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Combining hydroacoustic and point-intercept survey methods to assess aquatic plant species abundance patterns and community dominance

RAY D. VALLEY, MATTHEW B. JOHNSON, DONNA L. DUSTIN, K. DEAN JONES, MICHAEL R. LAUENSTEIN, JUSTIN NAWROCKI*

ABSTRACT

Many ecosystem goods and services are derived from aquatic plant–dominated environments and the abundance and composition of aquatic plant communities affects habitat, recreation, angling, aesthetics, and commerce. We describe standardized hydroacoustic methodology that complements species composition surveys and generates comprehensive aquatic plant abundance data with little additional assessment or analysis effort than is already put forth for species surveys. Using data from 22 lakes across the United States, collected by biologists with varying levels of expertise, we compare hydroacoustically derived biovolume with two other semiquantitative measures of whole-lake abundance (frequency of occurrence and "rake fullness"). Although we documented some significant correlations between hydroacoustically derived biovolume and frequency and rake fullness, frequency or rake fullness was difficult to interpret biologically on a lakewide scale. We also describe a dominance index that incorporates both species composition and vegetation biovolume to evaluate the degree that a species dominates a local assemblage. We found that the extent of aquatic plant growth and invasive dominance was related to lake productivity with highest biovolume and dominance occurring in mesotrophic to eutrophic study lakes. Using both empirical and simulated data, we also found no significant differences between dominance calculated from a simple metric that gives equal weight to all species at a survey site and a metric that incorporated rake fullness for each species.

Key words: acoustics, biovolume, invasive, macrophytes, mapping, SAV.

INTRODUCTION

The cumulative effects of changes to the climate, landscapes, and aquatic environments are having profound effects on lake ecosystems (Carpenter et al. 2007). Aquatic plants are key resilience mechanisms in natural lake systems that have important roles in maintaining "clear water regimes" (Carpenter and Cottingham 1997, Genkai-Kato and Carpenter 2005). As intrinsic resilience becomes impaired by the cumulative effects of various stressors (e.g., high runoff from urban or agricultural land uses, climate change), lakes become unstable and susceptible to regime shifts (Genkai-Kato and Carpenter 2005, Valley and Drake 2007). A lake "regime" is characterized not only by traditional pelagic water chemistry parameters (e.g., chlorophyll and phosphorus) but also by aquatic plant variables, such as community composition and abundance. Several studies demonstrate that as lakes become more eutrophic, species diversity declines and invasive species become more common (Beck et al. 2010, Sass et al. 2010, Mikulyuk et al. 2011, Radomski and Perleberg 2012). Further, with increased eutrophication, the depth of plant colonization declines and aquatic plant biovolume and patchiness becomes increasingly variable (Valley and Drake 2007).

Investigators have used various methodologies to analyze and monitor aquatic plant communities (reviewed by J. D. Madsen and R. M. Wersal, unpub. data). Methods used range from presence–absence sampling along transects or points, global positioning system (GPS) delineation of beds, diver or rake assessments of biomass, and remote sensing tools, such as satellite imagery or hydroacoustics. Two methods, point-intercept and hydroacoustic mapping, are gaining increased attention in the United States because of their objectivity and repeatability, ease of implementation, and scalability (e.g., small plot or whole lake; J. D. Madsen and R. M. Wersal, unpub. data).

The point-intercept method involves sampling aquatic plants at a grid of sampling points on a waterbody and recording the presence of plant species with a rake thrown from the boat (Madsen 1999). Several published studies have used point-intercept data to document effects of herbicides (Madsen et al. 2002, Nault et al. 2014), ecological patterns of species composition (Beck et al. 2010, Mikulyuk et al. 2011), as well as correlations between plant frequency and other aquatic biota (Cheruvelil et al. 2002, Bremigan et al. 2005). However, presence–absence data from point-intercept surveys is not sensitive to changes in biomass or biovolume, and very large changes in plant abundance must occur before being detected by presence–absence sampling methodology (Valley et al. 2006). Consequently, a range of protocols adapt species presence–absence methods by using

*First, second, fifth authors: Aquatic Biologist, Director of Business Development, and Global Lead, Navico Inc., 1229 Tyler St. NE No. 120 Minneapolis, MN 55413. Third author: Senior Research Biologist, Minnesota Department of Natural Resources, 14583 County Hwy 19, Detroit Lakes, MN 56501. Fourth author: Senior Biological Scientist, University of Florida, Center for Aquatic and Invasive Plants, 700 Experiment Station Road, Lake Alfred, FL 33850. Sixth author: Graduate Student, North Carolina State University, Crop Science Department, Box 7620 Raleigh, NC 27695. Corresponding author's E-mail: ray.valley@navico.com. Received for publication January 7, 2014 and in revised form May 16, 2014.

qualitative weighting schemes to infer relative abundance (Jessen and Lound 1962, Deppe and Lathrop 1992, MI DEQ 2005, Hauxwell et al. 2010). Two primary shortcomings with qualitative weighting are correspondence to actual biological measures like biomass and repeatability across surveyors.

Hydroacoustics is a long-established, objective, and quantitative method for mapping aquatic plant abundance in lakes (Maceina 1980, Thomas et al. 1990, Valley et al. 2005, Sabol et al. 2009). Until recently, hydroacoustic data collection was a dedicated process that required expensive hardware, strict data collection requirements, and specialized understanding of hydroacoustic outputs and data analysis in geographic information systems (GIS). More recently, advances in low-cost consumer hydroacoustics, GPS, and automated cloud-based technologies have allowed for passive hydroacoustic data collection of aquatic plant abundance data while conducting traditional species surveys (Netherland and Jones 2012). Today, practitioners can leverage the strength of both methods with little additional survey effort or expertise. As such, we describe a method that combines outputs from both survey techniques to derive meaningful statistics on plant species composition and abundance.

First, we investigate broad patterns of hydroacoustically derived, aquatic plant biovolume (percentage of the water column occupied by vegetation) as it relates to lake productivity and examine correlations with frequency of occurrence and relative abundance (rake fullness). Next, we describe and compare two indices of aquatic plant species dominance using simultaneously collected hydroacoustic biovolume and species presence–absence data in 22 lakes distributed across Minnesota, Wisconsin, North Carolina, and Florida. Study lakes varied from undisturbed, oligotrophic systems to urban, eutrophic systems infested with invasive species to systems bordering on too productive and too turbid to support much plant growth.

MATERIALS AND METHODS

Study area

Study lakes and data sets were opportunistic because involved partners assessed lakes for a variety of independent study or management needs. Numerous staff from three state natural resource agencies (Minnesota and Wisconsin departments of natural resources, Florida Fish and Wildlife Conservation Commission, and two universities (University of Florida, Gainesville, and North Carolina State University) assisted with data collection and adhered to standard data-collection protocols. Where possible, lakes were chosen to represent a wide range of geographic/geologic, environmental, and management gradients (Table 1). Lakes ranged from small, oligotrophic, glacial lakes in northern Minnesota to large, highly productive, karst seepage lakes in Florida. All aquatic plant data were collected between 2011 and 2013 (Table 1). Several Minnesota and Wisconsin lakes were managed for Eurasian watermilfoil (*Myriophyllum spicatum* L.) infestations, and hydrilla [*Hydrilla verticillata* (L.f.) Royle] was managed in both Florida study lakes.

Point-intercept

The point-intercept method (Madsen 1999) was used on all lakes to determine the frequency of occurrence of aquatic plant species in the littoral zone of each lake. Survey points ranged in spacing from 30 to 305 m apart, depending on lake size. Protocols for spacing points were based on Mikulyuk et al. (2010) for Wisconsin lakes, long-term monitoring protocols for Minnesota Lakes (http://www.dnr.state.mn.us/fisheries/slice/index.html), and informal protocols for Florida and North Carolina lakes. Each point was visited, and a double-headed rake, with or without a handle, was either thrown or used to grab a sample of plants near the boat. A qualitative weighting of rake fullness from zero to three was applied to each surveyed point in all Wisconsin and Florida lakes (Hauxwell et al. 2010). In all other lakes, only presence–absence data from species survey points were collected or incompatible relative-abundance schemes were used.

Hydroacoustic surveys

Hydroacoustic and GPS data were logged simultaneously during point-intercept surveys and analyzed for the percentage of area covered (PAC) and the biovolume percentage (Valley et al. 2005). Hydroacoustic data were collected with Lowrance HDS[1] consumer echosounders integrated with wide area augmentation system (WAAS)–corrected GPS. Data were logged at a rate of 15 to 20 data signals s^{-1} from a 200-kHz transducer with a 20° beam angle. Data were analyzed with BioBase 5.2 software[2]. BioBase is a cloud-based software platform that automates acoustic and GPS signal processing and creates GIS data layers of depth, PAC, plant height, and biovolume (Contour Innovations 2013). Map outputs were synced with users' sonar logs in an online account, so they could verify raster map outputs and edit outputs where needed.

The GPS position in Lowrance HDS is typically recorded every second, and bottom features from pings that elapse between positional reports are averaged for each coordinate and data point. Therefore, the attribute value (e.g., depth, plant height) of each data point along a traveled path comprises a summary of 5 to 30 pings. Each ping goes through a quality test to determine whether features can be extracted and, if so, is sent on to feature-detection algorithms. Those failing quality assurance tests are removed from the set considered for summarization.

Acoustic signals from the HDS 200-kHz transducers travel through submersed vegetation canopies on their way to bottom sediments. Bottoms typically register a sharper echo return than the aquatic vegetation above. The distance between the bottom acoustic signature and the top of the plant canopy is recorded as the plant height for each ping. Plant heights were averaged across all pings within a GPS coordinate point. Plant heights from pings within a coordinate point that together averaged less than 5% of the depth were considered not vegetated to minimize false detections by bottom detritus or other debris (i.e., minimum biovolume in a BioBase point feature = 5%). Any points that exceeded that 5% threshold were considered

TABLE 1. STUDY LAKES ORDERED BY TOTAL PHOSPHORUS (TP) CONCENTRATION.

Lake	State	Location	Size (ha)	Maximum Diameter (m)	TP (ppb)	Eurasian Watermilfoil (EWM) or Hydrilla (HYD)	Date Detected	Managed[1]	Species Survey Point Spacing (m)	Species Richness[2]	Date of Survey
Horseshoe	MN	46.8522N; −94.4734W	105	15.5	7	—	NA	No	80	20	8/17/2011
Portage	MN	47.0104N; −94.5522W	112	25.6	8	—	NA	No	80	21	8/17/2011
Bass	MN	46.9080N; −93.9594W	78	16.8	9	—	NA	No	80	23	8/18/2011
Sandbar	WI	46.3691N; −91.5294W	48	14.9	10	EWM	2004	Yes	40	16	7/11/2012
Hand	MN	46.8534N; −94.3145W	117	17.4	11	—	NA	No	80	29	8/16/2011
Seven Island	WI	45.4248N; −89.4693W	56	9.5	12	EWM	2004	Yes	40	20	8/9/2012
Berry	WI	44.8893N; −88.4789W	84	8.2	14	EWM	2007	Yes	50	24	7/3/2012
Elk	MN	47.1885N; −95.2186W	124	28.3	15	—	NA	No	80	16	8/9/2011
Tracy	FL	28.1115N; −81.6342W	51	6.7	18	HYD	1997	Yes	90	5	3/6/2013
Eagle	MN	47.0279N; −95.0987W	171	23.5	19	—	NA	No	80	20	8/11/2011
Waccamaw[3]	NC	34.2798N; −78.5078W	3588	4.0	20	HYD	2012	No	305	7	11/6/2012
Gray's Bay[4]	MN	44.9543N; −93.4946W	73	8.5	21	EWM	1986	Yes	50	21	8/24/2012
Gideon's Bay[4]	MN	44.9083N; −93.5791W	130	18.0	21	EWM	1986	Yes	50	21	8/24/2012
St. Alban's Bay[4]	MN	44.9075N; −93.5525W	65	11.3	21	EWM	1986	Yes	50	21	8/26/2012
Swan	WI	43.5444N; −89.3660W	165	25	28	EWM	2002	No	40	8	6/19/2012
Gibbs	WI	42.7825N; −89.1810W	30	7.0	29	EWM	1968	No	37	7	6/1/2012
Orchard	MN	44.7008N; −93.3090W	95	10.0	34	—	NA	No	80	10	7/17/2012
Wingra	WI	43.0546N; −89.4189W	136	4.3	43	EWM	1950's	Yes	50	14	8/26/2013
Istokpoga	FL	27.3656N; −81.2878W	9944	3.0	64	HYD	1979	Yes	285	17	2/25/2013
Round	WI	45.6601N; −92.5791W	84	8.2	71	EWM	2003	Yes	30	13	7/24/2012
Little Green[5]	WI	43.7366N; −88.9854W	194	8.5	199	EWM	1993	Yes	74	8	6/21/2012
Lost	WI	43.4464N; −88.9655W	102	2.5	309	—	NA	No	59	4	6/17/2013

Epilimnetic TP was summarized from state water quality databases for summer periods (June 1–September 30) during the past 10 yr.
[1]Qualitative descriptor of whether the lake has a history of invasive species management.
[2]Total submersed and floating-leaf species sampled.
[3]Lake is humic stained.
[4]Discrete bays of Lake Minnetonka.
[5]Lake is heavily infested with invasive curlyleaf pondweed, which results in prolific growth in spring, then senescence by midsummer (typically early July in the upper Midwestern United States).

vegetated in PAC calculations. To prevent bottom debris or other phenomenon (e.g., aquatic insect emergence) from generating false vegetation detections at depths well beyond the deepest rooting depth of vegetation, BioBase discards 2% of the deepest coordinate points registering vegetation. To prevent false detections in shallow water where target separation between the transducer and bottom is very narrow, the BioBase minimum depth for vegetation detection was set at 0.73 m.

Processed depth and vegetation point features are sent to an ordinary point kriging algorithm that predicts values in unsampled locations based on the geostatistical relationship of the input points. The kriging algorithm is an "exact" interpolator in locations where sample points are close in proximity and do not vary widely. Kriging smooths bottom feature values where the variability of neighborhood points is high. Given the high ping and GPS report rates, aggregated hydroacoustic data sets are typically large, ranging from thousands to tens of thousands of data points or grid nodes for each map data set created. Thus, standard errors and confidence intervals surrounding means from hydroacoustic data sets are generally always small.

Data analysis

Data were exported from BioBase as x,y,z grid tables and imported into ESRI's ArcGIS 10.1 software[3]. Grid-point features of biovolume were converted to raster grids using spatial analyst for ArcGIS. This allowed for the automated extraction of grid values for each point-intercept survey point, and a biovolume data column was appended to the point-intercept data file, so each survey point had a biovolume estimation. Therefore, the point-intercept sample size dictated the hydroacoustic sample size for species-specific results. The entire hydroacoustic data set was used for nonspecies-specific summaries, such as overall PAC and plant biovolume, for each lake. A 4.7-m-deep littoral boundary was established as the zone of analysis for all statistical summaries. Although the depth of plant colonization varied across study lakes, establishing a uniform analysis zone where most plant growth occurred, allowed for cross-lake comparisons.

Dominance index

A dominance-index point value was calculated for each species at each point-intercept survey point that incorporated species' contribution to the richness of all submersed and floating leaf species at the survey point with the biovolume of all vegetation at that point. A species was dominant if it was the only species present at a sample site and it grew almost to the surface of the lake. It was not dominant if there were several other species present at the sample point or if vegetation growth was sparse (according to the biovolume percentage) at the sample point. Specifically,

$$\text{Dominance} = \frac{SpeciesA(1,0)}{Localrichness(totalspeciespresentatpoint)} \times Biovolume\,(expressedasaproportion) \quad [1]$$

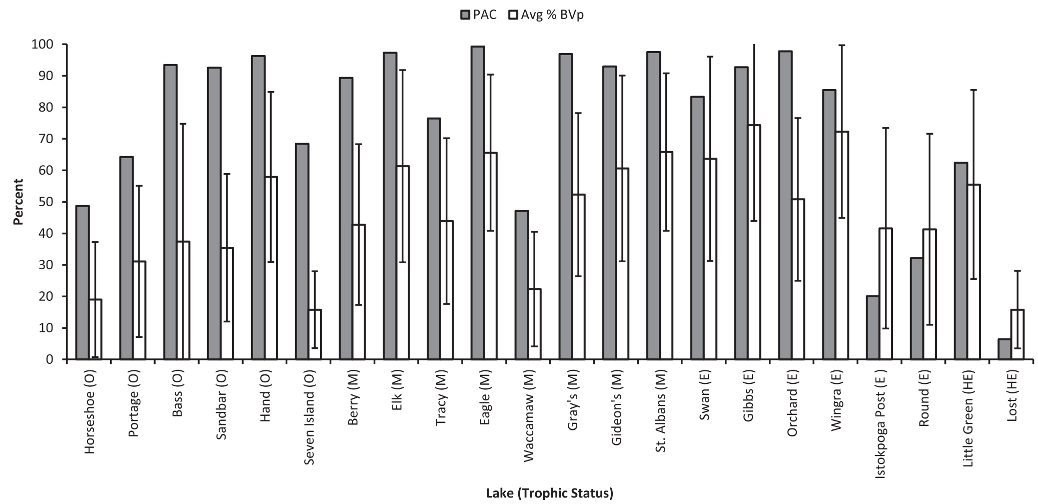

Figure 1. Percentage of area covered (PAC) and average biovolume percentage in vegetated areas less than 4.7 m (BVp ± SD) for 22 study lakes ordered by productivity: O = oligotrophic, M = mesotrophic, E = eutrophic, HE = hypereutrophic. Gray's, Gideon's, St. Alban's bays of Lake Minnetonka (Minnesota, USA); Berry Lake (Wisconsin, USA) and Istokpoga (Florida, USA) were treated with aquatic herbicides before this study.

This simple dominance metric gives equal weight to all species sampled, regardless of their relative abundance. For comparison purposes, we also calculated a weighted dominance index that incorporated rake-fullness relative abundance in lakes where it was assessed, such that

$$\frac{Relative\ \ weighting\ \ of\ \ speciesA}{Local\ \ sum\ \ of\ \ ranks} \times Biovolume\ \ (expressed\ \ as\ \ a\ \ proportion) \qquad [2]$$

"Simple" dominance (Equation 1) was estimated for all point-intercept survey points in all surveyed lakes $\leq$ 4.7 m deep, and "Rake fullness" dominance (Equation 2) was also computed for Wisconsin and Florida lakes where rake fullness was recorded and compared with the simple method (Equation 1).

A random data set of 100 point-intercept survey points for a hypothetical lake was also generated to compare both simple and rake fullness methods. Because it is rare to sample more than five species at a survey point, even in species-rich lakes, we set that number as our local species richness pool from which to generate random dominance values for both simple and rake fullness simulations. Presence–absence was randomly assigned to the five hypothetical species, and biovolume at each site was also randomly assigned. For the rake fullness simulation, the same process was applied, but for ranks that were randomly determined on a scale of zero to three. Maximum site dominance was assessed for each hypothetical survey point, averaged across all 100 points for both methods, and compared.

As a demonstration, dominance was also analyzed spatially to understand three-dimensional growth patterns of an invasive species in one lake (Wingra). Point values of simple dominance were modeled using a simple kriging algorithm of the Eurasian watermilfoil dominance values (n = 419) in Surfer 10.2 software[4] (Golden Software 2012, Valley et al. 2010). The 0.5 dominance contour, which indicated the area of dense, near-monospecific growth, was selected and converted to a polygon in ArcGIS.

Where statistical means were compared across lakes, 2 standard errors (SE) (which approximated a 95% confidence interval with our sample sizes) were used to judge whether means were significantly different from each other and to estimate magnitude of differences. Simple linear regression was used to evaluate relationships among continuous variables ($\alpha = 0.05$). Statistical analyses were performed with Microsoft Excel 2010 spreadsheet.[5]

RESULTS AND DISCUSSION

As expected, species richness ranged widely across study lakes with relatively few submersed and floating-leaf species in Tracy, FL; Waccamaw, NC; and Lost, WI; to $>$ 20 in oligotrophic and mesotrophic, northern, glacial lakes in Minnesota and Wisconsin (Table 1). Qualitatively, the PAC of submersed vegetation in depths $<$ 4.7 m was relatively low at both extremes of trophic productivity (Figure 1). At the oligotrophic end of the spectrum, nutrients and substrate composition likely limited the extent of macrophyte growth. At the opposite, highly eutrophic end of the spectrum, macrophyte coverage was likely limited by water clarity caused by either planktonic algae or sediment turbidity. However, two exceptions are noteworthy. First, PAC in mesotrophic Lake Waccamaw was likely limited by low water clarity caused by humic-stained water. Second, PAC was relatively high in hypereutrophic Little Green Lake (Figure 1). Invasive curlyleaf pondweed (*Potamogeton crispus* L.) typically grows abundantly in spring in Little Green and other nutrient-rich, North American glacial lakes (Nichols and Shaw 1986). The plant typically senesces by early summer and is often followed by spikes in total phosphorus and algae (James et al. 2002). Surveys on Little Green Lake occurred in late June 2012, when curlyleaf pondweed was beginning to senesce. Although formal aquatic plant surveys have not been conducted on Little Green in late July or August, based on summer Secchi clarity

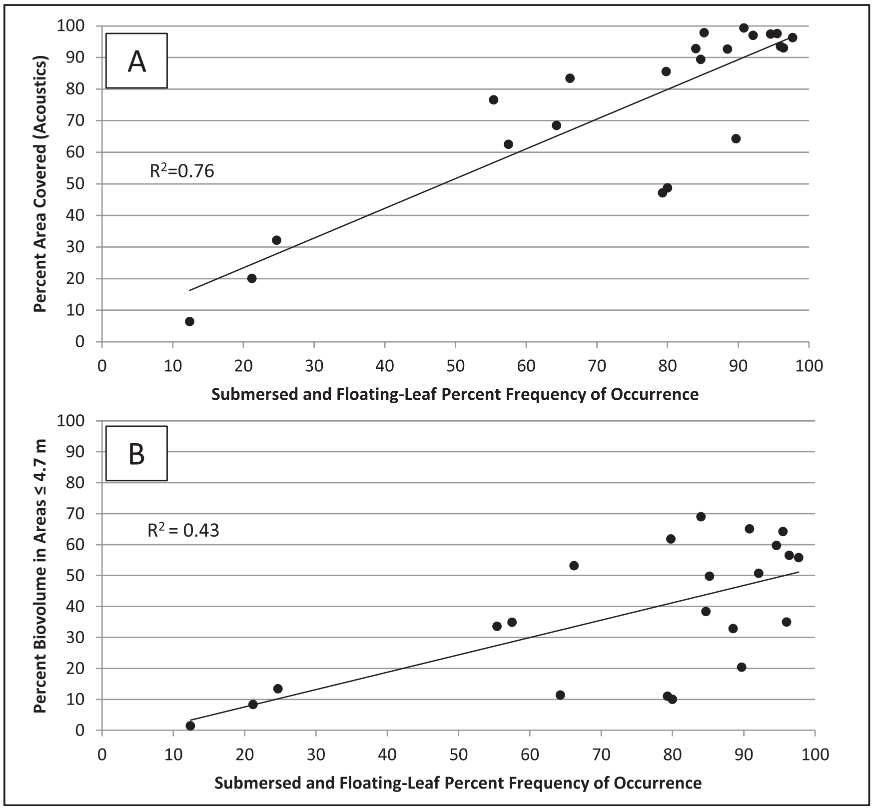

Figure 2. (A) Percentage of area covered and (B) average vegetation biovolume as estimated by hydroacoustics as it relates to the frequency of occurrence of aquatic plants from point-intercept surveys. Hydroacoustic and frequency data sets include all sampled areas in depths $\leq$ 4.7 m.

(1.3 m) and chlorophyll *a* (73.3 ppb), PAC is likely to be much lower in late summer than in late spring/early summer when curly leaf pondweed is present (M. Barton, WI Department of Natural Resources, Personal Communication).

Although not as pronounced as PAC, average biovolume in areas with vegetation present was also relatively low at both ends of the trophic spectrum (Figure 1). Vegetation biovolume in all lakes where it occurred was patchy, as indicated by the standard deviation. In most survey lakes, one could find several areas where vegetation grew near to the surface (e.g., $>$ 80% biovolume), or where it was hardly present (e.g., $<$ 10%).

Correlations among frequency, cover, and biovolume percentage

Point-intercept methodology is commonly used across the United States as a standard assessment protocol and many indicators (e.g., frequency of occurrence, species richness metrics, Index of Biotic Integrity [IBI]) have been derived from point-intercept data that have influenced aquatic plant and water resource decision making (Madsen et al. 2002, Beck et al. 2010, Hauxwell et al. 2010, Valley and Heiskary 2012). We found that the frequency percentage of vegetation occurrence correlated relatively well with PAC in the 4.7-m zone (regression $R^2 = 0.76$, $P < 0.001$; Figure 2a). However, we found that this relationship, in terms of slope and R^2, weakened considerably when frequency was used to make inferences on biovolume (regression $R^2 = 0.43$, $P < 0.001$; Figure 2b). Two outliers were particularly notable. In Horseshoe and Waccamaw lakes, where plants were frequently encountered with rakes (frequency of occurrence = 80% and 79%, respectively), overall plant biovolume was low (average biovolume percentage = 10% and 11%, respectively; Figure 2). Valley et al. (2006) also demonstrated only a weak relationship between plant frequency and hydroacoustically derived biovolume. In that investigation, herbicides had a very large effect on total plant biovolume in the lake and very little biovolume remained in the lake 2 yrs after treatment, but the frequency percentage only declined modestly (Valley et al. 2006). Likewise, Valley and Heiskary (2012) noted significant declines in the frequency percentage of curlyleaf pondweed that corresponded with snowier winters in Minnesota. Actual declines in plant biomass were likely much larger than what was indicated by the frequency statistics (Valley and Heiskary 2012).

Because of the insensitivity of presence–absence methods to changes in abundance, which is often a primary indicator for recreational nuisance, fish habitat, and water quality status, several weighting methods have been developed over the years to indicate qualitative differences in abundance (Jessen and Lound 1962, Deppe and Lathrop 1992, MI DEQ 2005, Hauxwell et al. 2010). In 11 of our study lakes, relative abundance from zero (absent) to three (full rake) were recorded at each point-intercept survey point, per methods described by Hauxwell et al. 2010. Indeed, even with this small sample size, rake fullness was positively related to

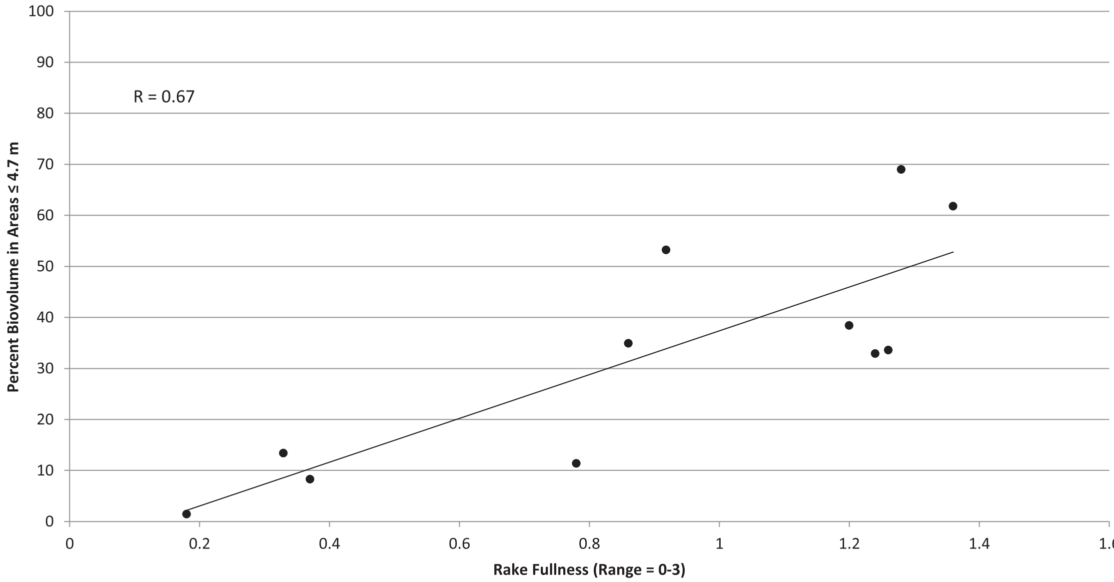

Figure 3. Average percentage of vegetation biovolume in depths $\leq$ 4.7 m as estimated by hydroacoustics as a function of average rake fullness rating of zero (none) to three (full) per Hauxwell et al. (2010).

biovolume (regression $R^2 = 0.67, P = 0.002$; Figure 3). However, the highest average rake fullness recorded was only 1.36 in Wingra Lake (few to moderate), whereas average biovolume was 62% according to hydroacoustic estimates. A value of 1.36 is difficult to interpret biologically, especially because companion biovolume values suggested vegetation biomass occupied a large proportion of the water volume in Wingra Lake. Previous studies demonstrated a high correlation between biovolume percentage or plant canopy height and biomass (in grams per square meter; Duarte 1987, Wood et al. 2012)

Patterns of dominance

The maximum site dominance value averaged across all survey sites ranged from 0.05 in Waccamaw and Istokpoga lakes, where all macrophytes were relatively sparse, to 0.37 in Orchard Lake, where frequency of surface-growing monocultures of native plants, such as northern watermilfoil (*Myriophyllum sibiricum* Komarov) or coontail (*Ceratophyllum demersum* L.) was modest (Figure 4). Despite a wide range of plant growth conditions in the study lakes and high frequency of occurrence of invasive plant species in some lakes, we did not document any situation where any plant species was dominating a lake's plant community (e.g., overall dominance > 0.5; Figure 4). Active aquatic plant management programs on most of the lakes with invasive species likely contributed to the low to modest dominance values.

Understanding three-dimensional patterns of dominance is an area in need of future research. With Figure 5, we

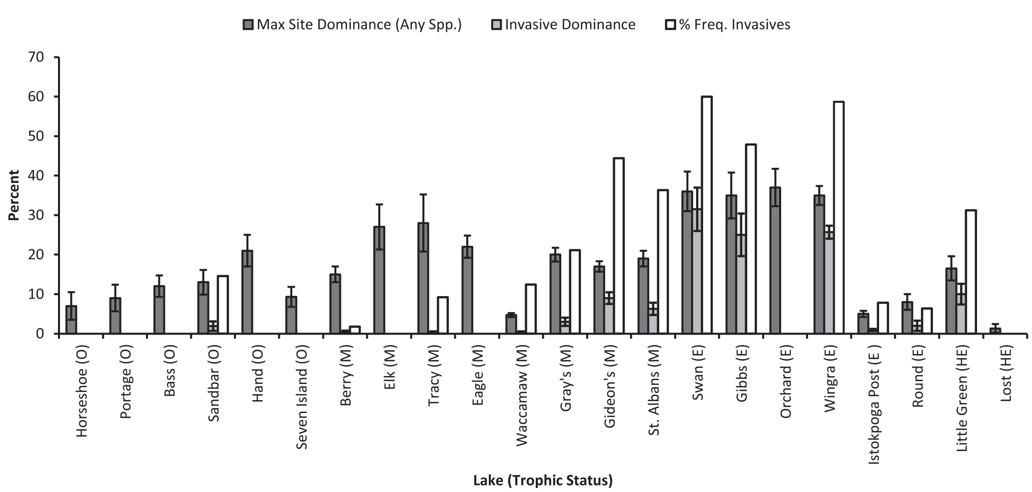

Figure 4. Average maximum dominance values (expressed as a percentage) of all aquatic plant species and invasive (Eurasian watermilfoil or hydrilla) dominance. Dominance was assessed at the species level at each point-intercept sampling site and was averaged across all sites in depths $\leq$ 4.7 m ($\pm$ 2 SE). Dominance values presented along with the frequency percentage of invasives at depths $\leq$ 4.7 m for comparison. Lakes are ordered according to productivity: O = oligotrophic, M = mesotrophic, E = eutrophic, HE = hypereutrophic.

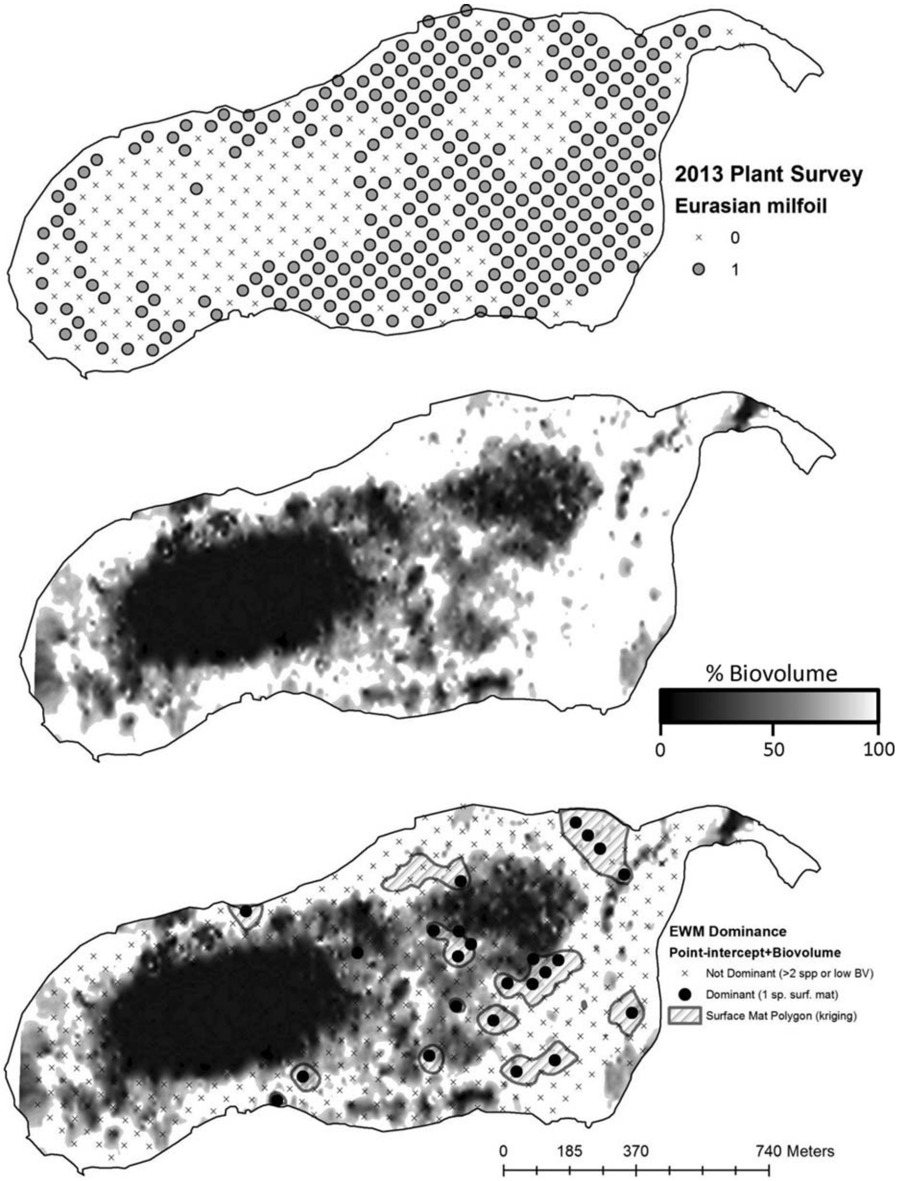

Figure 5. Top map: presence (circles) and absence (x's) of Eurasian watermilfoil sampled in August 2013 by the Wisconsin Department of Natural Resources in Lake Wingra (Dane County, WI). Middle map: hydroacoustically derived vegetation biovolume (percentage of water column occupied with vegetation—white = surface growth, black = no growth, gray = partial water column growth—collected with Lowrance HDS during plant species surveys and processed with BioBase (middle map). Bottom map: Surface-growing monocultures of Eurasian watermilfoil (black dots; dominance > 0.5) and surrounding polygons generated by kriging Eurasian watermilfoil dominance and contouring the 0.5-dominance zone.

demonstrate how spatial data can be generated and summarized for one of our study lakes (Wingra Lake, Dane County, WI). For example, monospecific surface-growing stands of Eurasian watermilfoil covered approximately 8% of the lake in 2013 (Figure 5). Using the same analysis with data in 2012, surface-growing Eurasian watermilfoil covered 45% of the lake surface (R. Valley, unpub. data). In other words, the extent of surface growing Eurasian watermilfoil declined by 82% between 2012 and 2013. Interestingly, Eurasian watermilfoil was not managed lakewide between the survey periods (M. Barton, Wisconsin Department of Natural Resources, pers. comm.). Hence, large changes in dominance may be common in eutrophic, unmanaged lakes and underscores the need to understand drivers of changes in dominance if aquatic plant management policies are to be successful.

Simple versus rake fullness dominance

The simple dominance metric is conservative and simple by design, in that all plants sampled get the same weight at each survey point, regardless of their local relative abundance. Despite the downsides of either overrepresenting or underrepresenting individual species, the simplicity of the metric enhances repeatability across different surveyors, and allows for the combination of data where

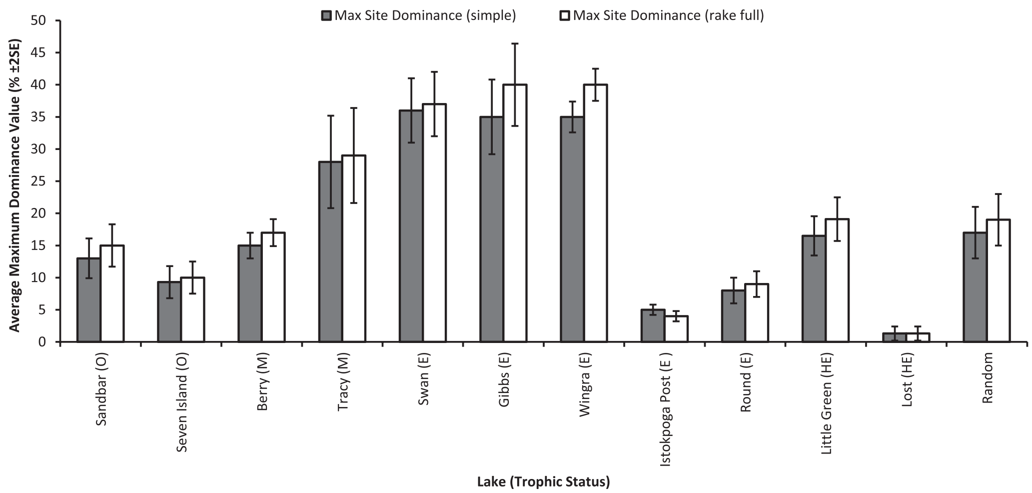

Figure 6. Average maximum aquatic plant dominance values (expressed as a percentage) using a simple metric (simple), where all species sampled at a site were equally weighted compared with a weighted metric (rake fullness), which used rake fullness at point-intercept survey sites to estimate the relative abundance of each species sampled. Dominance was assessed at the species level at each site, and maximum values were summarized in depths $\leq$ 4.7 m. Lakes are ordered according to productivity: O = oligotrophic, M = mesotrophic, E = eutrophic, HE = hypereutrophic. Random simulations were run and compared for both dominance methods for 100 sites ("Random"; See "Materials and Methods").

different protocols were used (e.g., rake fullness of zero to three vs. visual estimation of the percentage of cover). Still, the way the metric is designed, dominance will never be > 0.5 if more than two species are sampled at a site. Alternatively, species dominance > 0.5 can occur with the rake fullness metric with up to four species if one species gets a rake fullness rating of three, and the other species get ratings of one. Rake fullness dominance in this case would equal 0.5 assuming biovolume of the entire assemblage equaled one at the sampled site.

In the 11 lakes where rake fullness was collected at each site, we compared both the simple and rake fullness dominance methods (Equations 1 and 2). We also compared differences using two simulated data sets. Interestingly, in both empirical and simulated scenarios, we never found a significant difference between maximum dominance using the simple method compared with the weighted rake fullness method (Figure 6). Therefore, the simple dominance method generated informative and repeatable results. Nevertheless, where practitioners are interested in tracking rare species or species that start out locally rare but may become more dominant over time, the weighted-dominance method may be preferred to the simple method.

CONCLUSIONS

Many ecosystem goods and services are derived from aquatic plant–dominated environments and both the abundance and composition of aquatic plant communities affects the quality of those goods and services. As such, aquatic resource managers need robust quantitative methodology that can gage status and trends in abundance and composition of aquatic plants. We described complementary hydroacoustic methodology that would generate comprehensive aquatic plant abundance data with little additional assessment or analysis effort outside of what is currently put forth to get aquatic plant species composition data.

Although frequency and relative abundance metrics from standalone composition surveys are often loosely correlated with biovolume measures, they are difficult to interpret and relate to actual change in aquatic plant abundance. In contrast, the amount of water column that is filled with vegetation biomass (i.e., biovolume percentage) is visually intuitive, precisely reflects aquatic recreation condition (e.g., $> 80\%$ is near-surface growth and an impediment to recreation), and fish habitat quality (e.g., biovolume $< 20\%$ may be detrimental to some vegetation-dwelling species, Valley et al. 2010).

The simple method of calculating dominance described in this article requires no additional time at individual survey sites (as opposed to estimating relative abundance of each species) and produces an easy-to-understand map of where invasive species are dominating littoral areas and creating nuisance conditions (e.g., dominance > 0.5). Using simple geostatistical methodology (kriging), points can be modeled into more-informative polygons that lend insight into exactly where nuisance beds occur, their size, and how they respond to changing environmental conditions or management interventions. However, generating accurate maps of dominant beds and bed composition and precision (e.g., location of bed edges) is dependent on the number and spacing of species sampling points across a lake.

The standardized assessment and analysis protocols of point-intercept, hydroacoustics, and dominance metrics described here could lead to "big data" possibilities with widespread adoption by aquatic plant management programs. With a critical mass of data, it may be possible to build a predictive model that could precisely predict habitats that are at greatest risk of being dominated by an invasive species, thereby providing for efficient allocation of prevention and early detection/intervention programs.

SOURCE OF MATERIALS

[1]Lowrance HDS echosounder, Navico Inc. 4500 South 129th East Avenue, Suite 200, Tulsa, OK 74134.

[2]BioBase 5.2 software, Contour Innovations LLC, 1229 Tyler Street NE, Suite 120, Minneapolis, MN 55413.

[3]ArcGIS 10.1, Environmental Systems Research Institute, 380 New York Street, Redlands, CA 92373.

[4]Surfer Version 10.2 Surface Mapping System. Golden Software, Inc., 809 14th Street, Golden, CO 80401.

[5]Excel 2010 spreadsheet, Microsoft Corporation, 15010 NE 36th Street, Redmond, WA 98052.

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