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Evaluation of alternative interpolation techniques for the mapping of remotely-sensed submersed vegetation abundance

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Abstract

New remote sensing technologies have emerged to quantitatively assess submersed aquatic vegetation abundance and distribution. We evaluated a hydroacoustics global positioning system to map the percent of the water column occupied by submersed vegetation (referred to here as biovolume) in three Minnesota (USA) lakes. We evaluated the relative accuracy and precision of digital biovolume maps produced by three interpolation methods (inverse distance weighted (IDW), kriging and spline) after using a non-parametric regression smoother to remove a non-linear depth trend. Interpolated predictions with all methods were relatively accurate in all lakes; however, precision varied among lakes. In all cases, kriging interpolation produced the best predictions when compared with observations in independent verification data sets. However, IDW predictions were only slightly less precise. Map detail was lost when sampling effort was reduced from 10 m transect spacing to 20 or 40 m, although estimates of littoral-wide means did not change appreciably. We concluded that hydroacoustics combined with geostatistics and interpolation in GIS can accurately and precisely display multi-scale patterns in biovolume.

Keywords: Habitat mapping; Aquatic plants; Hydroacoustics; GPS; GIS

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1. Introduction

Hosts of direct and indirect perturbations caused by human stressors threaten aquatic habitats at a range of spatial and temporal scales (Naiman et al., 1995). Despite widespread impacts occurring to lake habitats, managers and policy makers often lack sufficient quantitative data to provide convincing evidence, a particular action or set of actions will adversely affect lake habitats.

Our inability to adequately quantify multi-scale changes in lake habitats stems, in part, from our inherent inability to see underwater (Lewis et al., 1996). Unlike terrestrial landscape assessments, traditional remote sensing tools such as aerial photography and satellite imagery are often ineffective at resolving deeply-rooted submersed aquatic vegetation (Madsen and Bloomfield, 1993; Vis et al., 2003).

Recently, new remote sensing technologies and innovations in GIS have emerged to map littoral habitat structure. In particular, the Submersed Aquatic Vegetation Early Warning System (SAVEWS) is a hydroacoustic system developed specifically for mapping and assessing submersed vegetation (Sabol and Melton, 1995). Accordingly, we evaluate the ability of SAVEWS and interpolation in GIS to map submersed vegetation in three Minnesota lakes. We focus specifically on mapping vegetation biovolume. Biovolume is the height of vegetation relative to water depth, expressed as a percent (100 × height/depth), and represents the quantitative measure of the vertical habitat dimension in lakes. The relative contribution of plants and open water in littoral zones and the vegetation–open water interface affects food web interactions and fish community dynamics (Werner et al., 1977; Weaver et al., 1997). By interpolating biovolume between transects in GIS, estimates of biovolume can be made across the surface of the lake, thus incorporating patterns in vertical and horizontal habitat dimensions in a map. Accordingly, our analysis includes evaluating the accuracy and precision of three conventional interpolation procedures (inverse distance weighted (IDW), kriging and spline) and evaluating data requirements by systematically removing transect data (10 m spacing to 20 m spacing and to 40 m spacing).

2. Methods

2.1. Study area

Three lakes in the Twin City metropolitan area of Minnesota, USA were surveyed with the SAVEWS hydroacoustic system during June 2002 (Table 1). In terms of size and depth, these lakes represent common north temperate glacial lakes and display a diversity of habitat conditions ranging from species diverse systems with a variety of pondweeds *Potamogeton* spp., watermilfoils, *Myriophyllum* spp. and coontail *Ceratophyllum demersum* to a species depauperate system dominated by Eurasian watermilfoil *M. spicatum.*

2.2. Equipment operation and survey design

We used a Biosonics DE-6000 echosounder equipped with a 430 kHz 6° split-beam transducer (Biosonics Inc., 2002) mounted on a 16 foot flat-bottom boat. A laptop

Table 1
Physical descriptions of lakes surveyed with hydroacoustics during June 2002

Lake	Latitude–longitude (decimal degrees)	Trophic status[a]	Size (ha)	Littoral size[b] (ha)	Mean depth (m)	Submersed species richness[c]
Square	45°09′30″N; −92°48′42″W	Mesotrophic	79	51	9.2	19[d]
Christmas	44°54′02″N; −93°32′53″W	Mesotrophic	104	42	12.4	23[d]
Schutz	44°52′23″N; −93°38′28″W	Eutrophic	38	19	6.9	8[e]

[a] Carlson's (1977) trophic state index was used to classify the trophic state of each study lake.

[b] Littoral size was defined as the area less than the maximum depth where vegetation growth commonly occurred.

[c] Number of species includes all submersed rooted angiosperm and macroalgal species (i.e., *Chara* spp. and *Nitella* spp.).

[d] Species surveys were conducted during 2003 by the Minnesota Department of Natural Resources (unpublished data).

[e] Species surveys were conducted during 2002 by the Minnesota Department of Natural Resources (unpublished data).

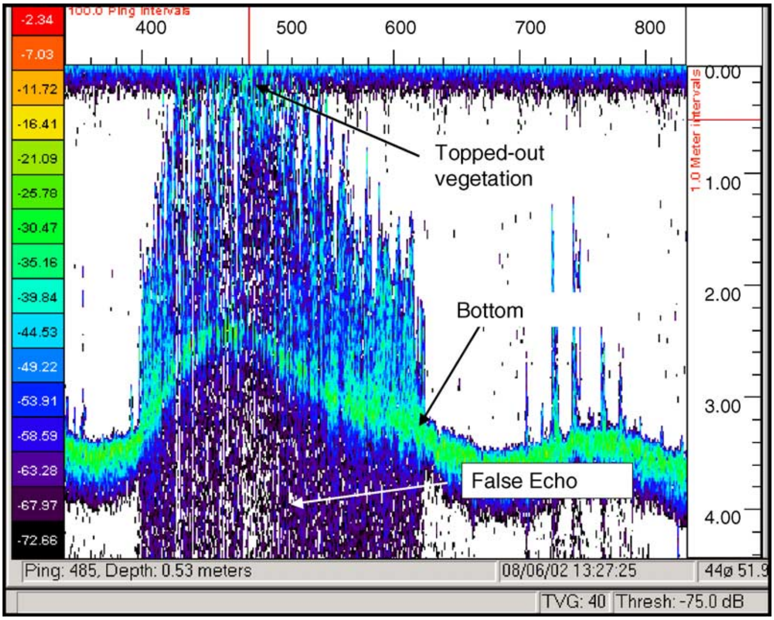
computer controlled the echosounder and collected the digital hydroacoustic data along with real-time, differentially-corrected latitude and longitude reported every 2 s from a *JRC* DGPS212 beacon receiver (RMS accuracy ≤ 5 m; Japan Radio Co. Ltd., 2000). Position dilution of precision (PDOP) was never above six and was generally under four during the surveys. Echosounder settings were the same as those used by Sabol et al. (2002): pulse rate was set to emit five monotone pulses per second and pulse length was set at 0.1 ms. This resulted in a collection of approximately 10 pings per DGPS location. One data point, summarizing the attributes for the 10 previous pings, was recorded every 2 s. Collectively, these recorded points produced a lake-wide GIS point coverage. Boat speed varied between two and four knots, separating data points approximately 3–5 m apart along 10 m spaced transects. Therefore, our finest data resolution was 3–5 m along transects and 10 m between transects.

To ensure efficient coverage of the entire lake surface, linear transects were arranged parallel to each other and perpendicular to the longest shoreline. Transects were navigated with a *Garmin*® GPSmap 76. Average GPS error (RMSE of GPS tracks repeated over fixed line transects) from preliminary tests was approximately 1.6 m (Valley, unpublished data). Point data from these transects served as the input data (z-variable) for interpolations. A second set of independent data used exclusively for interpolation model verification were collected along transects approximately perpendicular to the original transects. Sample sizes for verification equaled 4550 points across the littoral surface in Square Lake, 3063 points in Christmas Lake and 2487 points in Schutz Lake. Ground-truth surveys (Valley, unpublished data) and results from Sabol et al. (2002) demonstrate that hydroacoustic predictions of depth and plant height with properly configured Biosonics echosounders are accurate in a range of habitats.

Vegetation grew to the surface (i.e., topped-out) on 11 of the 42 littoral hectares in Christmas Lake and could not be sampled with hydroacoustics. Manual sampling procedures were used on a 30 m sampling grid to gather vegetation data from these areas. At each such location, we double-anchored the boat, recorded latitude and longitude, presence/absence of vegetation, vegetation height and water depth with a survey rod at seven points equally spaced across the length of the boat, which mimicked the average spacing between pings. These data were later appended to the hydroacoustic data so they could be mapped. The accuracy and precision of interpolated predictions were not assessed in large areas with topped-out vegetation because we could not sample them with hydroacoustics; however, one should expect high accuracy and precision in such large homogeneous areas. Small, patchy topped-out beds occurred in all three lakes, but did not require manual sampling. Acoustic data from these beds could be identified and their plant height reclassified from ‘noisy’ to the water depth (Fig. 1).

2.3. Data processing

Hydroacoustic data were processed with a custom build of Biosonic’s *EcoSAV*® software that retained the basic functions of commercially available software (e.g., Version 1.2; Biosonics Inc., 2002) but allowed us flexibility to reclassify signals in topped-out beds from ‘noisy’ classifications to ‘plant’ classifications (Biosonics Inc., unpublished data). *EcoSAV* uses a multi-step algorithm to extract information on plant attributes by examining the echo signal. The plant height reported at each DGPS location represents the mean plant height over the preceding 10 pings (Biosonics Inc., 2002). Biovolume reported at each DGPS location was the mean plant height divided by mean water depth for the 10 pings, expressed as a percent. Estimates generated by *EcoSAV* were verified with the echogram and accompanying oscilloscope displaying the digital echo for each ping. To prevent false



Ping: 485, Depth: 0.53 meters
08/06/02 13:27:25
44ø 51.
TVG: 40
Thresh: -75.0 dB

Fig. 1. Echogram displaying bottom and vegetation tracings over a sequence of approximately 500 pings. Echo backscattering strength (dB) is shown by the gray scale on the left axis and depth (m) on the right axis. False echoes below the bottom appear because some sound echoes from bottom to vegetation to bottom again before returning to the transducer; they are ignored in all data analysis.

classifications at depths, where vegetation rarely occurs (bottom debris can give erroneous plant characterizations), we set depth thresholds at 4 m for Schutz Lake and 8 m for Square and Christmas lakes, because vegetation rarely occurred beyond these depths.

2.4. Comparison of interpolation techniques

Three conventional interpolation methods, inverse distance weighted (IDW), kriging and spline, were tested. Interpolations were performed using *GS*+ 5.0 (Robertson, 2000) for IDW and kriging and *Spatial Analyst* 2.0 for *ArcView*® for spline. Isaaks and Srivastava (1989) and Rossi et al. (1992) comprehensively describe concepts and applications of geostatistics and interpolation; their methodology formed the basis for much of our geostatistical analyses.

Inverse distance weighted interpolation estimates the value of an unsampled area as a weighted average of a defined number of neighborhood points, or area, and the weight assigned to each neighborhood point diminishes as the distance to the neighborhood point increases. IDW interpolation produces a relatively rough surface because the map surface must pass through the input points. This procedure is sensitive to non-uniform sampling designs (Isaaks and Srivastava, 1989). IDW was performed for each lake using 30 neighborhood points and a weight of two.

Spline fits a curved surface to the input values compromising between fidelity to the data and minimizing the total curvature of the surface (Environmental Systems Research Institute Inc., 1996). Accordingly, the map surface is allowed to under- and over-shoot input points in order to maintain smooth curvature. In Spatial Analyst, we used the tension option with a weight of five. This weight created a range of biovolume values closest to the input values.

Like spline, the kriging algorithm also generates a smooth surface, exhibiting less fidelity to the input points when compared with IDW. Kriging is a geostatistical procedure that uses a variogram model that describes the spatial continuity of the input data to estimate values at unsampled locations (Isaaks and Srivastava, 1989). The variability between samples as a function of distance (i.e., semivariance) was evaluated and modeled prior to kriging. We used the variogram model that generated the best fit (lowest RMSE) to the biovolume data and set the kriging search window to 100 m or the variogram range (distance of spatial autocorrelation), whichever was greater. If less than 30 points occurred within the moving search window, window size was automatically increased until the local sample size equaled 30.

Exploratory data analysis prior to interpolation revealed a confounding, non-linear effect of depth on biovolume (Fig. 2). Interpolation, in the presence of a trend or ‘drift’ can bias results, particularly with kriging (Isaaks and Srivastava, 1989). Accordingly, we removed the depth trend data prior to interpolation simulations. We used a non-parametric regression smoother using the default settings in the MGCV library in the statistics software package *R* 1.8 (R Development Core Team, 2003) to describe the relationships between biovolume and depth for the each of the data sets (and reduced subsets) used in the mapping process (Hastie and Tibshirani, 1990). The smoothed relationship resembled an eighth-order polynomial. Each curve fit was highly significant (Chi-square; $P < 0.001$; Fig. 2). Biovolume residuals from these curves were interpolated by kriging, IDW and spline to produce surface grids of local features (i.e., predicting deviations from the depth trend).

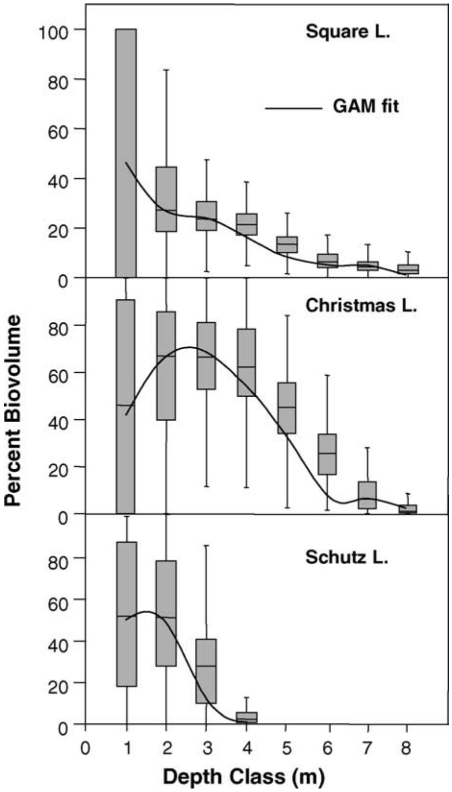


Fig. 2. Line of fit of non-parametric regression smoothers (approximately eighth-order polynomials) overlain on box-whisker plots showing the distribution of vegetation biovolume observations for each study lake, as measured with hydroacoustics. Each plot shows the median, interquartile range (box) and outer quartiles (whiskers) for all point observations within each lake.

Lastly, we evaluated the sensitivity of the three interpolation techniques to reductions in sampling effort by uniformly removing transects and reevaluating interpolation accuracy and precision. The first set of simulations included data from all transects (10 m spacing) with an output grid cell size of 2 m. The next set of simulations included data only from odd numbered transects (20 m spacing; 50% point reduction; 4 m grid cells) and the third set included data only from every other odd transect (40 m spacing; 75% point reduction; 8 m grid cells). Selection of larger grid cell size with each increase in transect spacing was necessary to account for decreases in sampling resolution (Krum and Jones, 1992).

2.5. Statistical analyses

Evaluation of the accuracy (degree of bias between observed and predicted biovolume) and precision (tightness of the correlation between observed and predicted biovolume) of interpolated maps followed recommendations by Isaaks and Srivastava (1989). Further, our geostatistical approach is consistent with studies in several other fields of discipline

Table 2

Total biovolume variance, mean squared error (MSE) after a smoothing to remove a depth trend, MSE after interpolation of detrended data by IDW, kriging and spline, percent of the total variance explained by combined depth and interpolation models, mean observed and predicted littoral biovolume with associated 95% confidence intervals for each interpolation model at 10, 20 and 40 m transect spacing within each lake

Lake	Transect spacing (m)	Total biovolume variance (s^2)	Depth-detrending smoother MSE ($\%^2$)	Interpolation method	Interpolation MSE ($\%^2$)	Percent total variance explained	Observed mean percent biovolume (±95% CI)	Predicted mean percent biovolume (±95% CI)
Square	10	417	275.6	Kriging	67.2	78	20.30 ± 0.50	19.87 ± 0.42
–	20	452	275.6	–	79.2	76	–	20.05 ± 0.42
–	40	462	272.3	–	98.0	70	–	20.17 ± 0.42
–	10	417	275.6	IDW	77.4	74	–	19.97 ± 0.43
–	20	452	275.6	–	86.5	73	–	20.19 ± 0.42
–	40	462	272.3	–	104.0	68	–	20.37 ± 0.43
–	10	417	275.6	Spline	100.0	67	–	19.89 ± 0.49
–	20	452	275.6	–	102.0	68	–	19.73 ± 0.48
–	40	462	272.3	–	123.2	63	–	21.93 ± 0.35
Christmas	10	1010	349.7	Kriging	246.5	79	44.56 ± 1.11	45.18 ± 0.90
–	20	1023	331.2	–	265.7	79	–	44.75 ± 0.90
–	40	1047	380.3	–	295.8	73	–	45.21 ± 0.89
–	10	1010	349.7	IDW	265.7	77	–	44.55 ± 0.93
–	20	1023	331.2	–	289.0	78	–	45.17 ± 0.90
–	40	1047	380.3	–	309.8	71	–	40.51 ± 1.01
–	10	1010	349.7	Spline	299.3	74	–	44.59 ± 1.02
–	20	1023	331.2	–	313.3	75	–	47.87 ± 0.85
–	40	1047	380.3	–	353.4	67	–	44.15 ± 1.20
Schutz	10	1027	635.0	Kriging	492.8	49	40.32 ± 1.25	40.43 ± 0.98
–	20	1001	625.0	–	492.8	50	–	39.94 ± 1.04
–	40	1017	585.6	–	506.3	54	–	41.41 ± 0.94
–	10	1027	635.0	IDW	501.8	49	–	40.51 ± 1.01
–	20	1001	625.0	–	497.3	49	–	40.16 ± 0.98
–	40	1017	585.6	–	510.8	53	–	41.79 ± 0.96
–	10	1027	635.0	Spline	529.0	46	–	40.92 ± 1.22
–	20	1001	625.0	–	529.0	46	–	41.35 ± 1.14
–	40	1017	585.6	–	620.0	43	–	34.39 ± 1.63

including geology and soil sciences (Heine, 1986; Kravchenko and Bullock, 1999), forestry (Lister et al., 2000), fisheries (Maravelias et al., 1996) and environmental toxicology (Qian et al., 2001). First, we evaluated the reduction in unexplained biovolume variance after smoothing to detrend the biovolume data according to depth. Second, we evaluated the additional reduction in explained variance after interpolation of the detrended data. The criteria we used to compare the relative precision of the interpolation methods at each transect spacing in each lake was the mean squared error (MSE) from linear regressions of observed against predicted values. All residuals from these regressions were normally distributed about the regression line. To evaluate interpolation accuracy, we checked whether the observed mean biovolume fell within 95% confidence intervals about the predicted mean. Finally, we evaluated the percent of the total biovolume variance that could be explained by combining depth models with interpolation models. Due to our large sample sizes ($n > 1000$), P-values from all model fits were highly significant at the $\alpha = 0.01$ significance level and thus are not cited in the text hereafter.

3. Results

Surveys produced a large number of data points across the surface of the littoral zone in each lake, ranging from 3090 in Schutz Lake to 7629 in Square Lake. Median littoral

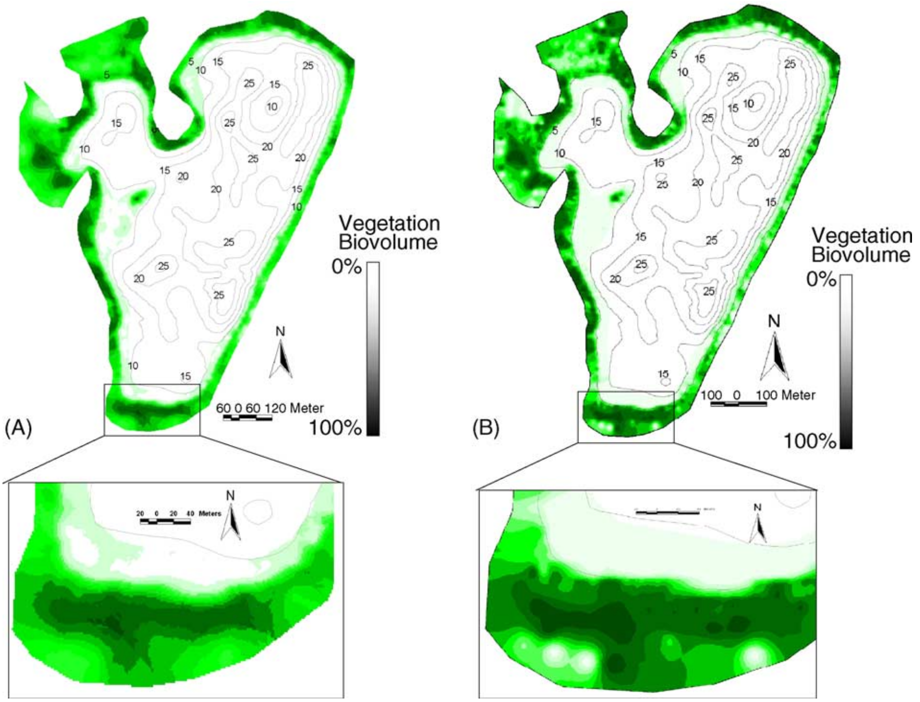


Fig. 3. Submersed vegetation biovolume in Christmas Lake as estimated by kriging (A) and inverse distance weighted (IDW) interpolation (B).

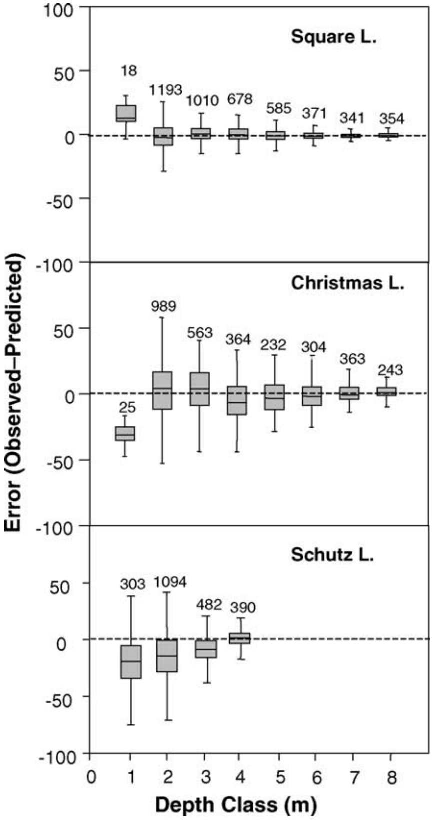


Fig. 4. Box-whisker plots of error (units = percentages) between observed and predicted (via kriging) submersed vegetation biovolume along a gradient of depth for each study lake. Each plot shows the median, interquartile range (box) and outer quartiles (whiskers) for all observations within depth class, within each lake. Numbers above the whiskers denote sample size.

biovolume was 15% in Square Lake, 30% in Schutz Lake and 45% in Christmas Lake. Despite harboring a diverse plant community, Square Lake displayed less variance in biovolume than Christmas and Schutz lakes (Table 2).

The depth-detrending smoother applied to the map transect data in Square, Christmas and Schutz lakes reduced the amount of unexplained variance in biovolume by 34, 66 and 38%, respectively at the full transect density (Table 2). After removal of the depth trend, interpolation in all lakes with all models further reduced the amount of unexplained variation (Table 2). In all cases, kriging produced the lowest MSE (i.e., the highest precision), closely followed by IDW (see Fig. 3 for comparison of kriging and IDW maps). Spline consistently produced the highest MSE (Table 2). Among lakes, analyses of Square Lake produced the lowest interpolation MSE values and the depth-detrending smoother combined with interpolation explained the most variation in biovolume (Table 2). The combined model also explained a large proportion of biovolume variability in Christmas

Lake (Table 2). In contrast, the total model could only explain approximately 50% of the variability in biovolume in Schutz Lake (Table 2).

Despite contrasts in model precision among lakes and methods, mean observed biovolume fell within the 95% confidence intervals about predicted means (Table 2), indicating all models produced relatively accurate predictions across the surface of the littoral zones in all lakes. However, a closer look at residual errors at different depths showed that predictions were variably biased in shallow littoral depths (Fig. 4). Sample sizes were considerably smaller at depths less than 1 m, which may be an explanation.

Map precision and accuracy was not greatly sensitive to sampling effort. In most cases, overall model fit decreased only slightly with each transect reduction and predicted means of whole-lake biovolume did not change significantly and remained similar to observed means (Table 2). Still, map resolution and detail was lost when transect spacing increased from 10 to 20 or 40 m.

4. Discussion

Hydroacoustics coupled with GPS can provide spatially-explicit information on submersed aquatic vegetation abundance and distribution. With this study, we demonstrate sampling and analysis techniques that can be used to produce digital maps of the distribution of biovolume. Percent vegetation biovolume describes habitat composition (space occupied by open water versus vegetation) for littoral fish and zooplankton communities (Werner et al., 1977; Schriver et al., 1995; Perrow et al., 1999), thus understanding patterns in the distribution of biovolume will be important for fisheries habitat management.

Within each lake, biovolume displayed a pronounced pattern with respect to littoral depth. At depths less than 2 m, percent biovolume varied widely; however, as littoral depth increased beyond 2 m, biovolume decreased proportionately. Habitats in shallow littoral areas are spatially variable because vegetation abundance in these areas is affected by many local factors such as substrate composition, wave action and human removal of vegetation (Duarte and Kalff, 1990; Radomski and Goeman, 2001). In contrast, broad-scale environmental factors such as light penetration or nutrient availability constrains vegetation growth at deeper littoral depths (Chambers, 1987; Duarte and Kalff, 1990). Consequently, interpolation predictions were relatively accurate in depths greater than 2 m. In shallow areas less than 2 m, where we observed patchy bare and vegetated areas, we found lower interpolation accuracy. Smaller sample sizes in shallow areas less than 1 m may have contributed to bias and error of interpolated maps. With larger sample sizes at shallow depths, we would expect less bias, but perhaps larger interpolation error. Intensive sampling and advanced geostatistical techniques such as local kriging (Walter et al., 2001) may improve interpolation accuracy and precision in shallow areas.

The use of non-parametric regression smoothers coupled with interpolation appears beneficial for spatial prediction and mapping of aquatic vegetation (Lehmann, 1998; this study). In Square and Christmas lakes, the combined model smoothed non-linear variability in three dimensions and produced relatively precise maps of biovolume. In contrast, in Schutz Lake, biovolume was variable at most depths as a result of patchy canopy growth of Eurasian watermilfoil that did not grow deeper than 4 m. Thus, all models produced a relatively poor fit in Schutz Lake.

Eurasian watermilfoil was also abundant in Christmas Lake and correlations similar to those of Schutz Lake were observed for depths less than 4 m. However, relatively consistent biovolume for deeper littoral depths (up to 8 m) in Christmas Lake increased the overall accuracy and precision of interpolation simulations. Square lake was dominated by *Chara* spp. and a diversity of low-growing pondweeds (*Potamogeton* spp.), thus relatively precise biovolume predictions could be made throughout most of the littoral zone.

4.1. Relative accuracy, precision and sensitivity of interpolation methods

Overall, each interpolation method produced relatively accurate estimations of biovolume in unsampled areas. However, the precision of these estimates varied among lakes and interpolation methods. In each lake, kriging most precisely predicted biovolume across the surface of each lake. Maps created by kriging are desirable when attempting to characterize general trends in a spatially-dynamic landscape, where results at specific points are generally not reproducible (i.e., presence of large nugget effects; Isaaks and Srivastava, 1989). This situation describes the structure of the littoral zone in many lakes because vegetation abundance changes continuously throughout the growing season. Kriging handles this phenomenon by creating a smoothed or 'averaged' surface (Fig. 3(A)). Kriged maps can serve as a valuable tool for monitoring lake-wide processes affecting overall vegetation abundance such as climate, nutrient loading, changes in water clarity. However, because of its behavior as a smoother, lake-wide kriging is not recommended for monitoring local changes in littoral habitats, unless disproportionately larger sample sizes are gathered at specific areas of interest. Rather, IDW or local kriging may be preferred to characterize small scale changes such as vegetation removal in front of lakeshore homes (See Fig. 3(A) and (B) for comparison of a kriged and IDW surface).

Surfaces created with IDW interpolation closely conform to the input points and local areas around the sampled point generally receive the greatest weight. As a result, in our study lakes, IDW produced relatively rough surfaces that were heavily influenced by where samples were taken. As a result, given a different sampling configuration, IDW maps may have been quite different. Nevertheless, by placing the most weight around sampled locations and conforming to the input points, areas, where vegetation was removed by lakeshore owners (i.e., biovolume = 0) could clearly be delineated (Fig. 3(B)). Ultimately, both kriging and IDW can be used to monitor both local and lake-wide effects of stressors on aquatic vegetation abundance.

Compared with kriging and IDW, the performance of spline interpolation was inferior. Spline is generally recommended for gently varying surfaces (Environmental Systems Research Institute Inc., 1996). Apparently, the variability of biovolume within interpolation neighborhoods was too great for spline to function effectively. Furthermore, three dimensional splining is currently under theoretical development and choice of optimum tension settings remain problematic (Leah Welty, University of Chicago, personal communication).

Map accuracy or precision was not greatly affected by reductions in transect density. Apparently, the effect of removing the depth trend and smoothing with interpolation maintained a relatively generalized surface regardless of transect density. In Square and Christmas lakes, predictions were consistently similar to observed values; however, precision between these values decreased slightly with each reduction. In Schutz Lake, predictions were consistently imprecise at all transect densities, likely because of the variable distribution of Eurasian watermilfoil at all littoral depths. Nevertheless, map detail was sacrificed as transect spacing and cell size was increased, resulting in an overly-generalized surface, particularly at the 40 m spacing. Ultimately, sampling design and intensity should reflect the objectives and scale of the investigation.

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