Eelgrass loss over time in Duxbury, Kingston, and Plymouth Bays, Massachusetts

Final Report

By

Massachusetts Division of Marine Fisheries

Submitted to

Massachusetts Bays Program

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May 9, 2016

Introduction

The Massachusetts Division of Marine Fisheries (DMF) assessed eelgrass trends in Duxbury, Kingston, and Plymouth Bays (DKP) from 1951 to present. The Massachusetts Department of Environmental Protection's (DEP) Eelgrass Mapping Program mapped eelgrass extent in the Bays using aerial photos from 1951, 1995, 2001, 2006 and 2012. These maps suggested a 45% loss over the time period studied by DEP. In 2014, a DMF eelgrass biologist received a complaint from a constituent that eelgrass was disappearing in the embayment. DMF used aerial photography collected by USGS in the summer of 2013 and acoustic data collected in the summer of 2014 to determine that eelgrass was no longer present in several areas mapped by DEP in 2012. In order to better understand changes in DKP's eelgrass meadows, this project performed higher resolution photo interpretation and recalculated eelgrass loss calculations.

Seagrass loss is a global phenomenon (Orth et al 2006, Short et al 2006, Short et al 2014) and often is correlated to habitat degradation, climate change, and direct physical impact. In Massachusetts, large declines of eelgrass extent in coastal salt ponds and estuaries on Cape Cod are thought to be related to the eutrophication of those water bodies (Costa et al 1992). DKP is similarly thought to be undergoing eutrophication (Howes and Samimy 2005). Eutrophication can result in increased decreased light penetration due to phytoplankton blooms and higher levels of sulfide in the sediment due to less oxygen; both of these effects are detrimental to eelgrass. However, eelgrass has also died back in parts of DKP that are very well-flushed and considered nitrogen limited based on inorganic N:P of <<16 (Howes and Samimy 2005). Also, the loss of large meadows over one or two seasons was cause for alarm. Since understanding the causative factors of loss are critical for determining management actions, specifically if restoration is possible, this project started to consolidate records of variables that could be potential causative factors for eelgrass loss.

The specific objectives of this project are to:

1. Calculate eelgrass areal extent in DEP aerial photography from all study years at a scale of 1:1,000 with at least two patchiness (density) classes.
2. Identify which meadows, if any, were no longer present in 2014 based on acoustic analyses.
3. Explore potential causes for the eelgrass loss by consolidating available records to determine if a) turbidity has increased; b) extent of ice (if known) has changed; c) average wind speed has increased; d) average wind direction has changed; e) aquaculture activities are coincident with eelgrass meadows; and f) other biotic and abiotic factors play a role such as wasting disease, green crabs, and silt-producing activities.
4. Make recommendations to prevent additional loss and explore potential for eelgrass restoration.
5. Write a DMF Technical Report which will be available online along with relevant project data and shapefiles.
6. Present at a local stakeholder meeting and at the 2016 EPA Eelgrass Summit.

An additional objective of the project is to provide access to the original imagery and data streams relevant to eelgrass growth and decline for future analyses. This report is the final report and is being submitted with the following files: . Online access to project data and shapefiles and the DMF Technical Report is expected within six months.

Background

Eelgrass

Zostera marina L. (eelgrass) is a submerged marine flowering plant, is primarily perennial but some annual and mixed annual-perennial varieties exist (Jarvis and Moore 2015). Rhizomes, which are subterranean stems aiding in propagation and food storage, grow horizontally in the sediment branching at nodes. In *Z. marina* two groups of roots extend from the bottom of each rhizome node and the shoots are terminal (located at the end node of a rhizome). Terrestrial plants that grow similarly include bamboo, rhubarb, and asparagus. During the summer growing season, new leaf growth is initiated every 10-14 days. Expansion of the meadow edge has been documented in the range of 12.5 to 16 cm/yr (Neckles et al 2005, Olesen and Sand-Jensen 1994). The leaves range in size from 6 inches to 5 feet in height and persist for about 1 month before being shed from the parent plant. *Z. marina* needs approximately 15-30% of the light available at the water's surface for photosynthesis to occur (Dennison et al 1993). Other marine primary producers such as algae can grow at light levels of only 1% of surface light (Kemp et al 2004, Zimmerman et al 1997). The primary nutrient uptake is through the roots, but leaves can also absorb nutrients from the water column.

At the onset of favorable temperature and light conditions in the spring, eelgrass grows rapidly starting from seeds that germinated over the fall and winter or vegetatively from rhizomes. High summer temperatures slow growth but growth sometimes resumes in the fall as temperatures decrease. In the first growing season, a seedling can produce a primary shoot and 2-12 lateral shoots (secondary shoots that form on the rhizome when it branches). In the winter, growth is slow and only short leaves remain in most meadows. In the second growing season, the primary shoot differentiates into a reproductive shoot and flower. The reproductive shoots detach and float for a month or more (Källström et al 2008) before the seeds sink to the bottom and get buried in the sediment. The reproductive shoot dies in the process, but seed "rafting" on the buoyant shoot can disperse seeds as far as 150 km (Källström et al 2008). Individual shoots do not live more than two years. Rhizomes can persist for years, branching and creating new shoots. Researchers have estimated the age of a *Z. marina* meadow at more than 1,000 years old (Reusch et al 1999), a *Lomatia tasmanica* meadow at 43,000 years old (Lynch et al 1998), and a *Posidonia oceanica* meadow at 200,000 years old (Arnaud-Haond et al 2012).

Z. marina is broadly distributed in the northern hemisphere. It is found on both coasts of the United States. On the Pacific coast it ranges as far south as the Baja peninsula and as far north as northern Alaska. On the Atlantic coast it ranges from North Carolina to Canada. DKP is near the middle of the geographic range for *Z. marina*. The optimal growth temperature for temperate seagrass species ranges from 11.5 to 26°C (53-79°F) and the optimum temperature for eelgrass is 15.3°C ± 1.6 (60°F) (Lee et al 2007). Abe et al (2008) reported that the optimal temperature for seed germination is 10-15°C (50-59°F), while that of seedling growth is 20-25°C (68-77°F). Eelgrass mortality can occur in sustained temperatures above 25°C (77°F) (Greve et al 2003, Reusch et al 2005). Eelgrass needs more light as temperature increases (Ewers 2013), and photosynthesis and respiration rates increase with increased temperature (Lee et al 2007). Because respiration responds more strongly to temperature increases, at certain temperature increases productivity declines (Marsh et al 1986).

Z. marina has a minimal light requirement between 18.2 and 29.4% of surface light in measurements taken globally, with 18.6% measured in Woods Hole, MA (Dennison et al 1993). It needs at least 35% to avoid suffering light-limiting morphological impacts such as reductions to below-ground carbon storage capacity (Ochieng et al 2010). Any factors that decrease water clarity, including phytoplankton blooms, suspended sediments, cloudy days, smog, and epiphytic coverage on eelgrass blades could have a detrimental effect on eelgrass. Light availability is the primary vulnerability consistently identified in the eelgrass literature. Water clarity is closely correlated with the depth distribution of eelgrass; in less turbid waters eelgrass grows to greater water depths. Light levels are not typically measured with sufficient temporal or spatial resolution to truly understand the impact acute and chronic light limitation may have on the distribution of eelgrass. A month-long turbidity event was shown to cause die-off of an eelgrass bed in Chesapeake Bay (Moore et al 1997), illustrating the potential sensitivity of eelgrass to acute events. Moore et al (1996) reported eelgrass loss when total suspended sediment (TSS) was 15-40 mg/L, Gallegos and Kenworthy (1996) reported no eelgrass deeper than 1 meter water depth if TSS >15 mg/L, and Kemp et al (1983) reported no eelgrass growth at light attenuation coefficient >2/m.

Studies have also linked eelgrass loss to nutrient loading, since nutrient fertilization increases algal and epiphytic growth (Twilley et al 1985). For example, Bohrer et al (1995) reported no eelgrass with N loading 39-45 gN/m2/yr. Latimer and Rego (2010) reviewed studies on nitrogen and seagrass throughout New England and found nitrogen loading in excess of 50 kg/ha/yr has a significantly deleterious effect on eelgrass, and eelgrass ceased to exist where loading was at least 100 kg/ha/yr.

Eelgrass is no longer used or harvested commercially. Historically, eelgrass was valued as house insulation in the North Atlantic region due to its high silicon content (Moe 2014). Eelgrass harvesting was a thriving commercial industry for nearly 50 years until the advent of synthetic insulation products (Wyllie-Echeverria and Cox 1999). Dead or uprooted, floating eelgrass was harvested along the shore and on walls designed to intercept dead eelgrass as it floated to shore (Moe 2014); live plants were not cut or harvested. Local gardening websites discuss the modern use of dead eelgrass collected from the beach as mulch and compost material (e.g. GardenWeb.com).

Duxbury, Kingston, and Plymouth Bays

The DKP embayment is defined as three sub-embayments based on town boundaries. DKP is bound on its seaward (easterly) extent by two barrier beaches: Duxbury Beach/Saquish Neck to the north and Plymouth's Long Beach to the south (Fig 1). Clarks Island is located north of Saquish Neck and both are officially part of the town of Plymouth, despite their proximity to Duxbury. The embayment has a semidiurnal tide with an amplitude of 3.2 m. The inlet is approximately one mile wide and maintains itself naturally through abundant tidal flow.

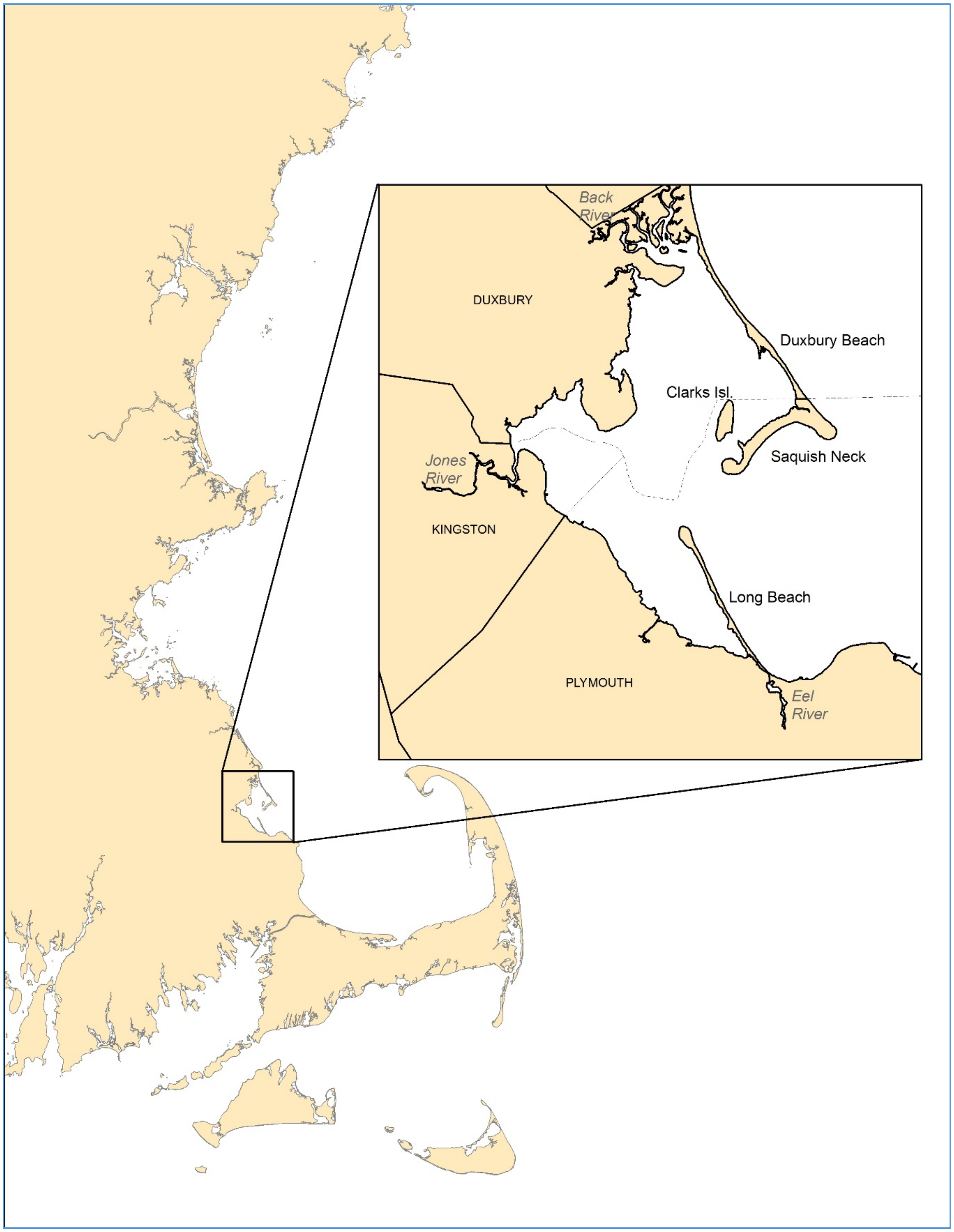

Figure 1. Map of DKP Embayment

Sixty-six percent of the water volume of the bay is exchanged in a tidal cycle (Iwanowicz et al 1974). The basic geomorphology of the bay is large intertidal flats bifurcated by tidal channels. Three rivers drain into the estuary: Eel River, Plymouth; Jones River, Kingston; and Back River, Duxbury. The entire embayment is listed as impaired by the DEP in the Integrated List of Waters (305(b)/303(d)) and has a TMDL for pathogenic bacteria (MADEP 2014). There are 85 sub-watersheds delineated within the overall DKP watershed (Eichner et al 2013).

In terms of potential nitrogen sources into DKP, Eichner et al (2013) found that there are 11 facilities with state Groundwater Discharge Permits within the DKP watershed, including wastewater treatment facilities in all three towns and municipal facilities in Kingston and Plymouth. Residential properties make up 72% of all parcels (35% of total area) within the watershed, and many utilize septic systems. The watershed also contains seven landfills, eight golf courses, 995 ac of cranberry bogs and 241 ac of agricultural fields.

DEP eelgrass polygons show that eelgrass in the DKP embayment has been decreasing over time (Fig 2). In 1951, an estimated 3440 ac existed. This areal extent is based on photo-interpretation of black and white imagery from the Massachusetts Department of Transportation (DOT); due to the reported poor quality of the imagery, the resulting eelgrass extent estimates should be considered approximate (Charles Costello pers comm). In 1995, an estimated 2249 ac existed, so between 1951 and 1995 as much as 35% of the eelgrass was lost. Loss continued through 2006. Between 2006 and 2012 minor increases in eelgrass extent occurred. Based on the acreage calculated by DEP, the overall loss from 1951 to 2012 was 44.4%, and the loss from 1995 to 2012 was 15%.

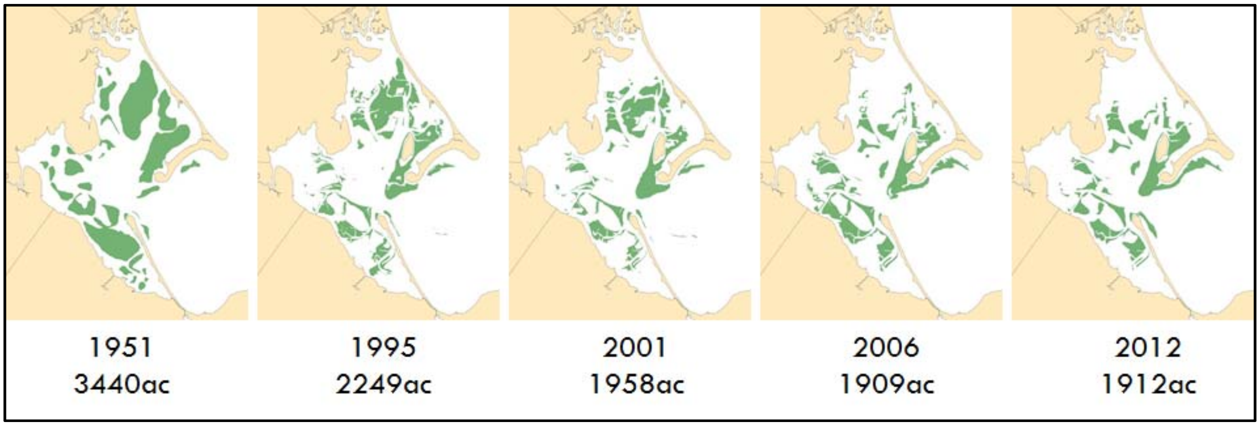

Figure 2. DEP Eelgrass Mapping Program polygons and calculated acreage between 1951 and 2012

Methods

In order to generate maps of eelgrass spatial extent at multiple time steps, this project utilized photos collected by the DEP Eelgrass Mapping Project, photos collected by the USGS, and photos collected by the Provincetown Center for Coastal Studies and DMF. Photos publicly available on Google Earth and Bing Maps were reviewed and used when additional context was needed. The imagery was augmented by acoustic data and groundtruthing data. In order to consider potentially causative factors of eelgrass decline, stakeholder input was solicited and relevant biotic and abiotic variable datasets were analyzed.

Photo Acquisition and Interpretation

DEP DEP Photos and Groundtruthing

DEP's Eelgrass Mapping Project has been collecting aerial photographs and field-groundtruthing data since 1995 in an effort to characterize gross eelgrass trends statewide. DEP standarizes image collection to ensure maximum eelgrass visibility, employs a standard photo-interpretation technique to identify eelgrass meadows, and collects groundtruthing data with underwater video surveys (Costello and Kenworthy 2011). In addition, DEP utilized DOT photos in an effort to establish an eelgrass baseline for 1951. The 1951 photos were not taken using the same specifications as DEP's, but were the earliest and best images available at that time.

Each set of images had a different storage protocol based on the technologies of the time. The 1951 photos were no longer available from either the DEP Eelgrass Program or the DOT Photo Archive. The 1995 imagery was available from DEP as a set of hard copy prints and negatives. Since the hard copy prints were high quality, we scanned them to TIFF images using a high resolution scanner and we did not request the negatives. We georeferenced the 1995 images in ArcGIS 10.2 using the Georeference toolkit using 2013 USGS aerial images for ground control points. The 2001 images were received as un-georeferenced negatives at the conclusion of this project; they will be analyzed at a future date. The 2006 and 2012 imagery were provided as georeferenced digital files (multiple GeoTIFFs (2006) and a single geodatabase (2012)) via pocket drive. DEP also provided two shapefiles of their field verification point data collected from 1994 to 2013.

CCS Photos

The Center for Coastal Studies (CCS) in Provincetown, MA has conducted aerial photo surveys up to four times a year since 2007 to collect eelgrass imagery over Cape Cod Bay embayments, including DKP. The flights were donated by LightHawk, a volunteer flight service focused on conservation projects. These flights are opportunistic and are typically flown on sunny, calm days. Images are taken with a variety of cameras and were not georeferenced. Images from 2007-2015 were provided as digital files via pocket drive. The varied angle and height of the CCS images provided supplemental perspective of questionable areas seen in DEP images and also helped qualitatively assess specific meadows between DEP mapping years.

DMF Photos

DMF conducted aerial photo surveys of DKP and several Buzzards Bay embayments in September 2014 in a partnership with LightHawk. Like the CCS imagery, these flights and the cameras used on the flights do not have standard data collection protocols and the images were not georeferenced.

Photo analysis

Originally we intended to re-delineate the eelgrass meadows at each time step. However, after some experimentation we were reluctant to revise DEP's eelgrass polygons since we were unable to groundtruth our photo-interpretation of each time step and the potential to mischaracterize areas was high. For example, areas that appeared bare in DEP aerials were often in fact vegetated (either very short or very sparse grass) based on DEP groundtruth data, and some areas that appeared heavily vegetated were actually comprised of algae, aquaculture operations, or rocks (Fig 3).

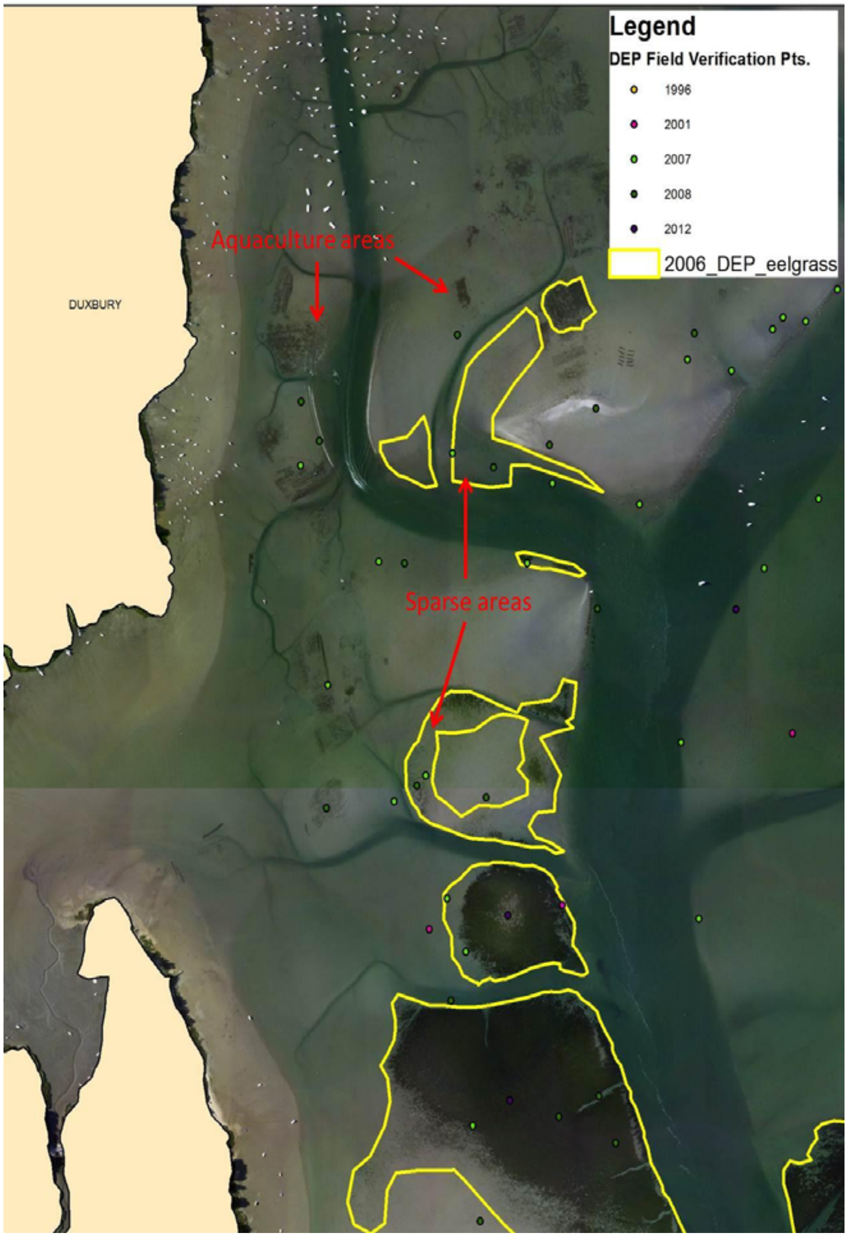

Figure 3. 2006 DEP aerial photograph of western Duxbury Bay with 2006 DEP eelgrass polygon and DEP field verification points. Aquaculture and sparse areas are indicated in red, demonstrating the need for groundtruthing over questionable signatures

Instead of redelineating the eelgrass polygons, we used the polygons as drawn by DEP combined with DMF, CCS, and Google Earth and Bing images and the groundtruthing data to classify the eelgrass polygons in ArcGIS 10.2 into "Dense," "Sparse," "Questionable Mapped," and "Questionable Unmapped" categories as follows:

- "Dense" polygon was drawn around continuous meadows and large patches that appeared to have greater than 50% aerial coverage within the bed (when comparing dark, vegetated areas to sandy areas).

- The “Sparse” polygon was drawn in portions of the DEP polygons that appeared to have less than 50% aerial coverage and, more often, areas that appeared void of vegetation surrounding dense areas.
- If entire polygons seemed questionable based on field point data or other resources, we mapped them as “Questionable Mapped”.
- If there were areas that appeared vegetated, lacked field-verification points, and were not mapped by DEP we mapped them as “Questionable Unmapped”.

With a distinct bed in view, we first determined if the polygon accurately portrayed the dark vegetated areas observed in the underlying aerial image. If presence or absence was questionable, field verification point data were queried to help understand the conditions in a bed. If field verification data were not available for a questionable area, a best educated guess was made to categorize the area utilizing information about the surroundings, the mapping history of the area in question, and other available aerial images as mentioned above. DEP’s field verification point data occasionally affected our polygon if information such as algae, rock presence, or notes about the eelgrass density were present. However, there were several instances where the field verification point data did not accurately reflect DEP’s drawn polygons or underlying conditions as seen in the imagery.

Within each polygon we delineated Dense and Sparse eelgrass and assessed the surroundings for Questionable Mapped and Questionable Unmapped areas. A new shapefile with the classified eelgrass polygons was produced for each year. Photo-interpretation was performed all years for which we were able to obtain imagery prior to the completion of the project: 1995, 2006 and 2012.

DMF Acoustic Mapping

In the late summer and fall of 2014 we conducted acoustic mapping surveys on the majority of the eelgrass meadows in DKP mapped by DEP in 2012. Two separate acoustic methods were used: a Biosonics DT-X dual beam system and a Humminbird 698SI sidescan system (Fig 4). The Biosonics DT-X digital echosounder has a 420-kHz, 6-degree transducer. It was pole mounted on a 20-foot skiff with a handheld GPS antenna attached directly above the transducer. The Biosonics was used on August 12, 2014 to survey six eelgrass polygons mapped by DEP in 2012 (Fig 5a). The Humminbird transducer includes a 455 kHz sidescan sonar and an 83/200 kHz dual beam downward-looking bathymetric sonar. The sidescan transducer was mounted at the stern of a jetski. The GPS is integrated into the sidescan processing unit located at the jet ski steering station 4 feet away from the transducer. The Humminbird was used on October 9, October 30, and November 4, 2014 to survey the six polygons surveyed with the Biosonics system and 22 additional eelgrass polygons mapped by DEP in 2012 (Fig 5b). The Biosonics data were processed with Visual Habitat into a point layer of percent cover of eelgrass. Sidescan sonar data were processed for water column removal and slant range and

Figure 4. Humminbird (left) and Biosonics (right) acoustic survey equipment.

beam angle corrections with SonarTRX Pro and then were exported as GeoTIFF mosaics. In the sidescan sonar mosaic, eelgrass has a characteristic pattern which can be used to delineate eelgrass spatial extent (Fig 6).

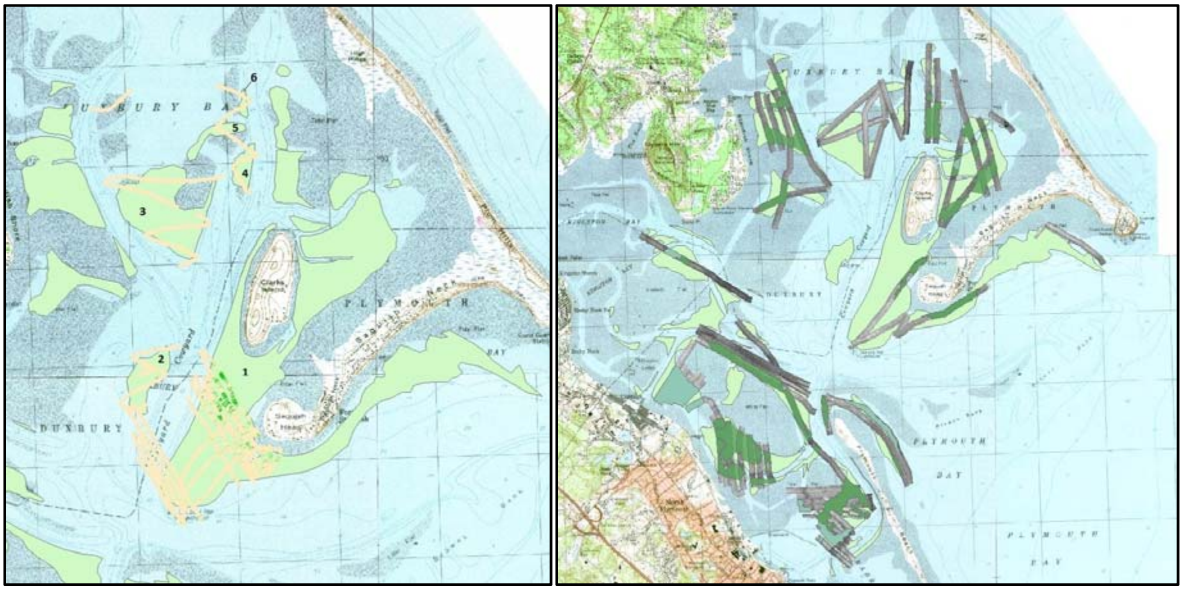

Figure 5. Biosonics (left) and Humminbird (right) acoustic survey results. Areas shown in dark green represent eelgrass detected by survey equipment. Light green underlying polygon is 2012 DEP eelgrass layer.

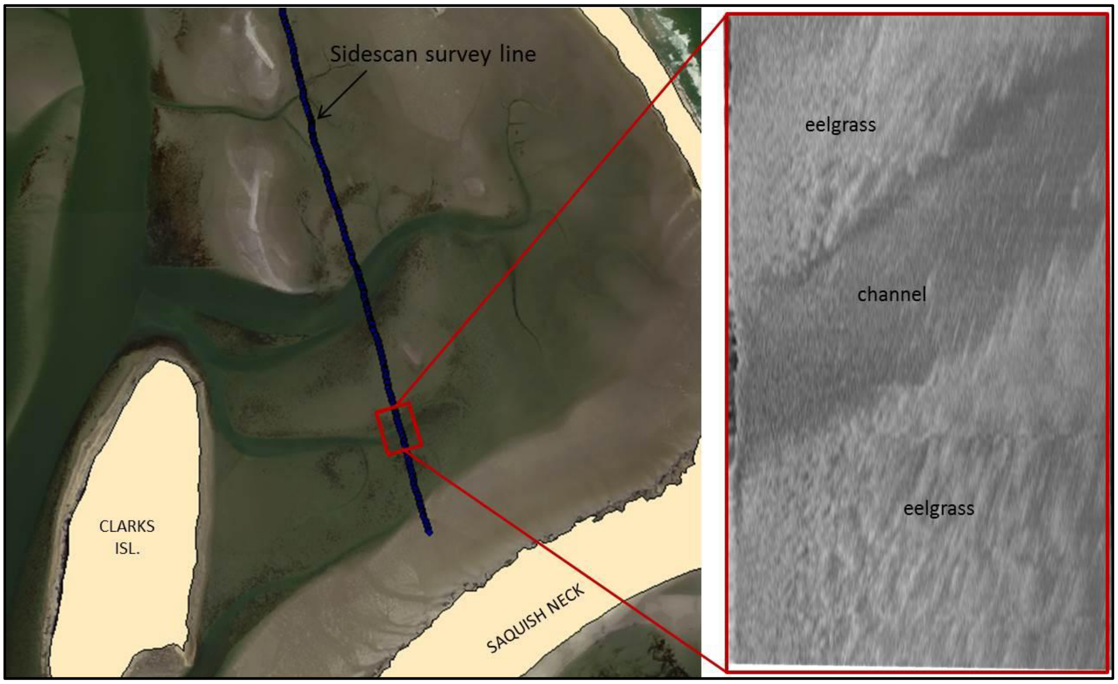

Figure 6. Example of survey location and sidescan image output in eastern Duxbury Bay

Groundtruthing was done by looking over the side of the survey vessel. This method was utilized in all shallow survey areas, comprising the majority of the survey, but was problematic in deeper water along channels and near the mouth of the embayment. The small survey vessel (jetski) with limited deck space precluded the use of traditional reeled submersible cameras. To address the lack of deep water groundtruthing, the survey crew attempted to observe eelgrass from the surface in any adjacent shallow areas surrounding deeper areas.

Since the acoustic mapping only covered a portion of the embayment, USGS aerial photography from 2013 was used to augment the acoustic mapping and create a whole-embayment estimate of eelgrass extent. Imagery from the High Resolution Orthoimagery (HRO) program was downloaded from USGS EarthExplorer (http://earthexplorer.usgs.gov/). Images have a resolution of 1-meter or better and are in a Georeferenced Tagged Image File Format (GeoTIFF). This imagery was collected primarily for assessing changing conditions on land; flights did not target low tide conditions which are optimal for eelgrass photo-interpretation.

Using the data from the acoustic surveys, groundtruthing, and 2013 USGS aerial imagery we created polygons of eelgrass meadows in ArcGIS 10.2. Some delineation decisions were guided by previous DEP mapping. First, existing DEP meadows were redelineated using the Biosonics data. If very few or no detections were found in a previously mapped eelgrass meadow, the meadow was removed. Next, existing DEP meadows were redelineated using sidescan sonar data. For areas beyond the footprint of sidescan or Biosonic surveys, photo-interpretation of the USGS imagery was used to modify existing DEP eelgrass delineations or remove meadows no longer clear in the aerial imagery. The area of all redelineated polygons was calculated to provide the 2013/14 estimated acreage of eelgrass. Density categories were not delineated as part of this estimate.

Embayment-wide estimates of areal extent of eelgrass were used to calculate the acreage loss rate per year within each time period (e.g. 1951-1995, 1995-2006, 2006-2012, and 2012-2013/14). The median, average, and most recent loss rates were used to estimate a time period when all eelgrass might be gone in DKP.

Stakeholder Surveys

Throughout this study, stakeholders were engaged to identify datasets and provide anecdotal evidence of activities and trends in DKP. Stakeholders were identified by their position within a town (e.g. harbormaster, shellfish warden, natural resource office), by their involvement on local water quality associations (e.g. North South River Watershed Association, Jones River Watershed Association), their commercial fishing activities in DKP, or as recommended by other stakeholders as experts. Informal survey methodology was used and consisted of several phone interviews or in-person interviews with individual experts. One in-person stakeholder meeting was held on February 23, 2016 at Duxbury Town Hall to provide mapping results and have a group discussion regarding potential causative factors (Appendix). Individual stakeholder feedback is included as pertinent to the methods and results for Biotic Variables and Abiotic Variables, below.

Biotic Variables

Wasting disease

Wasting disease is a pathogenic infection thought to be caused by the slime mold *Labyrinthula zosterae* and responsible for the die-off of up to 90% of the seagrass on the eastern seaboard in the 1930’s. Locally, Dr. Randall Hughes at Northeastern University is researching eelgrass genetics and wasting disease in MA waters. She was interviewed and local stakeholders who have been observing uprooted eelgrass plants were questioned to determine if we have any current information about wasting disease.

Predation

Several bird species directly consume eelgrass and numerous other organisms feed on its epiphytes, including *Carcinus maenus* (green crabs). Local stakeholders were interviewed for anecdotal observations. DMF staff involved in trapping green crabs north of Boston were also interviewed. The impact of bird predation on eelgrass was outside of the scope of this study.

Abiotic Variables

Temperature

Several regional temperature analyses are available for New England. To understand regional temperature trends, we summarized the Mass EEA Climate Adaptation Report which references peer reviewed literature on air and sea surface temperature analyses (MAEEA 2011). We also reviewed the Blue Hill Observatory reports which cover air temperature data from 1851-2014 at a station 30 miles from DKP (BHO 2015).

The local temperature record was compared to the regional analyses by analyzing datasets with stations within or proximal to DKP (Fig 7):

- DMF's Climate Change database. Cape Cod Bay Rocky Point station, also called "DMF Lobster," is just outside DKP with year-round continuous monitoring every two hours using a Hobo Pendant at the seafloor at 45 feet water depth. We analyzed seafloor temperature from 1989-2012.
- The Provincetown Center for Coastal Studies (CCS) Cape Cod Bay Monitoring Program. This program measures temperature in-situ at 11 fixed stations in DKP with a YSI handheld sonde bi-weekly between April and October. We analyzed surface (about 0.5 m) water temperature from 2006-2014 at 6 stations with the longest records of continuous measurements. Duplicate values were removed[1].
- Massachusetts Bay buoy. The Mass Bay buoy, NERACOOS A01, is owned and operated by Dr. Neal Pettigrew at the University of Maine. These data are available through the NERACOOS website. (http://www.neracoos.org/datatools). We analyzed monthly average surface (1 m depth) water temperature from 2003-2014.
- Boston Harbor buoy. The Boston Harbor buoy, NOAA 44013, is owned and operated by the National Data Buoy Center. These data are available through the NERACOOS website. (http://www.neracoos.org/datatools). We analyzed monthly average surface (1 m depth) water temperature from 2003-2014.

The summertime (June 1- August 31) mean of the CCS, DMF, and NERACOOS data was calculated for each year. Only summer data were utilized since summer was the time period with consistently available data. A linear regression through time was applied to the summertime means for each station and for the embayment average. A t-test was used to determine if there was a statistically significant

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[1] Duplicates were deleted. At station C3, between May 2007 and June 2008, 11 duplicates had different temperature, salinity, and DO. All other measured values were the same. The 2nd set of values were deleted as duplicates. At station P3, on 10/4/2009, had an identical set of duplicate values for all but ammonium and orthophosphate. The 2nd set of values were deleted as duplicates.

linear relationship. All graphing and statistics were done in MSExcel 2007. This is similar to the method used to analyze temperature trends in Buzzards Bay with volunteer monitoring data (Rheuban et al 2016).

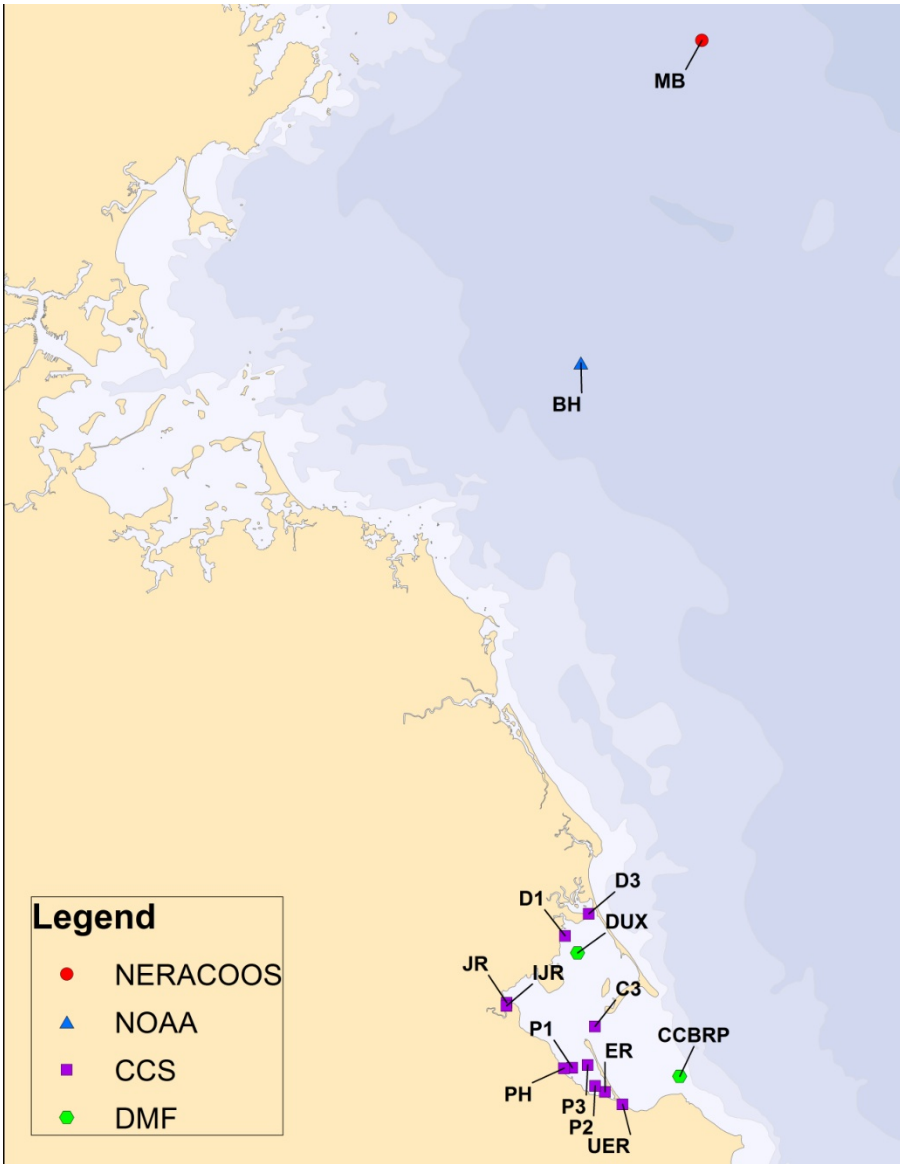

Figure 7. Monitoring stations for NEARCOOS (red), NOAA (blue), Center for Coastal Studies (purple), and DMF (green). Note that station "JR" is referred to as "29Jones" in this report.

Other datasets were discovered, but they were not analyzed since they were available only for short time periods or the data could not be analyzed for time series due to the data collection protocol.

- DMF Shellfish Sanitation Database. Thirty-five sites in DKP are sampled for surface water temperature. Sampling is not continuous and does not coincide with a specific tide stage. Continuous (seasonal) temperature data is available at one site but the dataset is too short for time series analysis.

- DEP Water Quality Study in 2003-2004 collected temperature data using a YSI sonde in 2-week intervals from June to mid-September in 2003 and 2004 (Howes and Samimy 2005). The dataset is too short for time series analysis.
- Cape Cod Cooperative Extension initiated continuous water temperature monitoring from March-November (http://www.capecodextension.org/marine-programs/water-quality-monitoring-2/). Data was available for 2013 and 2014. The dataset is too short for time series analysis.

Light availability

Several regional studies and datasets were available to understand regional light availability trends. we summarized the Mass EEA Climate Adaptation Report which references peer reviewed literature on precipitation and streamflow data analyses (MAEEA 2011). Increased precipitation and streamflow can increase turbidity in receiving waters due to runoff of sediment. We also reviewed the Blue Hill Observatory reports which cover precipitation and bright sunshine days from 1886-2015 at a station 30 miles from DKP (BHO 2014) to gain an understanding of regional trends.

To ascertain if there is enough light for eelgrass to survive and grow, the most direct measurement is the amount of photosynthetically active radiation (PAR) in the water. The Duxbury Bay Management Committee owns a LiCor PAR sensor, but measurements are not continuous. There were no other long-term PAR measurements in DKP, so several datasets related to light availability were explored to analyze local light conditions:

- Chlorophyll *a* from the Provincetown Center for Coastal Studies (CCS) Cape Cod Bay Monitoring Program. Chlorophyll *a* is measured in a state-certified lab using a Turner Trilogy Fluorometer (following EPA Method 445.0) on water samples collected at 11 fixed stations in DKP bi-weekly between April and October. We analyzed surface (about 0.5 m) log10 transformed chlorophyll *a* data from 2007-2014 at 6 stations with the longest records of continuous measurements. Duplicate values were removed. Using log10 transformation is a standard method for chlorophyll *a* data (Campbell 1995).
- Total Nitrogen (TN) from the Provincetown Center for Coastal Studies (CCS) Cape Cod Bay Monitoring Program. TN is measured in a state-certified lab using a persulfate digestion (Oviatt and Hindle 1994) on water samples collected at 11 fixed stations in DKP bi-weekly between April and October. We analyzed surface (about 0.5 m) TN data from 2007-2014 at 6 stations with the longest records of continuous measurements. Duplicate values were removed.
- Turbidity from the Provincetown Center for Coastal Studies (CCS) Cape Cod Bay Monitoring Program. Turbidity is measured in a state-certified lab with a nephelometer on water samples collected at 11 fixed stations in DKP bi-weekly between April and October. We analyzed surface (about 0.5 m) nephelometer data from 2007-2014 at 6 stations with the longest records of continuous measurements. Duplicate values were removed[2].
- Stream gage measurements collected by the USGS National Water Information Service at the Jones River (http://waterdata.usgs.gov/nwis/sw) from 1967-2014.

The summertime (June 1- August 31) mean of the CCS data was calculated for each year. Only summer data was utilized since it was the most available time period for the monitoring data. In the case of

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[2] See note 1. On 5/14/2014 there were very high measurements of turbidity. These were not removed.

streamflow, the annual average of the water year (Oct 1-Sept 30) was used. As was done for temperature, a linear regression through time was applied to the means for each station and for the embayment average. A t-test was used to determine if there was a statistically significant linear relationship. All graphing and statistics were done in MSExcel 2007.

Physical impact

Direct physical impact to eelgrass plants and rhizomes can occur as a result of alterations in wind speed and direction. A regional characterization of wind speed and direction was used to set the regional context Knorr (2013).

A variety of other more localized activities can result in direct and indirect physical impacts. We assessed information on several of the factors that could result in direct physical impact to eelgrass as follows.

- Aquaculture current spatial extent. We assessed the area of overlap between the 2013/2014 eelgrass map and an aquaculture GIS layer of license site boundaries generated by DMF in 2014.
- Aquaculture spatial extent over time. Neither DMF nor the US Army Corps of Engineers had accessible databases of license site boundaries over time.
- Aquaculture growth was assessed using shellfish landings from DKP as reported to the Standard Atlantic Fisheries Information System (SAFIS).
- Dredging location, frequency, and time period. Contacted Mass DEP, US Army Corps of Engineers, and Conservation Commissions in Duxbury, Plymouth, and Kingston. Discussed with stakeholders. Anecdotal information via stakeholders and Conservation Commissions was all that was readily available.
- Boating. Northeast ocean data portal, 2012 Northeast Recreational Boater Survey, conducted by SeaPlan and the Northeast Regional Ocean Council (NROC) (http://www.northeastoceandata.org/data-explorer/?recreation). Boating data covers 2012. We also conducted a visual assessment of overlap of eelgrass with boating routes, marinas, mooring fields and prop scars in USGS 2013 aerial photos.
- Coastal construction. DMF Technical Review database was queried for dredging and other major disturbances. The number of projects by town and the project type was summarized.
- Ice. No source of ice data (extent, timing) was identified. Interviews with harbormasters, the stakeholders, and US Coast Guard to document anecdotal information were held.
- Wind speed and direction (local). Mass Bay and Boston Harbor buoy data available through NERACOOS website (http://www.neracoos.org/datatools) for 2003-2014. Wind direction is reported relative to true north. Linear regression of annual average in MSExcel 2007.
- Peak discharge measurements collected by the USGS National Water Information Service at the Jones River (http://waterdata.usgs.gov/nwis/sw) from 1967-2014. Linear regression of peak annual discharge rate. Used water year (Oct 1-Sep 30) in MSExcel 2007.

At the conclusion of this study we identified local wind speed and direction measurements that are being recorded by the Duxbury Bay Maritime School via Windsurf (Chuck Leonard pers comm). These data were not available in time for this study, but could be pursued for future analysis.

Results

DEP Photos & DMF Acoustic Mapping

An embayment-wide decline in eelgrass was seen over the study period. The resulting acreages from photo-interpretation of DEP's 1995, 2006 and 2012 aerials are shown in Table 1. The larger proportion of Questionable Unmapped areas in 2006 was due to a large bed off the eastern shore of Plymouth Beach that was missed by DEP in 2006 but was mapped in other years. The remaining Questionable Mapped and Unmapped areas were generally small in size.

Table 1. Results of photo-interpretation in eelgrass acreage

Eelgrass extent, acres	**1995**	**2006**	**2012**	**2013/14**
Dense	1653	1537	946	
Sparse	598	345	945	
Questionable Mapped	7	28	22	
Questionable Unmapped	19	66	8	
DMF Total Estimate	2277	1976	1921	987
DEP Total Estimate	2249	1909	1912	

The area that experienced the greatest loss was the shallow upper Duxbury Bay area, especially between 1995 and 2006 (Fig 8). Throughout this area, depth is 1-2ft at Mean Low Water (MLW). Another notable loss occurred between 2012 and 2014 in an area south of Clarks Island. Throughout DKP, losses occurred in a variety of locales: inshore, offshore, shallow, deep, poorly-flushed, and well-flushed. Few gains were observed, but one includes a bed in the center of the embayment just west of Saquish Neck barrier beach between 1995 and 2006, as well as some growth in inner Kingston Bay in the same time period.

Trends in eelgrass density over time show that dense grass (≥50% coverage) is declining. In 1995, dense grass made up 72% of the total grass in the embayment. The proportion of dense grass remained similar in 2006, but by 2012 dense grass made up just 49% of the total. Between 1995 and 2012, 43% of the dense grass was lost. Meadows to the east and south of Clarks Island thinned out during the study period, as did smaller meadows in Kingston Bay and inner Plymouth Bay.

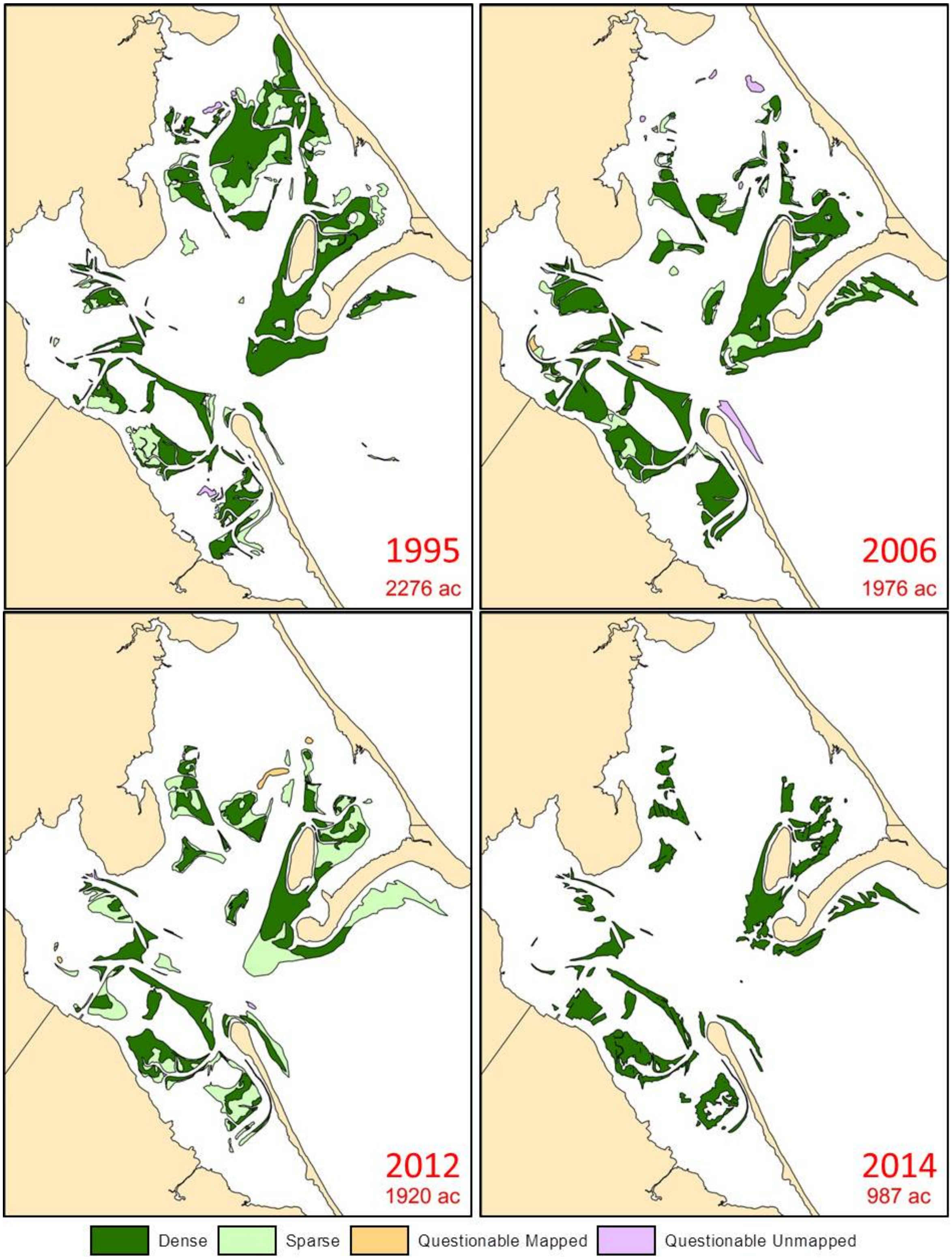

Figure 8. Results of photo-interpretation (1995, 2006 and 2012) and acoustic/photo-interpretation (2013/2014) in mapped polygons. In 2013/14 density classes were not assessed.

The acreage loss rate per year within each time period varies greatly (e.g. 1951-1995, 1995-2006, 2006-2012, and 2012-2013/14) (Table 2). The median, average, and most recent loss rates were used to estimate that all eelgrass might be gone in DKP as early as 2016 if the most recent loss rate is used or 2051 if the median loss rate is used (Table 3).

Table 2. Summary of acres lost

Time period	# years	Ac loss	% loss	Ac/yr
1951-1995	44	-1163	-34%	-26
1995-2006	11	-301	-13%	-27
2006-2012	6	-55	-3%	-9
2012-2013/14	2	-934	-49%	-467

Table 3. Projected total loss

	Loss rate (ac/yr)	# years for complete loss	Est. yr of complete loss
Median	-27	36.7	2051
Average	-132	7.4	2021
Most recent	-467	2.1	2016

The 1951 aerial photos were not accessible, and the 2001 raw hard copy images were provided to us at the end of this project. The photos from 1995 required scanning and georeferencing. The photos from 2006 and 2012 were available in georeferenced format. All photo acquisition was accomplished by request to DEP; no online photo downloads were available.

Biotic variables

Wasting disease

No recent or historic wasting disease monitoring data exist for DKP; most sources focus on New Hampshire and the north shore of MA (Dexter 1985, Short et al 1986). Local stakeholders have not specifically observed wasting disease, but did mention they see full, root-intact plants with brown leaves floating in clumps episodically during the season. It cannot be determined with confidence whether the leaves they observed were brown from the natural aging and sloughing cycle of the plants, from sun damage while floating, or from wasting disease. Stakeholders were sent wasting disease identification resources to help inform their observations going forward (Appendix).

Predators

No long-term observations or time series are available for green crabs and there are no quantified abundance measurements. Island Creek Oyster representatives reported that Duxbury Bay has a large population based on anecdotal evidence (Madison Hebert pers comm). The Town of Duxbury trapped crabs in the summer of 2015 and thinks the population has large fluctuations year to year (Joe Grady pers comm). The North South Rivers Watershed Association is planning to trap green crabs in salt marshes in 2016 (Sara Grady pers comm). Large population fluctuations have been observed in two years of trapping studies north of Boston in Essex Bay and Plum Island Sound (Peter Phippen pers comm) but longer time series are needed to better understand population trends. It is possible that extremely cold winters and ice events play a role in population control (Kelly Whitmore pers comm). DMF's harvest data collected from seafood dealers show a steady decline in statewide green crab harvest annually between 2012 (260,829 lbs) and 2015 (90,404 lbs). These numbers do not factor in effort, landings from recreational harvesters, or harvest for municipal bounty programs.

Datasets for other predators, such as waterfowl, were not analyzed.

Abiotic variables

Temperature

The Mass EEA Climate Adaptation Report cites peer reviewed studies that report air temperature has increased 1°C (1.8°F) and sea surface temperature has increased by 1.3°C (2.3°F) between 1970 and 2002 (MAEEA 2011). At the end of the century, air temperature is predicted to increase 3-5°C (5-10°F) and sea surface temperature is predicted to increase by 4°C (8°F) in the Gulf of Maine (MAEEA 2011, Frumhoff et al 2006). The Blue Hill Observatory, the longest running observatory in the United States, reports increases in average temperatures, decreases in the number of days with low minimum temperatures, later ice-in dates and earlier ice out dates for Houghton's Pond, and earlier dates for the first ripe blueberries (BHO 2015).

Data from stations in or near DKP were used to conduct a local-scale analysis of water temperature change. There is modest evidence that summertime water temperatures are getting warmer, but the linear model is not significant at any of the stations in DKP (Fig 9, Table 4). The temperature time series is relatively short (9 years). Temperature in DKP exceeded the upper end of the optimal range for eelgrass growth in several sampling events at stations D3 and 29Jones and in two sampling events at station D1 (Fig 10).

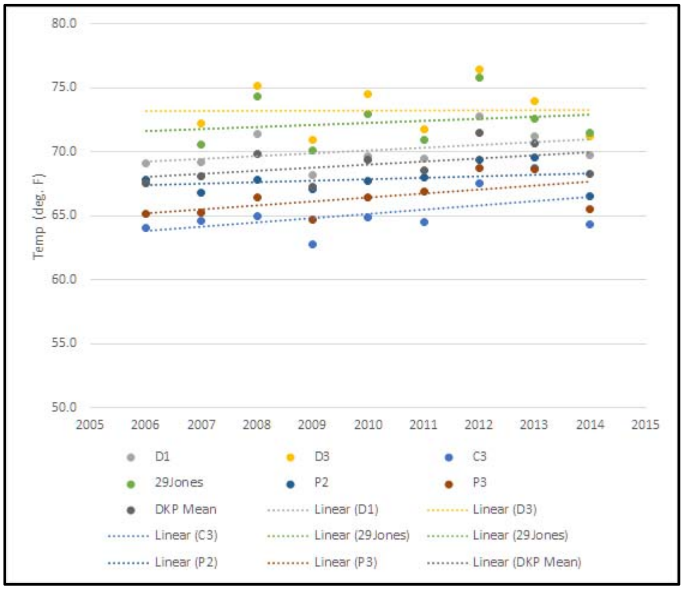

Figure 9. Mean summer temperatures at CCS stations

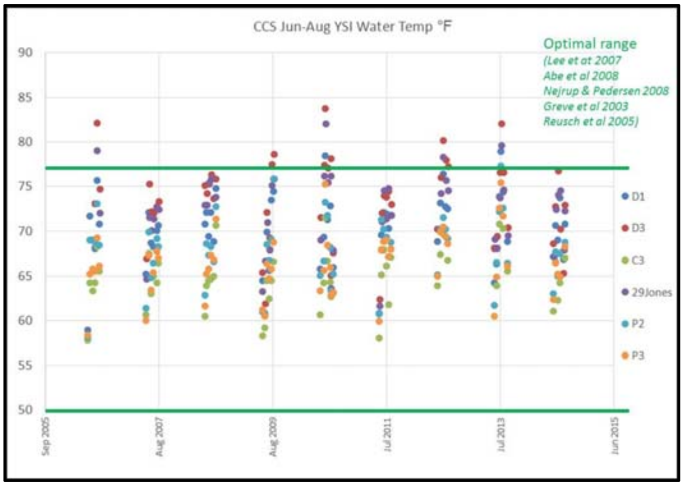

Figure 10. CCS summer water temperatures (°F) in DKP shown within and exceeding the optimal range for eelgrass.

At stations in Boston Harbor, Massachusetts Bay, and Cape Cod Bay, longer time series are available. All show temperature increases over time (Fig 11). The linear regression model is significant at the Boston Harbor station (p=0.03) (Table 4). Other studies have indicated that the number of days above a certain temperature may be highly relevant to the health and sustainability of local resources, such as the prevalence of lobster shell disease and mean number of days exceeding 20°C (Glenn and Pugh 2006).

Table 4. Summary of temperature statistics from Center for Coastal Studies, DMF, and NERACOOS datasets (significant regression shaded)

Summertime	Year	Year	max	min	mean	sd	n	dT/dt	r^2	p	Notes

mean temp	start	end									
D1	2006	2014	79.0	60.9	70.2	4.0	9	0.21	0.16	0.28	
D3	2007	2014	83.8	62.0	73.2	4.8	8	0.01	0.00	0.98	
C3	2006	2014	72.6	58.2	65.2	3.4	9	0.34	0.26	0.16	
29Jones	2007	2014	72.2	61.7	72.2	4.3	8	0.14	0.04	0.65	
P2	2006	2014	77.4	60.8	67.9	3.8	9	0.12	0.09	0.42	
P3	2006	2014	75.5	60.0	66.5	3.6	9	0.31	0.33	0.11	
DKP-all	2007	2014	71.5	67.3	69.2	1.4	8	0.2	0.12	0.40	
DMF lobster buoy	1989	2012	55.1	48.8	52	1.7	23	0.08	0.11	0.12	No data in 2010
Mass Bay buoy	2003	2014	65.1	61.1	63.2	1.1	12	0.12	0.13	0.24	
BH buoy	2003	2014	67.3	61.8	63.8	1.7	12	0.3	0.37	**0.03**	

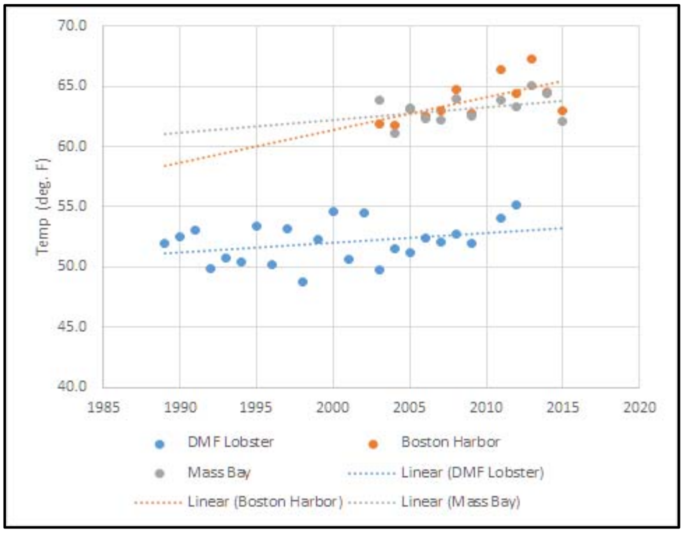

Figure 11. Mean summer temperatures at DMF and NERACOOS stations

Light availability

The Mass EEA Climate Adaptation Report summarizes peer reviewed studies that found that precipitation has increased about 10% over the past 50 years (MAEEA 2011). At the end of the century, winter precipitation is predicted to increase 12-30% and peak streamflow is predicted to occur earlier in spring by 11-13 days (MAEEA 2011). The Blue Hill Observatory measured no long-term apparent trend in annual mean bright sunshine days. Annual precipitation is increasing and the annual hours of heavy precipitation is increasing (BHO 2014, 2015). There have been no long-term trends in the amount of snowfall (BHO 2014) but it is predicted that more winter precipitation will be falling as rain (MAEEA 2011).

Data from stations in or near DKP were used to conduct a local-scale analysis of in-water light availability and assess other factors that could influence light availability in DKP. Chlorophyll *a*, Total Nitrogen (TN), and turbidity (NTU) were all highest at the two stations closest to rivers, 29Jones and D3 (Figure 12). The linear regressions are positive for chlorophyll *a* at all stations and the embayment average increase is significant at 90% significance level (p=0.06). Turbidity and TN do not exhibit significant linear trends. On June 29, 2010, four of six stations had record high TN concentrations (D1, C3, P2, and P3) and on August 12, 2010 station D3 had a record high TN concentration. As a result, station and embayment summertime means were high for 2010.

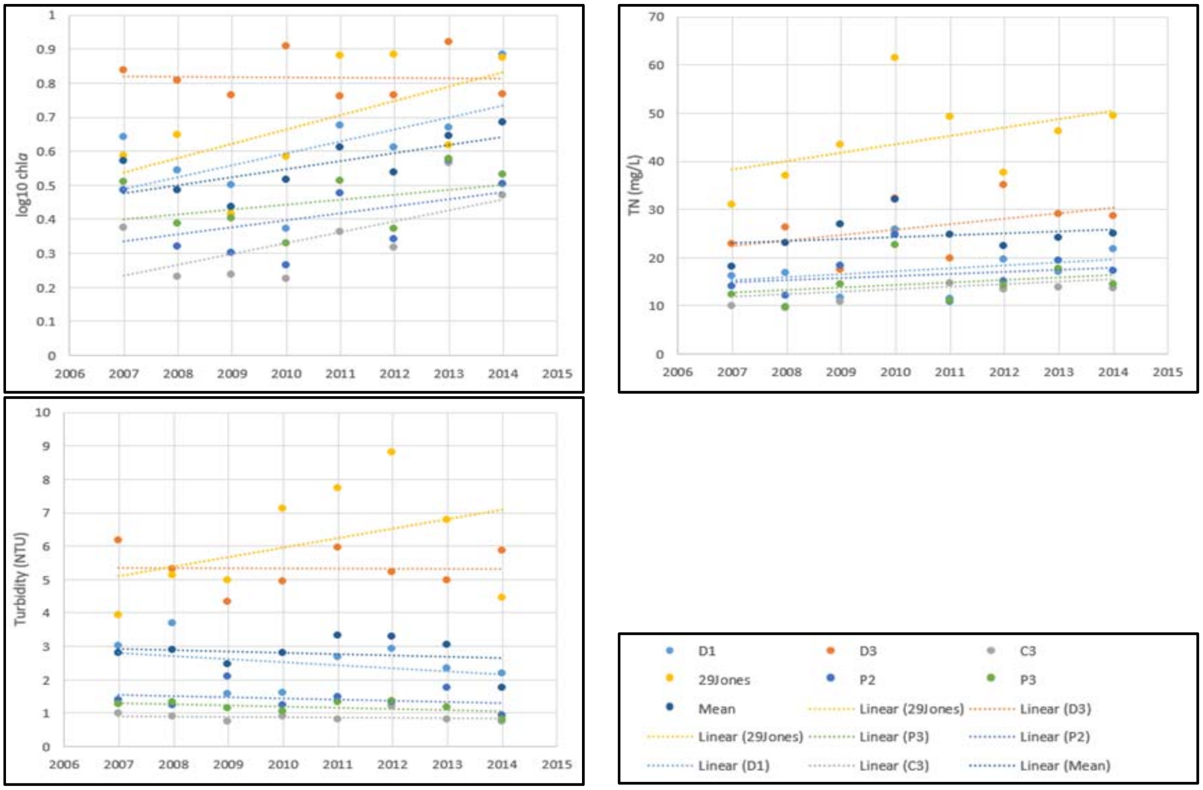

Figure 12. Chlorophyll *a* (top left), turbidity (bottom left), and total nitrogen (top right) trends in CCS datasets.

The streamflow discharge measured at the USGS gage in the Jones River is increasing over time (Fig 13). The increase is 0.24 cu ft per year and linear fit is significant at 95% (p=0.037). The highest annual average was in 2006 (64.2 cu ft) and the next highest annual average was in 2010 (59.7 cu ft). The peak streamflow discharge is decreasing over time (Fig 13). The decrease is 1.52 cu ft per year and the linear fit is not significant (p=0.12). The highest peak flow was in 1968 (575 cu ft) and the next highest peak flow was in 2010 (400 cu ft).

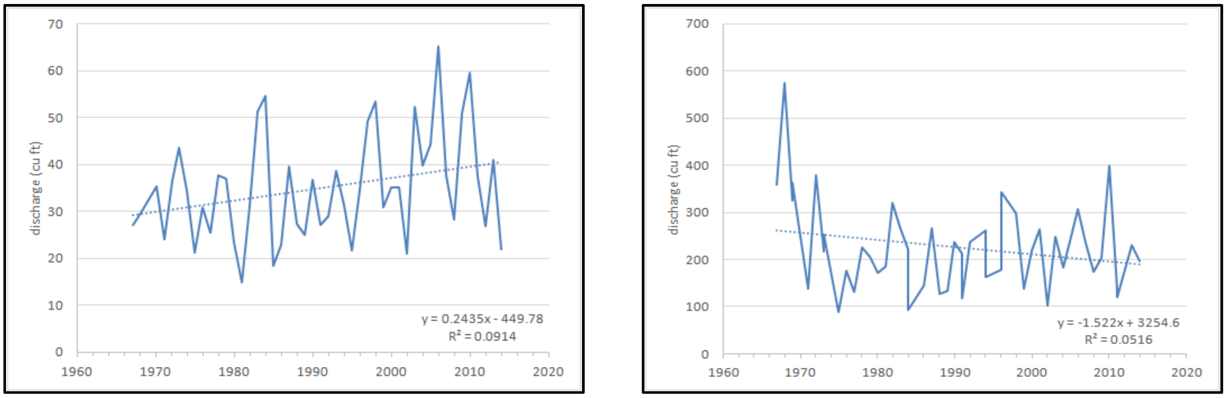

Figure 13. Average streamflow discharge (left) and peak streamflow (right) at USGS Jones River station.

Physical impact

Potential physical impacts from aquaculture include the placement of oyster cages in or near eelgrass, the boating activity necessary to tend gear, and the sediment disturbance of dredging or raking sediment to harvest shellfish. DMF surveys potential aquaculture sites proposed in permit applications and reorients sites to avoid eelgrass found at the time of the survey. However, since eelgrass can grow into an aquaculture site and surveys can miss eelgrass if done during certain seasons, some aquaculture activity abuts and overlaps mapped eelgrass (Fig 14). In 2014, permitted lease sites overlapped 5.47 ac of mapped eelgrass. Some sites have eelgrass growing adjacent to the gear (Fig 15). Due to the limitations of data availability, spatial changes in aquaculture leases over time have not been analyzed.

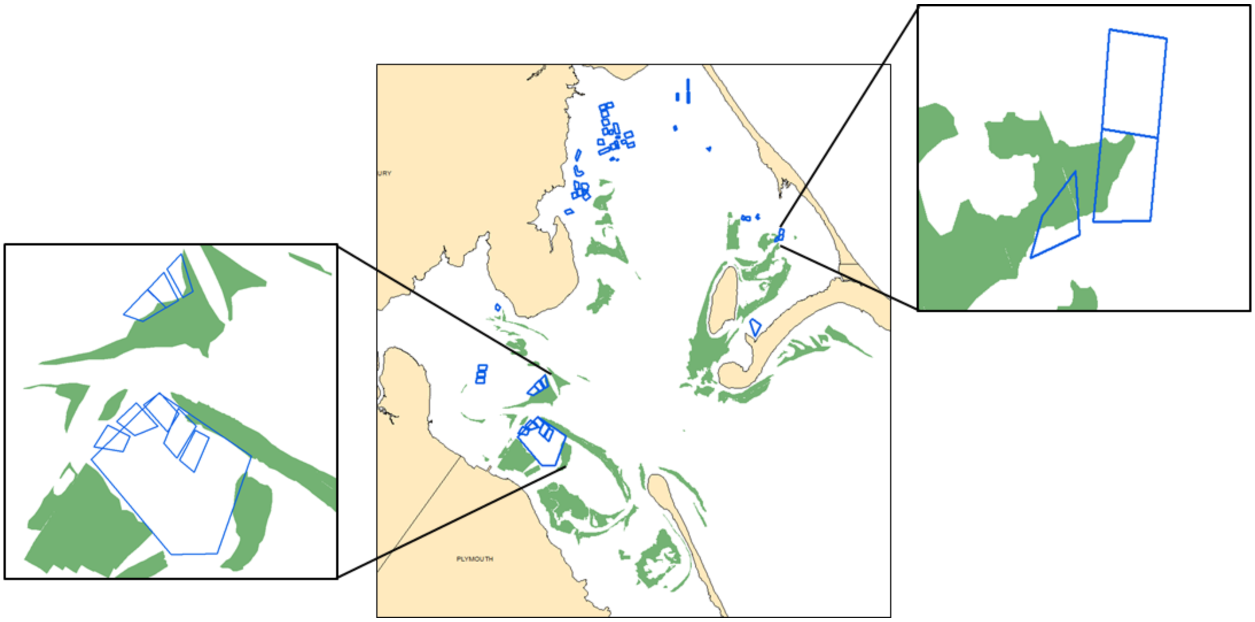

Figure 14. 2014 aquaculture sites (blue) overlap and abut eelgrass (DMF 2014 eelgrass, in green).

Figure 15. Eelgrass growing within an aquaculture site, adjacent to gear. Image source: Google maps, June 2014.

The DMF Trip Level Reports data show a substantial increase in the landings of and permits for cultured oysters since 2011, especially in Duxbury (Fig 16). Although spatial use has increased over time, a moratorium on issuing new leases in Duxbury has been in effect since January 14, 2005. Therefore, most of the landing increases are due to more efficient use of space. According to stakeholders, Plymouth will be seeing an increased interest in aquaculture and may expect a surge of grant applications in the near future.

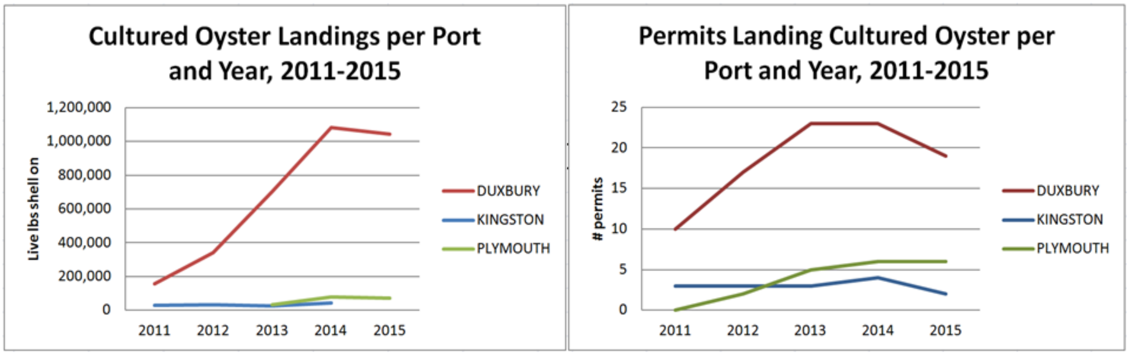

Figure 16. DMF Trip Level Reporting oyster landings (left) and number of permit holders (right) within DKP.

Another potential source of direct physical impact is dredging. We sought to record the frequency, location, volume, and time period of dredging over time. Dredging requires local, state, and federal permits. These permits can be issued for an area larger than is dredged in any given year, and the permits are valid over multiple years. There is a “start work” notification required prior to an individual dredge event under a given permit, but data requests to receive these notices were unsuccessful. DMF’s coastal alteration project review log showed four projects reviewed in Duxbury, none in Kingston, and eight in Plymouth between 2006 and 2015. These counts only represent projects or portions of projects that our reviewers commented on, and do not inform us about if, when, where and how dredging was completed. CCS aerial imagery captured dredging in Duxbury Bay in the fall of 2015. Communication with regulators, local harbormasters and natural resource agents suggested that dredging is an infrequent activity which occurs as infrequently as once in 20 years in some locations. The Town of Kingston has not dredged since the 1950’s (Maureen Thomas pers comm). Also, the extent of dredging is spatially limited to specific channels in the DKP system.

Motor boat use associated with fishing and recreational boating activity overlaps with eelgrass in DKP. Transit routes cross eelgrass meadows in shallow and deep areas, with the heaviest concentration at the mouth of the embayment and into Plymouth Harbor (Fig 17). Aerial images collected by CCS and DMF show propeller scars in eelgrass meadows (Fig 18). Docks, piers and boat moorings overlap and abut with historic eelgrass meadows that no longer exist (Fig 19). Based on DMF’s coastal alteration project review log, projects involving dock, pier and float installations were the most commonly reviewed in DKP, followed by dredging, aquaculture and shoreline armoring projects. Between 2013 and 2015, DMF reviewed 33 in-water projects within DKP with a total proposed impact (in all habitat types) of approximately 24 ac.

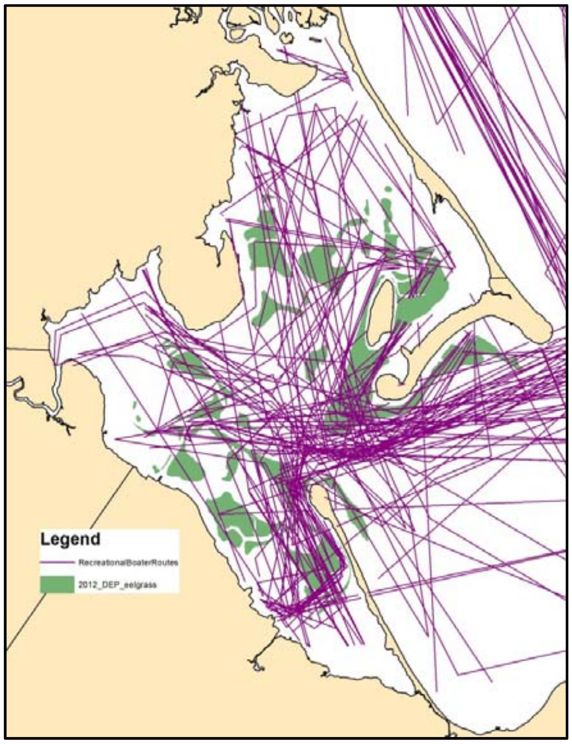

Figure 17. NROC recreational boater route data (2012) overlaid on 2012 DEP eelgrass layer.

Figure 18. DMF/LightHawk aerial image (Sept 2014) showing propeller scars through eelgrass bed in eastern Duxbury Bay.

Figure 19. DEP 1995 aerial with 1995 eelgrass (black line), 2001 eelgrass (green) and moorings placed within mapped eelgrass (Plymouth inner harbor).

Analysis of regional wind records suggests that terrestrial wind speed is decreasing (BHO 2014, Knorr 2013) but marine wind speed is increasing (Knorr 2013). Data from the Boston Harbor and Massachusetts Bays buoys were used to determine if there were significant changes in wind speed or direction (Fig 20) over time. The Mass Bay buoy wind direction increased 1 degree per year at a 90% confidence level (p=0.06). The wind direction is recorded as relative to true north, so this is not a result of declination. No other regressions were significant.

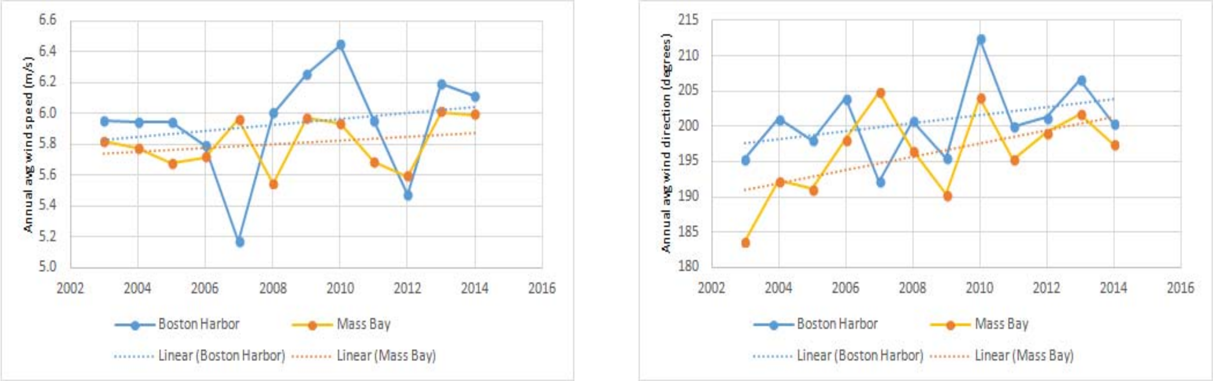

Figure 20. NERACOOS buoys annual average wind speed (m/s) (left) and annual average wind direction (degrees) (right).

We were unable to quantify changes in ice presence over time. Neither the harbormasters nor the U.S. Coast Guard log ice events for DKP. However, according to harbormasters and stakeholders, some winters experience frequent, heavy ice events while in some years icing is minor. During the winter of 2014-2015 Plymouth had several freezes of up to 10” of ice in the inner harbor that froze all the way out to Plymouth Beach (Chad Hunter pers comm). As waves chipped at the mass of ice, icebergs moved with the tide and shifting winds. Shallow areas could be scoured by moving icebergs if the tide is right. Eelgrass has persisted in some of the areas most likely to experience contact with ice, such as the shallow meadows fringing Plymouth beach, where dominant southwest and westerly winds would push icebergs shoreward.

Discussion

Mapping

Eelgrass coverage declined in DKP during the period investigated. The embayment may have supported as much as 3,440 ac in 1951. We estimate that approximately 987 ac of eelgrass remained in DKP in 2013/14. We estimate that eelgrass could be entirely lost within DKP as early as 2016 at the most recent rate of loss (467 ac/yr), or as late as 2051 at the median rate of loss (27 ac/yr). Due to varying meadow-specific trends, including gains in some areas, it is unlikely that complete loss will occur in the near term. The results of our photo-interpretation effort were very similar to DEP’s results for each time step. If we exclude one large, distinct eelgrass bed missed by DEP in 2006 but mapped in other years, our results were within 0.5-1.5% of DEP’s for all three study years. Note however that DEP’s eelgrass polygons were used as a guide in this project, and that performing a photo-interpretation on raw images without using existing polygons may have yielded different results. We took this approach because we lacked the ability to go back in time and ground-truth our interpretation. Rather, we employed the Questionable Mapped and Questionable Unmapped categories to identify areas where we disagreed with DEP. Disagreement with DEP’s interpretation was rare. Questionable Mapped and Questionable Unmapped areas combined accounted for 1-3% of the total mapped grass each year.

While the pattern of loss is undeniable, the loss estimates informed by the 2013/14 analysis (48% lost 2012-2013/14; 56% lost 1995-2013/14; 71% lost 1951-2013/14) may overestimate actual eelgrass loss to some degree. The higher resolution acoustic mapping in 2014 resulted in a more accurate edge of bed in deep water, as well as higher resolution coverage of bare areas within a larger bed, when compared to photo-interpretation alone (Sabol et al 2008, DMF unpub data). It should also be noted that the 2013/14 estimate was partially derived from photo-interpretation of a 2013 USGS aerial image, which was not flown to the same specs as DEP's flights, though we do not feel this significantly affected our results.

In 1995, roughly three quarters of eelgrass in the embayment was dense. In 2012, half was dense. The transition of dense grass to sparse is concerning because throughout the embayment, we generally saw eelgrass meadows transition from dense, to sparse, to gone. Some variation in density could be due to natural changes in the bed throughout the season, as aerial imagery was collected between May 15 and August 31 of any DEP survey year. We think the loss of eelgrass is primarily a gradual process, though we were unable to observe the bed dynamics in the five or more years between DEP mapping periods. We attempted to utilize other sources of imagery (i.e. PCCS, DMF, Google) to assess the gap years, but issues with scale, angle and visibility of eelgrass made any quantitative assessment problematic. The gradual change in density may indicate a chronic problem, and the increasingly sparse state of the remaining grass may suggest we can expect continued loss. A chronic problem is further indicated in the shallow inshore areas of Duxbury and Kingston, where eelgrass tended to recede with each mapping period, leaving only deeper patches along well-flushed channels. There were shallow eelgrass meadows in Plymouth Harbor that declined in recent years as well, however shallow areas were not lost uniformly. Several local fishermen stated that they see the deep edge act as an indicator of loss: it would begin to recede first, followed by rapid loss of the shallow edge. We are unable to confirm this since mapping a precise deep edge is problematic using photo-interpretation methods, and we also lack temporal coverage due to the 5-year DEP mapping schedule.

Potential causes of decline

In order to reverse eelgrass loss and plan for restoration, it is important to consider why the eeglrass is dying back. The summertime temperature record in DKP is increasing very modestly, and nearby embayments show significant increases over time, consistent with regional surface water and air trends. Temperatures at some stations within DKP are above the growth potential for eelgrass and are likely stressing the plants. Since temperature is increasing and predicted to continue to increase, temperature stress will likely increase. Respiration increases at a higher rate than photosynthesis at higher temperatures, resulting in decreased productivity (Ewers 2013). If the plants cannot store enough starch in their rhizomes to get through the winter, this could negatively impact plant survival.

Light limitation caused by eutrophication and turbidity is a major concern, as eelgrass requires as much as 35% of the surface irradiance to maintain healthy morphology (Ochieng et al 2010). In DKP, there is higher TN, chlorophyll *a*, and turbidity at stations closer to rivers, as expected. The embayment summertime average chlorophyll *a* concentration is increasing which is a sign of higher phytoplankton productivity. Increases in TN have also been measured in other embayments in Massachusetts, and related embayment-scale ecosystem shifts are in evidence (Costa 1988, Latimer and Rego 2010). Since TN is higher near the riverine sources of DKP and "stormwater impacts continue to contaminate shellfish on a regular basis" (Watershed Action Alliance 2006) nitrogen loading is likely an important variable. Once nitrogen loading estimates are developed, we can determine how DKP compares to known thresholds. Waterbodies with nitrogen loads in excess of 40-50 kg/ha/yr typically no longer have eelgrass (Latimer and Rego 2010, Bohrer et al 1995). In embayments, nutrient loading is also linked to shift in oxygen conditions when blooms die and their decomposition consumes oxygen. This pattern can result in alterations of sediment geochemistry, in particular an increase in sulfide. Also, the combination of increased temperatures and nutrient loading may be decreasing the resilience of eelgrass. However, eelgrass loss in areas that are well-flushed, such as the mouth of DKP, leads us to question whether light-limitation as a result of eutrophication is a driving factor of eelgrass loss in those areas.

The influence of precipitation and precipitation/drought events still needs more investigation. The occurrence and magnitude of peak discharge events are not increasing over time, but average discharge is increasing over time. Years with high concentrations of TN seem to be correlated to years with more precipitation but more work is needed to quantify this correlation.

Shifts in wind patterns might affect the natural sediment movement and scouring potential in eelgrass meadows or have the potential to alter hydrodynamics in DKP, thereby negatively affecting adult plants and seeding potential in the embayment. We relied on wind data from Boston Harbor and Mass Bays, since the wind data available in Duxbury Bay was unavailable for analysis in the timeframe of this study. Annual average wind speed is not changing, but there is some indication that wind direction is shifting slightly to the west. It is unlikely that average annual wind speed and direction are a major influence on eelgrass loss, but it is not out of the question that hydrodynamic impacts are relevant, particularly if shorter-term wind events are occurring. A better understanding of local circulation conditions and wind patterns on shorter time scales may elucidate why apparently well-flushed areas see eelgrass thinning and loss more consistent with a light limitation.

Tidal, riverine, and sediment dynamics, as well as related impacts of individual storm events, may be important factors to eelgrass loss. Sediment dynamics was raised several times by stakeholders as a cause for concern, both from the standpoint of gradual shallowing of parts of DKP and shifting shoals. Periodic sediment and erosion events are blamed for the persistent loss of shellfish year classes (Watershed Action Alliance 2006). A meadow that could be particularly vulnerable to sediment dynamics occurs in the center of the DKP embayment, due west of Saquish Neck, on the Cowyard flat. This meadow was mapped by DEP for the first time in 1995 (1.5 ac), was absent in 2001, was quite large in 2006 (45 ac) and 2012 (37 ac), present in 2013 USGS aerial imagery but disappeared before the 2014 acoustic survey. The fluctuation of eelgrass extent observed at this bed could be due to the shifting of the shoal, though we can’t at this time eliminate the possibility of other factors playing a role. Examining geomorphology using LIDAR would be beneficial to assess how DKP sediment is moving. Stakeholders spoke of holes on the flats caused by groundwater seeps, which may also deserve additional consideration.

Physical impacts or light limitation caused by ice, dredging, aquaculture, and dock construction may result in very localized impacts, but we do not think there is evidence suggesting a connection to the embayment-wide trends. Ice scour and iceberg shading may play a minor localized role in some loss, but are not expected to be a leading cause. Since we do not have a record of dredging activities, we are relying on stakeholder information that the dredging activities are limited in scale and occur relatively infrequently. Dredging could be linked to eelgrass loss particularly inside of Plymouth Harbor, where dredging and ferry activity occur in an area that used to have eelgrass. Aquaculture may also result in eelgrass loss due to gear contact, shallow-water boating and harvesting shellfish as all have the potential to remove eelgrass. Aquaculture grant sites overlapped approximately 5 ac of mapped eelgrass in 2013 and if aquaculture expands into areas that used to have eelgrass but don’t right now, we question if eelgrass can recolonize those sites. However, some aquaculture sites have eelgrass growing next to the gear, suggesting that at least some aquaculture practices are compatible with eelgrass (Fig 15). Furthermore, the overlap of a licensed site does not necessarily mean eelgrass impacts since aquaculture activity may not occupy the whole site. We have relatively poor records for the spatial extent of aquaculture activities over time; more work is warranted to explore aquaculture and dredging spatially. We're doubtful that direct physical impact is a major source of eelgrass loss, since the characteristic thinning and then loss of the eelgrass meadows is inconsistent with physical impact.

Boating also plays a role in localized, but not embayment-scale, eelgrass losses. Loss could be through direct removal of eelgrass (propeller scouring, grounding, anchoring, moorings, docks/floats) as well as indirect (increased water column turbidity, increased oil and gas pollutants entering the water). Stakeholders noted that a popular boating beach (likely Browns Bank, due east of Plymouth Beach head) is adjacent to an eelgrass bed; yet the eelgrass appears resilient to the boating activity in that location. While this project did not quantify past or present boater-use of DKP, it would be an interesting future project.

In other areas, eelgrass loss due to predation is a significant factor in rapid eelgrass decline (Rivers and Short 2007). We relied on anecdotal evidence of predation, in particular green crabs and waterfowl. Other possible predators include grazers that feed on epiphytes growing on eelgrass (i.e. snails, amphipods, shrimp, crabs). Predatory impacts are characterized by quick (single season) loss of entire meadows. Since we're seeing embayment-wide chronic losses characterized by the thinning and eventual loss of once-dense meadows, we are disinclined to think that predator mortality is a major factor here.

In general, we expect eelgrass should be resilient in the face of direct physical impact. Eelgrass persists and even expands in some areas heavily utilized by aquaculture and boating, including in some urban watersheds such as Boston Harbor. Predator populations have cycled in abundance over time and eelgrass has provided abundant forage for these animals. Although occasional predatory events may result in localized losses, we think the weight of evidence suggests that predation is not a major factor in the loss of eelgrass in DKP. This project highlighted our lack of information on wasting disease. Wasting disease has the potential to be a broad-scale stressor as it is spread rapidly in higher salinities (>25ppt), and is spread simply by plant to plant contact. Stakeholder reports of full plants floating with brown leaves could indicate death due to wasting disease or uprooting due to physical impacts or predation. Wasting disease caused rapid widespread loss of eelgrass in the 1930's, and a lower-level infection causing regular loss cannot be ruled out as an important variable in the eelgrass loss in DKP.

Recommendations to prevent additional loss and explore potential for eelgrass restoration

Embayment-wide eelgrass loss is characterized by a gradual thinning of existing meadows which is inconsistent with direct physical impact, but due to the scale of the loss, avoiding direct physical impacts is recommended. Future aquaculture sites should not be permitted within or immediately abutting eelgrass meadows and dredging should not occur in eelgrass or within at least 100 feet of eelgrass to account for turbidity. Exceptions may be warranted based on the type of aquaculture activity. Docks should not be built over eelgrass or in an orientation or location where eelgrass might be shaded or indirectly impacted by boats using the dock.

The Towns of Duxbury, Kingston, and Plymouth are actively monitoring water quality and making efforts to reduce bacterial loading and nutrient contamination of DKP. For example, since 2011 the town of Kingston has implemented BMPs following a protocol developed by the Town of Duxbury. The improved water quality resulted in reopening of 313 acres of shellfish beds in Kingston Bay in 2013. These efforts should be continued. The towns are currently finalizing a detailed nitrogen loading study of the embayment, which should include reference to eelgrass thresholds. We recommend continued water quality monitoring.

Eelgrass mapping at routine time steps, ideally annually, should be continued to document trends in eelgrass areal extent. Including an assessment of density is highly recommended.

Eelgrass restoration efforts would benefit from a better understanding of DKP sediment and hydrodynamics (Wicks et al 2009), the impacts of groundwater hydrology (Rodgers 2010), and assessing the potential impact of temperature on the ability of eelgrass to store enough starch reserve to survive the winter (Colarusso 2006). Physiological research focused on photosynthesis and respiration rates, growth rates, and starch storage would be helpful to determine restoration potential. A meadow-specific monitoring program similar to SeagrassNet that measures water quality, temperature, light, sedimentation, eelgrass density, epiphytes, wasting disease, and evidence of physical impacts would elucidate what regions of DKP are optimal for eelgrass growth and restoration. In addition to monitoring existing meadows, we recommend an assessment of several loss sites to determine if conditions are suitable for eelgrass restoration.

Transplanting or seeding eelgrass to existing meadows to keep them at a resilient density (Olesen and Sand-Jensen 1994) is worth considering in more detail. Experiments with eelgrass seeding could help determine if the cost of restoration can be low enough to have an annual seeding event to help eelgrass stay in DKP.

This study provided a preliminary consolidation of many available data sources and identified that more work is needed. There is a fair amount of water quality monitoring that would benefit from year-round stations and the establishment of light monitoring in eelgrass locations. Furthermore, considering the eelgrass trends in the context of shellfish and wastewater trends would be interesting. Additional detail regarding the history of dredging and aquaculture could be compiled, and would be beneficial to help elucidate areas where direct physical impact is a priority issue. It is also important to examine ways to track changes in geomorphology within the embayment. Such changes can dramatically impact wild shellfish populations, aquaculture productivity, and other natural resources.

This project also identified access issues associated with the original imagery. Due to lack of resources, DEP maintains its photo archive prior to 2006 as hard copy prints and negatives at its Boston office in file cabinets. We highly recommend these hard copy prints and negatives be fully archived as digital, georeferenced maps through a partnership with MassGIS, state archives, and DEP. The georeferenced images we utilized for this project will be available on the DMF website.

Conclusion

DMF remapping of DEP aerial photographs has confirmed large losses of eelgrass in DKP. The embayment has lost as much as 71% of its eelgrass between 1951 and 2014, with many beds shrinking and some disappearing altogether. The median loss rate is 27 ac/year and the loss rate dramatically accelerated between 2012 and 2014. The loss is characterized by dense beds thinning over time and eventually disappearing. All areas of DKP are affected and losses are occurring at a variety of water depths. The loss is likely caused primarily by degrading environmental conditions due to water quality impairments from runoff and wastewater, the effects of which are exacerbated by temperature increase. Once stressed and impaired in such a way, eelgrass is more vulnerable to weather and hydrodynamic related impacts. Local losses due to geomorphological changes and direct impacts as a result of human activities in DKP are relevant to eelgrass loss but the impact of wasting disease is unknown. We recommend the following:

- Preventing direct physical impacts to eelgrass (such as moving mooring fields out of eelgrass, marking eelgrass and channels to ensure boaters don't drive over eelgrass beds),
- Continuing efforts to reduce nutrient loading (wastewater and stormwater upgrades, vessel pumpouts),
- Mapping eelgrass routinely,
- Continuing CCS monitoring of water quality throughout DKP,
- Monitoring of light and sediment sulfide conditions throughout DKP,
- Monitoring of wasting disease, epiphyte load, stem density, nitrogen content, and carbohydrates at designated eelgrass stations in DKP,
- Exploring restoration potential of lost beds, and
- Digital archiving of all DEP photo datasets for retrospective analyses,
- Recording changes in aquaculture license spatial distribution, and
- Recording dredging events.

Acknowledgements

This work would not have been possible without the support of the North and South Rivers Watershed Association and the Massachusetts Bays National Estuary Program. The majority of the acoustic field work was conducted by Steven Voss and Wesley Dukes, Mass DMF. Without the cooperation of Michael McHugh and Charlie Costello at Mass DEP, we would not have been able to repeat their photo-interpretation. Our group of stakeholders who are the stewards of this embayment system included harbormasters, shellfish wardens, aquaculturists, natural resource managers, and non-profit coordinators. They provided abundant information about the region and provided helpful ideas to move this project forward. Jeffrey Kneebone, UMass Dartmouth, and Amy Costa, CCS, willingly provided their data for analysis. Tay Evans and Mark Rousseau of DMF improved the content of this report with their able editing.

References

Abe, M., A. Kurashima, and M. Maegawa (2008) Temperature requirements for seed germination and seedling growth of *Zostera marina* from central Japan. Fisheries Science 74.3: 589-593.

Arnaud-Haond, S., C.M. Duarte, E. Diaz-Almela, N. Marba, T. Sintes, E.A. Serrao. 2012. Implications of Extreme Life Span in Clonal Organisms: Millenary Clones in Meadows of the Threatened Seagrass *Posidonia oceanica*. PLoS ONE 7(2): e30454. doi:10.1371/journal.pone.0030454

Blue Hill Observatory (BHO) 2014. Watching the Weather for 129 Years: The History and Climate Record of the Blue Hill Meterological Observatory. Michael Iacono presentation to the Newton Rotary Club, January 2014. http://www.bluehill.org/climate/201401_BHO_Rotary_Iacono.pdf Accessed 4/28/2016.

Blue Hill Observatory (BHO) 2015. Graphs of long-term annual Blue Hill Observatory data. http://bluehill.org/observatory/2014/02/graphs-of-annual-blue-hill-observatory-climate-data/ Accessed 4/27/2016.

Bohrer, T., A.Wright, J. Hauxwell and I. Valiela (1995) Effect of epiphyte biomass on growth rate of *Zostera marina* in estuaries subject to different nutrient loading. Biological Bulletin 189:260.

Campbell, J. W. (1995) The lognormal distribution as a model for biooptical variability in the sea. Journal of Geophysical Research. 100:13237–13254.

Colarusso, P. (2006) The effect of varying initial non-structural carbohydrate concentrations on short term eelgrass (*Zostera marina* L.) transplant survival and growth. Doctorate thesis, Northeastern University. Chapter 5, pp81-101.

Costa, J. E. (1988) Eelgrass in Buzzards Bay: Distribution, Production, and Historical Changes in Abundance. EPA 503/4/88-002 204 pp.

Costa, J.E., B.L. Howes, A.E. Giblin, and I. Valiela (1992) Monitoring nitrogen and indicators of nitrogen loading to support management action in Buzzards Bay. In Ecological Indicators Vol. 1, eds. D. H. McKenzie, D.E. Hyatt, and V. J. McDonald, Elsevier Applied Science, Research Triangle Park. pp. 499-531.

Costello, Charles. Massachusetts Department of Environmental Protection, Wetlands Conservancy Program

Costello, C. and W.J. Kenworthy (2011) Twelve-year mapping and change analysis of eelgrass (*Zostera marina)* areal abundance in Massachusetts (USA) identifies statewide declines. Estuaries and Coasts 34(2):232-242. DOI 10.1007/s12237-010-9371-5.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A. (1993) Assessing water quality with submerged aquatic vegetation: habitat requirements as barometers of Chesapeake bay health. Bioscience 43:86–94.

Dexter, R.W. (1985) Changes in the standing crop of eelgrass, *Zostera marina* L., at Cape Ann, Massachusetts, since the epidemic of 1932. Rhodora 87:357-366.

Eichner, E.M., B.L. Howes, and R. Samimy (2013) Final Report/Technical Memorandum for Task 1B: Cumulative Nitrogen Loading Determination. http://www.plymouth-ma.gov/sites/plymouthma/files/uploads/projects_plymouth_harbor_nloading_rpt_task1b_final.pdf Accessed 5/4/2016.

Ewers, C.J. (2013) Assessing physiological thresholds for Eelgrass (*Zostera marina* L.) survival in the face of climate change. Masters Thesis. California Polytechnic State University, San Luis Obispo. http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=2049&context=theses Accessed 2/9/2016.

Frumhoff, P. C., J. J. McCarthy, J. M. Melillo, S. C. Moser, and D. J. Wuebbles (2006) Climate Change in the U.S. Northeast: A report of the Northeast Climate Impacts Assessment. Cambridge, MA: Union of Concerned Scientists. http://www.ucsusa.org/global_warming/science_and_impacts/impacts/northeast-climate-impacts.html#.VyIDdzArLtQ. Accessed 4/27/2016.

Gallegos, C.L. and W.J. Kenworthy (1996) Seagrass depth limits in the Indian River Lagoon (Florida) Areal Abundance in Massachusetts (USA): Application of an optical water quality model. Estuarine, Coastal, and Shelf Science 42:267-288.

Glenn, R.P. and T.L. Pugh (2006) Epizootic shell disease in American lobster (*Homarus americanus*) in Massachusetts coastal waters: interactions of temperature, maturity and intermolt duration. Journal of Crustacean Biology 26(4): 639–645.

Grady, Joe. Jones River Watershed Association

Grady, Sara. North South Rivers Watershed Association

Greve, T.M., J. Borum, O. Pedersen (2003) Meristematic oxygen variability in eelgrass (*Zostera marina*). Limnology and Oceanography 48(1):210-216. DOI 10.4319/lo.2003.48.1.0210.

Hebert, Madison. Island Creek Oysters

Howes, B. and R. Samimy (2005) Summary of Water Quality Monitoring Program for the Plymouth, Kingston, and Duxbury Harbor Embayment System (2003-2004). http://www.plymouth-ma.gov/sites/plymouthma/files/uploads/projects_plymouth_kingston_duxbury_604breport_drftfnl072005.pdf Accessed 2/29/2016.

Hughes, Randall. Northeastern University

Hunter, Chad. Town of Plymouth Harbormaster

Iwanowicz, H.R., R.D. Anderson, and B.A. Ketschke (1974) A study of the marine resources of Plymouth, Kingston and Duxbury Bay. Massachusetts Division of Marine Fisheries Monograph Series No. 17.

Jarvis, J.C. and K.A. Moore (2015) Effects of seed source, sediment type, and burial depth on mixed-annual and perennial *Zostera marina* L. seed germination and seedling establishment. Estuaries and Coasts 38:964-978. DOI 10.1007/s12237-014-9869-3.

Källström, B., A. Nyqvist, P. Åberg, M. Bodin, and C. André (2008) Seed Rafting as a dispersal strategy for eelgrass (*Zostera marina*). Aquatic Botany 88:148–153.

Kemp, M.W., R.R. Twilley, J.C. Stevenson, W.R. Boynton and J.C. Means (1983) The decline of submerged vascular plants in upper Chesapeake Bay: Summary of results concerning possible causes. Marine Technology Society Journal 17:78-89.

Kemp, M., R. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, C.L. Gallegos, W. Hunley, L. Karrh, E.W. Koch, J.M. Landwehr, K.A. Moore, L. Murray. M. Naylor, N.B. Rybicki, J.C. Stevenson, and D.J. Wilcox (2004) Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors. Estuaries 27(3):363-377.

Knorr, K.I. (2013) Distribution, Variability, and Trends in Wind Characteristics in New England Coastal Areas. Open Access Master's Theses. Paper 22. http://digitalcommons.uri.edu/theses/22 Accessed 5/2/2016.

Latimer, J.S. and S.A. Rego (2010) Empirical relationship between eelgrass extent and predicted watershed-derived nitrogen loading for shallow New England estuaries. Estuarine, Coastal and Shelf Science 90:231-240.

Lee, K.S., Park, S.R., & Kim, Y.K. (2007) Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: A review. Journal of Experimental Marine Biology and Ecology 350(1-2): 144–175.

Leonard, Chuck. Duxbury Bay Maritime School

Lynch, A.J.J., R.W. Barnes, R.E. Vaillancourt, and J. Cambecedes. 1998. Genetic Evidence that *Lomatia tasmanica* (Proteaceae) is an Ancient Clone. Australian Journal of Botany 46(1):25-33.

Marsh, J.A., W.C. Dennison, and R.S. Alberte (1986) Effects of temperature on photosynthesis and respiration in eelgrass (Z*ostera marina* L.). Journal of Experimental Marine Biology and Ecology 101:257-267.

Massachusetts Department of Environmental Protection (MADEP) (2014) Final Pathogen TMDL for the South Coastal Watershed. https://ofmpub.epa.gov/waters10/attains_impaired_waters.show_tmdl_document?p_tmdl_doc_blobs_id=67200 Accessed 4/29/2016.

Massachusetts Executive Office of Energy and Environmental Affairs (MAEEA) (2011). Climate Change Adaptation Report. http://www.mass.gov/eea/docs/eea/energy/cca/eea-climate-adaptation-report.pdf Accessed 4/28/2016.

Moe, K. (2014) Insulating Modernism: Isolated and Non-isolated Thermodynamics in Architecture. Birkhauser Verlag, pp. 145-152. https://books.google.com/books?id=qH_oBQAAQBAJ& Accessed on 5/9/2016.

Moore, K.A., H.A. Neckles and R.J. Orth (1996) *Zostera marina* (eelgrass) growth and survival along a gradient of nutrients and turbidity in the lower Chesapeake Bay. Marine Ecology Progress Series 142:247-259.

Moore, K.A., R.L. Wetzel, and R.J. Orth (1997) Seasonal pulses of turbidity and their relations to eelgrass (*Zostera marina* L.) survival in an estuary. Journal of Experimental Marine Biology and Ecology 215(1):115–134.

Neckles, H.A., F.T. Short, S. Barker and B.S. Kopp (2005) Disturbance of eelgrass *Zostera marina* by commercial mussel *Mytilus edulis* harvesting in Maine: Dragging impacts and habitat recovery. Marine Ecology Progress Series 285:57–73.

Ochieng, C.A., F.T. Short and D.I. Walker (2010) Photosynthetic and morphological responses of eelgrass (*Zostera marina* L.) to a gradient of light conditions. Journal of Experimental Marine Biology and Ecology 382:117-124

Olesen B. and K. Sand-Jensen (1994) Patch dynamics of eelgrass Zostera marina. Marine Ecology Progress Series 106:147–156.

Orth, R.J., T.J.B. Carruthers, W.C. Dennison, C.M. Duarte, J. Fourqurean, K. Heck, A.R. Hughes, G.A. Kendrick, W.J. Kenworthy, S. Olyarnik, F.T. Short, M. Waycott, and S.L. Williams (2006) A global crisis for seagrass ecosystems. BioScience 56(12): 987-996.

Oviatt, Candace A., and K. M. Hindle, eds. *Manual of biological and geochemical techniques in coastal areas*. Marine Ecosystems Research Laboratory, Graduate School of Oceanography, University of Rhode Island, 1994.

Reusch, T.B.H., C. Bostrom, W.T. Stam, and J.L. Olsen. 1999. An ancient eelgrass clone in the Baltic. Marine Ecology Progress Series 183:301-304.

Reusch, T.B.H., A. Ehlers, A. Hammeril, and B. Worm (2005) Ecosystem recovery after climatic extremes enhanced by genotypic diversity. Proceedings of the National Academy of Sciences of the United States 102(8):2826(6).

Rheuban, J.E., S. Williamson, J.E. Costa, D.M. Glover, R.W. Jakuba, D.C. McCorkle, C. Neill, T. Williams, and S.C. Doney (2016) Spatial and temporal trends in summertime climate and water quality indicators in the coastal embayments of Buzzards Bay, Massachusetts. Biogeosciences 13:253-265.

Rodgers, B.S. (2010) How does groundwater impact eelgrass in Long Island? The role of nitrogen and herbicide in reducing eelgrass growth, survival and photosynthetic efficiency. Masters thesis, Stony Brook University.

Rivers, D.O. and F.T. Short (2007) Effect of grazing by Canada geese *Branta canadensis* on an intertidal eelgrass *Zostera marina* meadow. Marine Ecology Progress Series 333:271-279.

Sabol, B., E. Lord, K. Reine, and D. Shafer (2008) Comparison of acoustic and aerial photographic methods for quantifying the distribution of submersed aquatic vegetation in Sagamore Creek, NH. DOER Technical Notes Collection. ERDC TN-DOER-E23. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/dots/doer/

Short, F.T., A.C. Mathieson and J.I. Nelson (1986) Recurrence of the eelgrass wasting disease at the border of New Hampshire and Maine, USA. Marine Ecology Progress Series 29:89-92.

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

Short, F.T., R. Coles, M. Fortes, S.Victor, M. Salik, I. Isnain, J. Andrew and A. Seno (2014) Monitoring in the Western Pacific Region shows evidence of seagrass decline in line with global trends. Marine Pollution Bulletin 83:408–416.

Twilley, R.R., W.M. Kemp, K.W. Staver, J.C. Stevenson and W.R. Boynton (1985) Nutrient enrichment of estuarine submersed vascular plant communities. 1. Algal growth and effects on production of plants and associated communities. Marine Ecology Progress Series 23: 179-191.

Watershed Action Alliance (2006) South Coastal Watershed Action Plan. Chapter 5: Kingston and Duxbury Bay Watersheds. http://jonesriver.org/getfile/southcoastal/5duxburyjones.pdf Accessed 5/9/2016.

Whitmore, Kelly. Massachusetts Department of Fish and Game, Division of Marine Fisheries

Wicks, E.C., E.W. Kock, J.M. O'Neil and K. Elliston (2009) Effects of sediment organic content and hydrodynamic conditions on the growth and distribution of *Zostera marina*. Marine Ecology Progress Series 378:71-80.

Wyllie-Echeverria, S. and P.A. Cox (1999) The seagrass (*Zostera marina* [Zosteraceae]) industry of Nova Scotia (1907-1960). Economic Botany 53(4):419-426.

Zimmerman, R.C., D.G. Kohrs, D.L. Steller, and R.S. Alberte (1997) Impacts of CO2 enrichment on productivity and light requirements of eelgrass. Plant Physiology 115: 599–607.

Appendix: Stakeholder meeting report

Duxbury-Kingston-Plymouth Bays Eelgrass Study
Stakeholder Meeting
February 23, 2016
Duxbury Town Hall, 1-3:30 p.m.

ATTENDEES

Name	Email	Affiliation
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Joe Grady	Grady@town.duxbury.ma.us	Duxbury Conservation
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Valerie Massard	Town-Planner@town.duxbury.ma.us	Duxbury Planning
John Bunar	jbironskippy@gmail.com	Fisherman
Bill Doyle	bill@proysters.com	Plymouth Rock Oysters
Chris Sherman	chris@islandcreekoysters.com	Island Creek Oysters

Powerpoint presentation by Jill Carr. Eelgrass loss confirmed, estimate of 3000 acres in 1951 down to 1200 acres in 2014. A variety of potential causative factors are being explored. Right now, no clear "silver bullet."

DISCUSSION

Issues raised that we should follow up on and/or make recommendations on are identified in bold.

Are we missing any data sources – water temp, any aquaculture data? No. Is anyone aware of other analyses looking at water temp increase in the bay? No.

Is the eelgrass loss the same as we see elsewhere? Eelgrass loss is a global phenomenon. In Massachusetts, loss is occurring in many embayments on the Cape that have been blamed on eutrophication. This embayment seems to be relatively healthy, and losses are being seen in areas with very good water quality. We're not sure if it's the "eutrophication story" but it may be. Could there be a climate change nexus?

Ice – in Duxbury, ice back up and gets distributed across the flats. Esp. behind Clark's Island and east side gets covered in ice. Connection between ice and wind. 2004 was a bad ice year (i.e. there was a lot of ice that year). No ice monitoring.

Wind and water temp connected – SW wind = colder water in the summer.

Freezing – **surface of flat can be frozen, does that affect the rhizomes**?

Sedimentation – Sandy 2012 and no name storm in 2012, Blizzard in 2013, Ichabod Flat had 4" of sand. Broad agreement that sedimentation is an issue that could be negatively affecting eelgrass.

Flats pitted with holes of different sizes in the late winter. Could be **groundwater** bubbling up, can freeze and make ice cakes that then thaw. Like kettle holes almost.

More work on shellfish landings needed; soft shells high in 1930's, mussels in 1980's. Aquaculture no expansion in Duxbury since 2006 moratorium. Some deeper water mussel harvest, link between mussels and sedimentation.

Boating – can we do a field survey of boating activity? Seems to be a lot and in eelgrass areas.

Dredging – not in last 10-15 years in Duxbury; activities are infrequent and occupy a very small portion of the bay. Joe Grady – his farm is right next to dredge channel and he did not see sedimentation.

Some meadows are growing.

Predators – green crab trapping informally for 8 years (associated with aquaculture activities). Increased until crazy numbers in 2014 then sharp decline in 2015.

Disease/physiological change? -- plants found floating, not just during shedding season, leaves turn brown then whole plant including rhizomes float up.

General feeling that the **watershed (esp. Duxbury) hasn't changed that much**. –but fertilizer and herbicide use way up.

Duxbury

- Back River outflow and sedimentation could be an issue
- Oyster growth rates vary east to west
- **Different redox depth in sediment** (shallower to the east)
- Higher organics as you move north
- Razor clams and worms still abundant and doing well, no evidence of habitat degradation
- Sediment coring and benthic infauna would be interesting to examine degradation

Kingston

- Same patterns in Kingston as you move closer to the Jones River
- Salt marsh degradation causing sedimentation
- Is there coring? Has sediment changed?

Plymouth

- Depth changes have occurred, flats changing
- Sparse meadows always go away – have we passed a tipping point and we'll lose it all?

The data shows a higher rate of shallow bed loss which is counter intuitive. You would think that if turbidity is the issue, deeper meadows would go first. Is it a scour issue? More energy on flats? But John Bunar explained he sees that the **deeper edge goes first, then the flats**. Small bits may survive along the channel edges. Three meadows are expanding, they're right on the edge of channels. One has gone from ½ and acre to 3-4 acres.

N-loading done in 2008; some more work in 2013 which is due this April (Brian Howes).

Look at sewage treatment reports, groundwater work, John Bunar data.

Predators – some folks think they're worth looking at, others say no evidence of leaves damaged by crabs.

No consistent dynamic seems to emerge—**we need more year-round measurements**.

In 1951 all eelgrass or mussel beds. The mussel beds are gone—once disturbed, the flats are more mobile. Did this cause a cumulative or domino effect?

In Plum Island Sound, UNH blamed turbidity for lack of restoration success. In Essex Bay, a 1 acre bed came back after 75 years.

SUMMARY

Eelgrass loss is more extensive than originally thought, tracking the loss is important to tell the story. Identifying the cause is important to reverse the trend and understand how to manage the problem (for example, can aquaculture coexist with eelgrass?). No silver bullet. Turbidity and the "usual" eutrophication story may be a factor, but unlikely to be the only factor (large losses right at mouth of harbor in clear, well-flushed area). Lots of interest in examining sedimentation in more detail and teasing out acute vs chronic impacts.

WHAT TO LOOK AT IN MORE DETAIL

Test specific hypotheses in remaining meadows, areas where eelgrass has been lost, and areas where eelgrass never grew.

Most important: track the resource, continue at least annual eelgrass surveys. Report this work to towns.

Variables to look it in more detail:

- Sedimentation (LIDAR data?)
- backwaters at the USGS gage
- MSX-temperature relationship
- Wind
- Herbicides
- Herbivores
- wind & water temperature (John Brawley, Greg Skomal)
- light availability (but this is not thought to be an issue)

- sediment quality/changes
- storm frequency causing acute impacts/erosion (7 100-year events in the past 4 years) – surge and tide data
- look into Plymouth circulation model (EIR for wastewater treatment plant, dye study DMF)
- Corps channel surveys for dredging (ask Chad Hunter and Bob Boeri)
- wasting disease not thought to be an issue but should be confirmed
- nutrients (DEP work, sewage treatment plant work)
- circulation
- groundwater
- land use changes

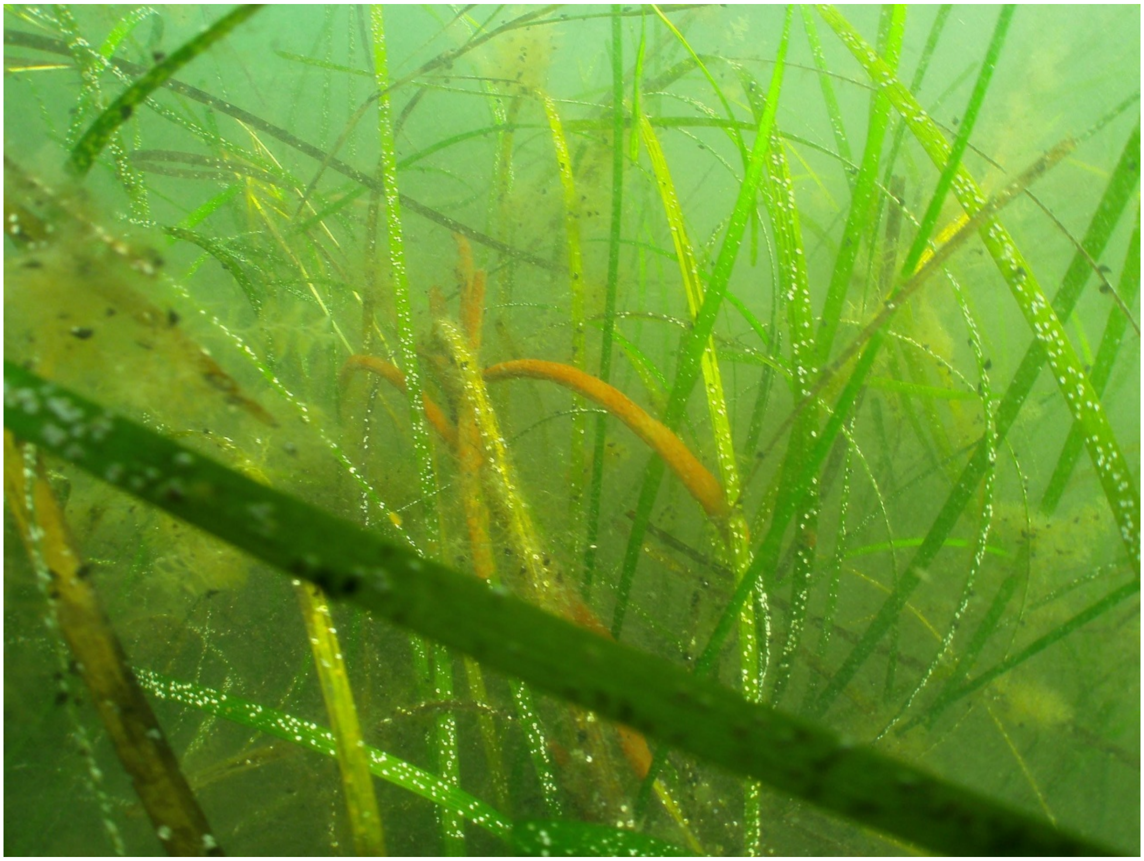
Should signs be put up so boaters can avoid eelgrass?

TO DO

ITEM	**WHO/WHEN**	**UPDATE 3/17/2016**
Send out minutes.	DMF as soon as possible	Doing today.
Send out pictures of wasting disease and epiphytes.	DMF as soon as possible	As part of minutes.
Check weather data from Maritime Academy (Chuck Leonard); other south coast weather contact is Wayne in Duxbury.	DMF with Sara Grady introduction as soon as possible	Download can be done on a month to month basis for a few years. Dataset too time consuming to download right now.
Connect with John Bunar about how to use his acoustic data/setting up more work for next summer.	DMF and John	DMF sent email.
Write final report and consolidate and make available the data. No consensus on good method to disseminate report and data; will use existing traditional methods. Both shapefiles and KMZs are helpful. MORIS and MassGIS are utilized by the towns. Prassede might connect it with a NERACOOS	DMF	Zosterapalooza talk is last week of March. Goal is to finish report by end of April.

project.		
Continue to try and get 2000 images from DEP.	DMF	Ongoing.
Consider how to manage imagery and water quality data.	DMF, MassBays	For this project, data will be released on DMF website. Maybe MassBays too. Will probably happen in summer of 2016.

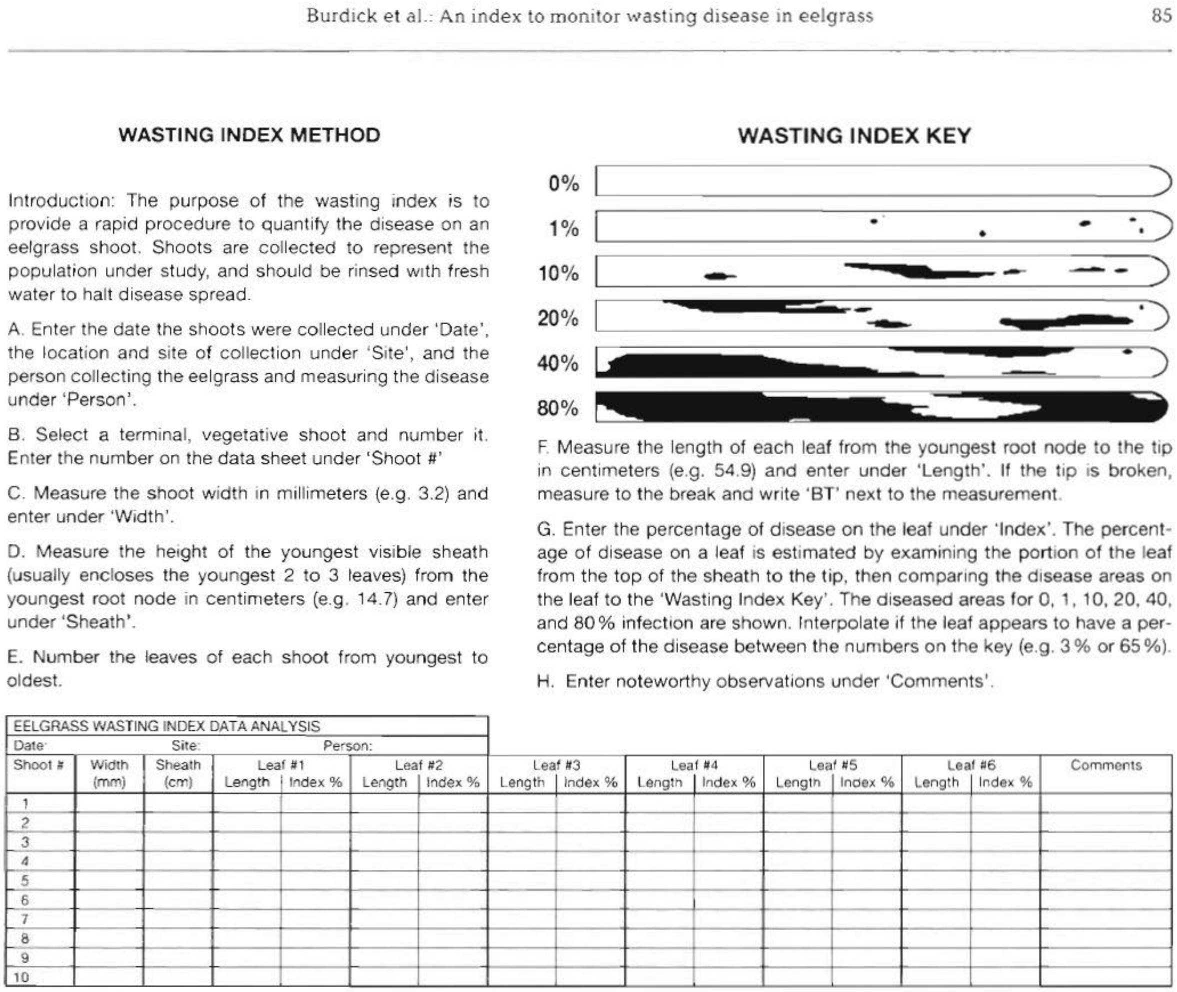
PICTURES



Epiphytes on eelgrass in West Falmouth, MA, Aug. 2014. Epiphytic filamentous algae (fuzz), snails (black), worms (white) and colonial tunicates (orange).

Epiphytes on eelgrass in Quisset, MA, Sep. 2015. Epiphytic filamentous algae (fuzz).

Wasting disease. Photos courtesy of Cornell Cooperative Extension.



Burdick et al.: An index to monitor wasting disease in eelgrass 85

WASTING INDEX METHOD

Introduction: The purpose of the wasting index is to provide a rapid procedure to quantify the disease on an eelgrass shoot. Shoots are collected to represent the population under study, and should be rinsed with fresh water to halt disease spread.

A. Enter the date the shoots were collected under 'Date', the location and site of collection under 'Site', and the person collecting the eelgrass and measuring the disease under 'Person'.

B. Select a terminal, vegetative shoot and number it. Enter the number on the data sheet under 'Shoot #'

C. Measure the shoot width in millimeters (e.g. 3.2) and enter under 'Width'.

D. Measure the height of the youngest visible sheath (usually encloses the youngest 2 to 3 leaves) from the youngest root node in centimeters (e.g. 14.7) and enter under 'Sheath'.

E. Number the leaves of each shoot from youngest to oldest.

WASTING INDEX KEY

F. Measure the length of each leaf from the youngest root node to the tip in centimeters (e.g. 54.9) and enter under 'Length'. If the tip is broken, measure to the break and write 'BT' next to the measurement.

G. Enter the percentage of disease on the leaf under 'Index'. The percentage of disease on a leaf is estimated by examining the portion of the leaf from the top of the sheath to the tip, then comparing the disease areas on the leaf to the 'Wasting Index Key'. The diseased areas for 0, 1, 10, 20, 40, and 80 % infection are shown. Interpolate if the leaf appears to have a percentage of the disease between the numbers on the key (e.g. 3 % or 65 %).

H. Enter noteworthy observations under 'Comments'.

EELGRASS WASTING INDEX DATA ANALYSIS

Date: Site: Person:

Shoot #	Width (mm)	Sheath (cm)	Leaf #1		Leaf #2		Leaf #3		Leaf #4		Leaf #5		Leaf #6		Comments
			Length	Index %	Length	Index %	Length	Index %	Length	Index %	Length	Index %	Length	Index %	
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

Wasting index methods from Burdick, D.M., F. T. Short, and J. Wolf. 1993. An index to assess and monitor the progression of wasting disease in eelgrass *Zostera marina*. Marine Ecology Progress Series, 94:83-90.