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Predicting submerged aquatic vegetation cover and occurrence in a Lake Superior estuary

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ABSTRACT

Submerged aquatic vegetation (SAV) provides the biophysical basis for multiple ecosystem services in Great Lakes estuaries. Understanding sources of variation in SAV is necessary for sustainable management of SAV habitat. From data collected using hydroacoustic survey methods, we created predictive models for SAV in the St. Louis River Estuary (SLRE) of western Lake Superior. The dominant SAV species in most areas of the estuary was American wild celery (*Vallisneria americana* Michx.). Maximum depth of SAV in 2011 was approximately 2.1 m. In regression tree models, most of the variation in SAV cover was explained by an autoregression (lag) term, depth, and a measure of exposure based on fetch. Logistic SAV occurrence models including water depth, exposure, bed slope, substrate fractal dimension, lag term, and interactions predicted the occurrence of SAV in three areas of the St. Louis River with 78–86% accuracy based on cross validation of a holdout dataset. Reduced models, excluding fractal dimension and the lag term, predicted SAV occurrence with 75–82% accuracy based on cross validation and with 68–85% accuracy for an independent SAV dataset collected using a different sampling method. In one area of the estuary, the probability of SAV occurrence was related to the interaction of depth and exposure. At more exposed sites, SAV was more likely to occur in shallow areas than at less exposed sites. Our predictive models show the range of depth, exposure, and bed slope favorable for SAV in the SLRE; information useful for planning shallow-water habitat restoration projects.

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Introduction

Submerged aquatic vegetation (SAV) provides the biophysical basis for multiple ecosystem services in aquatic ecosystems (Kahn and Kemp, 1985), including coastal systems in the Laurentian Great Lakes (Sierszen et al., 2012). SAV is a component of rearing and adult habitat for commercially and recreationally important Great Lakes sport fishes (Cvetkovic et al., 2010; Jude and Pappas, 1992; Randall et al., 1996). SAV beds provide habitat for invertebrates (Krieger, 1992) and forage for waterfowl (Knapton and Petrie, 1999; Prince et al., 1992). SAV also has an important role in ecosystem functions including nutrient cycling (Carpenter and Lodge, 1986; Wigand et al., 2000), wave attenuation (Christiansen et al., 1981; Koch, 2001), and sediment and water quality dynamics (Barko et al., 1991; Best et al., 2008; Madsen et al., 2001).

The St. Louis River Estuary (SLRE) is located within the St. Louis River "Area of Concern" (AOC; http://www.epa.gov/glnpo/aoc/stlouis/index.html; accessed 7 August 2013), an international designation recognizing that the system has experienced significant environmental degradation, and some ecosystem services or "beneficial uses" of the estuary have been lost or are degraded. In the SLRE AOC, beneficial use impairments include those that are related to SAV abundance and distribution. An example is the beneficial use impairment "loss of fish and wildlife habitat." SAV is a critical shallow-water habitat for fish and wildlife populations. In the SLRE, much of this habitat has been lost or degraded due to sediment contamination, wetland filling, and channel dredging. For this use impairment to be "delisted" for the AOC, shallow water and wetland habitat must be restored. Prior to restoration, it may be necessary to remediate sediments containing non-native material (e.g., wood waste, industrial debris) or sediments contaminated with metals and organic compounds. Following remediation and in areas of uncontaminated sediments, restoration of natural substrates and bathymetric contours to within limits favorable for SAV (and other wetland types) is a key restoration objective (SLRCAC, 2002).

Efficient SAV restoration planning requires reliable information about the physical habitat requirements that underlie the local distribution of native SAV species. The objective of this study was to examine factors accounting for variation in the distribution and abundance of

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SAV in the SLRE within the context of spatially explicit predictive models. These models can inform restoration efforts and conservation in the SLRE and elsewhere and will enhance understanding of ecological response to changing conditions in Great Lakes estuaries.

The St. Louis River Estuary

The SLRE was formed when post-glacial isostatic rebound caused Lake Superior to rise in the northeast, flooding the lower portion of the St. Louis River at the southwestern end of the lake (Ojakangas and Matsch, 1982). The SLRE is a Great Lakes "rivermouth" ecosystem as defined by Larson et al. (2013). The 5000-ha estuary forms a section of the state border between Duluth, Minnesota and Superior, Wisconsin (Fig. 1). The estuary is at the terminus of the St. Louis River Basin (9250 km^2), but also receives discharge from several tributaries, the largest of which is the Nemadji River (1140 km^2 basin area). Land cover in the St. Louis River watershed is 94% forest, wetland, and water; 4% agriculture; and 2% developed.

Allouez Bay at the southeast end of the SLRE (Fig. 1) is a shallow, semi-enclosed embayment with minimal human development. Superior Bay is a lagoon formed behind a natural 16 km-long sand bar and is open to Lake Superior at its northwestern and southeastern end. The bay contains the outer Duluth–Superior Harbor, a large commercial seaport, with extensive ship channels and industrial development. St. Louis Bay includes the inner harbor and is likewise industrialized and channelized. It is shallower than Superior Bay and is less hydrologically influenced by Lake Superior. Spirit Lake, a large flooded backwater of the river, is generally shallow and undeveloped. Above Spirit Lake, the estuary is riverine.

Physical aspects of the SLRE relevant to this study are its relative shallowness (mostly <3 m deep outside of dredged shipping channels and slips), the general absence of coarse substrates except in the upper, riverine portion of the estuary (which is not included in this study), and the restricted open water period, usually from April through November. Estuary morphometry is irregular and fetch distances are highly variable. For the prevailing northeast wind, maximum fetch distance is ≈4.5 km. Tributaries to the Allouez Bay, the Nemadji River, and the Pokegama River (Fig. 1) drain highly-erodible clays deposited in Glacial Lake Duluth (Magner and Brooks, 2008) and these areas are generally more turbid than the rest of the SLRE (DeVore, 1978).

SAV beds are widespread across shallow areas of the SLRE. A vegetation survey of the SLRE conducted in 2010 (John Lindgren, MN DNR, unpublished data) collected 21 species of SAV at 688 sites. At sites where SAV was present, the most frequently collected species (present at 83% of sites) was American wild celery, *Vallisneria americana* Michx.

In June 2012, a 500-year recurrence interval flood occurred across the lower St. Louis River Basin (Supplementary Information Appendix A; Czuba et al., 2012). To evaluate the effects of this event on SAV, we resurveyed portions of Allouez Bay, St. Louis Bay, and Spirit Lake in 2012, post-flood. This aspect of our study was unplanned and opportunistic, but we include the results here because they provide insight into interannual variation in SAV across the SLRE.

Methods

Survey methods and instrumentation

Methods for sampling SAV include grab or rake sampling (Havens et al., 2002; Rodusky et al., 2005; Skubinna et al., 1995), direct observation by diving or video (Hudon et al., 2000), remote sensing (Narumalani et al., 1997; Wolter et al., 2005), photo interpretation (Zhu et al., 2007), and hydroacoustic methods (Depew et al., 2010). In the SLRE, SAV beds are often patchy, turbidity varies considerably among areas (DeVore, 1978) and over time, and the growing season is short. Given these conditions, hydroacoustic survey methods were the best option for generating the extensive, high resolution data needed for modeling.

From late July through mid September in 2011, we surveyed SAV in Allouez Bay, part of Superior Bay, eastern half of St. Louis Bay, and Spirit Lake (Fig. 1). Transects were aligned along gridlines plotted on a GPS unit (Garmin GPSMAP 536, Garmin International, Olathe, KS) aboard the survey vessel. Total survey transect length in 2011 was 365 km. In 2012, we resurveyed transects in each area during the same weeks as in 2011. The survey vessel was a 5.7-m long flat-bottomed aluminum boat with outboard power. Because of vessel size, the operational depth limit for the hydroacoustic survey was ≈0.5 m. This means that models based on our data should not be extrapolated to shallower depths.

Hydroacoustic instrumentation included narrow beam (6°), 120 and 420 kHz BioSonics transducers, and an onboard BioSonics DT-X digital echosounder (BioSonics Inc., Seattle, WA). Data were captured on a notebook computer using Visual Acquisition software (BioSonics, 2010). Hydroacoustic data for each GPS "fix" along each transect was summarized into SAV indicators for that GPS location. Many additional details of hydroacoustic methods and instrument and software settings used in this study are given in Supplementary Information Appendix B.

An underlying assumption of this method is that the digital signal is detecting SAV and is not systematically detecting something else. In areas of relatively shallow water, where SAV was visible from the boat, we could confirm that the transducer was passing over visible SAV beds or bare bottom from the display of digital signal from the echosounder. The reliability of this method for surveying aquatic vegetation has been demonstrated, and its use for this purpose is widespread (e.g., Depew et al., 2010; Sabol et al., 2009; Valley et al., 2005; Winfield et al., 2007).

Previous recent SAV sampling (Brady et al., 2010) and our own observations showed that SAV was almost never collected deeper than 2.5 m in the SLRE. We therefore excluded locations with a mean depth > 2.5 m to focus the predictive modeling on sources of variation in SAV in areas of the estuary within the depth range currently capable of supporting SAV.

Bottom typing parameters were extracted from digital data from the 120 kHz transducer using Visual Bottom Typer (VBT) V. 1.12 software (BioSonics, 2007). We retained three parameters related to substrate characteristics: E1, E1′, and fractal dimension (BioSonics, 2007). E1 is based on the first part of the bottom echo for a ping and may correspond to bottom roughness. E1′ is based on the second part of the bottom echo for a ping and may correspond to bottom hardness. Fractal dimension has been correlated with physical and chemical properties of bed sediment (Anderson and Pacheco, 2011).

We determined the fetch distance by wind direction for each location (0–360 in 10-degree increments) using the SPM-restricted method of Rohweder et al. (2008). Wave height is a function of fetch, wind speed, and wind duration (Keddy, 1982). The relative exposure index (after Keddy, 1982) integrates these variables into an index computed as the sum across wind directions of mean monthly wind for April–October from each direction multiplied by the proportion of the month that the wind was blowing from that direction, scaled from 0 to 1, and multiplied by the fetch distance for the direction. Hourly wind data were from Sky Harbor Airport on Superior Bay (46.7219 N, 92.0433 W). Bed slope in percent was calculated from bathymetry raster data (10 × 10 meter cell size) using the Slope tool in ArcGIS for Desktop 10.1 which is based on the average maximum technique (Burrough and McDonell, 1998).

We used the measured SAV percent cover at the location immediately previous to each useable record location along each transect as a lag variable to correct for possible serial autocorrelation of model error. SAV percent cover, substrate parameters, corrected depth, and exposure and bed slope data were combined in Arc-GIS.