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REVIEW ARTICLE

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Study of Sediment and Landscape-level

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ABSTRACT

Land-use activities affect water quality by altering sediment, chemical loads, and watershed hydrology. Some land uses may contribute to the maintenance of water quality due to a biogeochemical transformation process. These land-use/land-cover types can serve as nutrient detention zones or as nutrient transformation zones as dissolved or suspended nutrients or sediments move downstream. These data suggest that the current distribution of eelgrass within the study area is strongly influenced by physical and chemical subaqueous soil characteristics. Knowledge of environmental factors impacting anadromous salmonids in their freshwater habitats, particularly at large spatial scales, may be important for restoring them to previously recorded levels in Iran. Soil survey techniques proved useful for the delineation of sediment characteristics (e.g. texture, salinity) that influence plants distribution patterns at landscape-level scales. # 2005 Elsevier B.V. All rights reserved. These results provide a starting point for fish biologists and managers attempting to map approximate status and quality of rearing habitats for chinook salmon and steelhead at large spatial scales.

Keywords: *Submerged aquatic vegetation; Land-use complex and Soil.*

INTRODUCTION

Numbers of anadromous salmonids have greatly decreased from previously recorded levels for many stocks in the northwestern United States. One factor thought to be influencing these declines is loss or degradation of freshwater spawning and rearing habitats (Nehlsen et al. 1991). Unfortunately, empirical data supporting this assertion at the landscape or basinwide scale are lacking in the published literature because fishery research has traditionally been conducted on smaller spatial scales. Thus, there is a need for empirically based models to investigate relationships between large-scale habitat and land management attributes and numbers of anadromous salmonids in their rearing environments.

Estuarine sediments support dense beds of submerged aquatic vegetation and provide habitat for a highly diverse benthic faunal community (Phillips, 1974; Rhoads, 1974; McCall and Tevesz, 1982). Studies have shown that sediment characteristics are important in determining submerged aquatic vegetation growth, germination, survival, and distribution (Phillips, 1974; Valiela, 1984; Short, 1987; Barko et al., 1991; Moore et al., 1993; Terrados et al., 1997; Koch et al., 2000; Halun et al., 2002). Sediment texture, in particular, affects diffusion of oxygen, rhizome elongation, and levels of nutrients and phytotoxins, such as sulfides (Thayer et al., 1984; Chambers et al., 1994; Fonseca et al., 1998). In a study in Sinepuxent Bay, MD, Demas (1998) attributed low submerged aquatic vegetation biomass to dense sandy sediments (referred to as subaqueous soils) with low fertility or soils with high sulfide concentrations as related to elevated levels of organic carbon. Sandy-textured sediments will tend to diffuse oxygen more readily, obstruct rhizome elongation, and have lower fertility (Thayer et al., 1984; Fonseca et al., 1998; Koch et al., 2000). Conversely, finer-textured sediments will tend to have higher fertility, allow rhizome elongation, and will tend to have greater levels of anoxia as pore water will have less interaction with the overlying water column (Koch et al., 2000). The effects of anoxia on eelgrass are complex as anaerobic conditions may stimulate germination (Moore et al., 1993); but also result in elevated sulfide levels, an inhibitor to leaf biomass production in more mature plants (Terrados et al., 1999), and a known toxin to eelgrass seedlings (Goodman et al., 1995). While there have been a few studies describing the sediment characteristics of eelgrass beds, what is presently known is “not sufficient to establish the ‘best’ sediment types for submerged aquatic vegetation growth at this time” (Koch et al., 2000). The goals of this study were to describe eelgrass distribution in a portion of a coastal lagoon in Rhode Island, USA, in relation to sediment characteristics and the associated subaqueous landscapes. To do this, we take a landscape-level pedological approach. An advantage of using the pedological approach to study shallow water substrates is that soils are studied as a collection of layers (horizons) that are linked both with depth and across the landscape (Demas et al., 1996; Demas and Rabenhorst, 1999; Bradley and Stolt, 2003). These subaqueous soils are studied and characterized by examining a combination of physical and chemical properties and characteristics, instead of a single component or parameter (i.e. grain size). Because subaqueous soil properties are a function of the estuarine environment, and thus reflect conditions, such as wave and current energy, water column attributes, the flora and fauna, and the pedogenic processes that operate in these subaqueous soils (Demas and Rabenhorst, 1999), soil types follow landscape unit boundaries (Bradley and Stolt, 2003). Landscape-level approaches, although developed in terrestrial ecosystems, have proven to be quite useful in understanding seagrass distributions (Marba` et al., 1994; Robbins and Bell, 1994, 2000; Vidondo et al., 1997; Fonseca and Bell, 1998;

Frederiksen et al., 2004). Using a soil science approach to study the sediment allows for classification of the sediment into a comprehensive hierarchical taxonomic system having both narrow and broad categories (Soil Taxonomy, Soil Survey Staff, 1999). This system has advantages over the traditional classification of sediment, which uses broad classes, such as mud, silty sand, muddy sand (see Flemming, 2000). For example, a sediment classification of silty sand (see Fegley, 2001) could be better described as a coarse-silty over sandy skeletal, Sulfaquent soil (Soil Survey Staff, 1999). This soil classification conveys that: the upper portion of the subaqueous soil has <18% clay and >70% silt-sized particles; the lower soil materials (to a meter) are sandy with >35% gravels and that there are considerable sulfides within 50 cm of the soil surface. Such additional knowledge of the physical and chemical characteristics of the sediment can be used for decisions regarding the use, management, and restoration of an estuary.

2. Materials and methods

2.1. Study area

Ninigret Pond is a 677 ha coastal lagoon in southern Rhode Island, USA (Fig. 1). This coastal lagoon is relatively shallow with water depths reaching 2.5 m in only isolated portions of the lagoon (Bradley and Stolt, 2002). An inlet channel provides an exchange of marine waters from Block Island Sound and the Atlantic Ocean into Ninigret Pond. The inlet channel of Ninigret has been stabilized with jetties since the 1950s (Conover, 1961). As a result of stabilization of the inlet, greater exchange of tidal water occurred within the pond in the 1950s and 1960s and a dramatic increase in eelgrass was observed (Conover, 1961; Thorne-Miller et al., 1983). Within Ninigret Pond, a 116 ha area was chosen to conduct detailed studies of eelgrass distribution. This area was chosen because of the range of eelgrass cover and the diverse shoreline geomorphology.

Eelgrass cover and subaqueous soil mapping and sampling subaqueous soil types were delineated within the study area. Bathymetric maps, formatted with isolines showing depths (i.e. contour lines), were used to identify subaqueous landforms (Bradley and Stolt, 2002). Fourteen subaqueous soil map units were identified and delineated (Fig. 1). Mapping units were delineated based on geographic location, subaqueous landforms, and 69 soil descriptions (Bradley and Stolt, 2003). Subaqueous soils were described and classified by examining the physical and chemical characteristics of the layers (horizons) that combined constitute the soil (Soil Survey Staff, 1993, 1999). Characteristics described in the field included soil color, color patterns, fluidity, textural class, shell and rock fragment content, and abundance of roots. A global positioning system (GPS) was used to record locations, where soils were sampled and described. At the soil sampling and description locations, eelgrass cover were estimated with a point-intercept transect (Bauer, 1943). The presence or absence of eelgrass was noted by a diver at 1 m intervals along a 15 m transect. For example, if eelgrass was present at 10 of the 15 m marks, then, cover was estimated as 67%. Average eelgrass cover was determined for each subaqueous soil map unit by calculating a mean for the transect data within each delineation. Water depth at most transect locations was measured to the nearest centimeter using an elevation pole. Although tidal fluctuations within Ninigret are small (7–16 cm; Boothroyd et al., 1985), water depths were standardized by adding or subtracting 10 cm for high and low tides, respectively. Representative soils (we will refer to these as typical pedons) from each subaqueous soil map unit were sampled for characterization. Locations of the typical pedons were based on the soil survey description data described above. A total of 17 typical pedons (the Gfb unit was sampled in three locations and the GMs in two locations (Table 1, Fig. 1)) were described, sampled, and analyzed to at least a meter. Soils were sampled using a vibracore, bucket auger, or a

McCauley peat sampler. Samples collected with a bucket auger and McCauley were kept in a cooler until transported to the lab, where they were frozen. Vibracores were sealed and transported to the lab, where they were stored at 5 °C. Vibracores were cut open lengthwise and horizons were identified and described. Subsamples of each horizon were immediately frozen and saved for laboratory analysis.

2.3. Laboratory analysis Soils were analyzed for both physical (relative amounts of sand, silt, clay, rock, and shell fragments) and chemical properties (pH, salinity, levels of organic carbon, CaCO₃, total nitrogen, and sulfides). Percent sand, silt, and clay were determined by using methods described by Gee and Bauder (1986). The sand fraction was separated by sieving and the percent clay was determined by pipette. Soil salinity was determined from a 10 g saturated paste extract (Soil Survey).



Figure 1. Map of the study area, sampling locations, and location of subaqueous soil map units in Iran.

Table 1. Soil-landscape units, family particle size, Great Group classification.

Subaqueous soil-landscape unit, family particle size and Great Group	Average eelgrass cover (% ± S.D.) (n)	USDA soil texture classification
Barrier Cove (Bc), coarse-silty Sulfaquents	100 ± 0 (2)	Very fine sandy loam
Shallow Lagoon Bottom (LBs), coarse-silty over sandy-skeletal Hydraquents	89 ± 3.81 (3)	Silt loam
Flood-tidal Delta Slope (FtdS), coarse-loamy Fluvaquent	82 ± 14 (4)	Silt loam
Lagoon Bottom (LB), fine-silty Hydraquent	66 ± 37.9 (15)	Silt loam
Barrier Submerged Glacial Beach (GBb), sandy-skeletal Endoaquent	13 ± 21.3 (7)	Fine sand
Glacial Fluvial Submerged Island (Gi), sandy-skeletal Endoaquent	8 ± 14.4 (5)	Gravelly coarse sand
Mainland Submerged Beach (sand phase) (GMs), sandy-skeletal Endoaquent	5 ± 10 (4)	Very fine sand
Glacial Fluvial Point Bar (Gfb), sandy-skeletal Endoaquent	5 ± 10 (4)	Loamy sand
Flood-tidal Delta Flat (Ftd), Psammaquent	0 (2)	Very fine sand
Back-barrier Flat (Bb), sandy Sulfaquent	0 (4)	Sand
Mainland Submerged Erosional Beach (GMb), sandy-skeletal Endoaquent	0 (9)	Coarse sand
Back-barrier Slope (Bbs), Psammaquent	0 (2)	Coarse sand
Mainland Cove (Mc), fine-silty Sulfaquent	0 (1)	Silt loam
Mid-lagoon Channel (Gch), sandy-skeletal Endoaquent	0 (2)	Gravelly coarse sand

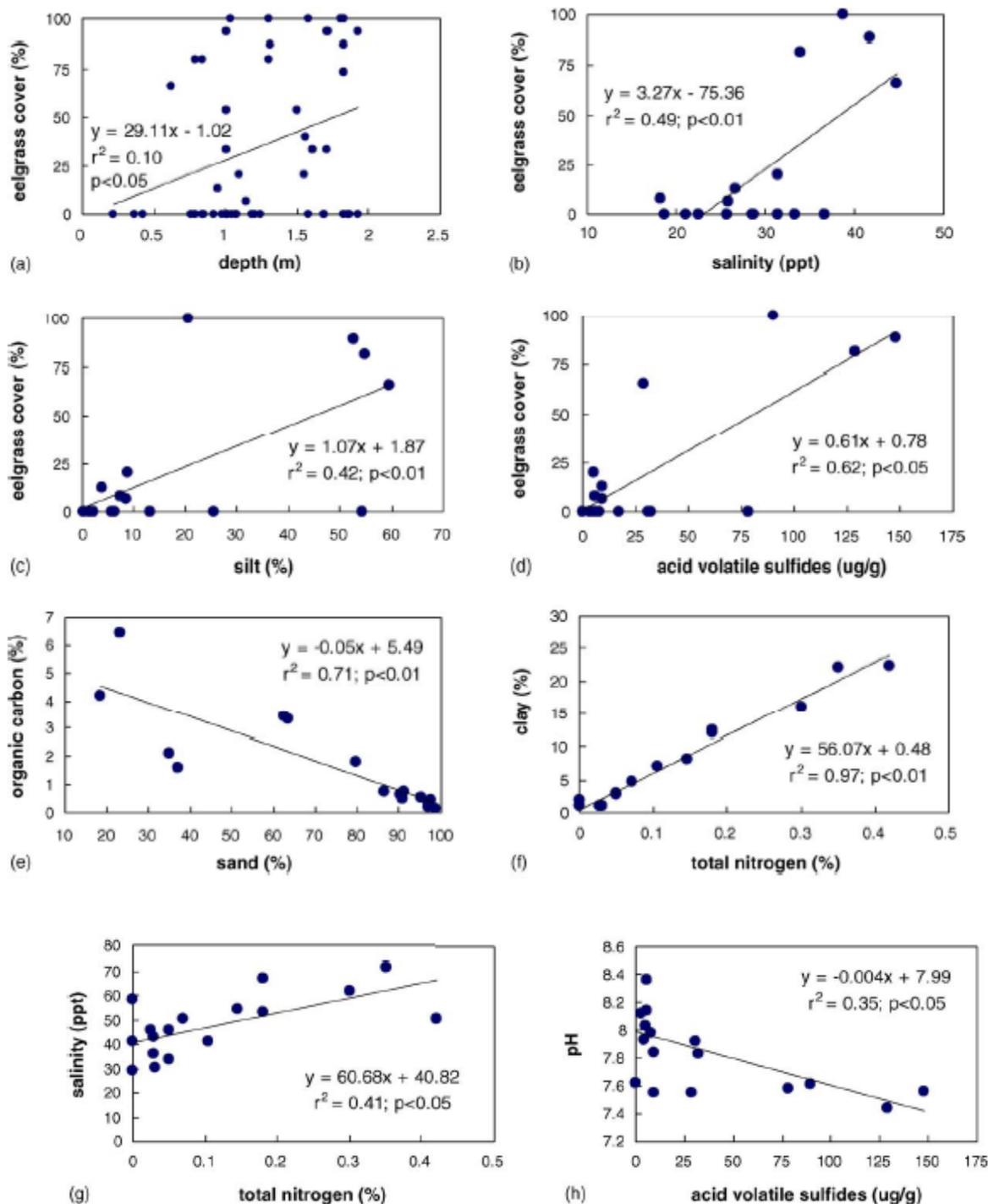
Table 1 Soil-landscape units, family particle size, Great Group classification (soils having the same kind of horizons and in the same sequence), eelgrass cover, and soil surface texture for each of the 14 map units in the Ninigret Pond study area measured using a Carlo Erba EA 1108 Elemental CHN Analyzer (Carlo-Erba, Milan, Italy). Acid-volatile and Crreducible sulfides (AVS and CRS, respectively) were measured following procedures similar to those described by Cline (1969), Fossing and Jorgensen (1989), and Ulrich et al. (1997). From 0.50 to 1.50 g of frozen soil was added to 150 ml serum bottles filled with N-gas. A second set of frozen samples was dried at 105 8C to determine air-dry weight. Within each serum bottle was placed a Zn-acetate (ZnAc) trap comprised of a 10 mm diameter by 10 cm long test tube filled with 2.5 ml of O₂-free 11% ZnAc (Ulrich et al., 1997). Oxygen was purged from the ZnAc solutions by bubbling N₂ gas through the solution for 20 min prior to pipetting 2.5 ml into the test tubes. The serum bottles were purged of O₂ with N₂ gas and stoppered. Soils were reacted with 12 ml of O₂-free 2N HCl. The HCl was added with a syringe through the rubber serum bottle cap. Serum bottles were rotated at 150 rpm overnight after which the ZnAc trap was removed for AVS analysis. Another ZnAc trap was added to the same serum bottles for CRS analysis, the bottles purged of O₂, and solutions of 4 ml of O₂-free 12N HCl and 8 ml of Cr²⁺ were added using a syringe and rotated overnight. The Cr²⁺ solution was prepared by adding 1 M CrCl₃·H₂O in 0.5N HCl to a modified Jones Reductor (Fossing and Jorgensen, 1989). The Jones Reductor was built from a separatory funnel filled with mossy Zinc and a glass wool filter that was kept under N₂ headspace, until the Cr³⁺ was reduced (approximately, 10 min). Concentrations of CRS and AVS in the ZnAc traps were determined using spectrophotometric methods. Absorbances were measured at 670 nm (Cline, 1969) and correlated to standards made from Na₂S₉H₂O in 11% ZnAc. Samples were diluted to stay within the linearity range for the standard (Cline, 1969). 2.4. Statistical analysis Soil properties of the surface horizon, which ranged from 5 to 20 cm in thickness, were statistically analyzed with respect to eelgrass cover. All locations and variables were tested for spatial autocorrelation using the Morans I index (ESRI, 2004).

A Pearson's correlation matrix was used to survey correlations between soil variables and eelgrass cover. Principal component analysis was used to identify significant relationships considering collinearity among variables. Relationships between subaqueous soil characteristics and eelgrass cover were investigated using multiple linear regression models. All statistical analyses were done using SPSS statistical software (SPSS, 2005).

RESULTS

Of the 64 locations measured for eelgrass cover, 52% had virtually no eelgrass cover (<10%), while 18% had very high (>90%) eelgrass cover (Table 1). A weak relationship between eelgrass cover and water depths ($r^2 = 0.10$, $p = 0.024$) was observed, whereas other environmental variables correlated more strongly (i.e. AVS: $r^2 = 0.62$, $p = 0.001$; salinity: $r^2 = 0.49$, $p = 0.002$; % silt: $r^2 = 0.42$, $p = 0.005$) (Fig. 2). Eelgrass was absent at depths between 0 and 0.5 m (Fig. 2), possibly indicating excessive solar irradiance or scour from wind or ice. The highest eelgrass cover occurred at depths between 1 and 2 m. Thirty-seven percent of the 35 locations sampled between these depths, however, contained no eelgrass indicating the influence of other physical variables at these locations on eelgrass distribution (Fig. 2). Four subaqueous soil-landscape units had more than 65% eelgrass cover: Barrier Cove (100%), Shallow Lagoon Bottom (89%), Flood-tidal Delta Slope (82%), and Lagoon Bottom (66%) units (Fig. 1, Table 1). Surface soil textures of these four units were silt loam and very fine sandy loam. These soils classified as coarse-silty Sulfaquents (soils having considerable

sulfides and dominated by silt particles to a depth of at least a meter), coarse-loamy Fluvaquents (soils dominated in the upper meter by both sand and silt, and having buried layers rich in carbon suggesting the location of relict eelgrass beds), and finesilty (silt and clay dominated) or coarse-silty over sandy skeletal (silty materials over sandy materials with >35% gravels) Hydraquents (soft soils with minimal bearing capacity).



These units were characterized by surface horizons with relatively high amounts of clay and silt (8 and 21% respectively), soil salinity (34 ppt), total nitrogen (0.15%), and relatively high levels of acid-volatile sulfides (29 mg/g). The other 10 soil map units had <15% eelgrass cover, with six map units with no eelgrass at all (Table 1). Sand textures dominated

9 of the 10 units with little or no eelgrass. These units tended to have higher amounts of rock and shell fragments, lower soil salinities, total nitrogen, and AVS than units with higher eelgrass cover, and classified as sandskeletal Endoaquents (subaqueous soils with >35% gravels) and Psammaquents (subaqueous soils dominated by sand throughout).

Table 2 Principal component analysis of all subaqueous soil variables and standardized factor loadings of most significant variables.

PCA component	% Variance explained (rotated)	Factor loadings (r)
1. Texture	43	Clay (0.81), silt (0.94), sand (-0.93)
2. Carbonaceous remains	13	Shell fragments (0.99), CaCO ₃ (0.75)
3. Non-calcareous rock	13	Rock fragments (0.97)
4. Interstitial salinity	12	Soil salinity (0.86)

The only exception was the Mainland Cove, which had similar classification and surface textures as the soils having >65% eelgrass cover. Based on the Morans I index of spatial autocorrelation, all variables at the 17 sampling locations were spatially independent. Eelgrass cover was significantly correlated to 7 of the 13 soil variables, although many were collinear (Fig. 2). Four principal components accounted for 81% of the total variance (Table 2). The first principal component reflected strong loadings (43%) for soil texture (Table 2). Shell fragments and percent calcium carbonate were the strongest loadings for component 2, while non-calcareous rock fragments and soil salinity were the strongest loadings for components 3 and 4, respectively (Table 2). A step-wise linear regression model showed that PC4 (soil salinity) explained the highest amount of variation in eelgrass cover ($r^2 = 0.30$, $p = 0.023$). The linear regression model for PC1 (soil texture) was also significant ($p = 0.01$) indicating a correlation between texture and eelgrass cover. A linear regression model using both PC1 and PC4 explained 56% of the variation in eelgrass cover ($p = 0.005$).

DISCUSSION

We observed a strong relationship between certain soil types, physical and chemical soil properties, and eelgrass cover. These findings are supported by other studies of the relationship between eelgrass beds and the physical and chemical properties of the sediment in which they are rooted (Harlin and Thorne-Miller, 1981; Kenworthy et al., 1982; Laugier et al., 1999).

These researchers concluded that eelgrass beds were able to modify substrate characteristics by initiating sedimentation of finer particles in the water column by slowing water currents. This phenomenon may be occurring in the Flood-tidal Delta Slope landscape unit in Ninigret Pond. The surface soil textures of the Flood-tidal Delta Slope are silt loam while below the surface, the soil layers are composed of alternating silty and sandy materials (coarse-loamy, Table 1). The silt loam materials likely represent particles trapped by eelgrass. Soils on the Flood-tidal Delta Slope are classified as Fluvaquents, meaning that

buried layers rich in carbon are present. These buried layers are silt loam-textured and contain eelgrass fragments indicating that eelgrass became established and was subsequently buried by sand. These observations suggest that where water depths are sufficient, eelgrass from the adjacent Lagoon Bottom was able to colonize the very fine sand of the Flood-tidal Delta Slope. As more plants colonized the habitat, finer particles are trapped, rhizomes extend through the softer substrate, and the size of the bed expands. Most eelgrass beds in the study area were found within the Lagoon Bottom, Shallow Lagoon Bottom, and Barrier Cove subaqueous soil-mapping units. Characteristically, Lagoon Bottom, and Barrier Cove units have surface horizons that are fine-textured and have relatively high levels of organic carbon and total nitrogen. These units are found within the low-energy depositional basin, where fine mineral and organic particles are deposited and nitrogen accumulates irrespective of the presence of eelgrass (Boothroyd et al., 1985). Thus, these soils develop their subaqueous soil properties independent of eelgrass cover. These data suggest that eelgrass beds in Ninigret are able to colonize and develop on two different soil types: the very fine sand of the Flood-tidal Delta Slope and the soft (low bearing capacity), fine-textured, and fertile soils associated with the low-energy depositional basin. Eelgrass occurs in a wide range of water salinities (0–35 ppt) from virtually fresh water to ocean water (Thayer et al., 1984). However, little work has been done investigating the edaphic salinity levels for eelgrass beds. Based on regression models of principle components, we found that soil salinity was the most important soil variable in explaining eelgrass cover in Ninigret Pond. Soil salinity levels within the study site for soils that supported most eelgrass ranged from 34 to 44 ppt. Lower salinity levels were measured in coarse-textured soils and in subaqueous soil map units adjacent to the shoreline (Mainland and Barrier Submerged Beach units), which suggests that lower soil salinities at these locations may be the result of freshwater inputs. Additionally, the subaqueous soils adjacent to the mainland had lower soil salinities than the soils adjacent to the barrier (19 ppt versus 27 ppt) suggesting that more groundwater is entering the pond along the mainland shoreline than the barrier shoreline. Groundwater inputs may have implications for eelgrass restoration sites, as areas of major groundwater inputs have been linked to declines in eelgrass within Ninigret as a result of eutrophication from an increase in housing development (Taylor et al., 1995). These decreases may be the result of a combination of elevated nutrient and lower salinity levels. Water depth clearly plays a part in eelgrass distribution in Ninigret Pond as eelgrass was absent at depths between 0 and 0.5 m. When considering all depths, however, eelgrass cover and water depth was only weakly related ($r^2 = 0.10$; Fig. 2). In addition, although the greatest eelgrass cover occurred at water depths between 1 and 2 m, 37% of the 35 observations at these depths were void of eelgrass. Robbins and Bell (2000) reported similar results and suggested that water depth was not an adequate predictor of seagrass distribution. These researchers suggested that seagrass distribution patterns may be directed by external forces related to bioturbation or hydrodynamic effects, and/or related to variations in sediment composition.

Table 3. Model selection results for logistic regression models containing landscape habitat predictor variables and count categories of steelhead parr sampled during 1990 ($n = 79$ subwatersheds in USA).

Candidate model	QAICc	Δ QAICc	Δ QAICc weight	% of maximum Δ QAICc weight
Precip, Unconsol	81.51	0	0.280	100
Precip, Mafic	82.10	0.59	0.208	74.3
Precip, Slope, Unconsol	82.96	1.45	0.136	48.6
Sumtemp, Mafic	83.23	1.72	0.119	42.5
Precip, Slope, Mafic	84.28	2.77	0.070	25.0
Precip, Slope, Unconsol, Georoad	84.90	3.39	0.051	18.2
Unconsol, Georoad, Mngclus	85.76	4.25	0.034	12.1
Slope, Mafic	85.82	4.31	0.033	11.8
Sumtemp	86.39	4.88	0.024	8.6
Georoad	87.05	5.54	0.018	6.4
Precip	88.30	6.79	0.009	3.2
Global Model	88.58	7.07	0.008	2.9
Precip, Slope, Georoad	89.44	7.93	0.005	1.8
Mngclus	91.89	10.38	0.002	0.7
Georoad, Mngclus	92.76	11.25	0.001	0.4
Slope, Mngclus	94.13	12.62	<0.001	0.2
Sumtemp, Mngclus	94.73	13.22	<0.001	0.1

Water clarity has been shown to be one of the main environmental variables that drives eelgrass distributions. In our study, however, subaqueous soil-mapping units, which were directly adjacent to one another and where there is likely no difference in water clarity, had very different distributions of eelgrass. For example, the Back-barrier Slope (BbS) soil map unit just east of Marshneck Point in Fig. 1 is devoid of eelgrass, whereas the adjacent Barrier Cove (Bc) unit has nearly 100% eelgrass cover (Table 1). Water clarity, at least down to 1.8 m, would very likely be identical over such a short distance, suggesting that the differences in eelgrass distribution between these two soil-landscape units can be explained mostly by the physical and chemical characteristics of the subaqueous soils or hydrodynamics.

Eelgrass colonization may be hindered on the Flood-tidal Delta Flat, Back-barrier Flat, Submerged Glacial Beaches, Islands and Point Bars by the dense, low-fertility, and sandy and/or gravelly characteristics of these soils which affects rhizome elongation, seed germination, and nutrient levels (Harlin and Thorne-Miller, 1981; Thayer et al., 1984; Short, 1987; Moore et al., 1993; Fonseca et al., 1998). In addition, landscape parameters related to wave exposure and possibly ice-scour could restrict eelgrass growth in the Flood-tidal Delta Flat, Back-barrier Flat and the Submerged Beaches. Excessive depths and currents may also affect eelgrass establishment in the Mid-lagoon Channel. Our work suggests that Further, model averaging explicitly incorporates model selection uncertainty into model parameter estimates and also provides a statistically rigorous means to handle the common situation where there is no single model that is clearly better than other models.

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