SPATIAL ANALYSIS OF THE RECOVERY OF SUBMERGED AQUATIC VEGETATION IN THE HUDSON RIVER ESTUARY FOLLOWING THE 2011-2012 HURRICANE SEASONS

by

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A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2019

DEDICATION

I would like to dedicate this paper to my partner, Nicole. Without your love, motivation, and unwavering patience throughout this process, I would never have gotten this far. After three years of work and countless stressed-out evenings and weekends, you never ceased to support me and encourage me to push on towards success. I could never have done it without you.

Also, to my parents – You both instilled in me at young age a deep love for the outdoors, respect for all living things, and motivation to work hard at protecting the land, water, and creatures of this beautiful planet we call home. I cannot thank you both enough for the tremendous amount of support you have given me over the years and the constant encouragement when the goings got tough.

ACKNOWLEDGEMENT

I would like to acknowledge a number of people who helped me tremendously with this project. First and foremost, I would like to thank Dr. Scott Powell for all of his guidance with not only this project, but throughout my academic career at Montana State University. Dr. Powell’s willingness to help, his attention to detail, and his knowledge of landscape ecology and remote sensing were crucial to the success of this paper and my graduate work as a whole.

I would also like to acknowledge my graduate committee members, Dr. Bob Peterson and Dr. Tracy Sterling, as well as program manager Marni Rolston for all of their assistance and insight.

Lastly, I would like to acknowledge Dr. Stuart Findlay of the Cary Institute of Ecosystem Studies and Neil Curri of Vassar College, both of whom assisted me greatly with this project. Their knowledge of aquatic ecology and geographic information systems, and willingness to provide guidance throughout this process was invaluable.

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ABSTRACT

Submerged aquatic vegetation (SAV) is a critical habitat found in estuarine ecosystems throughout the world. SAV performs a multitude of ecosystem functions ranging from water quality improvement to habitat for macroinvertebrates and juvenile fish, and acts as a significant contributor to dissolved oxygen throughout the estuarine system. In the Hudson River Estuary (HRE), native SAV beds have been greatly reduced or altered by threats such as sedimentation, water quality issues, and the spread of invasive aquatic plants, as well as by disturbance from natural events such as large-scale storms. In 2011 and 2012, three hurricanes made landfall in the northeastern United States, having a tremendous impact on the Hudson River and the Hudson Valley region as a whole. SAV in the estuary was impacted by both storm surge as well as significant sediment deposition from the river's tributaries. However, in the wake of these events, there is uncertainty about the spatial patterns of SAV loss and recovery, and how these patterns are affected by the hydrology and physical characteristics of the river. Therefore, my study seeks to address this knowledge gap by investigating the impacts of these storms on SAV spatial patterns and the influence of SAV proximity to shoreline, tidal wetlands, and persistent "colony" SAV beds. I investigated these effects by analyzing overall (whole system) SAV recovery, the spatial patterns of recovery, and the correlation of recovery to prior SAV coverage and proximity to these features. Analysis was done using three years of remotely-sensed SAV GIS data, and was done at three different spatial scales. SAV coverages were determined at each scale for all three years and areal-change and percentage-change were calculated. Distance to the three aforementioned features was calculated for the fine-scale analysis. The results suggest that there was significant SAV loss river-wide between 2007 and 2014, followed by significant recovery between 2014 and 2016. Loss between 2007 and 2014 was greatest in the most upstream approximately100 km of the river, likely a result of proximity to the Mohawk River, a major tributary and large sediment source during the storms. SAV recovery showed a similar pattern, occurring most in these upstream reaches. Distance from shoreline, tidal wetlands, and persistent SAV beds had varying impacts on SAV loss and recovery. The findings of this study help to elucidate both the potential impacts on the magnitude and patterns of vegetation loss following a large storm event and subsequent sediment flux, as well as the recovery potential of this vegetation during 'normal' years. Such information can help inform future biological studies of the HRE and watershed management decision-making.

INTRODUCTION

Ecological Context

Submerged aquatic vegetation (SAV) is a critical component of aquatic ecosystems throughout the world. Aquatic vegetation, or *macrophytes*, can be found in nearly all aquatic environments – ranging from freshwater to brackish water to saltwater, and occurring in both lentic (palustrine) and lotic (riverine) systems. SAV plays an important role in performing a multitude of ecosystem functions, namely: 1) providing habitat for juvenile and adult fish, shellfish, and macroinvertebrates; 2) being a food source for estuarine fish, waterfowl, and aquatic vertebrates; 3) providing dissolved oxygen; 4) improving water quality by absorbing nutrients and settling out suspended and dissolved sediments; and 5) acting as a physical barrier from storm surge, wave energy, and sediment erosion (Orth et al. 2017).

In the Hudson River Estuary (HRE) and other estuarine systems of the northeastern United States, SAV provides habitat for a multitude of fish, particularly littoral species. Some of the fish species that rely on this underwater vegetation in the HRE include: spottail shiner (*Notropis hudsonius*), tessellated darter (*Etheostoma olmsted*), banded killifish (*Fundulus diaphanous*), fourspine stickleback (*Apeltes quadracus*), American eel (*Anguilla rostrata*), white perch (*Morone americana*), smallmouth bass (*Micropterus dolomieui*), largemouth bass (*Micropterus salmoides*), redbreast sunfish (*Lepomis auratus*), pumpkinseed (*Lepomis gibbosus*), bluegill (*Lepomis macrochirus*), and common carp (*Cyprinus carpio*) (Daniels et al. 2005).

SAV also provides habitat for a number of aquatic invertebrates, such as freshwater worms (oligochaetes), chironomids, amphipods, cladocerans, midges, damselfly/dragonfly larvae, snails, and freshwater bivalves (Strayer et al. 2003; Strayer 2006), and is an important food source as well as habitat for migrating and overwintering waterfowl and other birds such as canvasback (*Aythya vallisneria.*), Canada goose (*Branta canadensis*), mallard (*Anas platyrhynchos*), American black duck (*Anas rubripes*), Wilson's snipe (*Gallinago delicata*), sandpipers (*Calidris* spp., *Tringa* spp.), and rails (*Rallus* spp.) (Yozzo et al. 2005). As both habitat and forage, SAV is a vital element in the food web of the HRE (Figure 1).

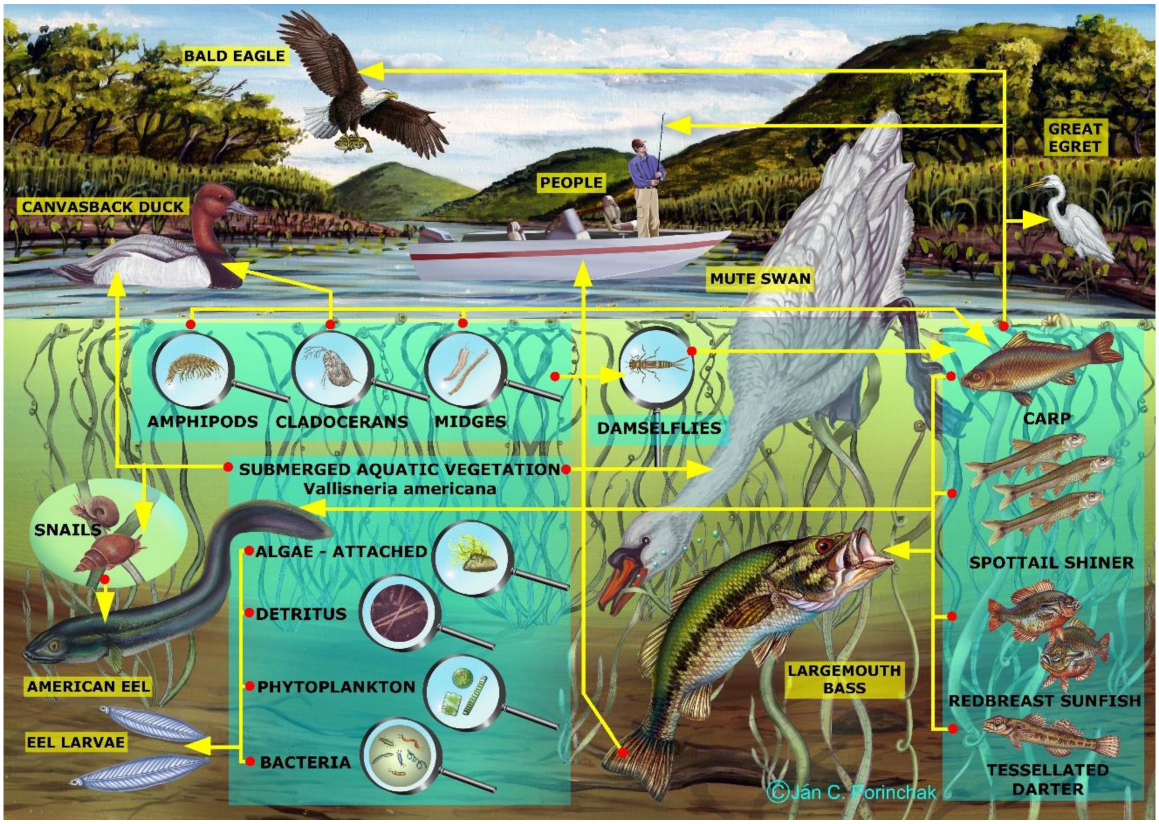

Figure 1. Ecosystem and food web of freshwater shallows common to the Hudson River Estuary. SAV plays an integral role as habitat as well as a food source (Diagram credit: Jan C. Porinchak, courtesy of the Cary Institute of Ecosystem Studies).

SAV provides not only biological ecosystem services, but physical and water quality benefits as well. Aquatic vegetation has the ability to flocculate and settle out suspended sediment, thus improving water quality and turbidity in the deeper portions of the river (Findlay et al. 2006) and is a potential sink for dissolved nitrate (Findlay & Fischer 2013). SAV is a significant contributor to dissolved oxygen within the estuarine system (Arrigioni et al. 2008; Findlay et al. 2006; Orth et al. 2017). Lastly, as a result of this sediment flocculation and deep rooting, SAV can help to reduce the impacts of erosion from storm surge and wave energy, acting as a shoreline buffer (Li et al. 2007).

Submerged Aquatic Vegetation (SAV) Overview

In the HRE, native SAV beds have been greatly reduced or altered by threats such as sedimentation, water quality issues, boating, and the spread of invasive aquatic plants, as well as by disturbance from natural events such as large-scale storms and flooding events (Hamberg et al. 2017).

The most common and prevalent species of native SAV in the HRE is *Vallisneria americana*, commonly referred to as water-celery or eelgrass (NYSDEC 2019) (Figure 2). *Vallisneria americana* is a native deep-rooting macrophyte found primarily in eastern North America, parts of the Caribbean, and northern South America, although it has been naturalized in parts of Asia and Australia as well (USDA 2019). *Vallisneria americana* reproduces vegetatively by both stolon and bud during the summer months, producing a plant with long, thin (2-3 cm) leaves and a tuberous stem, which acts as an energy source for the plant’s growth the following spring (Lowden, 1982). The plant often grows to approximately 2 m in length, sometimes exceeding that depending on water depth and sunlight availability (Korschgen & Green 1988). Although *V. americana* is fairly shade tolerant, competition with non-native macrophytes for light can be a growth-limiting factor, as can water depth as this species is rarely found at depths greater than 1 m below mean low water (Findlay et al. 2014).

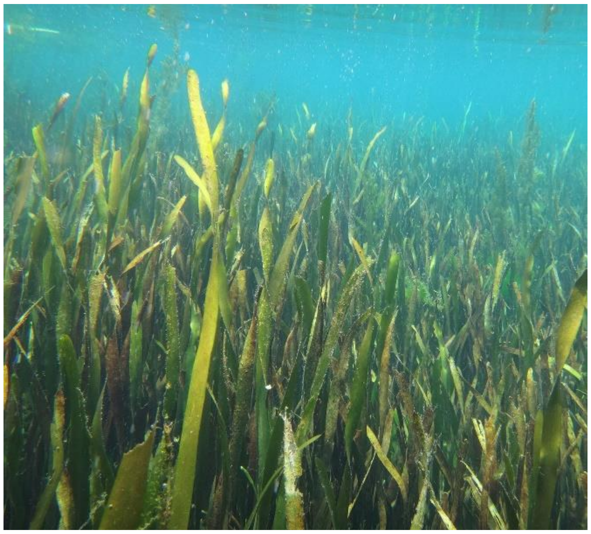

Fig. 2. Water-celery (*Vallisneria americana*).

Fig. 3. Water chestnut (*Trapa natans*).

Another aquatic plant becoming more and more common to the HRE is the non-native water chestnut (*Trapa natans*) (Figure 3). *Trapa natans* is an invasive plant native to western Europe, Africa and eastern Asia, and was brought into the eastern United States in the mid-1800s as an ornamental plant (Pemberton, 2002). *Trapa natans* has colonized numerous freshwater lakes, ponds, and slow-moving rivers throughout New York State, including the Hudson River where it is now abundant. The plant reproduces both vegetatively through runner or propagule as well as by seed, allowing for dense localized propagation and widespread seed dispersal, further complicating its containment and management (Hunt & Marangelo, 2012). In most cases the foliage of *T. natans* forms large impenetrable mats, as the plant's rosette leaves are kept afloat by buoyant bladders just below them. These large swaths of floating vegetation prevent sunlight from penetrating into the water column, thus preventing competition from other SAV species, including the native *V. americana* (Mullin, 1998).

While these two species are the dominant aquatic plants in the HRE, they do exist in communities with other less prevalent species, such as: Eurasian watermilfoil (*Myriophyllum spicatum*), rigid hornwort (*Ceratophyllum dermersum*), claspingleaf pondweed (*Potamogeton perfoliatus*) duckweed (*Spriodela polyrhiza*), and spatterdock (*Nuphar advena).* (Nieder et al. 2004; Nieder et al. 2009).

Study Area

The Hudson River is a 507 km (315 mi) stream within the state of New York that flows south from its headwaters in the Adirondack Mountains (Lake Tear of the Clouds) to its mouth at New York. The river is tidal for approximately half of its reach, or the southern/downstream 246 km (153 mi), which is referred to as the Hudson River Estuary (NYSDEC). The study area for this research encompasses the entirety of this estuarine portion of the Hudson River, including the main stem of the Hudson River from the Federal Dam at Troy, NY to New York Harbor, as well as the tidal mouths of the major tributaries to the Hudson River over this same extent (Figure 4).

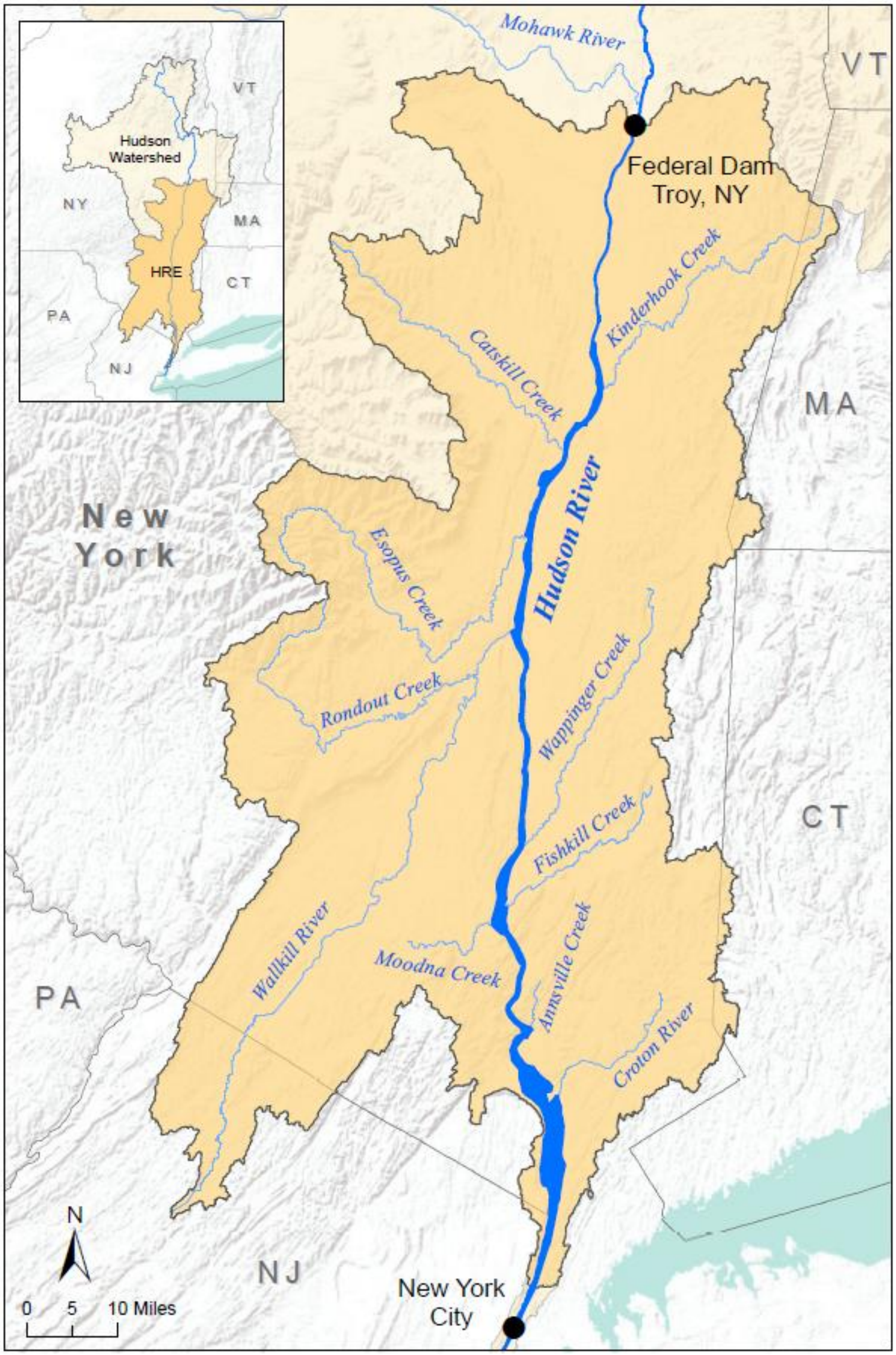

Figure 4. Map of the Hudson River Estuary Watershed, shown within the context of the larger Hudson River (tidal & non-tidal) Watershed.

The HRE watershed is approximately 1,354,700 hectares (5,230 mi^2) and drains roughly 14,260 km (8,861 mi) of freshwater rivers and streams (NYSDEC). Major tributaries to the HRE (from north to south) include: the Mohawk River, Kinderhook/Stockport Creek, Catskill Creek, Esopus Creek, Rondout Creek/Wallkill River, Wappinger Creek, Fishkill Creek, Moodna Creek, Annsville Creek and the Croton River.

Historically, SAV (here, *V. americana*) has been present throughout the majority of the HRE, south as far as Piermont, NY. South of this point, river salinity and hydrology have been the main limiting factors in SAV growth and presence (Limberg et al. 1986). As *V. americana* reproduces vegetatively, revegetation and dispersal are often limited to adjacent habitat of appropriate depth. As such, historical large core SAV beds likely play a critical role in the recovery and revitalization of the vegetation after periods of disturbance or decline (Wainger et al 2017). As such, analysis of SAV recovery with relation to the proximity to several large persistent “colony” beds in the HRE will be a part of this study.

Large Storm Impacts on SAV

Large storm events can affect submerged aquatic vegetation in a variety of ways. The three main impacts associated with freshwater-tidal SAV in the HRE are 1) large sediment flux and disturbance of the plant biomass by sediment; 2) disturbance by physical wave energy (storm surge/erosion); and 3) diminished light penetration into the water column as a result of increased turbidity (Wang & Linker 2005). Disturbance of plant biomass by sedimentation (burying of plant shoots and leaves) is perhaps the most severe effect that can result from large storm events, and results from sediment flux and loading from tributaries following heavy precipitation and flooding. The timing and seasonality of this sediment disturbance is also a factor, as that storms occurring during peak SAV growing season or during the period of peak SAV shoot biomass (typically September and October) tend to have the greatest impact (Wang & Linker 2005).

In 2011 and 2012, the Hudson River Estuary and the northeastern United States as a whole were tremendously impacted by three extreme storms (≥ 100-year storms): Hurricane Irene (August 2011), Tropical Storm Lee (September 2011), and Hurricane Sandy (October 2012) (Figures 5 & 6).

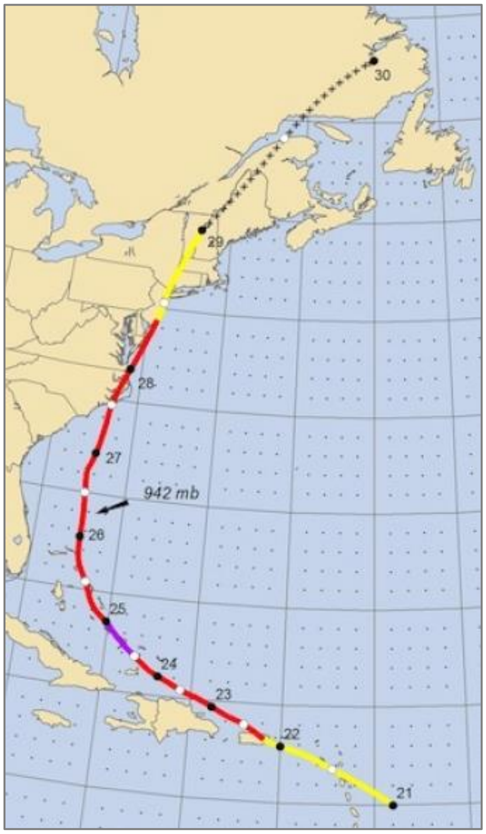

Fig. 5. Track of Hurricane Irene (2011).

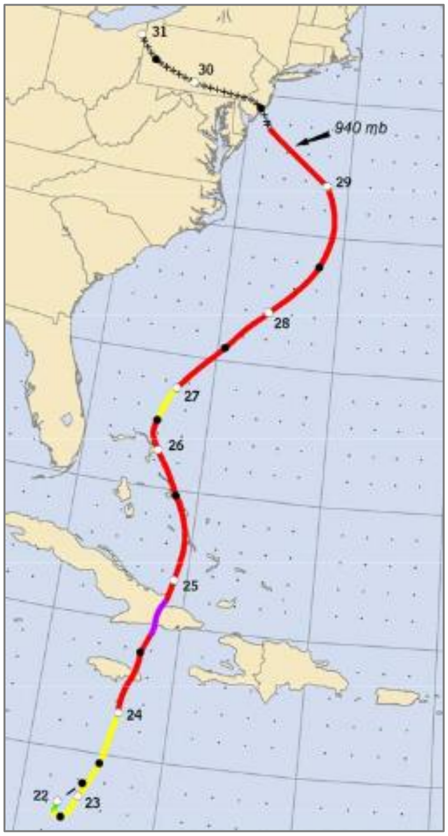

Fig. 6. Track of Hurricane Sandy (2012).

In the HRE, the impacts were catastrophic flooding, storm surge, wind and wave erosion, and massive sediment flux. Following the two storms in 2011, the amount of sediment entering the tidal portion of the Hudson River (from the Upper Hudson River and the Mohawk River, a major tributary) nearly tripled the annual average (USGS) (Figure 7).

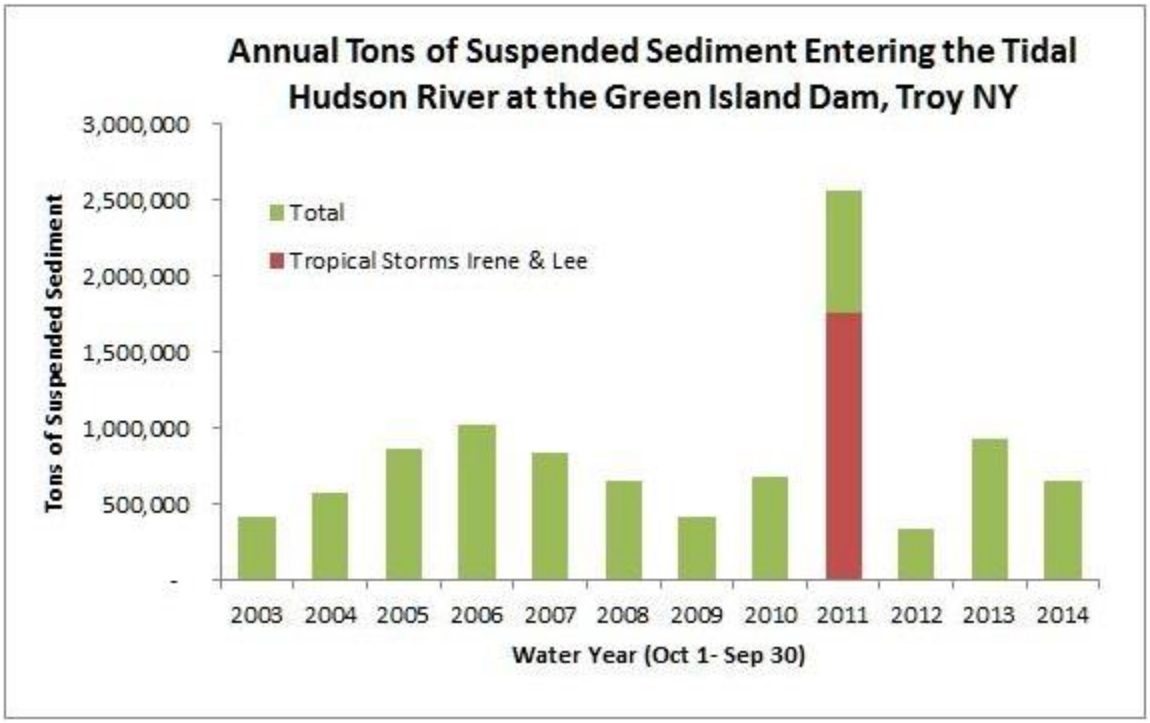

Figure 7. Annual metric tons of suspended sediment entering the tidal Hudson River at the Green Island Dam, Troy, NY (USGS).

As Hurricane Irene and Tropical Storm Lee hit New York State, only roughly ten days apart, there was little recovery period, and floodwater and sediment loading by the major tributaries from one storm following the other dramatically compounded the issue, with a peak of approximately 4000 m^3/sec (140,000 cfs) following Irene and approximately 3000 m^3/sec (105,000 cfs) following Lee (Ralston et al. 2013) (Figure 8).

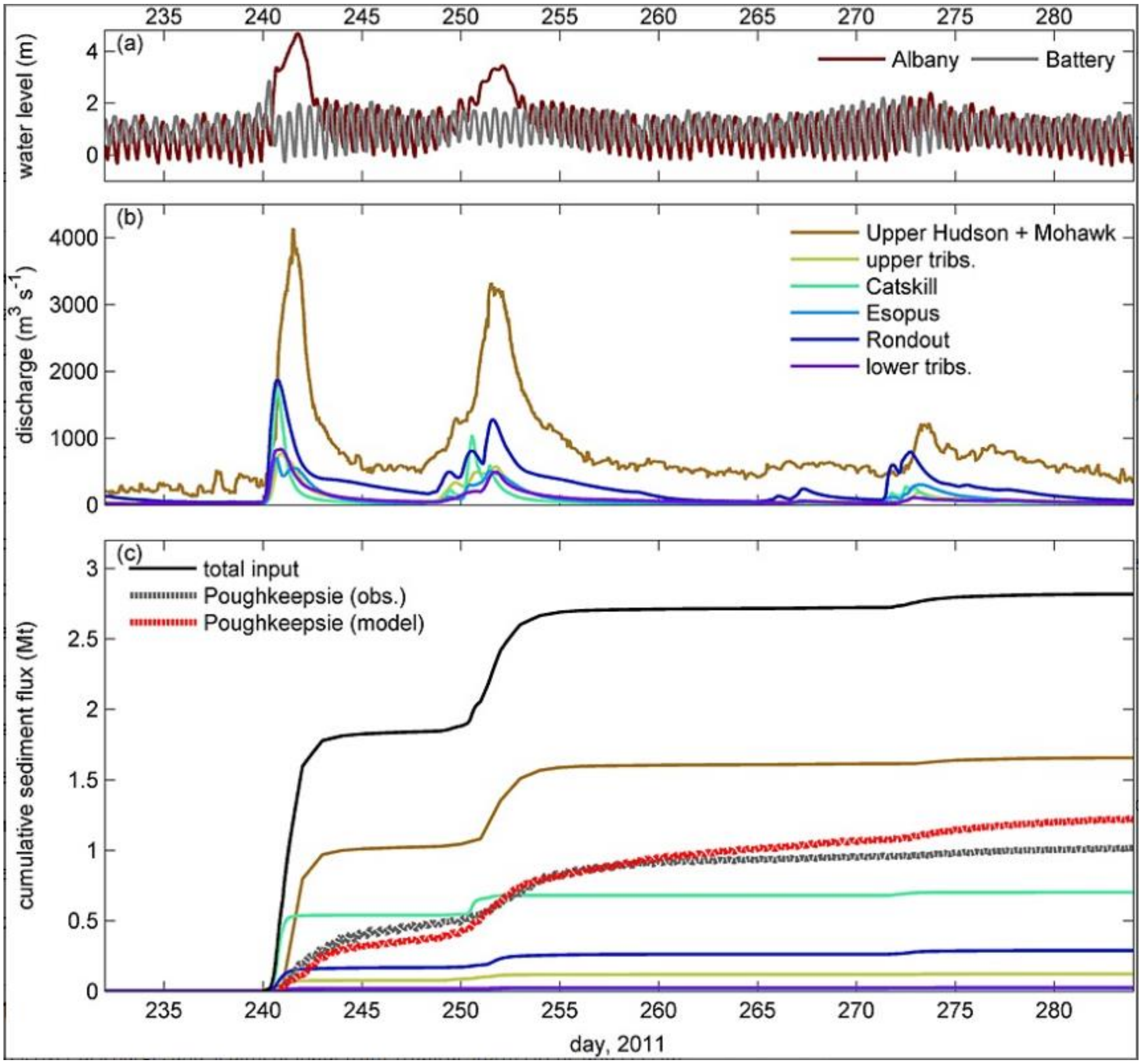

Figure 8. Water level, river discharge, and sediment input from Tropical Storms Irene and Lee (Ralston et al. 2013).

Sedimentation as a result of high tributary discharge was distributed unevenly throughout the HRE, with the highest sediment deposits occurring in the upper third of the watershed, centered around Catskill Creek (~150-200 km from the Battery in New York City) (Figure 9). The largest tributary contributors of sediment to the Hudson River mainstem were the Mohawk River, Catskill Creek, and Rondout Creek (Ralston et al. 2013).

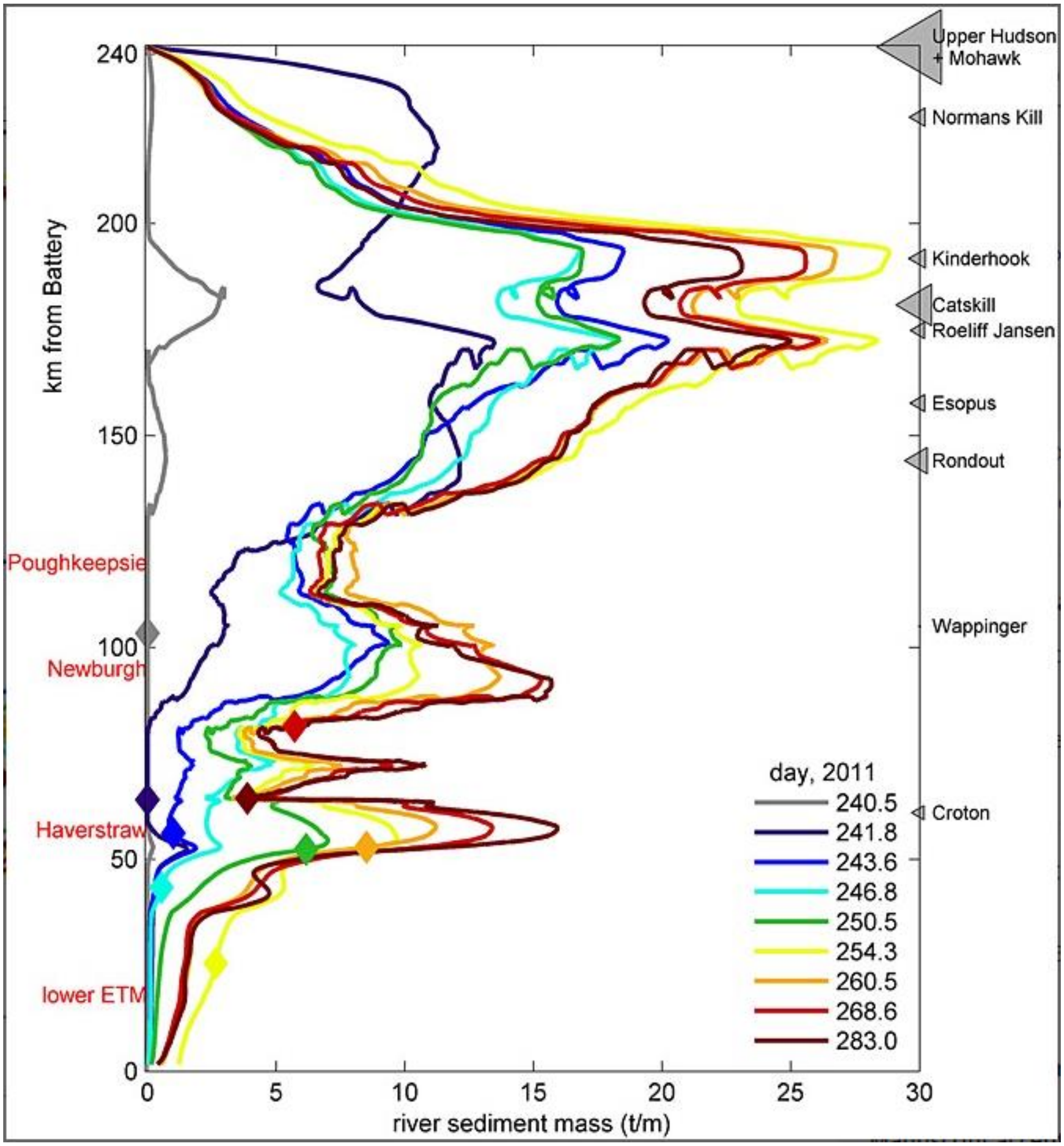

Figure 9. Sediment distribution into the HRE over time (year 2011). Diagram shows the major tributary contributors of sediment on the right axis, with the marker size being scaled to sediment input. Diagram runs upstream to downstream, top to bottom (Ralston et al. 2013).

Previous Studies

This study seeks to build on a considerable body of previous research in the field of submerged aquatic vegetation monitoring and remote sensing analysis. One of the foundational studies that influenced this research was the Findlay et al. (2014) investigation of spatial patterns of change of Hudson River SAV within the ten-year period of 1997 to 2007. They introduced a methodology for GIS analysis that laid the framework for a similar analysis in this body of research, and it is a goal of my study to both follow and elaborate upon this framework so as to provide data that can both be used in comparative studies (comparing spatial patterns of 1997-2007 to 2007-2016) as well as look into further detail to address remaining uncertainties.

The main difference between this study and that of Findlay et al. (2014) is that although the 2014 study examines spatial changes following typical annual disturbances in the watershed, this study examines the spatial recovery and changes in SAV coverage following a series of extreme storm events. Also, Findlay et al. (2014) examined only proximity to shoreline as a factor of changes in SAV coverage, whereas this study examines the proximity of documented SAV to tidal wetlands and large persistent beds as well, as it is hypothesized that these two features might be co-located within similar environmental conditions (water depth, water velocity, water quality, substrate, etc.) or might produce parent material for SAV vegetative reproduction and therefore recovery.

Another seminal study pertaining to Hudson River SAV is Hamberg et al. (2017), which more closely investigates the mechanisms of SAV decline as a result of sedimentation following the 2011-2012 storms. Hamberg et al. (2017) examines sprouting and growth patterns of *V. americana* within different sediment depths and suggests possible restoration strategies but does not examine the spatial patterns of SAV loss and/or recovery, a research gap this study looks to address, as these results can help to inform studies of sediment flux from upstream tributaries and overall improved watershed management decisions.

A significant amount of research has also been done on SAV in the Chesapeake Bay watershed, a much larger but ecologically-similar estuary to that of the Hudson River. Moore et al. (2000) investigated SAV community composition, biomass, and bed location/migration in the Chesapeake, and Orth et al. (2010) examined these trends in relation to changes in salinity regimes within the estuary ten years later. Orth et al. (2017) further elaborated on their 2010 work to provide a more general overview of SAV in the Chesapeake and to suggest potential restoration/management practices. This set of publications has served as a great resource to inform this study, as many of the environmental/ecological conditions within the Hudson and the Chesapeake are analogous.

Lastly, Lathrop & Haag (2011) serves as another excellent case study for the remote sensing and analysis portion of this study as they investigate changes in seagrass biomass and location in the estuaries of Barnegat Bay and Little Egg Harbor, New Jersey. In the case of this 2011 study, the main culprits of seagrass disturbance were scarring by boats, dredging, and dock installation.

Research Questions

This study examines the impacts of Hurricanes Irene and Sandy and Tropical Storm Lee and the resulting sediment flux on the loss of submerged aquatic vegetation in the HRE as well as the spatial recovery of SAV following these storms (post-2012). It is also the goal of this study to develop a feasible, reliable, and replicable methodology for continued spatial analysis and monitoring of Hudson River SAV. This research seeks to meet these goals and objectives by answering four specific research questions:

1. Has there been significant SAV recovery following the 2011-2012 storms?
2. Is recovery spatially coherent (i.e. Do the sites recover north to south?)
3. Is recovery related to adjacent shoreline or tidal wetlands?
4. Is recovery related to prior coverage of SAV (persistent “colony” SAV beds)?

The hypotheses of this study are 1) there has been significant recovery of SAV following the 2011-2012 storms; 2) SAV will show greater recovery in the north (upstream) reaches of the watershed and continued monitoring will show a pattern of north-to south recovery as SAV densities are historically greater in these reaches and there is a net-southward (downstream) flow; 3) SAV recovery will be greatest near shore and near tidal wetlands as these locations favor SAV growth; and 4) SAV recovery will be greatest nearer to large, persistent SAV beds, as these locations may potentially act as “colonies” for SAV biomass and genetic material.

SAV Data Information

As this study investigates both SAV loss following the 2011-2012 storms as well the potential recovery of SAV in more recent years, SAV coverage data were needed for a time period before 2011-2012, for a time period shortly after 2011-2012, and for a more recent time period. Hudson River SAV data exist for a series of five years: 1997, 2002, 2007, 2014, and 2016 (NYSDEC Hudson River Estuary Program 2018). For this study, years 2007, 2014, and 2016 are used for the change analyses, which fit the necessary categories mentioned above.

In 1994, a collaboration was initiated between the Cary Institute of Ecosystem Studies (CIES), the Hudson River National Estuarine Research Reserve (HRNERR), the New York State Department of Environmental Conservation (NYSDEC), and the Cornell Laboratory for Environmental Applications of Remote Sensing (CLEARS), now Cornell's Institute for Resource Information Sciences (IRIS), in partnership with the Hudson River Estuary Program (HREP). Prior to this partnership, no baseline information on SAV extent, distribution, or change in extent in the Hudson existed (Cornell IRIS, 2018).

The Hudson River SAV data were developed by Cornell IRIS and were published by HRNERR/NYSDEC, with funding through the NYS Environmental Protection Fund (EPF). The data for each time period show the spatial extent of both native SAV (dominated by *V. americana*) and non-native water chestnut (*T. natans*) for the entirety of the Hudson River Estuary mainstem, coves, and the tidal mouths of a number of the river's major tributaries.

METHODS

Remote Sensing & Data Collection

Hudson River SAV data for years 2007, 2014, and 2016, were acquired from the New York State GIS Clearinghouse (https://gis.ny.gov/). These data were developed by Cornell IRIS. High quality, true-color aerial photographs were acquired in the month of August so as to capture the SAV during its period of peak productivity and vegetative extent. Photographs were taken at the scale of 1:42,000 under ideal river and atmospheric conditions within two hours of low tide. This procedure followed the protocol laid out by the National Oceanic and Atmospheric Administration Coastal Change Analysis Program (NOAA C-CAP, 1995). The classification of vegetation types was developed by HRNERR and IRIS, creating three classes: "SAV", "water chestnut", and "Upland" (this last class used for georeferencing purposes) (Figure 10). More information on this procedure can be found in the metadata associated with these datasets (Cornell IRIS, 2018).

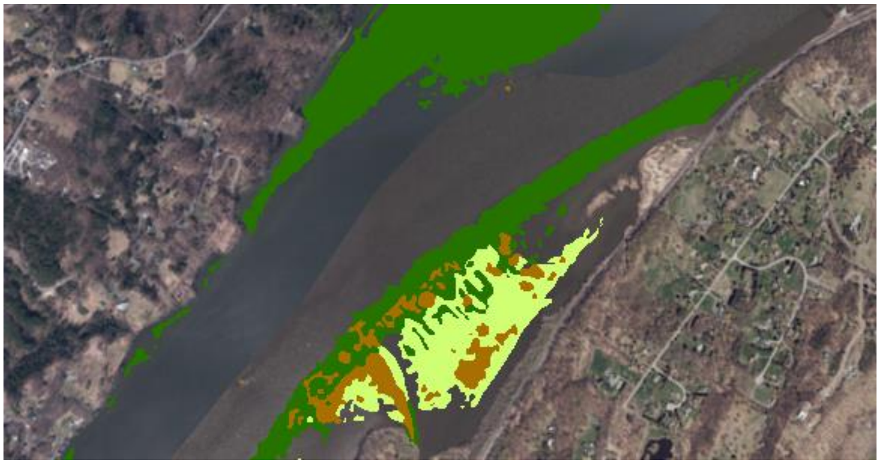

Figure 10. The three classes used in the SAV mapping: SAV (dark green), water chestnut (light green), and upland (brown; for reference).

Data Manipulation & Analysis

The data were brought into a GIS and mapped using ArcGIS version 10.6. For the system-wide (whole river) SAV change analysis, areal coverages of both classes “SAV” and “Trapa” (water chestnut) were calculated for all three years using the “calculate geometry” feature in ArcMap using the entirety of each dataset (full Hudson River SAV coverage from Troy, NY to New York Harbor). The third class, “upland”, was disregarded for this analysis. Percentage change in area was calculated for both SAV and water chestnut for the periods 2007 to 2014, 2014 to 2016 and overall change (2007-2016).

For the river segment analysis, the Hudson River was divided into 26 segments based on rectangular polygons approximately 10 nautical miles (~18.5 km) long. This segmentation was done using the Hudson River Estuary Benthic Survey Index data (Lamont-Doherty, 2005; http://gis.ny.gov/gisdata/metadata/nysdec.survey.index.html for metadata) (Figure 11).

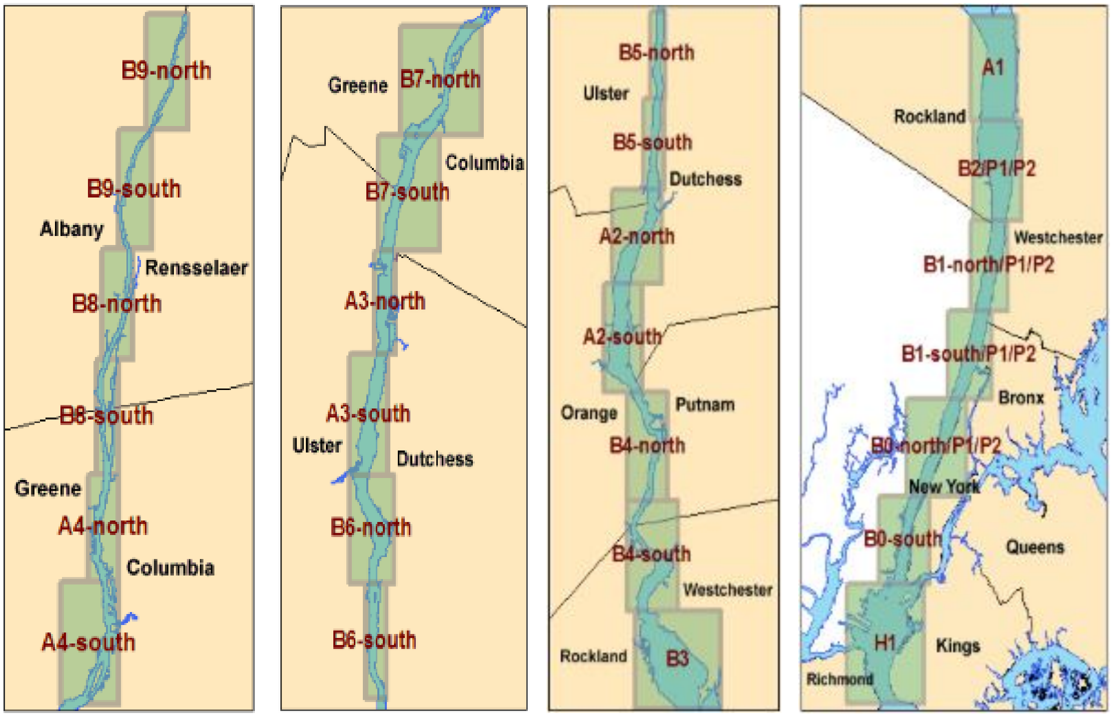

Figure 11. River segments (26) for analysis (HRE Benthic Survey Index. Lamont-Doherty, 2005).

The “SAV” class was isolated from each of the three datasets (“Trapa” [water chestnut] and “Upland” were disregarded) and was then clipped to each of the 26 river segment polygons (SAV was absent in the 5 southernmost/downstream segments, resulting in 21 usable segments for the analysis). For each segment, segment area, number of SAV beds, minimum bed size, maximum bed size, total SAV area, mean bed size, and bed size standard deviation were calculated. This was done for all three datasets. The total number of beds and the mean bed size (m^2) for all 21 segments were also calculated for all three years. Using the total SAV areas per river segment, percentage change was calculated for 2007 to 2014, 2014 to 2016 and the overall change (2007-2016). Finally, the average percentage change for all river segments was calculated for each time period.

For the persistent SAV bed change analysis portion of this study, 13 large (> 20 ha) core SAV beds or patches were identified, north from near Athens, NY south to Croton Point (see Table 3 under “Results”). It is important to note that this > 20-ha size limitation was set so as to minimize the number of potential SAV beds used for the analysis, but has no real ecological implications aside from greater SAV biomass and low potential for total loss in coverage (i.e. high potential for bed survivorship and persistence of genetic material).

Lastly, a fine-scale quadrat-level analysis was done in ArcGIS 10.6 to investigate spatial patterns in more detail. First, a rectangular polygon was laid over the entire study area (Hudson River Estuary, from Troy, NY to New York City). The ‘Create Fishnet’ tool was used to create a 30-m x 30-m grid within the aforementioned rectangular area of interest (AOI). The three SAV datasets were merged to develop a “historical SAV coverage” layer, representing the total possible range of SAV for the time period of this study. Using ‘Select by Location’ within ArcGIS, a refined grid layer was generated, representing only the grid cells that intersected the merged SAV data, so as to remove any grid cells that had no SAV coverage from 2007-2016 or were over land or other water features non-related to this study, resulting in 6,808 grid cells for analysis. SAV coverage within each grid cell was calculated by proportion (0 to 1; 0 = no coverage, 1 = full coverage), and change in area (m^2) and percentage change from 2007-2014, 2014-2016, and 2007-2016 were calculated, this time for each grid cell. Grid cells were 10m x 10m (area = 10,000 m^2), therefore change in area ranged from -10,000 m^2 to +10,000 m^2, using the proportion at a multiplier. Qualitative “Change Categories” were generated for the percent change of each grid cell for all three time periods using categories based on the cells' vectors of change, as well as generalized change categories (Table 1). Frequency distributions were then created using these data.

Table 1. Specific and generalized "Change Categories" for each range of percent change vectors.

Percent Change Range	**Specific Change Category**	**Generalized Category**
-100.00%	Total Loss	Loss
-99.99% to -66.67%	Large Loss	Loss
-66.66% to -33.34%	Moderate Loss	Loss
-33.33% to -0.01%	Minor Loss	Loss
+/- 0.00%	No Loss or Gain	No Change
+0.01% to +33.33%	Minor Gain	Gain
+33.34% to +66.66%	Moderate Gain	Gain
+66.67% to +100.00%	Large Gain	Gain
> +100.00%	Gain over 100%	Gain

Finally, the 'Near' tool was used to calculate the distance from each grid cell to the shoreline, to the nearest tidal wetland, and to one of thirteen core persistent "colony" SAV patches. The shoreline layer was developed from the "Hudson River Estuary Shoreline" dataset (Lamont-Doherty, 2004 – Metadata: http://gis.ny.gov/gisdata/metadata/nysdec.hr_shoreline.xml) by using the 'Polygon to Polyline' tool. The tidal wetland layer was developed from the "Hudson River Estuary Tidal Wetlands 2007" dataset (Cornell IRIS, 2011 – Metadata: http://gis.ny.gov/gisdata/metadata/nysdec.hre_tidal_wetlands2007.shp.xml) by running a definition query to remove undesired classes from the layer ('Open Water', 'SAV', and 'Trapa natans'). The "persistent SAV patch" layer was developed using the 2007 dataset by isolating SAV beds ≥ 20 ha, resulting in 13 large SAV beds. In addition to using this layer for the quadrat analysis ‘Near’ calculation, percent change in area was also calculated for each of these beds over the same three time periods.

Scatterplots were created for both loss and recovery of SAV area versus distance from shore, distance from tidal wetlands, and distance from persistent SAV beds. The “loss” plots were generated using the negative changes in SAV area (-10,000 m^2 to -0.01 m^2) from the 2007-2014 data and the “recovery” plots were generated using the positive changes in SAV area from 2014-2016 (0.01 m^2 to 10,000 m^2). Regression lines and equations were generated in Microsoft Excel, and R^2 coefficients and *p*-values were calculated for the slope term to test hypotheses about significant relationships between SAV change and distance from shore, tidal wetlands, and persistent SAV beds (i.e. H_0: $\beta = 0$, H_a: $\beta <> 0$).

RESULTS

System-wide Change Analysis

Looking first at the change in native, desirable SAV (*V. americana*) coverage for the entire HRE, there was a clear and evident loss from 2007-2014 and recovery from 2014-2016. From 2007 to 2014, SAV decreased from 1,343 ha to 483 ha, a percentage change of -64.1%. From 2014 to 2016, SAV increased from 483 ha to 1,091 ha, a percentage change of +126.1% (and an overall change of -18.7% from 2007 to 2016) (Table 2).

Table 2. Areal coverages of SAV (*Vallisneria americana*) and water chestnut (*Trapa natans*) (hectares) for 2007, 2014, 2016, and percentage change in coverage for both for 2007-2014 and 2014-2016.

Year	SAV Area (hectare)	Water Chestnut Area (hectare)	SAV % Change	Water Chestnut % Change
2007	1,342.77	788.88	-	-
2014	482.69	880.80	-64.05%	+11.56%
2016	1,091.46	856.12	+126.12%	-2.80%

Whereas SAV coverage changed considerably, water chestnut (*Trapa natans*) coverage changed much less dramatically over the same time periods (Figure 12). From 2007 to 2014, water chestnut increased from 789 ha to 881 ha, a percentage change of +11.7%. From 2014 to 2016, water chestnut decreased slightly from 881 ha to 856 ha, a percentage change of -2.8% (and an overall change of +8.5%) (Table 2).

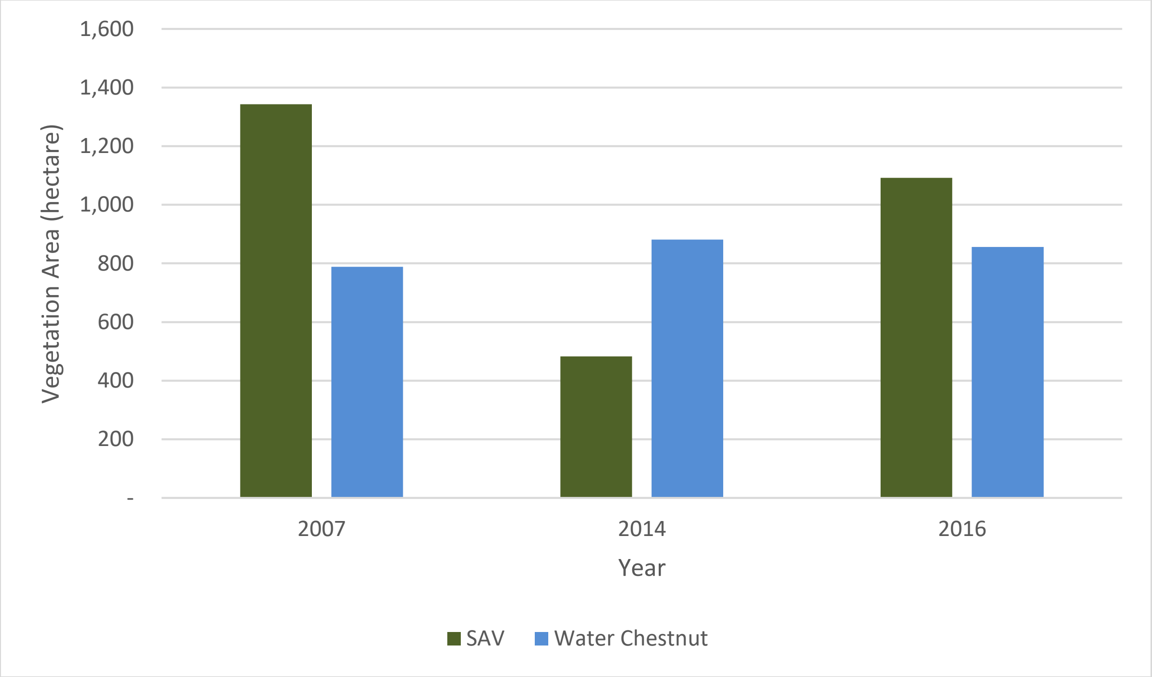

Figure 12. Vegetation area (hectares) for both SAV (*Vallisneria americana*) and water chesnut (*Trapa natans*) for the entirety of the Hudson River Estuary study area for years 2007, 2014, and 2016.

River Segment Change Analysis

Before the storms of 2011-2012 (2007 data), the largest density of SAV was found in the upper half of the HRE, and within the lower half of that reach, from the Stockport Flats segments south to the Hyde Park North segment (Figure 13). In the wake of the storms, there was a dramatic decrease in SAV coverage in this part of the river, and the greatest SAV coverage was found in the Haverstraw segment, at the south end of the watershed (2014 data) (Figure 13). Finally, in 2016, a fair amount of recovery was documented in the upper half (second “quarter”) of the river, with the area around the Catskills South segment returning to the highest coverage of SAV within the HRE (Figure 13).

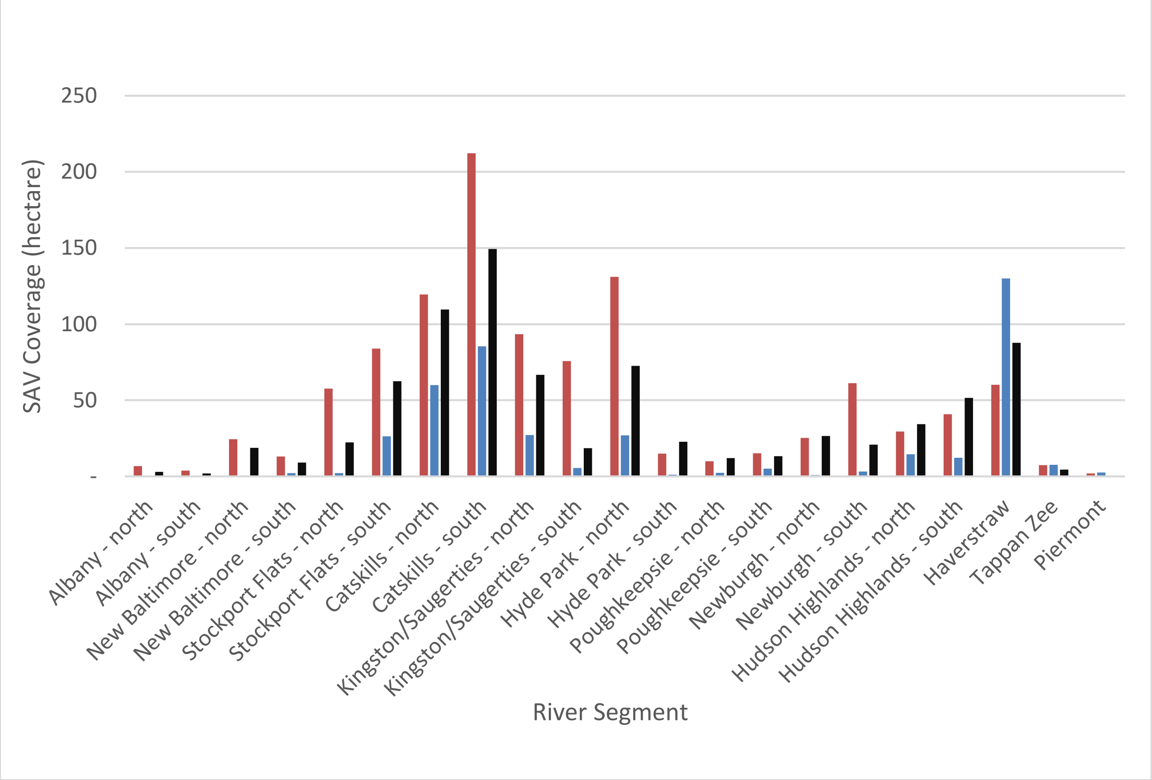

Figure 13. SAV coverage by river segment (north to south, left to right) for 2007 (red), 2014 (blue), and 2016 (black).

Using this river segment analysis, similar patterns of SAV loss and recovery were quantified as compared to the system-wide analysis. From 2007 to 2014, 18 of the 21 river segments demonstrated a loss in SAV while the remaining three segments demonstrated a gain. From 2014 to 2016, a similar pattern resulted, with the same 18 of 21 segments demonstrating SAV recovery (+ percentage change) and the same remaining three segments showing loss (Figure 14 a-b). In both cases, the 18 segments were the northernmost (farthest upstream) sections of the river and the 3 remaining segments were the southernmost (farthest downstream), demonstrating a strong north to south pattern of loss and recovery. Examining the overall change for each river segment (2007-2016), 15 of the 21 segments showed a loss in SAV while the remaining 6 segments showed a gain

(Figure 14c). The spatial pattern for this time period is less well defined, with some adjacent segments alternating from positive to negative percentage changes going north to south, however, the bulk of the overall loss appears to have occurred in the northernmost half of the river.

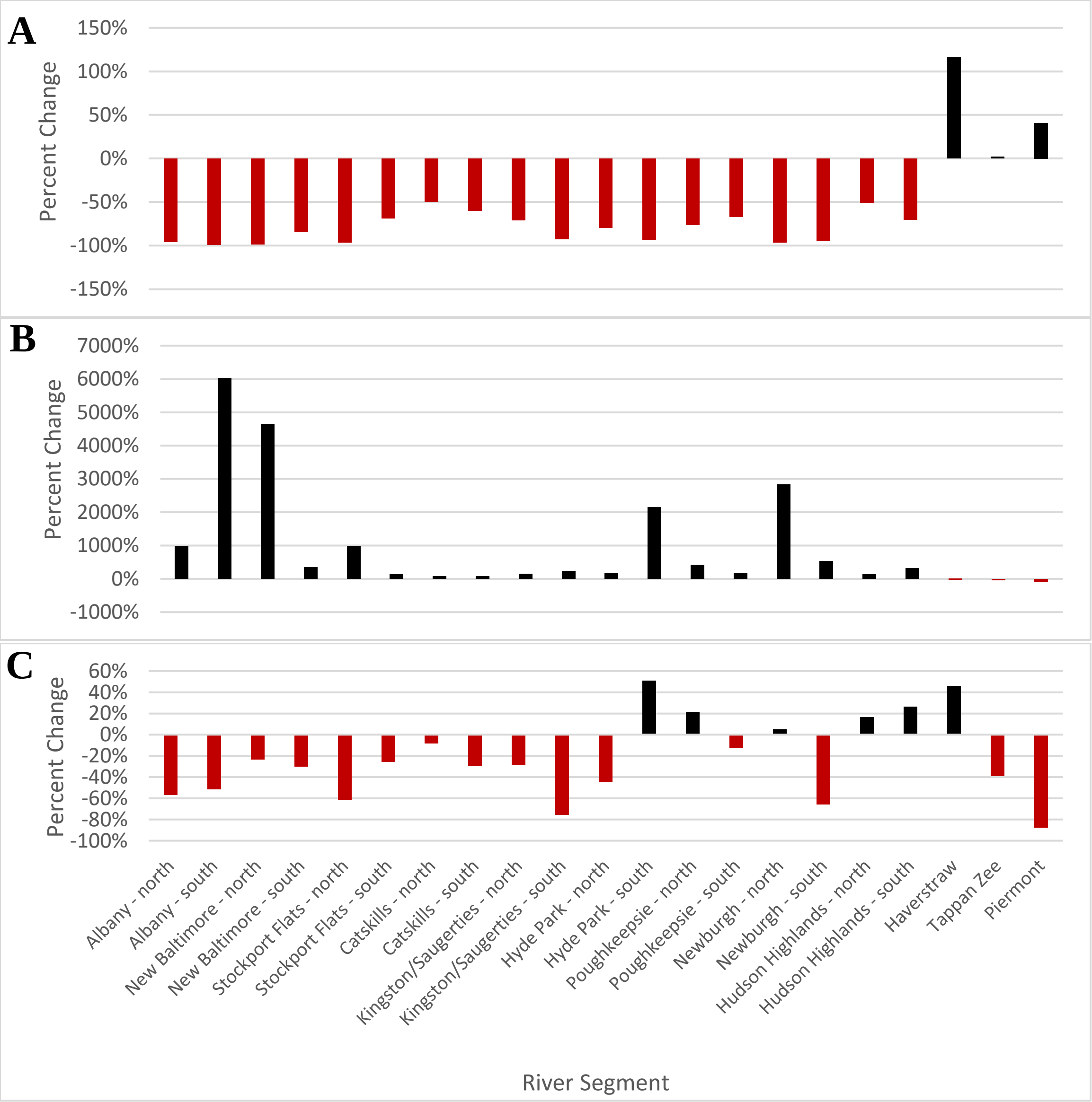

Figure 14. Percentage change in SAV area by river segment for all three time periods: (A): 2007-2014; (B): 2014-2016; and (C): Overall (2007-2016). Black represents positive change (growth), red represents negative change (loss). Left to right = north to south.

Persistent SAV Bed Change Analysis

Of the thirteen large “colony” SAV beds (> 20 hectares), all but one (#13 Croton Point) demonstrated a decrease in area from 2007-2014, and three were lost altogether (#8, #11, and #12) (Table 3). From 2014-2016, all but one of the colony SAV beds that had lost area from 2007-2014 demonstrated some degree of recovery (#8 did not recover), and two beds (#1 and #13) have grown in size from their pre-storm coverage (positive % change from 2007-2016).

Table 3. Percentage change of each “colony” SAV bed from 2007-2014, 2014-2016, and overall (2007-2016). * ‘-100%’ represents the complete loss of an SAV bed **‘DIV/0’ represents the recovery of a previously lost/nonexistent bed.

“Colony” SAV Bed (N to S)	General Location	Percent Change 2007-2014	Percent Change 2014-2016	Percent Change 2007-2016
1	Athens	-24.30%	35.43%	2.52%
2	Catskill	-60.50%	152.65%	-0.20%
3	Linlithgo	-92.10%	555.72%	-48.17%
4	Germantown	-56.58%	64.55%	-28.56%
5	Clermont	-43.96%	30.81%	-26.69%
6	Saugerties North	-60.85%	86.43%	-27.00%
7	Saugerties South	-93.54%	469.89%	-63.20%
8	Kingston-Rhinecliff Bridge	-100.00%*	0.00%	-100.00%*
9	Esopus Meadows	-70.13%	121.39%	-33.88%
10	Staatsburg	-87.55%	320.06%	-47.71%
11	West Fishkill	-100.00%*	DIV/0**	-10.39%
12	Cornwall	-100.00%*	DIV/0**	-59.41%
13	Croton Point	20.26%	-0.61%	19.52%

Quadrat-Scale Analysis

Investigating SAV loss and recovery at a much finer scale (30m x 30m quadrat grid analysis), a similar pattern emerges yet again, but with greater precision. From 2007 to 2014, 4,876 of the 6,808 grid cells (71.6%) exhibited a loss of SAV coverage (Figure 15a), with 3,795 cells showing a complete loss of SAV (77.8% of the total loss) (Figure 15b). From 2014 to 2016, 4,057 of the 6,808 grid cells (59.6%) showed a gain of SAV coverage (Figure 16a), with the majority of the recovery coming from "minor gains" in SAV area (Figure 16b).

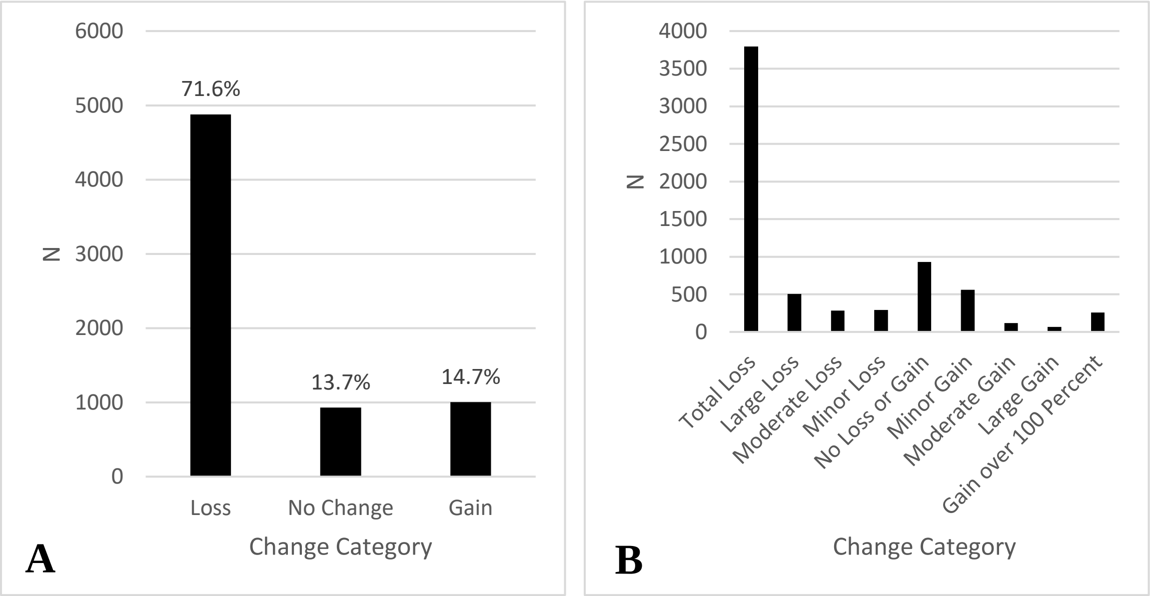

Figure 15. 2007-2014: A) number of quadrat grid cells by general change category; B) number of quadrat grid cells by specific change category.

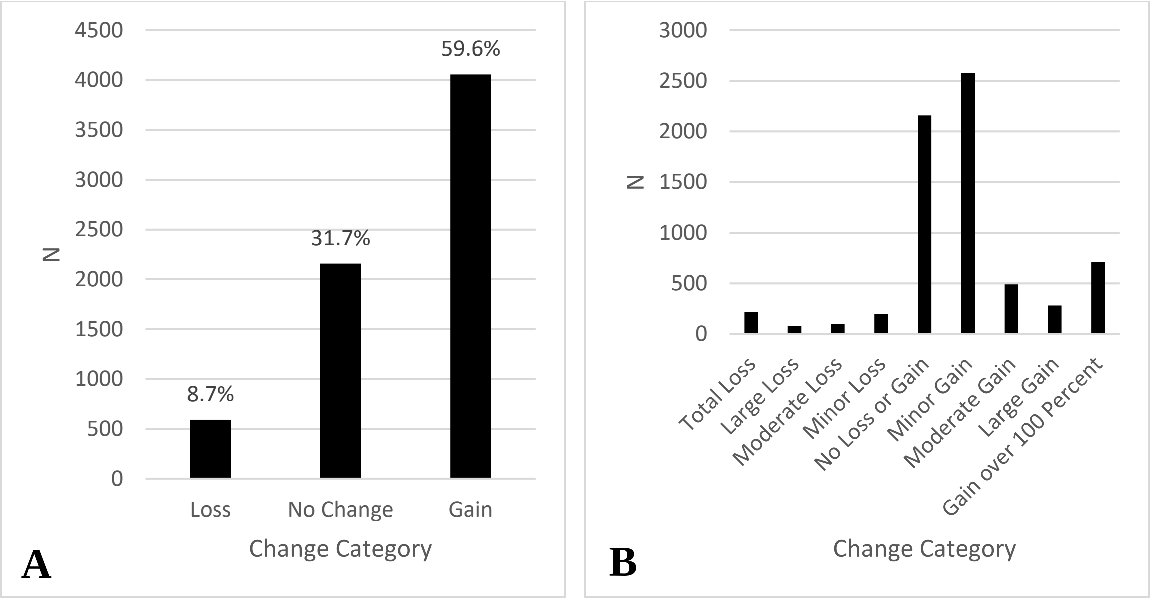

Figure 16. 2014-2016: A) number of quadrat grid cells by general change category; B) number of quadrat grid cells by specific change category.

Lastly, the results from the quadrat-scale analysis were used to investigate the relationship of SAV loss and recovery with proximity to shoreline, to the nearest tidal wetland, and to the nearest of the aforementioned thirteen persistent SAV beds. The negative percent change data from 2007-2014 (majority loss period) was used to look at SAV loss and the positive percent change data from 2014-2016 (majority gain period) was used to look at SAV recovery.

Looking first at SAV loss following the 2011-2012 storms, both proximity to shoreline and proximity to a large persistent SAV bed had a significant impact on the loss of SAV in the Hudson River ($p < 0.0001$ for both) (Figures 17, 19). There was no correlation between loss in SAV and proximity to a tidal wetland ($p = 0.73$) (Figure 18). There was a positive trend in the relationship between distance from shore and SAV loss (i.e. greater distance from shore = greater SAV loss) (Figure 17) and an inverse trend between distance from a persistent SAV bed and percent SAV loss (i.e. greater distance from persistent bed = less SAV loss) (Figure 19).

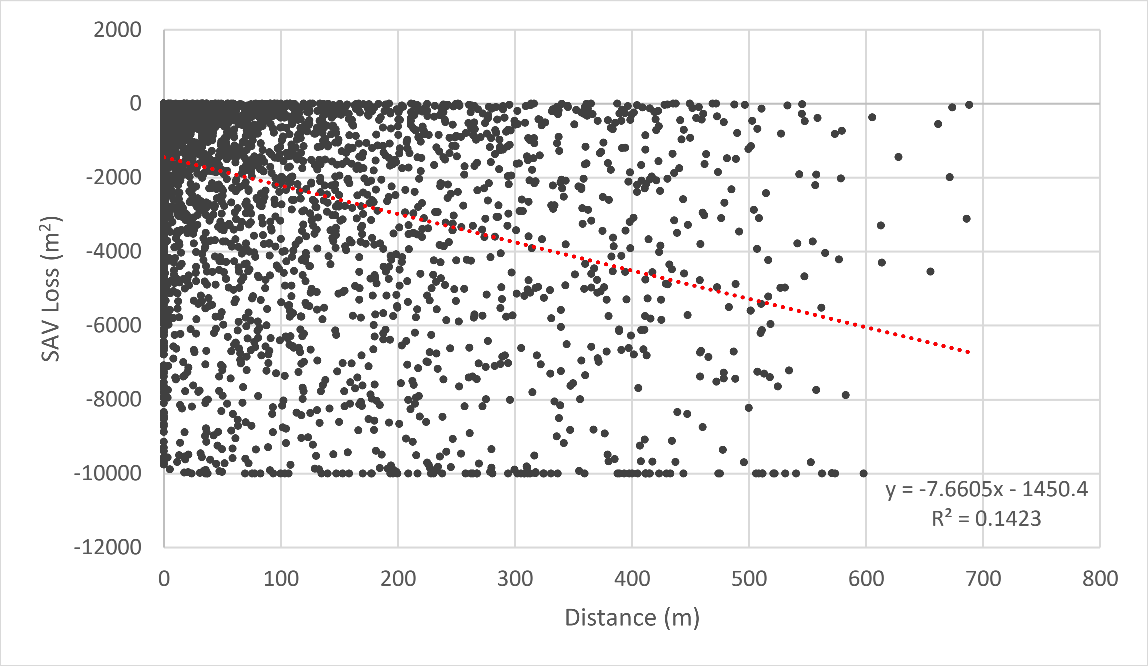

Figure 17. SAV loss (m^2) from 2007-2014 vs. distance from shore (m). $p < 0.0001$.

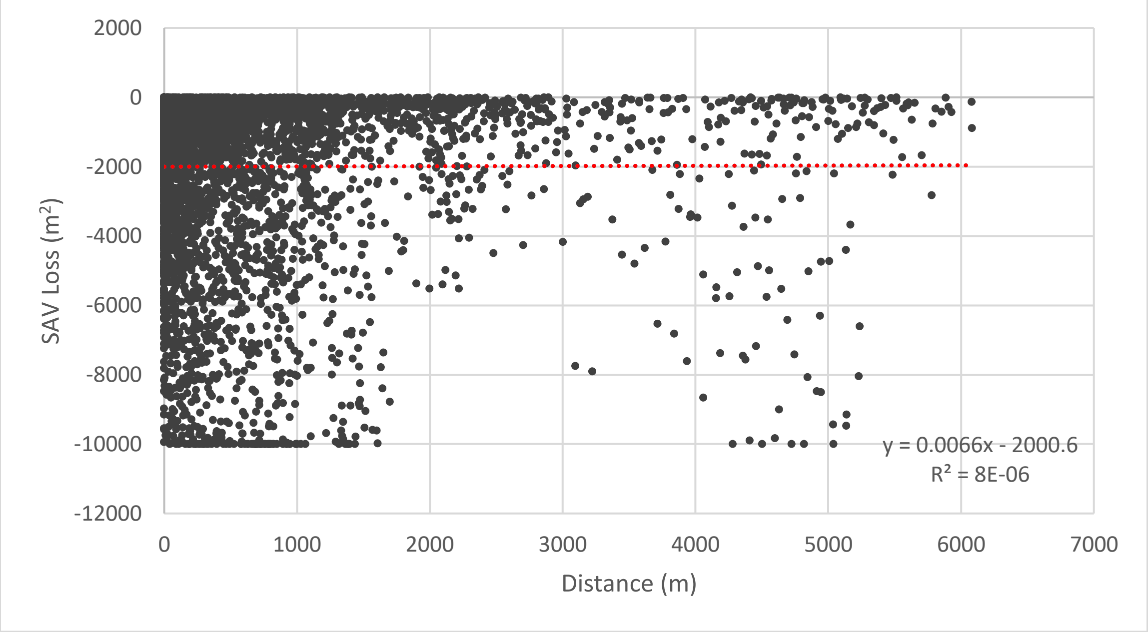

Figure 18. SAV loss (m^2) from 2007-2014 vs. distance from tidal wetland (m). $p = 0.73$.

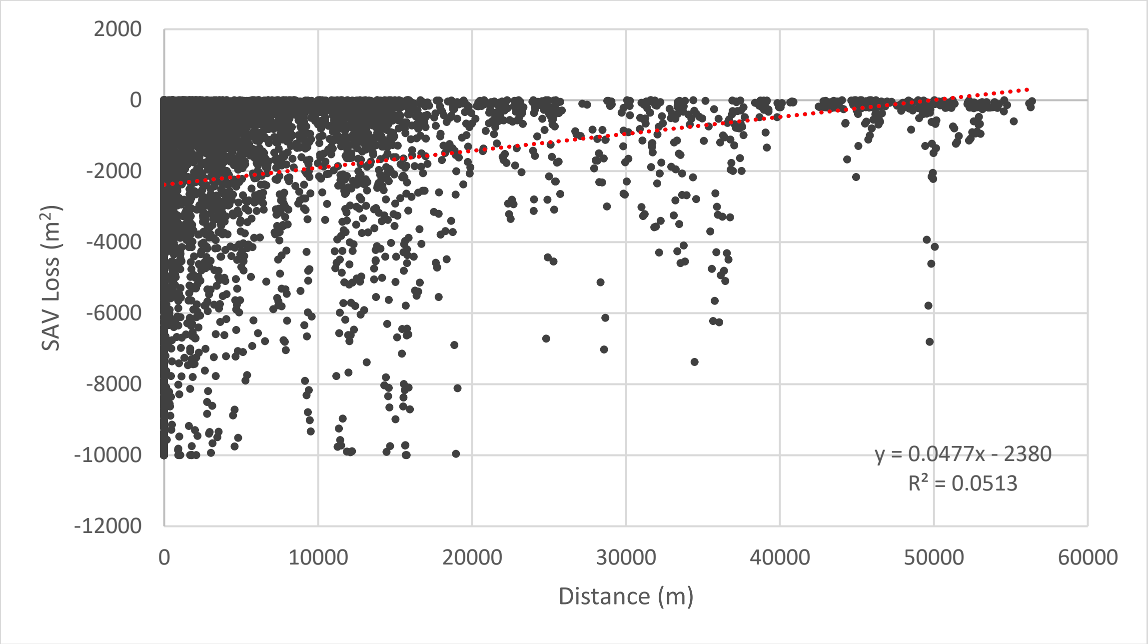

Figure 19. SAV loss (m^2) from 2007-2014 vs. distance from persistent SAV bed (m). $p < 0.0001$.

Lastly, examining the recovery period (2014-2016), there was a significant correlation between the magnitude of SAV recovery (%) and all three variables: distance from shore, tidal wetland, and persistent SAV bed ($p < 0.0001$, $p < 0.001$, and $p < 0.0001$, respectively) (Figures 20, 21, 22). There was a positive trend in the relationship between both distance from shore and distance from tidal wetlands and percent SAV recovery (i.e. greater distance from shore/greater distance from tidal wetlands = greater SAV recovery) (Figure 20, 21) and an inverse trend between distance from a persistent SAV bed and percent SAV recovery (i.e. greater distance from persistent bed = less SAV recovery) (Figure 22).

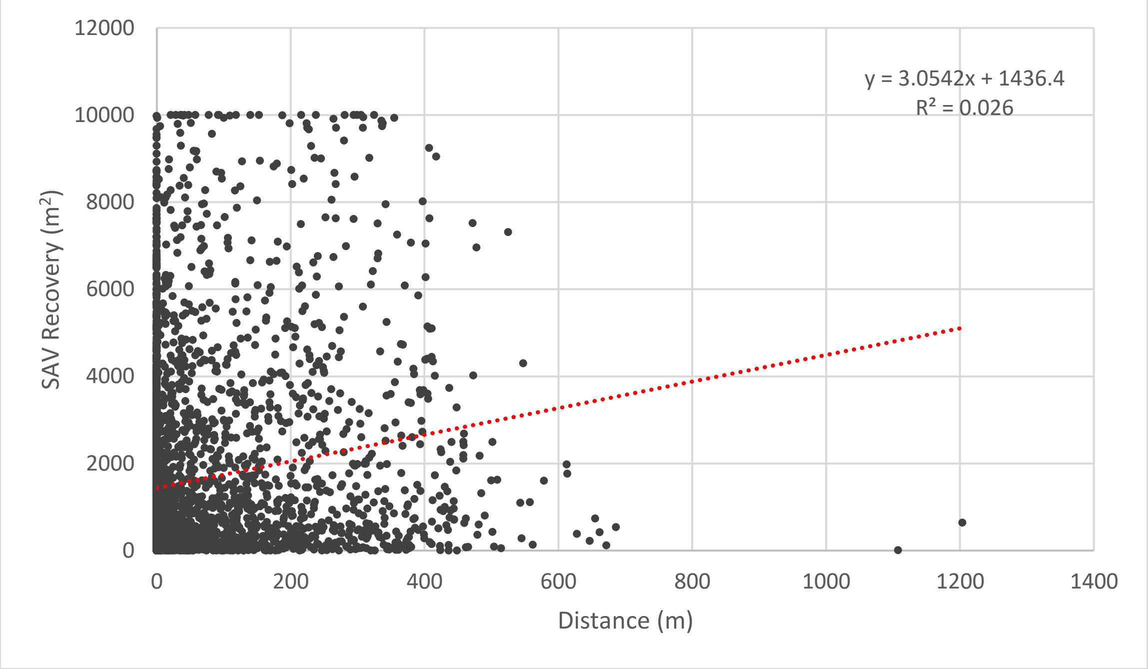

Figure 20. SAV recovery (m^2) from 2014-2016 vs. distance from shore (m). $p < 0.0001$.

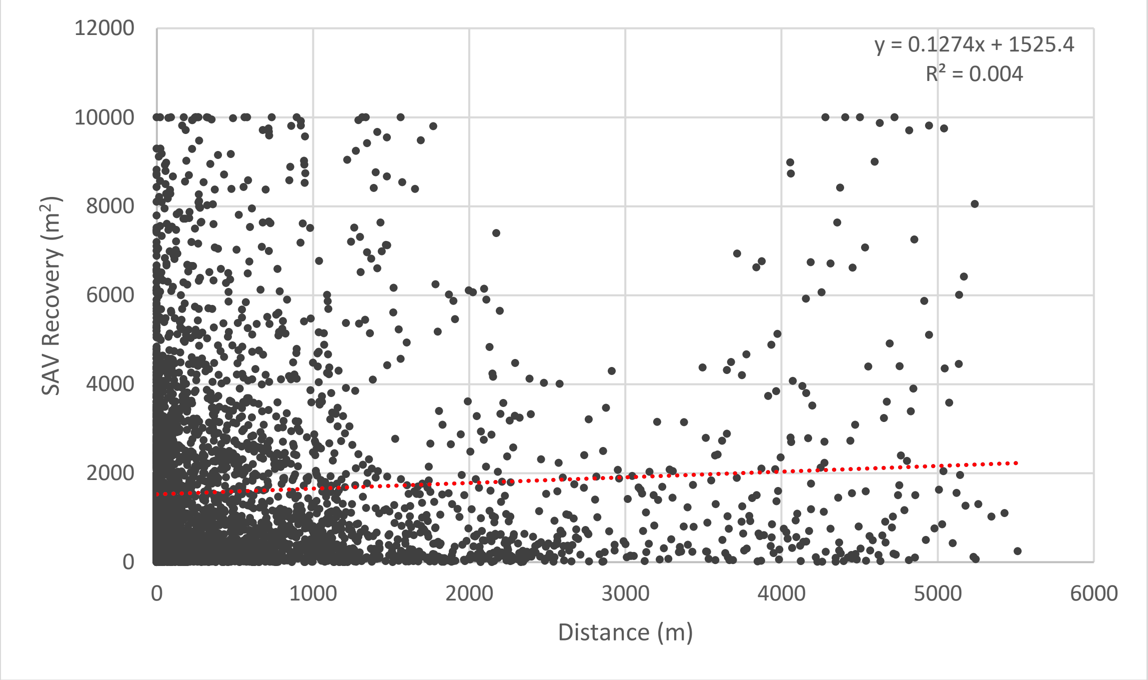

Figure 21. SAV recovery (m^2) from 2014-2016 vs. distance from tidal wetland (m). $p < 0.001$.

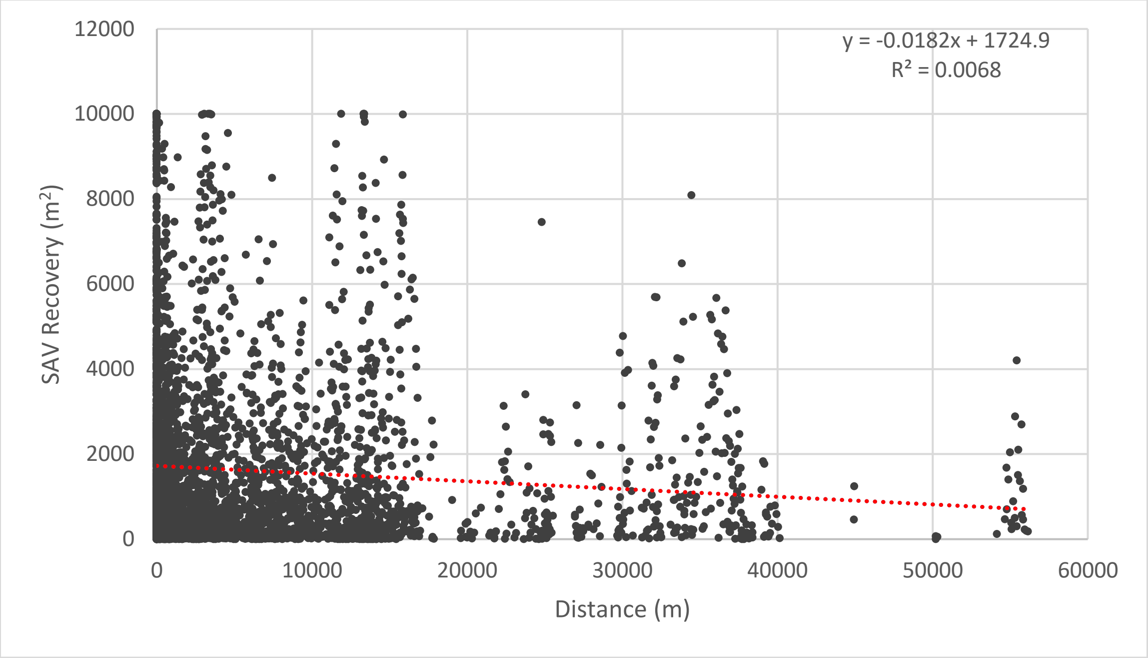

Figure 22. SAV recovery (m^2) from 2014-2016 vs. distance from persistent SAV bed (m). $p < 0.0001$.

DISCUSSION

SAV Loss & Recovery

Over the entire Hudson River Estuary system, submerged aquatic vegetation (namely *V. americana*) declined dramatically (-64% change) between the period of 2007 to 2014. Within that time frame, three extreme storms (≥ 100-year storm) made landfall over the region and impacted the ecology of the HRE watershed and its vegetation. The decline in SAV is closely tied to these storms and the main mechanisms of this vegetation disturbance were likely high tributary discharge and the resulting increased sediment flux and dispersal, storm surge and physical wave energy, and changes to water quality parameters, namely turbidity. Unfortunately, there are no additional spatial/GIS data for any of the years in between (2008-2013) to examine these impacts at a finer temporal scale and to isolate the impacts of the storms. As the terminal year during the "loss" period (2014) was two to three years after the storms Irene, Lee, and Sandy, it is likely that SAV decline was actually greater than 64% following the storms, and that some amount of recovery likely occurred in the 2012-2014 timeframe, which is in line with similar patterns of SAV loss noted observed by Hamberg et al. (2017).

The "recovery" period examined in this study (2014-2016) revealed a ~ 126% gain in SAV coverage – a significant recovery from 2014, but still ~19% less than the 2007 (pre-storm) coverage. Invasive water chestnut (*Trapa natans*) remained fairly stable over the 2007-2016 period of this study, increasing in coverage slightly from 2007 to 2014 when SAV declined, and decreasing slightly from 2014 to 2016 when SAV increased. Although it is not a major focus of this research, understanding the ecology and population dynamics of water chestnut is an important factor in the study of the dispersal and spatial patterns of native SAV as they are competitors for resources.

Spatial Patterns

Dividing the HRE into segments allowed for a better visualization of the north-south coverage and distribution of SAV in the HRE as well as patterns of loss and recovery over the study period. Historically, SAV was found at its highest densities in the upper half of the estuary, especially in the reach from Hudson, NY south to Hyde Park, NY. Examining the degree of SAV loss during the 2007-2014 period, declines were fairly uniform throughout the northern three-quarters of the watershed, with a number of segments showing near total net loss in SAV. Interestingly, during this same period, the three southernmost segments showed net gains in SAV. While only a hypothesis, it is possible that these segments were buffered from the massive sediment fluxes and deposition the more upstream reaches received due to the fewer number of large tributaries in this reach and due the channelization and geomorphology of the Hudson River mainstem just upstream of the reach (Figure 23).

Recovery (2014-2016) showed a similar spatial pattern, recovering most robustly in the upper quarter of the estuary, where SAV had nearly been extirpated previously. While it makes sense that recovery might indeed be highest in locations where previous loss was so significant, it is promising that SAV in these reaches rebounded so vigorously over only two years.

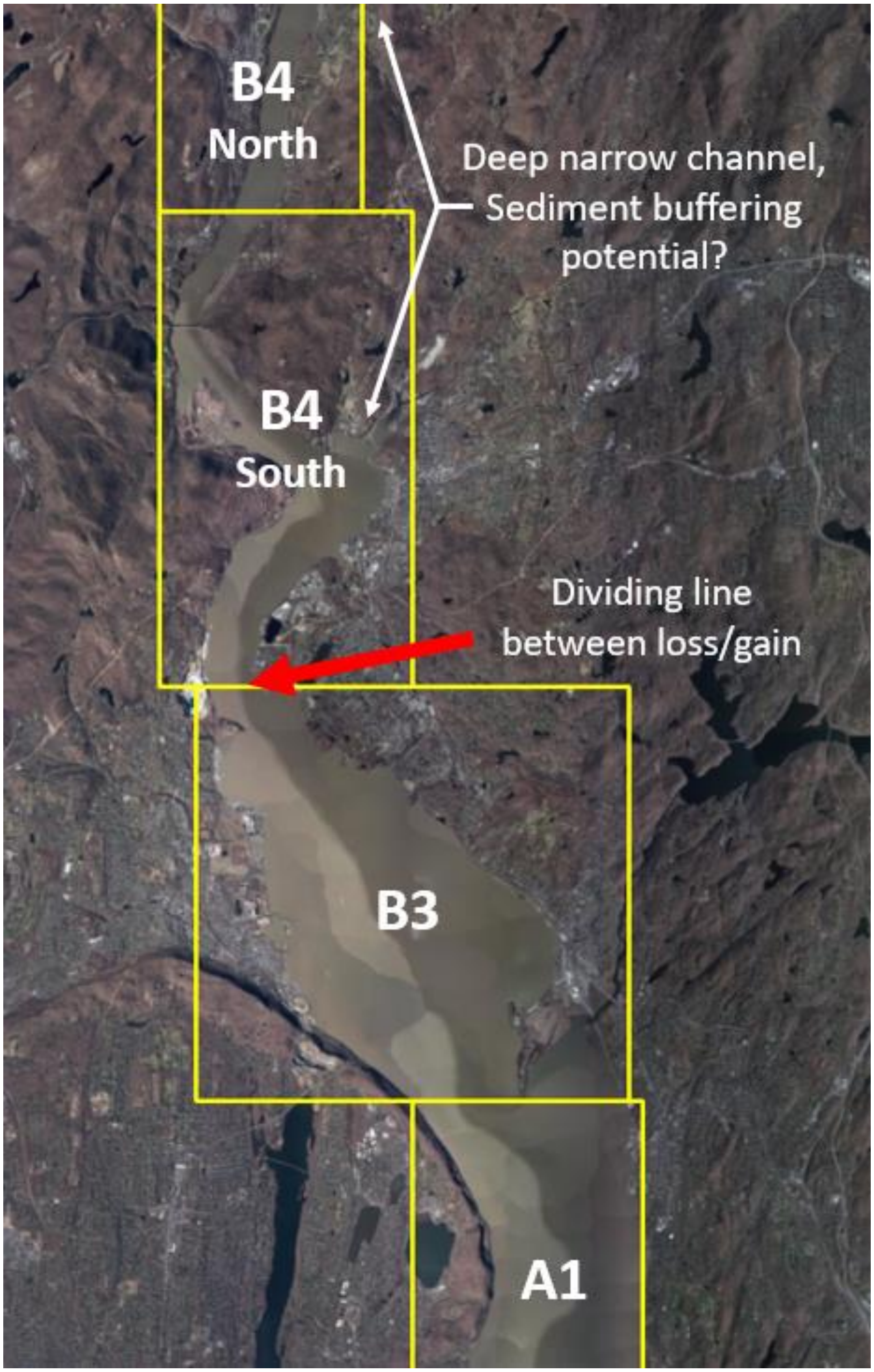

Figure 23. South-central section of HRE (Highland Falls, NY to Nyack, NY) showing the dividing line between river segments B4 South and B3. All segments north of this line saw SAV loss and all segments south saw SAV gain from 2007 to 2014 (and the opposite pattern from 2014 to 2016). The figure also highlights the stream channel upstream of this point, which is relatively narrow and deep, with the potential for sediment buffering.

Proximity to Shore, Tidal Wetlands, and Persistent Beds

In most cases, the proximity to the shoreline, tidal wetlands, and large, persistent SAV “colony” beds had a significant impact on both the loss and recovery of SAV in the HRE. Examining the period of net loss first (2007-2014), both proximity to shore and to large SAV beds showed a significant correlation, with increased loss occurring further from shore and closer to the identified persistent SAV “colonies”. The increased loss further from shore is likely due increased river current and sediment carrying potential as well as greater water depths at these distances. There was no significant correlation between proximity to tidal wetlands and loss of SAV during this period.

During the net recovery period (2014-2016), there was a significant correlation between gain in SAV area and proximity to all three features. Greater recovery of SAV occurred at greater distances from shore, which is likely due to the fact that the greatest amount of loss occurred in these areas during the 2007-2014 period. With regards to proximity to tidal wetlands, there was a slight positive trend in the recovery of SAV, again with greater recovery occurring at greater distances. This trend is at odds with the original hypothesis that greater recovery would occur closer to these wetlands as they might be co-located in similar environmental conditions as SAV. However, this outcome is possibly a result of less initial loss of SAV near these wetlands, although the data cannot statistically confirm this. Lastly, with regards to proximity to large persistent SAV beds, there was an inverse correlation between SAV recovery and distance, as hypothesized, with greater recovery occurring closer to these large beds.

Similar patterns arose in terms of the pattern of SAV loss, with greater loss occurring at greater distances from shore when comparing these results to previous studies. Findlay et al. (2014), who examined similar spatial patterns of SAV in the Hudson River, but in previous years and with normal disturbance regimes, also saw this trend. The Findlay et al. (2014) study did not, however, have the opportunity to look at recovery, as SAV declined in between both of their two study periods (1997-2002 and 2002-2007), nor did they investigate change in SAV with relation to distance from tidal wetlands or large SAV beds for further comparison to this study.

Significance of Recovery for Habitat and Water Quality

Understanding the ecology and population dynamics of SAV in the HRE is critical to the health and well-being of this estuarine ecosystem. These aquatic plants play an important role in acting as a nursery for juvenile fish and habitat for adult fish and a wide array of macroinvertebrates, and are an integral component of the food web of the entire estuarine system. They are also a major contributor to dissolved oxygen in the river and have the potential to improve water quality by taking up nutrients and capturing and settling out suspended solids and sediment (Orth et al. 2017). Continued recovery of SAV is imperative to the health of the Hudson River and its ecosystem, and the results of this study will help to highlight the potential magnitude and spatial patterns of this recovery following a large disturbance. This increased understanding can have tremendous implications for the management of this resource and its impacts on wildlife and water quality.

CONCLUSIONS & LIMITATIONS

Although it is clear that there was a significant amount of recovery following the storm-related SAV loss, the mechanisms for that recovery are still largely unknown. Spatial patterns examined in this study suggest a north to south recovery, with gains in SAV coverage being highest in areas of greatest loss in the previous time period. However at the time of this study, the data were already three years old, and the current magnitude and distribution of SAV recovery is largely unknown.

One of the main goals of this study was to develop a replicable methodology to be utilized with future SAV data to analyze similar patterns. Although this study highlights a number of new and important findings, continued monitoring, research, awareness, and management are key to the success and fecundity of this important resource and biological community, and the methodology developed in this study can serve as a basis for this future research.

The main limitations of this study pertain to the reliance on remotely-sensed data. While the data are relatively fine resolution (30-m x 30-m), interpretation of the data was based on aerial photography from a single instance in time, and environmental conditions at that time may not have accounted for delineation of the full coverage of SAV. Also important, and previously alluded to, is the fact that there are periods of lag between datasets and the time of analysis, as new data interpretation and analysis requires new aerial imagery to be flown, edited, and processed. Another major limitation in this study is the lack of reliable, fine-resolution bathymetry data for the HRE, and while some HR bathymetry data do exist, they are relatively inaccurate in the shallow water near shore.

FURTHER RESEARCH

Continued research and monitoring are key to further understanding and protecting the HRE. Replicating this study with new datasets will be extremely important to confirm that the pattern of SAV recovery has continued on to pre-2011 levels and coverages, or if recovery has since stalled or even reverted to SAV loss. Further research involving Hudson River sediment flux and improved bathymetric data of the river's shallows and shorelines would aid tremendously, as would additional research exploring the mechanisms and finer-scale population dynamics of SAV recovery following large or total loss of biomass.

To help improve understanding of sediment flux, research involving upstream land use and land cover at a tributary watershed scale would be valuable. Analysis of land-use decisions and their impact on flooding, stormwater runoff, erosion, and nutrient and sediment loading can help to inform proper watershed management, improve water quality, and reduce sedimentation downstream.

Understanding the spatial patterns of SAV loss and recovery are indeed useful, but further research into the impacts of these changes on fish and wildlife populations and interactions, as well as impacts on long-term water quality trends are paramount. As SAV functions as a critical component in the Hudson River food web, studies examining the stability of fish and other wildlife populations as a result of SAV recovery would help to highlight the importance of this work and might help to secure more funding for this kind of research.

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