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ACCURACY AND PRECISION OF HYDROACOUSTIC ESTIMATES OF AQUATIC VEGETATION AND THE REPEATABILITY OF WHOLE-LAKE SURVEYS: FIELD TESTS WITH A COMMERCIAL ECHOSOUNDER[1]

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Abstract- Hydroacoustics, coupled with GPS and GIS represents a promising tool in monitoring changes to submersed vegetation biovolume, which is important for many Minnesota fish species. However, prior to establishing operational survey programs using these technologies, the performance of the equipment, software, and survey methodology must be rigorously evaluated. Accordingly, we conducted ground-truth experiments with a BioSonics Inc. digital echosounder by comparing estimates of bottom depth, plant height, and depth to the top of the plant made with *EcoSAV*® vegetation analysis software with measurements made with divers. *EcoSAV*-estimated and diver-measured plant heights did not differ significantly, however, the *EcoSAV*-estimated position of the plant in the water column did differ from the diver-measured position. On average, *EcoSAV* over-estimated bottom depth by 0.18 m and over-estimated the depth from the surface to the top of the plant by 0.23 m. As a result, the *EcoSAV* estimates indicated that plants occupied less of the water column than diver-measured values. Bias in bottom measurements was likely due to signal penetration of the soft sediments in Square Lake by the echosounder. Bias in top of plant measurements was likely a result of difficulty placing the transducer directly over the marker buoys, so the top of the plant sometimes fell outside and above the acoustic cone. We also evaluated whether boat navigation error affected the accuracy and precision of vegetation maps, and the repeatability of whole-lake surveys. To do so, we conducted surveys on three consecutive days in two diversely vegetated lakes. Boat navigation RMSE averaged 3.5 to 4.0 meters; however, GPS location error was only ± 1.06 m. These errors had little effect on the overall accuracy and precision of maps of biovolume in both lakes. Precision of biovolume estimates was lower at depths less than 2 meters than at deeper depths.

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INTRODUCTION

Submersed aquatic vegetation provides critical habitat for numerous Minnesota fish species and is an integral component of fish community integrity (Valley et al. 2004; Drake and Valley 2005). The cumulative effects of lakeshore and watershed development has had negative effects on fish communities in the upper Midwest (Christensen et al. 1996; Jennings et al. 1999; Radomski and Goeman 2001; Drake and Valley 2005). Unfortunately, habitat assessment techniques have lagged behind impacts occurring to lake habitats, and spatially explicit quantitative data on the distribution of aquatic vegetation in lakes is lacking. Hydroacoustics coupled with differentially corrected GPS, analyzed in a GIS represents a promising new tool in the acquisition of important habitat data (Valley et al. 2005).

Hydroacoustics has been an effective tool for assessing the abundance of submersed aquatic vegetation for some time (Maceina and Shireman 1980; Duarte 1987; Thomas et al. 1990). However, until the advent of global positioning systems (GPS) in the 1990s, our abilities to map the distribution of vegetation was greatly limited. Sabol and Melton (1995) describe an automated hydroacoustic system coupled with GPS to estimate bottom depth, vegetation cover, and vegetation height at numerous georeferenced locations. This system (a BioSonics Inc. digital echosounder, GPS, and bottom/plant detection algorithm) was originally termed the Submersed Aquatic Vegetation Early Warning System (SAVEWS; Sabol and Melton 1995). Tests on the performance of this system and algorithm have been performed in some hard bottom riverine and estuarine systems, and demonstrated high precision and accuracy in those environments (Sabol and Johnston 2001; Sabol et al. 2002a,b).

BioSonics Inc. has a Cooperative Research and Development Agreement with the Corps of Engineers for development and distribution of the patented vegetation detection algorithm marketed under the trade name *EcoSAV*®. Using characteristics of the acoustic signal, *EcoSAV* uses a multi-step algorithm with user-defined parameter settings to determine depth, plant presence, plant absence, and plant height (BioSonics Inc. 2002). *EcoSAV* 1.2 processes BioSonics echosounder files and creates an ASCII text file with records for every GPS report (recorded every 2 seconds). Each of these records includes a collection of pings (number dependent on user-defined ping rates) where vegetation attributes are averaged between GPS reports (BioSonics Inc. 2002). Evaluating multiple pings per data record is critical for confidently identifying bottom in dense plants, where signal can periodically be attenuated in the plant canopy (Sabol and Johnstone 2001).

Because this system holds promise for assessing and mapping vegetated habitats (i.e., a window to see littoral zones as landscapes; Wiens 2002), we tested the performance of BioSonics echosounders and *EcoSAV* in two Minnesota lakes. This involved a ground-truth experiment and a comparison of repeated whole-lake surveys. First, we compared diver-measured depth and plant height with *EcoSAV*-estimated depth and plant height for a variety of individual plant species (henceforth referred to as “fixed-point experiments”). Our analysis differs from that by Sabol et al. (2002) because we evaluate precision of estimates for single plants rather than comparing average signal returns with average field measurements. This alternative approach is necessary because *EcoSAV* uses a collection of single plant measures, averaged between GPS records, in its reports of plant height. We sought to quantify the error going into these average measures.

In addition, we evaluated the repeatability of whole-lake surveys. This is important to quantify because plant habitats in Minnesota lakes are highly diverse, and boat navigation error precludes sample transects from being precisely where intended. Local variability in plant height may affect the robustness of these surveys to boat navigation error. We assessed local- and lake-wide effects of sampling error by repeating three surveys on two lakes with methods described by Valley et al. (2005; henceforth referred to as “whole-lake surveys”). We quantified navigation and location error, the accuracy and precision of biovolume maps, and the repeatability of survey results.

Percent vegetation biovolume is a habitat metric that has previously been referred to as Percent Vertical Area Infestation or Percent Volume Infestation (Maceina and Shireman 1980; Canfield et al. 1984). This quantity is estimated by planimetry of vegetated areas displayed by hydroacoustic transect echograms (Maceina and Shireman 1980; Canfield et al. 1984) or by dividing plant height by water depth and multiplying by percent cover (Schriver et al. 1995; Burks et al. 2001). *EcoSAV* does not estimate biovolume as described by Maceina and Shireman (1980), but reports measures of plant height, water depth, and percent cover (frequency of plant occurrence along a transect). These data provided us a means by which to estimate biovolume.

METHODS

Study site–Fixed-point experiments were conducted in Square Lake (Washington Co.; 45°09' N -93°48' W) during July 2003. Square Lake is 79 ha and exhibits a diversity of native plant species (submersed species richness = 19 spp.) including several broad and narrow-leaved pondweeds *Potamogeton* spp., coontail *Ceratophyllum demersum*, northern watermilfoil *Myriophyllum sibiricum* and the macroalgae chara *Chara* sp. A diversity of depths (ranging from 1 to 8 m) and plant species were surveyed. For the whole-lake surveys, repeated surveys were conducted in Square Lake on three consecutive days during August 2002. Three repeated surveys were also carried out in Christmas Lake (Hennepin Co. 44°54' N -93°32 W; 104 ha) during August 2003. Macrophytes in Christmas Lake are also diverse (submersed species richness = 23 spp.), and include the canopy-growing Eurasian watermilfoil *M. spicatum* that creates high biovolume variability throughout the lake.

Sampling equipment–Hydroacoustic data were collected with a BioSonics DE-6000 digital echosounder equipped with a 430 kHz 6° split-beam transducer. For the fixed-point experiments and the whole-lake surveys, we set ping rates at 5 monotone pulses per second with a pulse-width of 0.1 milliseconds. Ping data were analyzed with *EcoSAV* version 1.2.5.1. Unlike the commercially available version of *EcoSAV*, this modified beta version allowed us to evaluate vegetation attributes for individual pings. For the fixed-point experiments, default parameter settings for plant analyses in *EcoSAV* were used with exceptions that the threshold for plant detection parameter setting was decreased from the default –65 to –75 dB for increased sensitivity, plant detection persistence distance was increased from 0.09 m to 0.14 m, and bottom thickness threshold was increased from 0.21 m to 0.25 m because of soft sediments. For detailed descriptions of the *EcoSAV* algorithm and its parameters consult the *EcoSAV* user manual, available from BioSonics Inc. (www.biosonicsinc. com).

Fixed-point experiments–Divers located and marked with numbered buoys, multiple littoral zone microhabitats exhibiting a variety of cover types, ranging from monotypic stands of dense vegetation, to diverse stands, to long, solitary coontail or whitestem pondweed *P. praelongus* growing at the edge of the littoral zone. At the surface, divers held the transducer in place directly over the area marked by the buoy and the area was pinged numerous times until a consistent signal directly over the targeted area was achieved. After each of the buoy sites were pinged, divers marked four corners of the ensonified area with marker buoys. The four buoy strings were held together at the surface by one diver, thus creating a pyramid-shaped sampling area, approximately equal to the size and shape of the acoustic cone. The second diver descended to the bottom, identified the tallest plant intercepting the simulated cone, and marked its length on a buoy string. Bottom depth at the sediment-plant interface and plant height were recorded at each sampling station by a diver. Bottom depth and plant height were also recorded with the echosounder and *EcoSAV*. To account for the minor vagaries of a stationary acoustic signal (i.e., ambient in situ noise has a small effect the backscattering of an acoustic signal), the mean depth and plant height from a collection of 8 – 241 pings at each fixed-point were calculated. Standard deviations were calculated to determine the quality (i.e., precision) of each acoustic estimates at each fixed-point. One-sample t-tests evaluating the null hypothesis that differences between diver-measured and *EcoSAV*-estimated depths and plant heights were zero ($\alpha = 0.05$).

Whole-lake surveys–We completed three mapping runs on consecutive days, targeting the same GPS transects using a *Garmin*® GPSmap 76 handheld GPS unit with WAAS (Wide Area Augmentation System) differential-correction enabled. We mapped biovolume using methods described by Valley et al. (2005). Briefly summarized, this entailed collecting hydroacoustic vegetation data over transects perpendicular to the longest shoreline spaced 10 m apart. Boat speed was 2 – 4 knots, separating DGPS reports every 3 – 5 meters. This represented the distance between data records and defined the size of the ping cycles (typically 10-11 pings per cycle). *EcoSAV* records one data location for each record as the mid point between GPS cycle boundaries. From the plant variables reported by *EcoSAV*, we calculated percent biovolume for each ping cycle using the following formula:

$$\mathit{Biovolume}\ (\%) = \left(\frac{\mathit{PlantHeight}}{\mathit{Depth}}\right) x\ \mathit{Plant\ Cover}$$

where: *PlantHeight* = the mean plant height for only those pings signaling the presence of plants; *Depth* = a best depth estimate for a ping cycle determined from a patented heuristic algorithm (Sabol and Johnston 2001); and *Plant Cover* = the percent of all pings in a report cycle signaling the presence of plants. To estimate plant height, *EcoSAV* subtracts the distance where the signal crosses the threshold for plant detection from the distance to the bottom signal (typically the sharpest rise in voltage).

Biovolume at all unsampled areas was estimated and mapped by kriging, which is a geostatistical interpolator and smoother (Isaaks and Srivastava 1989; Figure 1). We tested the precision and accuracy of biovolume estimates at the whole-lake scale by collecting one independent set of verification data in each lake along transects approximately perpendicular to the map transects. For comparisons to predicted values, we assumed verification data sets were true measures. Navigation error was computed in *ArcView* for each survey as the root mean squared error (RMSE) of the distance of the recorded track points from the targeted transect line.

Exploratory data analysis from our previous study and this one showed a negative relationship between biovolume and depth. Therefore, models relating biovolume to depth and spatial location were constructed from each whole-lake survey and then used to predict biovolume across all grid cells of the lake. Models were fitted in two steps. First, a nonparametric regression smoother was fitted with *R* to describe the relationship of biovolume to depth and to remove this trend (Chi-square $p < 0.001$). Next, the local spatial patterns within the detrended residuals were fitted by kriging. Finally, for each grid cell, the predictions from the regression and kriging were added to produce a predicted biovolume accounting for both depth and local spatial patterns (Valley et al. 2005). Biovolume grids were imported into *ArcView* with *Spatial Analyst* 2.0 for all other GIS analyses.

We evaluated results from the whole-lake study at two levels of resolution: (1) consistency of kriging predictions and model fits to verification data over the entire littoral surface, and (2) consistency of individual 5-m grid cell predictions produced after repeated surveys. Model fit was assessed by regressing predicted grid cell biovolume values against corresponding verification data recorded within the same grid cell. All residuals from these regressions were normally distributed about the regression line. Adequacy of maps for each lake was examined by qualitative comparisons of mean squared errors (MSE), and percent reductions in unexplained variance. To evaluate whether predictions for the whole-lake surveys were accurate, we compared verification means to the mean predicted values and the 95% confidence intervals around the mean predicted biovolume. At the local scale, the standard deviation of predictions for individual grid cells over the three days (n = 3) was calculated to describe the precision of biovolume estimates. Because we identified lower map precision at shallow littoral depths (Valley et al. 2005), we evaluated local survey precision in biovolume along a gradient of littoral depth.

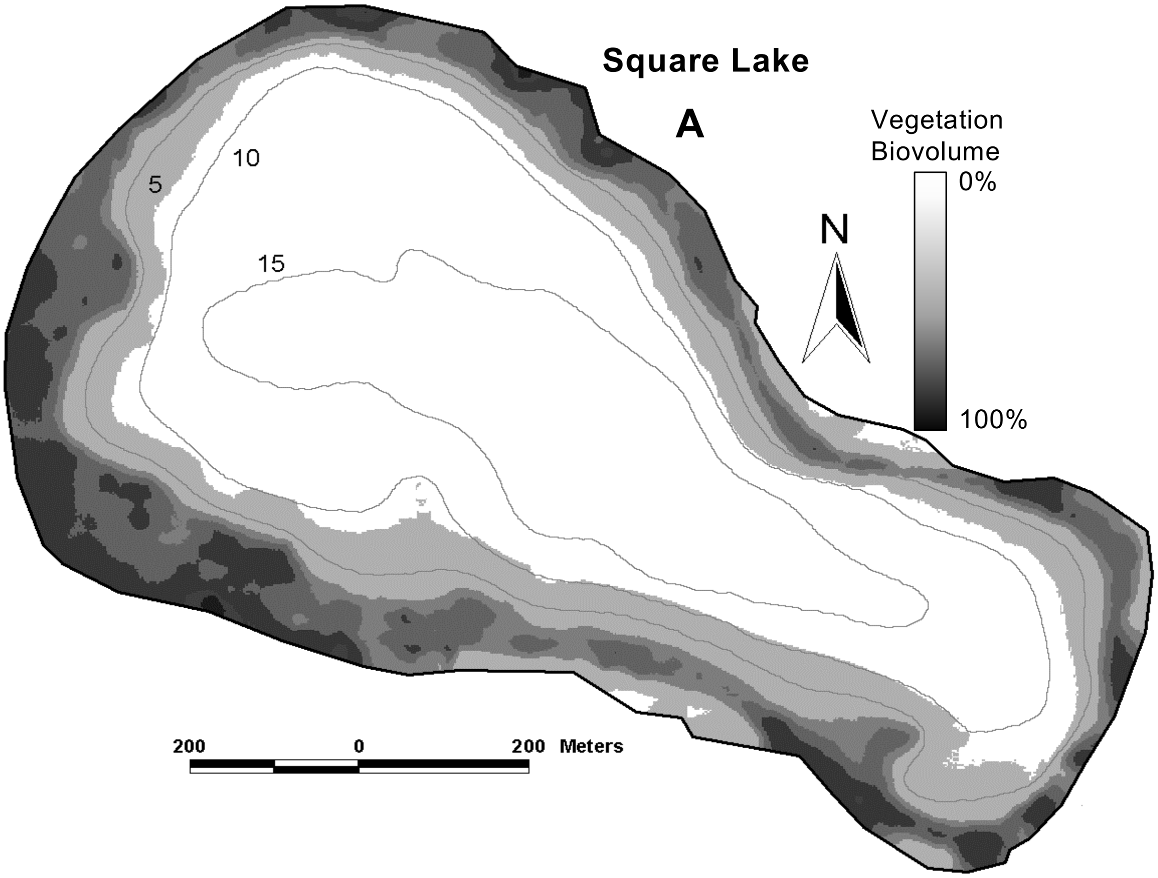

Figure 1. The abundance and distribution of submersed vegetation biovolume in Square Lake. Map created by interpolating hydroacoustic measurements of vegetation biovolume with kriging in GIS.

All map analyses were made for the vegetated zone of each lake, which we define as the littoral zone. The outer boundaries of the littoral zone were defined by the average maximum depth of contiguous bottom coverage of vegetation, interpreted from a sample of 10 – 15 transects from each survey. Transects were sampled uniformly across the littoral surface of each lake. Sparse vegetation growing at deeper depths was omitted from analysis.

Tests of location error–Estimates of navigation error were a function of actual driver error and location error from our DGPS unit. To approximate location error, we conducted seven fixed-transect experiments on Square Lake over seven days in July 2004. Transect lengths ranged from 50 to 100 m, were arranged perpendicular to shore, and were distributed evenly around the perimeter of the lake. Transects were fixed with marker buoys spaced 1 m apart. A swimmer equipped with the DGPS completed three passes along the length of the transect. Tracks (a collection of points) from each pass and from each transect were uploaded as themes into *ArcView*. Because we could not identify the true location of the fixed transects, a reference line was placed parallel to each transect theme, and distances of DGPS records from the line were computed. The standard deviation of these distances represented the average location error for each transect. The mean standard deviation from the seven transects represented the average location error for the entire lake.

RESULTS

Fixed-point experiments–EcoSAV-estimated plant height did not significantly differ from diver-measured plant height (one sample t-test p=0.36). We did, however, find appreciable differences between diver-measured and *EcoSAV* estimated bottom depths and top of plant depths. EcoSAV estimated bottom depth was 0.18 m (±0.18 m SD) deeper on average than diver-measured bottom depth (one sample t-test p<0.001, N=38; Figure 2A). The *EcoSAV* bottom depth error results in overestimated water column depths.

Next, we assessed the error in estimated depth from the surface to the tops of plants. Plant height is estimated in *EcoSAV* by subtracting the depth of the top of plant signal from the bottom signal, but only plant height and bottom depth are reported, thus we had to recalculate depth to the top of the plant as the difference. Diver-measured depth to top of plant was estimated by subtracting diver-measured plant height from diver-measured bottom depth. On average, the *EcoSAV* top of plant depth was 0.23 m deeper than our diver-measured depth to top of plant (t-test p<0.001; Figure 2B). In addition, the bias in estimated depth to top of plant appeared systematic across all plant species sampled (Figure 3).

The overall result of these errors is that the estimated portion of the water column occupied by plants (plant height/water depth) would be 0.41 m lower based on EcoSAV estimates than if based on diver-measured values. The magnitude of this error on biovolume estimates would vary by water depth.

Whole-lake surveys–As a combined result of wind, location error, and delayed position display, navigation RMSE ranged from 3.6 to 4.7 meters in surveys in Square Lake, and 3.5 to 3.9 meters in Christmas Lake. The average standard deviation GPS fixed-transect experiments from the arbitrary line of reference was 1.06 m (Table 1), thus locations were accurately recorded. The MSE from the regression smoothers and kriging models was consistent across the three survey days in each lake. Overall, detrending and kriging models explained 70-74% of biovolume variance in Square Lake in depths ranging from 0.5 m to 7.8 m (i.e., limit of contiguous bottom cover of vegetation), and 29-36% in Christmas Lake in depths ranging from 0.5 m to 6.2 m (Table 2). In Square Lake, mean biovolume from verification samples fell within 95% confidence intervals about grid-cell means predicted from kriging for all surveys (Table 2). In Christmas lake, 95% confidence intervals did not overlap for two of the three surveys; however, the magnitude of these differences is very small (Table 2).

Over the entire littoral surface of each lake, the mean deviation of individual grid cells across surveys was only 3.4% in Square Lake and 4.6% in Christmas Lake. Survey precision increased with depth in both lakes (Figure 4).

DISCUSSION

Fixed-point experiments–Precise field evaluations in aquatic environments are difficult, and we cannot tease apart the effects of imprecision in diver measures of the depth to the top of plants from *EcoSAV*-estimation error. Tests in controlled laboratory environments may be necessary for more precise measurements of algorithm performance. Nevertheless, our evaluation places bounds on potential error of the *EcoSAV* algorithm, with actual error in top of plant depths measurements likely being much less than our reported errors. We are more confident that our diver measures of bottom depth were precise. The bias in depth detection with *EcoSAV* 1.2 may arise from signal penetration of soft bottom substrates (Pouliquen and Lurton 1992; Collins et al. 1996). Adjusting the bottom thickness threshold parameter in current versions of *EcoSAV* does not affect the placement of bottom, only the minimum thickness of the signal above the bottom before a ping is classified as 'plant.' (BioSonics Inc. 2002). This bias may be corrected given increased functionality of a new version of *EcoSAV* that calibrates bottom placement with sediment thickness data entered by users. Depth measurements by *EcoSAV* over hard substrates such as clay, sand, or gravel are unbiased and precise (Sabol et al. 2002).

Sabol et al. (2002) published plant height errors that were approximately ± 0.08 m,

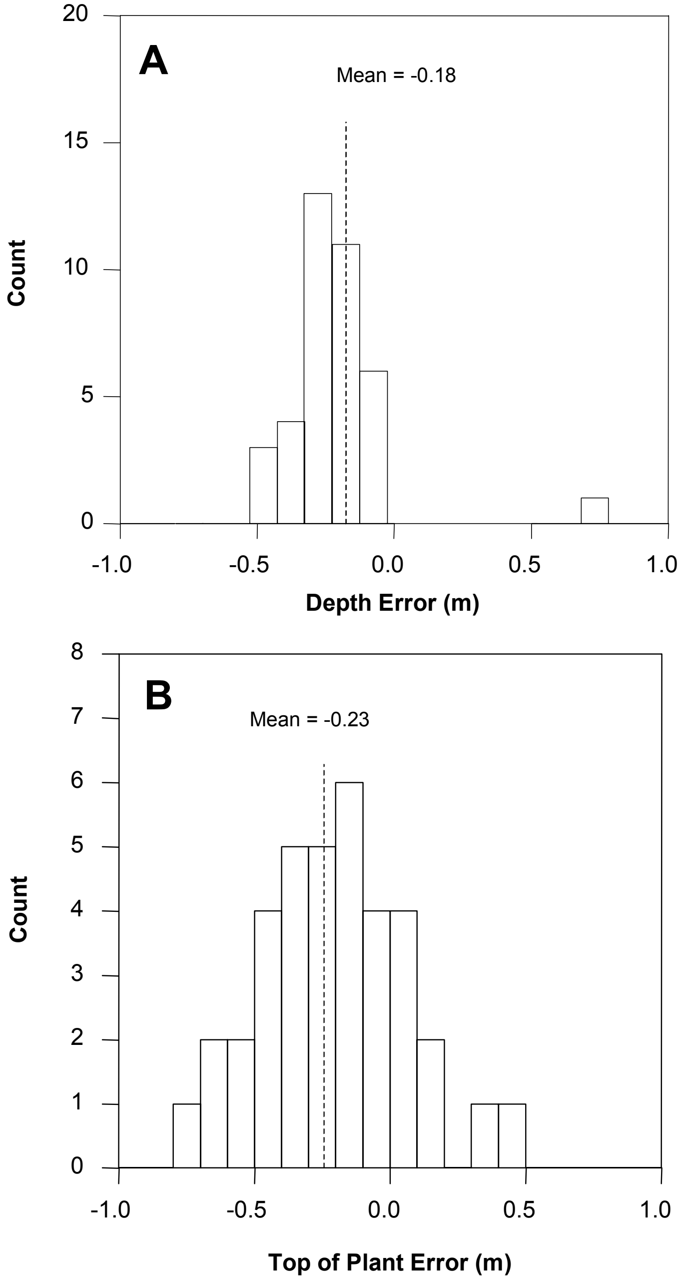

Figure 2. Histograms of the distribution of *EcoSAV* estimation errors (*EcoSAV*-estimate – diver-estimate) from the fixed-point experiments. A) water depth errors (*EcoSAV*-estimated depth was deeper than diver measured depth). B) top of plant errors (Top of plant signals were deeper than diver estimates). Means from both distributions were significantly different from zero (one sample t-test $p < 0.001$).

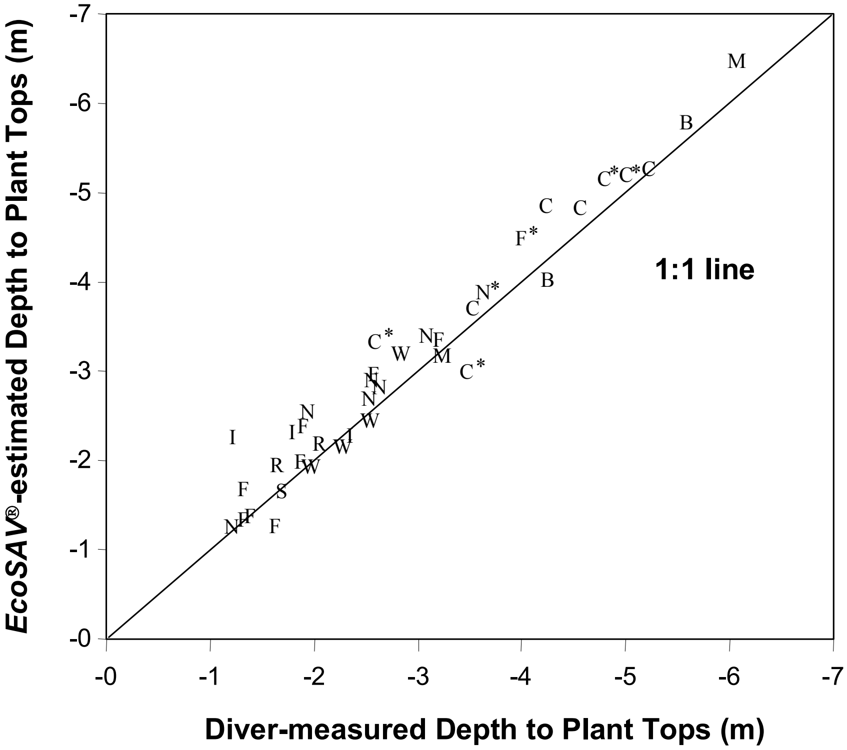

Figure 3. Depth to top of plant signal estimated with *EcoSAV* plotted against depth to top of plant surveyed by divers over the ensonified area. Letters represent the species of the tallest plant intercepting the cone [B = Bare, C = coontail, F = flatstem pondweed *P. zosteriformis*, I = Illinois pondweed *P. illinoensis*, M = *Chara* spp., N = northern watermilfoil, R = Richardson's pondweed *P. richardsonii*, S = sago pondweed *P. pectinatus*, W = whitestem pondweed *P. praelongus*. Asterisks denote where standard deviations of acoustic samples were greater than 0.1 m indicating imprecise acoustic estimates of height (see **METHODS**).

Table 1. Results from GPS location error transect experiments in Square Lake in 2004. PDOP = position dilution of precision.

Date	Transect	PDOP	Standard Deviation (from arbitrary line of reference)
July 20	1	2.44	0.61
July 21	2	2.41	1.22
July 22	3	2.40	1.38
July 26	4	1.80	1.56
July 27	5	1.62	1.19
July 29	6	2.12	0.99
July 30	7	1.19	0.67

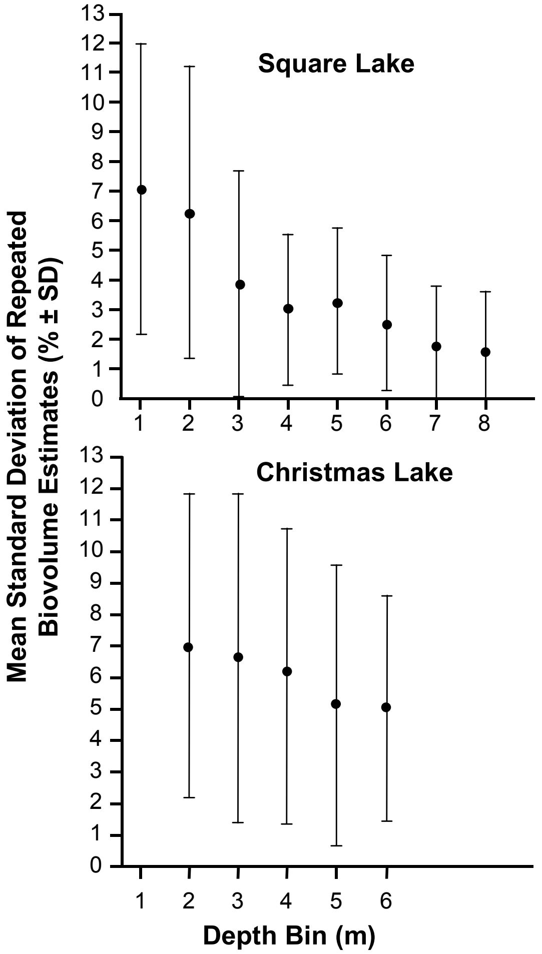

Figure 4. Survey precision as a function of depth. Standard deviations of repeated biovolume estimates were calculated for each 5-m grid cell. The mean of these is then the measure of survey precision (± associated standard deviation) (n = 3 for 1000’s of 5-m grid cells) in Square and Christmas lakes (± associated standard deviation).

Table 2. Percent vegetation biovolume mean squared error (MSE) from the depth smoother (smoothed with 8-10 df), kriging interpolation model, mean biovolume from verification samples, mean biovolume estimated from kriging, and navigation root mean squared error (RMSE) for three repeated surveys in each study lake.

Lake	Day	Total Biovolume Variance	Depth Smoother MSE[a]	Kriging MSE[a]	Percent Total Explained Variance	Mean Verification Biovolume (± 95% CI)	Mean Kriging Biovolume (± 95% CI)	Navigation RMSE (m)
Square	1	317.5	176.5	95.3	70	23.8 ± 0.7	24.9 ± 0.7	4.7
	2	294.0	156.9	89.5	70	--	24.8 ± 0.7	4.0
	3	276.5	151.2	71.1	74	--	23.7 ± 0.6	3.6
Christmas	1	350.4	292.0	248.2	29	40.1 ± 0.7	38.9 ± 0.4	3.5
	2	423.0	350.2	273.2	35	--	41.9 ± 0.5	3.7
	3	458.8	364.6	291.7	36	--	41.5 ± 0.5	3.9

[a] The units for squared errors are squared percentages

much smaller than our reported errors. However, it is important to note that error estimations from Sabol et al. (2002) represent differences between average predicted and average observed plant heights within ensonified 0.3m x 0.3m quadrats, and not over individual plants like our fixed-point experiments. Because Sabol et al. (2002) averaged data over larger sampling units than our study, the central limit theorem, in part, may explain their smaller errors.

Whole-lake surveys–Our methods produced consistently accurate and precise maps of biovolume for Square Lake. For Christmas Lake, maps were accurate but not precise. These results for Christmas Lake are contrary to results published by Valley et al. (2005) that documented high map precision in this lake. However, in our earlier study, we extended analyses to a depth of 8 m in both Square and Christmas lakes. This depth was an appropriate cut-off for analyses in Square Lake because vegetation usually covered all bottom areas close to 8 m deep. However, in Christmas Lake, vegetation was sparse beyond 6.2 m. Biovolume in areas between 6.2 m and 8 m in Christmas lake was often zero, thus artificially inflating map precision. The effect of analysis boundaries on statistical distributions illustrates the importance of carefully defining the boundaries of the littoral zone. Morris (1992) defined the littoral zone as the area of shallow fresh water in which light penetrates to the bottom and nurtures rooted plants. Our operational definition as a zone of contiguous bottom cover by vegetation fits this concept.

Valley et al. (2005) demonstrated that the degree of agreement between verification and predicted data increased as littoral depth increased. Similarly, in this analysis, as depth increased, our survey precision increased as well. Lower survey and map precision at shallow depths is not surprising given the suite of localized disturbances that cause vegetation patchiness in such areas (e.g., harvesting, sedimentation, wind/ice scour). In addition, small deviations in plant height in shallow depths lead to large deviations in biovolume. As a result, we suggest focusing greater sampling effort at depths less than two meters and less effort at deeper depths. Fortunately, kriging is not greatly affected by unbalanced survey designs, and its behavior as a smoother makes it robust to modest environmental noise (Isaaks and Srivastava 1989). Ultimately, the scale of the question and level of spatial resolution supported by the data must be carefully considered prior to interpreting results.

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