted for by Carr et al., (2010; 2012). The physiological impacts of poor water clarity on seagrass meadows is similar to that of eutrophication induced phytoplankton densities, except for the gas inhibition stress by sedimentation.

4. Effect of Climate Change and Disturbances

Despite the importance of seagrass already noted, these submerged plant forms are facing global decline. Short and Wyllie-Echeverria (1996) approximated a total of 90 000 hectares of seagrass lost between 1985 and 1995, and pointed out that the actual loss could even be greater. Using global mapping studies and observational data from 1879 to 2006, Waycott et al (2009), quantified about 51,000 km^2 seagrass area decline in that time period, and suggested more declines noting that the yearly decline had increased from a previous low of <1% per year (in 1940) to about 5% per year since 1980. Threats to seagrass abundance can be human induced or associated with natural events. Following their definition of a threat as a process that alters

resource availability to plants resulting in degradation or loss (Short and Wyllie-Echeverria, 1996), natural disturbances encompass direct grazing of seagrass (Preen, 1995), hurricanes (Duarte, 2002; Short and Wyllie-Echeverria, 1996), disease (Ralph and Short, 2002) and earthquakes.
The effect of global climate warming (Short and Neckles, 1999) has been found to affect the physiology and ecology of seagrasses, by modifying timing and duration of summer die offs, and indirectly by increasing depths through sea level rise (Lloret et al., 2008). Moreover, sea level rise brings about accelerated erosion (Duarte, 2002), leading to possible a modification of depth ranges of seagrass, limiting seagrass growth to narrow extends where light conditions remain suitable. Sea level rise, may also induce marsh edge erosion (Simas et al., 2001), which increases the amount of sediment transported to seagrass meadows, thus escalating light attenuation. The reduction of seagrass cover would then lead to increase in marsh edge erosion due to reduced wave attenuation. The direct impacts of a rise in temperature affects seagrass species differently; species that grow in temperate regions such as *Z. marina* experience an increase in leaf respiration in relation to photosynthesis (Short and Neckles, 1999). Short and Neckles (1999) suggest that high temperatures favor algal blooms which in turn outcompete seagrass leading to declines in seagrass cover, and eventual sediment resuspension which might lead the system into a eutrophic state (Lloret et al., 2008), and back to a state devoid of seagrasses. Indirect temperature effects on seagrass include increase in water depth through sea level rise (Short and Neckles, 1999), intensification of storm and hurricane (Koch and Orth, 2003), which would likely cause seagrass burial and erosion by waves in shallow environments.

Negative human impacts arise mostly due to the growth of coastal populations and the development practices that go with it (Duarte, 2002). The increasing human population in coastal environments, and the constant need for socio economic development that encompasses agricultural practices and recreational water sports, various fishing methods, dredging and shoreline arming have made the nearshore environments hotspots for accelerated erosion, pollution, and elevated eutrophication (Koch et al. 2013;Orth et al. 2006 ;Duarte, 2002; Short and Neckles, 1999). Factors that contribute to water column turbidity and thus light attenuation through the water column pose a challenge to seagrass existence and abundance. Anoxic conditions formed by sediment smothering lead to production of sulfide which has a negative effect on seagrass metabolism and growth (Al-Haj, 2010; Ralph et al. 2007). Nutrient loading to estuaries and nearshore environments due to fertilizer use in nearby agricultural areas has been found to induce algal blooming and reduce light penetration (Burkholder et al. 2007; Lee et al.2007; Ralph et al. 2007; Short and Wyllie-Echeverria, 1996). This process of nutrient over-enrichment, eutrophication, stimulates high biomass algal growth, including phytoplankton and epiphytes (Burkholder et al. 2007; Lee et al. 2007), primarily improving light attenuation across the water column, sediment resuspension due to initial loss of seagrass and positive growth by some seagrass species (Burkholder et al. 2007). In their review of seagrass and eutrophication studies, Burkholder et al. (2007), describe response to nutrient overloading as not only die-backs, but point out that it can involve displacement of some seagrass species by those that can tolerate the elevated levels of nutrients. Collectively, these factors act as a disturbance on seagrasses and reduce the spatial extent and density of their canopies, though the effect of some of these anthropogenic drivers on seagrass ecophysiology remains poorly understood (Ralph et al., 2007). The effect of diseases on seagrasses can be devastating because seagrass stands are commonly composed of only one species of seagrass, In North America disease outbreaks have occurred in the Northern Atlantic Ocean (Orth et al. 2006a and b), with diebacks that killed more than 4000 hectares of turtlegrass (*Thallasia testidunum*) in Tampa Bay, Florida (Waycott et al. 2009).

Despite the deleterious impacts imposed upon seagrass ecosystems, humans do have positive impacts on these ecosystems too. Restoration activities in parts of the world that have furthered research in seagrass biology, ecology and conservation. Seagrass restoration is taking place in the USA, Australia and parts of the Mediterranean Sea (Waycott et al. 2009; Orth et al. 2006a). Reduction of point sources for nutrient overload in Tampa Bay, Florida have resulted in 50% reduction of nitrogen compounds in the estuary, about 50% improvement in water clarity, and recovery of about 27square kilometers of seagrass meadows since 1982 (Waycott et al. 2009). Seagrass restoration in the seaside bays of the eastern shore of USA started in 1997-1998 and was followed by decisions by the Virginia Marine Resources Commission to designate hundreds of acres in different bays for restoration (Orth et al. 2009; Orth et al 2006a). Efforts to monitor, collect seeds and continue restoration of seagrass in these areas by government bodies and academic institutions is one testament of the positive impacts humans have on these ecosystems.

5. Eelgrass (*Zostera marina*) in the Eastern Shore, USA

The Eastern shore of the United States across the four states of Delaware, Maryland, Virginia and North Carolina, is characterized by numerous estuaries and barrier-island coastal lagoons with expansive salt marshes and seagrass beds in most shallow-water areas and few to no rocky shores (Koch and Orth, 2003). Sediments are predominantly quartz sand in shallow exposed areas with finer grain sediments in deeper or well-protected areas. Climatic variations are large with air temperatures ranging from -10°C to 40°C and water temperatures ranging from 0°C to 30°C. Tides are equal and semi-diurnal but relatively small in range (maximum of 1.3 m during spring tides). The largest seagrass beds in the eastern shore are mainly *Zostera marina* even though previous work shows a composition with *Ruppia maritima* (Orth and Moore, 1986). Seagrass ecosystems in the eastern shore, alike those worldwide, provide food and refuge from predators for a wide variety of species, some of which have recreational and commercial significance. The invertebrate production in just one seagrass bed in the lower Chesapeake Bay was estimated to be 0.4 metric tons per year (Koch and Orth, 2003).

In the Eastern shore of the United States a combination of a wasting disease in 1930 and a hurricane in the 1933 sent eelgrass (*Zostera marina*) into a dramatic decline (Moore and Short, 2007; Orth et al. 2006b). This decline saw a decline of coastal services offered by seagrass meadows such as scallops fisheries (Orth et al. 2006b). This decline also saw a decline of recreationally important species such as brant (*Branta bernicla*) and the disappearance of a mollusk (*Lottia alveus*) attributed to it (Orth et al. 2006b). In addition to these, the 1960s and 70s experienced a high input of sediment and nutrients due to hurricanes (Golden et al. 2010; Short and Wyllie-Echeverria, 1996; Orth and Moore, 1983). The Tropical storm Agnes of 1972, not only increased sediment input but was responsible for a four-week reduction of salinity in the bay that saw noticeable alterations to the few seagrass beds that were evident at the time (Orth and Moore, 1983). The northern bays of the Eastern shore are reported to have experienced natural recovery in the late 80s expanding at an average rate of 305 hectares per year between 1986 and 2003 (Orth et al. 2006b), however, there is no evidence known to this assessment that the southern bays had any natural seagrass regrowth prior to restoration attempts. Scallops and other fisheries, an important source of livelihood for local populations, declined (Orth et al 2006a). The state of eelgrass in the Eastern shore underwent deterioration until the discovery of a few patches in the late early 80s and early 1990s (Orth et al. 2006a; Orth et al. 2003; Koch and Orth, 2003), which prompted restoration efforts that saw the re-establishment of seagrass meadows at rates as high as 305 hectares per year (in the Chincoteague Bay) (Orth et al. 2006a). Consistent with water quality requirements for seagrass growth, the Northern Delmarva Coastal Bays have not experienced the same rates of regrowth as the South, which suggests the North-South population decrease had an influence in the varying water quality conditions (Orth et al. 2006a). Restored seagrass meadows had an impact on the improved water column clarity (McGlathery et al. 2012), flow and sediment dynamics (Hansen and Reidenbach, 2012).

This work is an assessment of seagrass conditions in the Chincoteague Bay in the Eastern shore of USA. Using datasets of mapped seagrass occurrences in 2014 from Chesapeake Submerged Aquatic Vegetation (SAV) Program (http://web.vims.edu/bio/sav/gis_data.html) and a bathymetry dataset from the Virginia Coast Reserve, Long Term Ecological Research (VCR-LTER) database (http://www.vcrlter.virginia.edu/cgi-bin/showDataset.cgi?docid=knb-lter-vcr.210), this assessment aims to find depths at which seagrass occurs and quantify density relations with depth.

6. Methods

Area of Study

Chincoteague is a relatively shallow coastal lagoon with limited freshwater inputs and long residence times (Koch and Orth, 2003). Salinities in this region are high (26-31 psu) and nutrient levels are low. The western shore of Chincoteague is mostly covered by marsh and low human population while the eastern part is relatively unpopulated, but attracts and is accessible by humans (Koch and Orth, 2003). According to Koch and Orth, (2003), the eastern shore of Chincoteague was covered by seagrass but did experience a period of nutrient loading in 1999-2002, resulting in algal blooms that saw a reduction of the seagrass.

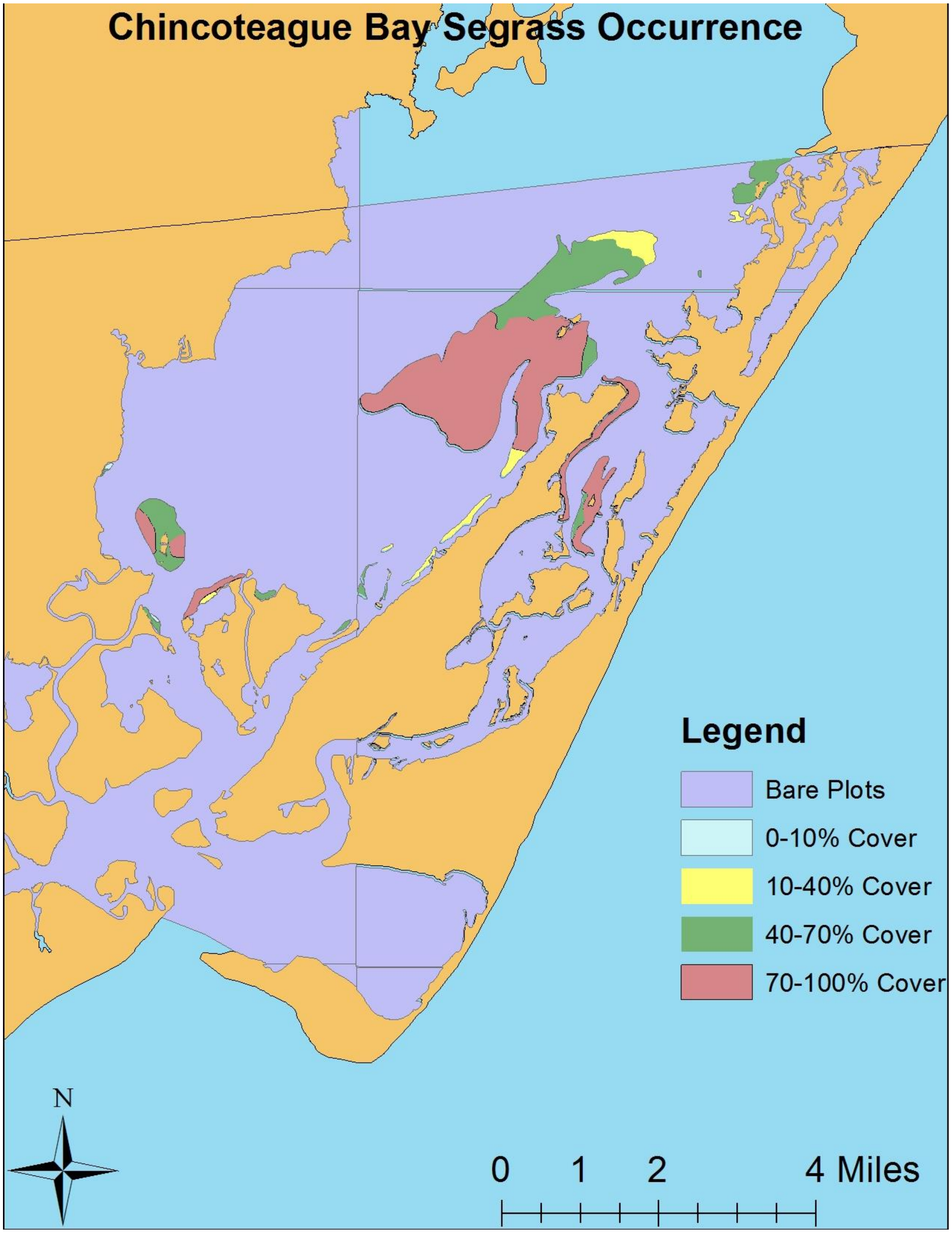

Figure 2: Map of seagrass occurrence and density proxies, (*Densities 1, 2, 3, 4 represent 0-10%, 10-40%, 40-70%, and 70-100% cover respectively*) in Chincoteague Bay.

6.1. Data

6.1.1. Chincoteague Bay Seagrass Maps

The seagrass maps used in this study were acquired from the William and Mary Virginia Institute of Marine Sciences (VIMS) datasets of Submerged Aquatic Vegetation (SAV) in Chesapeake Bay and other Coastal Bays Program.

The 2014 Chesapeake Bay dataset used in this study was mapped from aerial images of scale; 1:24, 000 and digital multispectral imagery. The four density classes identified in these shapefiles were estimated through an interpretation and remediation process. The datasets were corrected to depict submerged vegetation in all areas that were flown. At these scales the datasets carry errors of underestimation of seagrass cover in narrow channels that may not have been discernable in aerial photographs (http://www.vims.edu/bio/sav).

An essential field in this dataset is density, which shows five categories from zero to four representing density as percentage cover (Table 4).

Table 4: Description of the density attribute of the 2014 SAV shapefile

Density Class	Percentage Cover	Description
0	0	No seagrass/ not surveyed
1	0-10%	Very sparse
2	10-40%	Sparse
3	40-70%	Moderate
4	70-100%	Dense

6.1.2. Global Seagrass Distribution

The points for global seagrass locations were acquired from the United Nations Environmental Program, World Conservation and Monitoring Center (UNEP-WCMC) as shapefiles that were superimposed on a world map from ArcGIS online database. These were used to create Figure 1.

6.1.3. Bathymetry

I used the Integrated Topography and Bathymetry of the Eastern Shore of Virginia, Data Set (knb-lter-vcr.210.9).

This dataset is a product of multiple sources: airborne LIDAR, bathymetric surveys conducted by VCRLTER, NOAA navigational data, NOS oceanographic surveys, USGS NED data including topographic maps. The pixel resolution for these data was matched to that of LiDAR at 3.048 m, and it is projected in UTM Zone 18N coordinates relative to the WGS84 horizontal datum. Elevations in this digital elevation model (DEM) is in meters (Richardson et al., 2014)

6.2. Data Manipulations and Analyses

I limited the seagrass dataset primarily to the state of Virginia, and the Chincoteague Bay. Using ArcGIS 10.4 raster tools, I extracted the part of the bathymetry that intersects seagrass maps using seagrass maps as mask. The Seagrass data contained polygons that were described as zero cover and extended more into the middle of the bay (the deeper end). To limit errors associated with using these many records I focused my interests to depths between 0 and 3 m, following previous studies that recognized these depths as the expected seagrass depths in the Eastern shore coastal bays (Carr, 2011; Carr et al. 2010; Lawson et al. 2007; Duarte et al. 2006; Duarte, 1991; Orth and Moore, 1988; Dennison, 1987). On ArcGIS 10.4, I used a layer of each density class to extract the part of the bathymetry underlying said class. I performed a raster to point conversion, with which I performed extraction of values to points to get elevations/depth at each point. I created histograms of the data from 0 to the deepest value on a 0-3 meter range, which in this case turned out to be 1.2 meters

7.0. Results

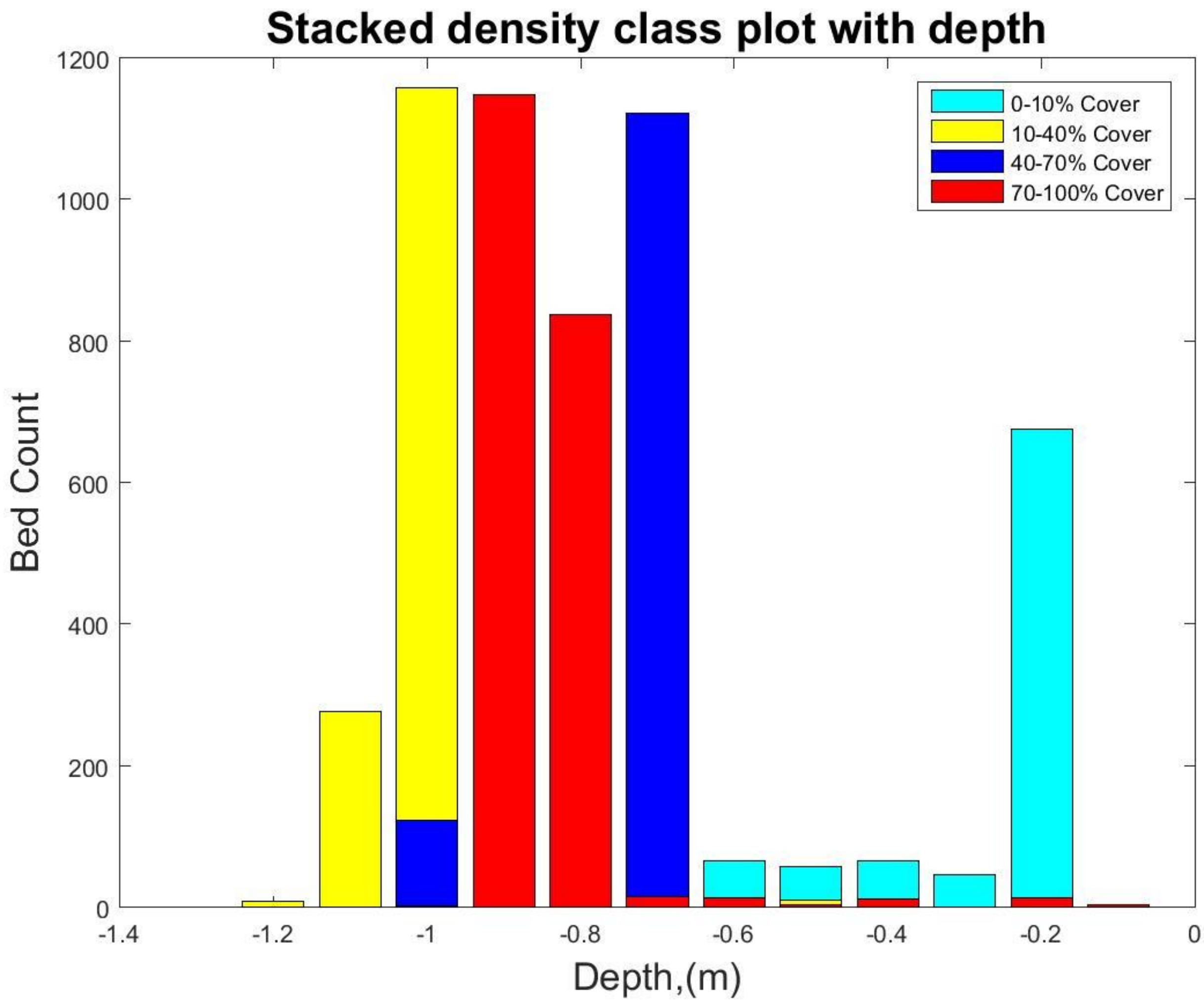

Figure 3: Stacked pixel counts of seagrass density (cover) classes with depth of occurrence.

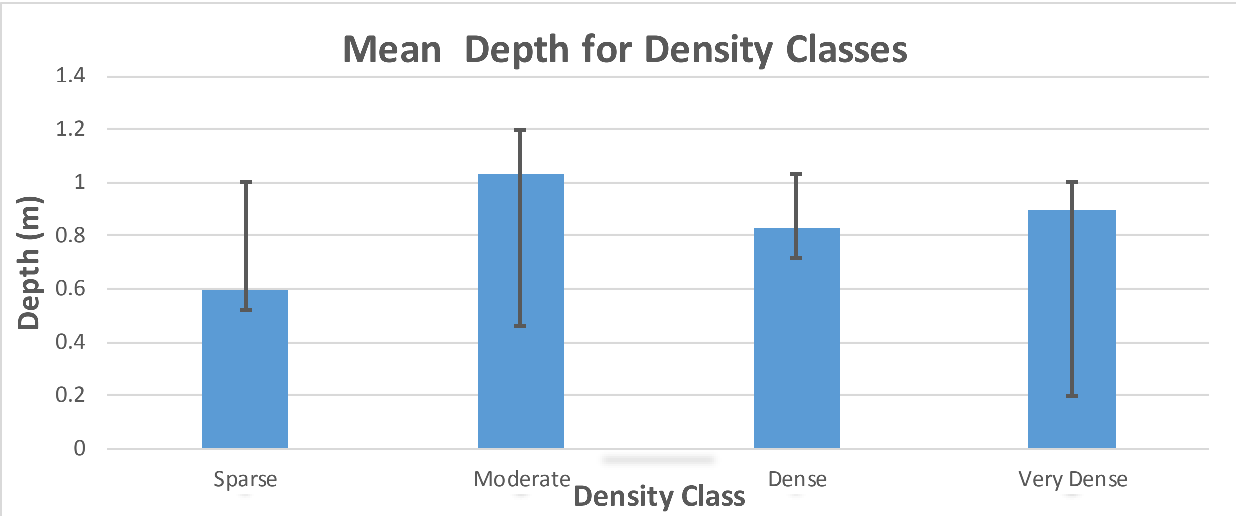

Figure 4: Mean depth of density classes in Chincoteague Bay in 2014

The results of the distribution of different density classes show a common occurrence of seagrasses at depths less than 1.2 meters. Beds of cover less than 10% show a distribution that does not show any trend across depths, with the peak occurrences at a depth of 0.2 meter and the second highest at 0.8 meters. The other three density cover classes show a tendency to cluster around the 0.8- 1.0 m depth. Beds with cover class 10-40% show minimum counts at very shallow depths, starts to rise at 0.8 m and peaks at 1 m depth, this density class is the only one that registered deepest counts at 1.2 meters. The 40-70% cover class is constrained between 0.7 and 1 meter depth, with an eventual peak at 0.7 meters. The very dense beds showed up in most depths from 0.1 meter to a sudden rise at 0.8 meters to make the peak at 0.9 meters, and a dramatic fall at 1 meter depth. Figure 4 was calculated represent the depths of occurrence with minimal spread.

8.0. Discussion

The results presented here do not account for water quality, sediment characteristics or any other factors that determine seagrass growth in this study area. However they do depict a tendency of seagrasses to adhere to where beds already exist. Moreover, these results do not take into consideration human practices such as aquaculture (Koch and Orth, 2003). Most of the Chincoteague Bay has the potential to support seagrass growth based on knowledge of depth only (Figure 5 and Figure 6). About 79% of Chicoteague Bay is has water depths that are suitable for seagrass growth. Koch and Orth, (2003) discuss a problem of recurring algal blooms (*Chaetomorpha lenum*) whose mats in 1990-2000 grew as thick as over a meter in thickness and smothered seagrass, causing a significant decline. This could be the one of many reasons seagrass in this area had not covered more of the potential sites in 2014. But why in this Bay are seagrasses found only in relatively shallow waters. Combined experimental and modeling work in the eastern shore of Virginia, indicates that seagrasses can extend into deeper waters. The astern shore of Virginia and the Chincoteague Bay are just few miles apart and exposed to the same climate conditions. These differences in depth range indicate that there are other factors contributing to seagrass habitat suitability. As noted in the introduction, seagrass productivity and survival is often determined by light limitations. Light availability depend on water depth but also on nutrient concentrations and suspended sediments. Unlike the Eastern Shore of Virginia the Chincoteague Bay is located downstream from an agricultural area used for crop production and farming, and therefore prone to the release of nutrients, which in turn deplete water clarity and induce algal blooms. Differences in sediment properties, sediment resuspension, marsh edge erosion, and water column turbidity between these two sites still need to be documented but could also contribute to enhanced light extinction in the Chincoteague Bay, thereby explaining the shallower seagrass depth range therein. The presence of organic matter in the sediment could also limit seagrass expansion, though its impact on the depth limits remains poorly understood.

Overall, in comparison with the coastal bays in the eastern shore of Virginia, Chincoteague Bay seems to contain seagrasses in shallower areas. Some studies (e.g. Lefcheck et al. 2015) are showing that restored meadows in areas like the South Bay (VA) tend to fare much better than the natural beds of Chincoteague in invertebrate populations and diversity, suggesting a possible low suitable habitat status in Chincoteague. A study comparing seagrass depth limits in the Virginia coastal bays and Chincoteague, while accounting for possible differences in sediment dynamics and tidal range would likely shed more light on seagrass depth limits these areas.

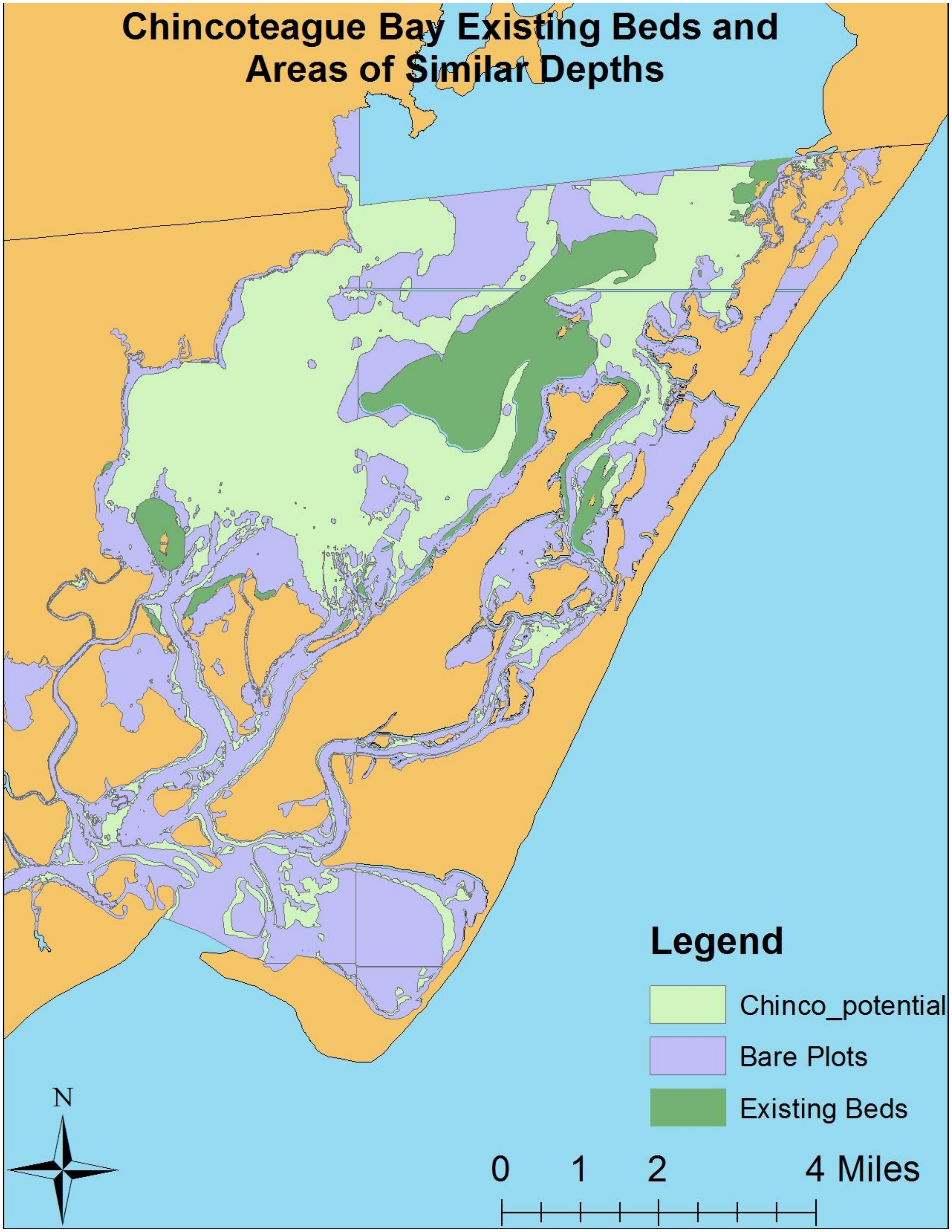

Figure 5: Existing plots and areas at depths suitable for seagrass occurrence and growth in Chincoteague Bay.

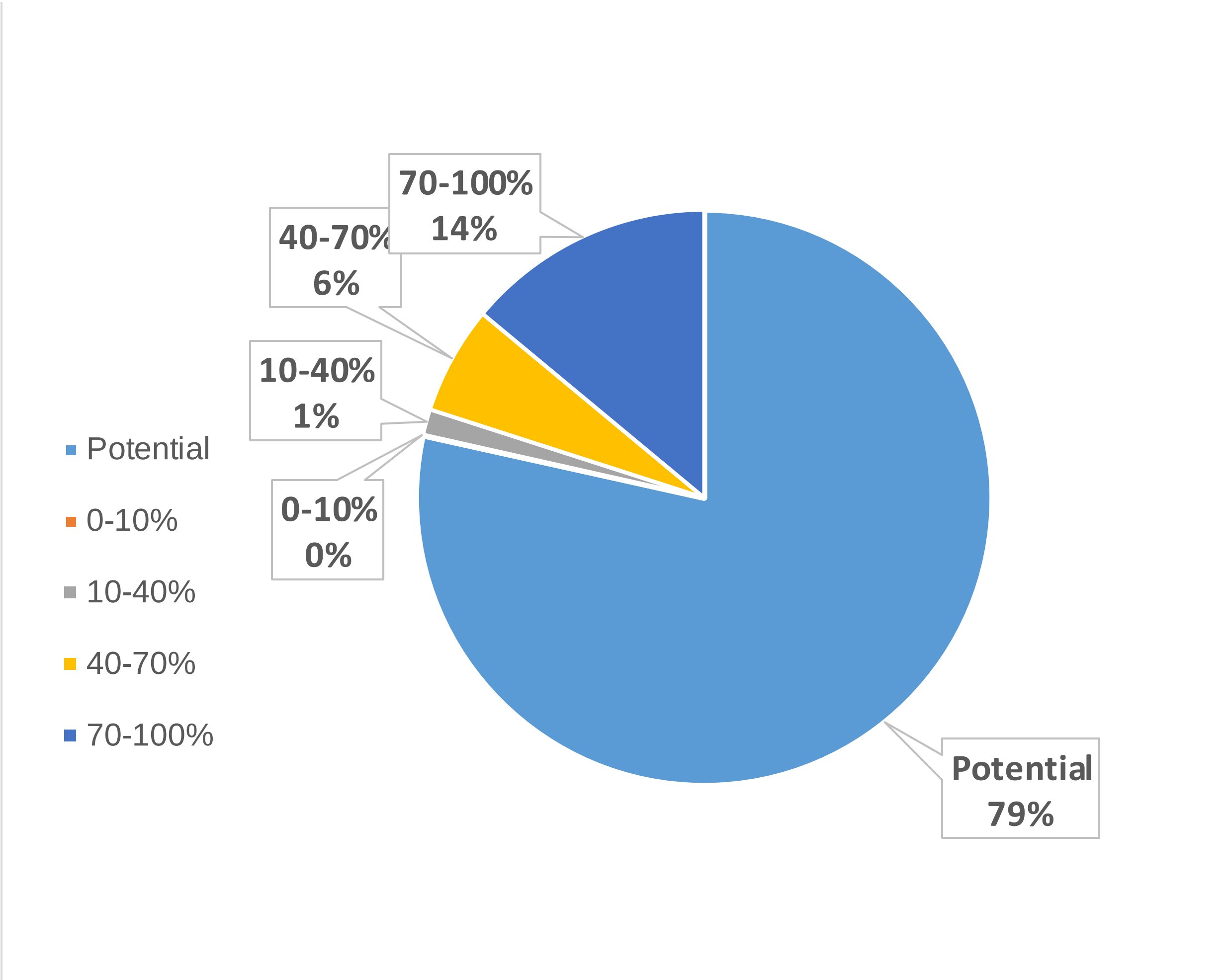

Figure 6: Existing seagrass beds in Chincoteague at different density classes presented as percentage with potential areas for suitability studies (depths at similar depth as existing seagrass beds)

9.0. References

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