J. Aquat. Plant Manage. 47: 44-52

Integrating Acoustic Mapping into Operational Aquatic Plant Management: a case study in Wisconsin

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ABSTRACT

Efficient planning, execution, and post-treatment monitoring of a submersed aquatic plant management operation require early detection and detailed information on the distribution of target and nontarget species within the treated waterbody. This requirement was the motivation behind the development of the acoustic-based Submersed Aquatic Vegetation Early Warning System (SAVEWS™). After initial development in the late 1990s, the associated processing software was licensed to Biosonics, Inc., and is currently marketed as EcoSAV™, along with the required hardware for conducting acoustic plant surveys. Since becoming commercially available in 2001, approximately 70 systems are in use world wide. While the system is used by a number of aquatic plant management researchers and operators, by far greater use is found in other fields, primarily ecological and applied studies of estuarine vegetation and coastal hydrography. While usage in any form is considered beneficial, a significant potential for operational usage within the aquatic plant management field is largely unrealized. Discussions with various aquatic plant management personnel identified concerns related to using the system operationally, including system acquisition and operations cost, data processing complexity, data accuracy, and acceptance by regulatory agencies. To address these concerns, a mapping demonstration was performed in conjunction with a chemical control application to treat Eurasian watermilfoil (*Myriophyllum spicatum*) in a 515-acre (2.08 km^2) Wisconsin lake. One pretreatment and 2 post-treatment surveys were conducted. A ground-truth sampling effort was performed as part of the first post-treatment survey. The cost of conducting the mapping survey is broken out in terms of equipment costs and labor for planning, execution, and data analysis. We present techniques and summaries for data analysis and evaluate the added value of information provided by acoustic mapping to the overall management operation.

Key words: chemical control, cost effectiveness, Hydroacoustics, mapping, *Myriophyllum spicatum.*

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INTRODUCTION

The ability to successfully plan and execute a management operation for submersed aquatic vegetation (SAV) is dependent on having knowledge of the waterbody to be treated and the plants inhabiting it. This includes knowledge of the species present and their spatial distributions, waterbody bathymetry, and phenology of the target and nontarget plant species. Determining the spatial distribution of plants can be problematic, particularly for early season chemical treatments occurring well before the plants are readily visible from the surface. Knowledge of the previous year's spatial distribution during peak biomass is typically used in treatment regimens; however, this can be confounded by year-to-year variability (Skogerboe and Getsinger 2006). It is clearly best to base treatment plans on current information.

Current techniques for assessing the distribution of SAV in waterbodies include physical, optical, and acoustic techniques. Direct observation or physical sampling provides the highest level of certainty for information such as species distribution and density or biomass. However, very little area can be sampled using techniques such as diver sampling, rakes, grab samplers, and core samplers. Thus, the true spatial distribution of SAV for large waterbodies is either unknown or is based on little data, even if a large sampling effort is undertaken. Aerial photographic surveys, a standard method for aquatic vegetation mapping (Leonard 1984, Finkbeiner et al. 2001, Fitzgerald et al. 2006), can provide a large-scale synoptic view of submersed plant distributions provided certain requirements are met (Jackson et al. 2006), including medium solar elevation, low clouds, minimal winds, low turbidity, and low tide for tidal areas. The simultaneous occurrence of all these conditions is not common; thus, aerial photography for submersed vegetation mapping is often taken under suboptimal conditions resulting in underestimating vegetation coverage (Sabol et al. 2008), particularly for low density early season growth. Acoustic techniques for mapping plant distribution detect vegetation based on the density differences between plants and adjoining water (Medwin and Clay 1998). In a boat-based operation, this technique provides information at an intermediate spatial scale between the physical and optical techniques. Recently, fully automated procedures for acoustic submersed vegetation surveys have been developed and shown to be effective at detecting low density early growth of submersed vegetation (Sabol et al. 2002).

The automated acoustic detection technique uses a high frequency (420 kHz) narrow beam (6 degrees) calibrated digital echo sounder, mounted vertically, coupled with a real-time differentially corrected global positioning system (GPS). Both data streams are recorded on the laptop PC that controls the sounder. After recording, a heuristic-based digital signal processing algorithm examines the recorded spatial distribution of echo strengths to determine bottom depth and detect bottom-attached plants. Outputs consist of position-referenced depth, plant height, and plant coverage at the GPS output rate (typically once per second). Species discrimination is not currently possible. This procedure automates and advances earlier work (Maceina and Shireman 1980, Maceina et al. 1984, Duarte 1987), which manually collates strip chart sounder output and manually measured position data. The system is operated from a small boat that typically navigates a pre-planned transect pattern using GPS navigation capability at a modest speed ($\leq$2.5 m s^{-1}). Validation testing showed that the system was capable of detecting submersed vegetation as short as 7 cm with biomass as low as 60 g m^{-2} (wet weight). A detailed description of the system, its use, and performance may be found elsewhere (Sabol et al. 2002).

Initial development of the system, referred to as the Submersed Aquatic Vegetation Early Warning System (SAVEWS™), was completed in 1996. A patent was granted in 1998 (U.S. Patent No. 5,805,525), and the SAVEWS software was licensed to Biosonics, Inc. (Seattle, WA) in 2001, which marketed it under the name EcoSAV™ as part of a suite of software for shallow water environmental characterization to be used with their acoustic hardware. There are currently 70 registered EcoSAV users, 15 outside of North America.

Since becoming commercially available, the system has been tested by others, analysis and interpretation techniques have been developed, and it has been used for a range of applications from basic ecological studies to highly applied usages. Independent verification studies (Valley and Drake 2005, Valley et al. 2005, Winfield et al. 2007) have shown that EcoSAV performs well on a wider range of species and for different frequencies than those originally tested (Sabol et al. 2002). The system outputs orders of magnitude more data than other techniques for determining submersed plant distribution (with equal level of effort). Consequently, analysis procedures have been examined to take full advantage of the level of data. Guan et al. (1999) examined accuracy of spatial interpolation techniques for mapping spatial distribution of seagrasses in a south Florida estuary. Valley et al. (2005) examined the accuracy of biovolume estimates subject to various geostatistical and interpolation procedures from EcoSAV data obtained for Minnesota lakes. Valley and Drake (2007) subsequently studied how spatial variability in submersed macrophyte biovolume, derived from EcoSAV data, varied as a function of trophic status of Minnesota lakes. Zhu et al. (2007) examined historical changes in submersed aquatic vegetation in Lake Ontario embayments using multiple techniques, including acoustic analysis with EcoSAV. EcoSAV has been used to: study the aquatic vegetative structure of fish habitat (Godlewska et al. 2004, Brenden et al. 2006, Fitzgerald et al. 2006) and aquatic bird habitat (O'Connell et al. 2007); study the effects of dredging on eelgrass (*Zostera marina*) in New England small boat harbors (Sabol et al. 2005); examine the accuracy of single-beam and multibeam hydrographic systems operated in small boat harbors with established seagrass beds (Sabol and Johnson 2002, Sabol et al. 2007) and: examine effectiveness of low-dose Fluridone treatment of nuisance aquatic vegetation (Stewart et al. 2005, Valley et al. 2006).

Despite the various documented applications of EcoSAV, no papers specifically examine how this technology could be best integrated into field operations of aquatic plant management. We document an operational usage of acoustic mapping in conjunction with a chemical control operation and describe the complete process of planning, executing, and analyzing data from an acoustic plant mapping survey performed in conjunction with a chemical control operation performed to manage Eurasian watermilfoil in a 515-acre (2.08 km^2) Wisconsin lake. One pre-treatment and 2 post-treatment whole-lake surveys were conducted. All steps in the process were described, costs and labor associated with the operation were recorded and described, and an analysis of data presented. Data derived from this exercise was used to assess the value of information that acoustics brings to operational aquatic plant management.

MATERIALS AND METHODS

Description of Study Site and Control Operation

Eagle Lake is a relatively shallow eutrophic (Gall 2006) lake located in the southern part of Racine County in southeastern Wisconsin. Its surface acreage is approximately 515 ac with a maximum depth of only 13 ft (3.96 m). The lake has a large littoral area supporting abundant SAV, which reached sufficiently high densities in 2005 to prompt the Eagle Lake Management District to seek grant funds from several governmental organizations and to cost-share for lake treatment by Marine Biochemists (Germantown, WI). At the time, the lake was dominated by Eurasian watermilfoil and, to a lesser extent, the invasive species curly-leaf pondweed (*Potomogeton crispus*; Kathy Aron, Aron and Associates, pers. comm.). Historically, mechanical harvesting and near-shore chemical treatments have been used to attempt to control nuisance SAV. Large-scale chemical treatments were initiated in 2006 to achieve control lacking from these previous efforts. These efforts consisted of treating a 110-acre (0.45 km^2) section (Figure 1) on the western end of the lake with liquid 2-4D amine at a level of 2 mg/L active ingredient on 25 April 2006.

Equipment and Personnel

Equipment used in these surveys consisted of a Biosonics sounder, a GPS, a laptop PC, and a 12-volt deep-cycle car battery (Table 1; Sabol et al. 2002, Sabol 2003). Equipment was mounted on a 16-ft boat (4.88 m) with a canopy and an outboard motor[4]. Mounting brackets and accessories had previ-

[4]All equipment used in this study was owned and operated by Marine Biochemists, Germantown, WI.

Figure 1. Aerial photograph with treatment area indicated.

ously been fabricated using standard hardware-store parts. The GPS antenna was positioned over the transducer. Under normal circumstances the boat and equipment would be operated by one person. A crew of 2 was used in this demonstration.

Acoustic Survey Procedures

Acoustic surveys were conducted 24 April 2006 (1 day before treatment), 31 May 2006 (36 days after treatment) and 29 June 2006 (65 days after treatment). Standard EcoSAV data collections settings (Sabol 2003) were used for all surveys. During the first survey, parallel straight-line transects were run in an east/west orientation at an approximate spacing of 164 ft (50 m). The selection of a specific interval distance between transects is a trade-off between the need for detailed spatial resolution and available time (and budget). The 50-m spacing used here corresponded to a full-day survey and has been shown to generate adequate maps for large areas of contiguous vegetation (Sabol, unpubl. data). The first transect in the first survey was navigated by sighting on a distant shoreline feature. Subsequent transects in the first survey used GPS position display to run east/west recording transects at the 50-m spacing. In addition to these straight, parallel transects, a single around-the-lake transect was run as close to the water's edge as possible. During the May and June surveys the original April transect paths were followed using the GPS display monitor that showed the original April transects and the current position. This procedure facilitated conducting 3 nearly identical surveys without spending time programming waypoints into the GPS. Exact repeats of the original transect lines using GPS navigation are neither possible nor necessary to evaluate trends in SAV over time (Sabol, unpubl. data).

Boat speed during acoustic measurements was maintained at approximately 4.5 knots (2.3 m s^{-1}) to avoid cavitation around the transducer and subsequent data quality degradation that would occur at higher speeds. Data were recorded only during the straight part of each transect; when the shoreline was reached, recording was suspended until the boat was navigated to the beginning of the adjoining transect running in the opposite direction. Thus very little time was

TABLE 1. SPECIFICATIONS AND COST OF EQUIPMENT USED FOR ACOUSTIC SURVEY.

Item	Description	Approximate Current Cost (USD)	Note
Hydroacoustic sounder w/ transducers	Biosonics, DT-X sounder with single-beam 6° 420-kHz transducer and cable	$26,500	
Laptop PC	Panosonic Toughbook 30	$4,700	Possible to use lower cost non-ruggedized PC
GPS	Real-time differentially corrected GPS (Leica MX420/2)	$3,500	Lower cost systems are also suitable
Spatial analysis software	Golden Software Surfer ver.8.0	$600	Any of several low cost mapping software packages are suitable
TOTAL		$35,300	

lost navigating between transects. At the end of each sampling day the lake level was determined based on water height relative to the top of the retaining wall by the dam. These data were used to correct recorded depths to the first survey.

Ground Truth Sampling and Analysis Procedures

During the first post-treatment survey (31 May 2006), 62 locations along the acoustic transects were sampled for vegetation. Numbered self-spooling buoys were dropped from the acoustic survey boat at haphazardly selected locations to generate a pseudo-random distribution of points throughout the lake. Whenever a buoy was dropped, a position mark was recorded on the GPS equipment of the acoustic survey boat. A second GPS-equipped boat with a single operator followed the acoustic boat. Within minutes of dropping a buoy, the sampling boat was positioned by the buoy, a GPS measurement was made, and a weighted, double sided, rigid-prong, 14-in (0.36 m) wide, rake was dropped (Skogerboe and Getsinger 2006). Plant material retrieved from the rake was bagged and labeled for laboratory processing. In the laboratory, plants were sorted by species, and maximum stem length was recorded by species. Samples were oven-dried at 65 C, and dry weight was measured by species.

Data Processing Procedures

Following completion of each day's sampling, all recorded data were processed with EcoSAV using high sensitivity default processing parameters (Sabol 2003). EcoSAV outputs include: position (latitude and longitude), date and time, depth (m, uncorrected for transducer depth and lake level), plant height (m), and percent coverage (portion of pings in localized areas in which plants were detected). Following initial processing by EcoSAV, the output files were processed by FINALIZE version 2.0[5]. This program concatenates all individual transect files into a single file for each survey, verifies correct bottom tracking (flagging or deleting outputs of uncertain tracking quality), makes depth corrections for transducer depth and lake level, converts angular geographic coordinates (latitude and longitude) into a user-selected state plane coordinate system, and computes distance along transects. Specific procedures used follow Sabol (2003).

Data Analysis

Data were examined in a series of steps. Plant height and coverage were potentially independent measures of the plant canopy. Coverage represented the percentage of pings between successive GPS outputs (output at 1 Hz) in which plants were detected. Plant height represented the mean height of plants for pings in which plants were detected. It is thus possible to get a large value for plant height with just a few tall plants in an otherwise unvegetated area, a somewhat counterintuitive situation. To avoid confusion, we introduce a new metric that combines plant height and coverage:

$$\text{Effective Canopy Height (ECH, ft)} = (\text{\% coverage}/100) * \text{plant height (ft)} \quad (1)$$

This represents the equivalent average height occupied by plants within the water column and does not give undue weight to a few tall plants.

A file of the lake boundary points (2588 horizontal position points with zero depth) obtained online (http://gos2.geodata.gov/wps/portal/gos) was appended to the data file for each survey for mapping purposes. Maps were generated using the PC-based mapping software Surfer 7.0 (Golden, CO). To generate a map from irregularly spaced source data points, a spatial interpolation technique was employed to generate points on a regular grid spacing. Variables of interest (depth, cover, height, and ECH) from each survey were gridded on an arbitrary grid spacing of 50 ft (15.24 m) and for a common starting point. Gridding of depth was performed using linear triangulated irregular network interpolation, the standard used within the hydrographic community.

Vegetation variables were gridded using natural neighbor interpolation (Sibson 1981), a data-driven technique involving minimum assumptions, which we have used in other

[5]FINALIZE was developed by ERDC. Version 1.0 is currently available by contacting Biosonics (www.biosonicsinc.com). We anticipate releasing version 2.0 soon.

studies (Sabol et al. 2005). This standardized the spatial detail between surveys and allowed the gridded data to be mathematically manipulated between surveys. Change detection was graphically facilitated by differencing gridded arrays of plant attributes using Surfer. Graphical portrayal of changes in height and ECH along individual transects were generated using other graphical software.

Nonspatial analyses of data were performed to examine overall distribution of depth and canopy attributes and to evaluate coverage and ECH as a function of depth. In addition to the steps described above, time required to complete each phase of the study was recorded. These data were used to estimate cost of executing the study.

RESULTS

Data Generated

Each survey was completed in about 7 hr and collected data over approximately 27 mi of transects consisting of 40 separate transects. The number of EcoSAV output points for the first survey was 16,383. At the 1 Hz output rate, this indicates that 4.5 hr (65% of total time) were spent recording data. The nonrecording time represented time spent traveling between transects and down time. The approximate total area of bottom insonified was calculated to be 69,000 ft^2 (0.3% of total lake area), based on a 10-Hz ping rate, 6-degree acoustic beam, and an average depth of 7 ft (2.13 m). Slightly fewer output points were collected in the second and third surveys because dense topped-out vegetation[6], which EcoSAV does not process and which impedes navigation with an outboard motor, occurred in parts of the southeastern embayment.

Maps and Statistical Summaries

Depth, coverage, plant height, and ECH were generated for each survey, and change detection maps were generated between surveys for coverage, plant height, and ECH. A subset of these maps is illustrated here. Bathymetric results (Figure 2), generated using gridded data from the second survey, indicate a maximum depth of approximately 13 ft (3.96 m) located near the middle of the lake and a median depth of approximately 7 ft (2.13 m).

Plant coverage and ECH maps (Figure 3a) show a decrease in both coverage and plant height over the course of the three surveys. Coverage declines slightly between pre- and 4-week post-treatment surveys, then shows more substantial decline between 4- and 8-week post-treatment periods. The ECH showed much more dramatic declines between the same periods. Before treatment, vegetation occupied at least 3 ft (0.91 m) of the water column over large areas of the lake. By 8 weeks after treatment no vegetation exceeded 1.5 ft (0.46 m) of water column, with most areas containing <0.5 ft. This decline in ECH is directly evident in change detection maps generated by differencing ECH gridded data between surveys 1 and 2 and surveys 2 and 3 (Figure 3b). The large decline in vegetation has primarily been in terms of canopy height; vegetation is still widely present over the entire lake.

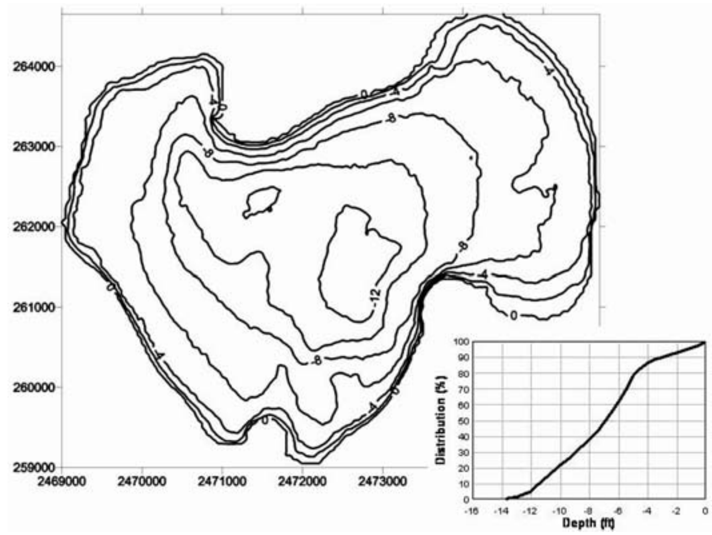

Figure 2. Bathymetric contour map from survey 2 with depth distribution graphic insert.

The data are also examined in more traditional nonspatial ways. A useful technique is to examine the mean coverage and ECH as a function of depth bins (Figure 4). In this case the mean coverage and ECH are computed within half-foot depth increments. The modest decrease in coverage and substantial decrease in ECH are readily apparent.

Ground truth data

Ground truth samples collected during the 4-week post-treatment survey were well distributed throughout the lake. Some buoys drifted from their original drop location before the sample boat arrived. The GPS measurements taken by the acoustic survey boat and the ground truth sampling boat showed that 45 of the 62 points were within 3 sigma (15 ft; 4.57 m) of the horizontal position error of the GPS units used. These 45 data points were kept and the rest were discarded. Physical attributes of the plants sampled showed highly significant positive linear agreement ($r^2 \geq 0.40$, $p < 0.01$) with corresponding acoustically measured plant attributes (Figure 5). The most commonly occurring species sampled was curley-leafed pondweed in 34 of 62 samples, followed by coontail (*Ceratophyllum demersum*) in 8 of 62, Chara (*Chara* spp.) in 6 of 62, and Eurasian watermilfoil in 3 of 62.

[6]The SAVEWS algorithm tests for the presence of an "acoustically quiet" layer of water, of a user-selected depth and signal threshold, above the plants or the bottom. This test verifies that the water column is acoustically quite, and therefore, that data quality is good. If this condition is not found the ping is discarded. In topped-out vegetation this condition is not met so SAVEWS does not generate data in topped vegetation. An additional confounding problem is that topped vegetation frequently wraps around the transducer preventing transmission of the acoustic pulse. This can be overridden (Valley et al. 2005), but we do not recommend doing so on a routine basis since it would be too easy to misclassify poor acoustic conditions as topped-out plants.

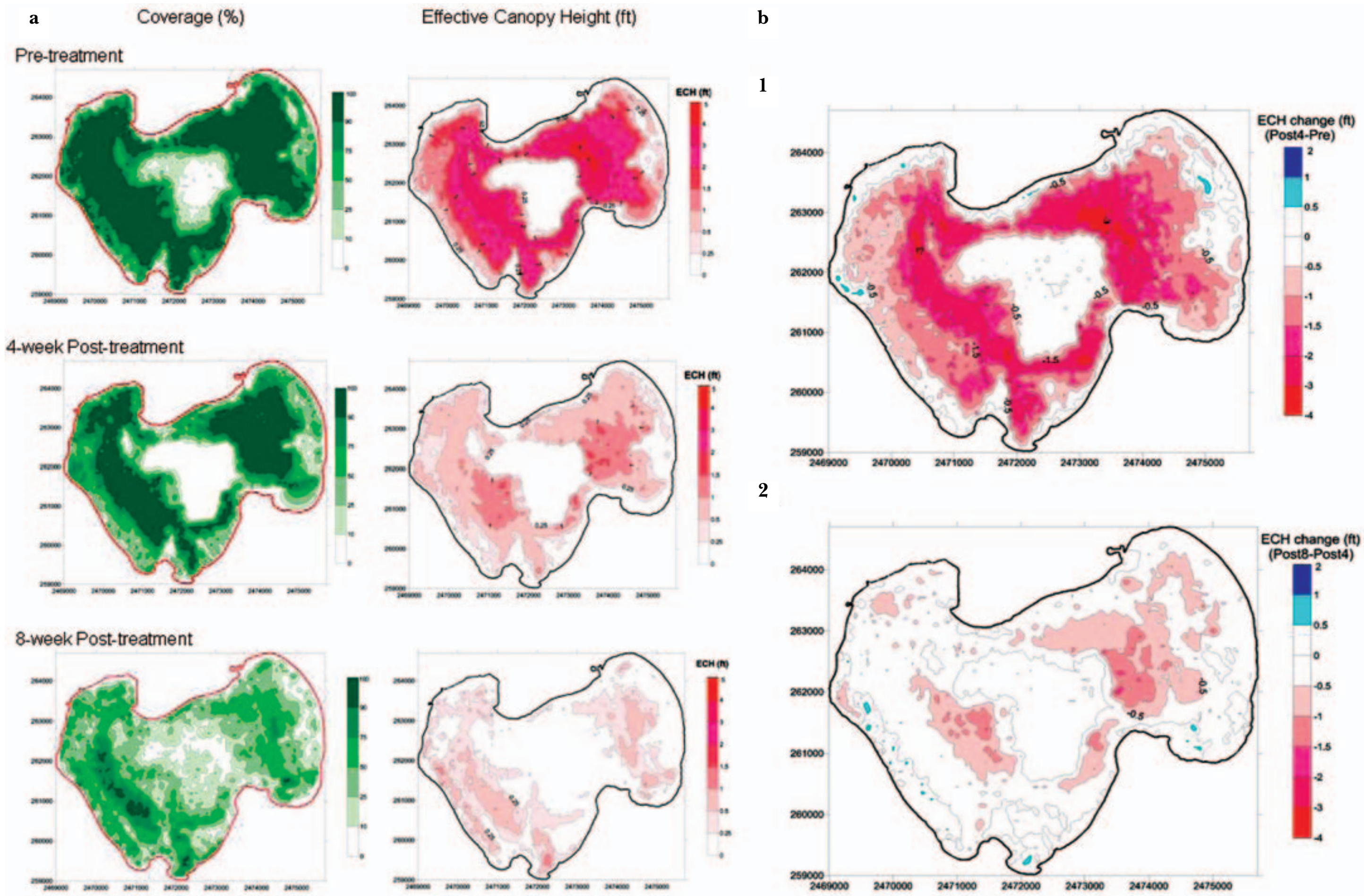

Figure 3a. Coverage (%) and effective canopy height (ft) for all 3 surveys (could be gray or color). Figure 3b. Change detection of ECH generated by subtracting the pre-treatment gird from the 4-week post-treatment gird (1), and the 4-week post treatment grid from the 8-week post treatment grid (2).

Cost

We summarized the labor required to conduct this survey and process the data (Table 2). Acoustic surveys of the type performed here are routinely performed by a single person who operates the boat and the equipment, so labor for conducting this survey only included one person. A second person was on the acoustic survey boat solely for the purposes of observing and recording for this study. No time was allowed for travel time to and from the site, which would be involved for any field survey method. Ground-truth procedures tend to be time consuming, particularly the laboratory portion. Procedures used here were more involved than is typical of routine operations because we wanted to quantitatively compare physical and acoustic measurements. Routine procedures would collect enough data to generate a species list and some presence/absence data to compare with the acoustics, probably about half the effort here. Data analysis times reflect operational analyses, that is, performing a predetermined set of analysis procedures. Exploratory data analysis performed for research purposes can take considerably more time.

Costs of this survey were estimated by including and summing labor costs and costs for use of the acoustic equipment, but not the boat. The skill level needed to operate this equipment is that of a technician (or college student); we assumed a labor rate of \$20/hr. We further assumed an operational ground-truth sampling effort performed for each survey that is half the effort performed here. Resulting total labor time for the 3 surveys is 100 hr, with associated cost of \$2000. Equipment usage costs were estimated by amortizing the \$35,300 cost over a short pay-off period (5 years) at 9% interest. Daily cost was computed by assuming a full use of 45 days per year. The one week of use for the 3 surveys (rounded up) then costs \$1200. Summing these costs, then dividing first by 3 (surveys) and then by 515 ac (2.08 km^2) resulted in a cost of \$2.06 per acre per survey.

DISCUSSION

The acoustic surveys demonstrated the rapid decline in SAV following chemical treatment. Prior to treatment, coverage exceeded 50% over three-quarters of the lake area, and averaged more than 90% coverage between the 6-ft (1.83 m) and 10-ft (3.05 m) depth contour. The average ECH peaked at 3.5 ft (1.07 m) between the 8-ft (2.44 m) and 10-ft (3.05 m) depth contours and exceeded 5 ft at many areas. Systematic plant sam-

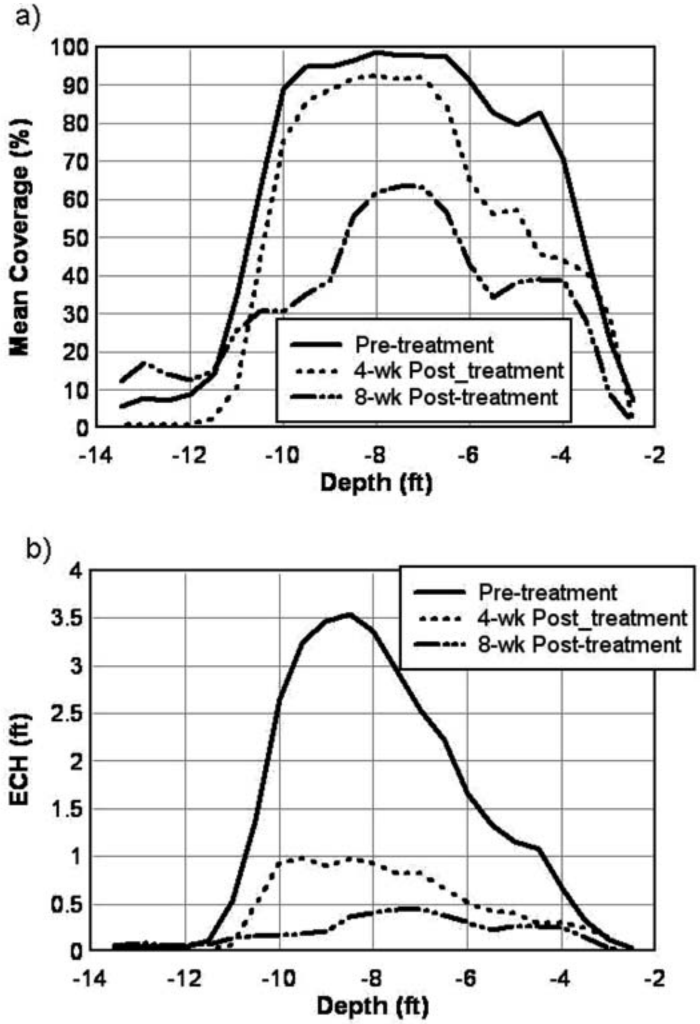

Figure 4. Mean coverage (a) and mean ECH (b) by depth increments of 0.5 ft.

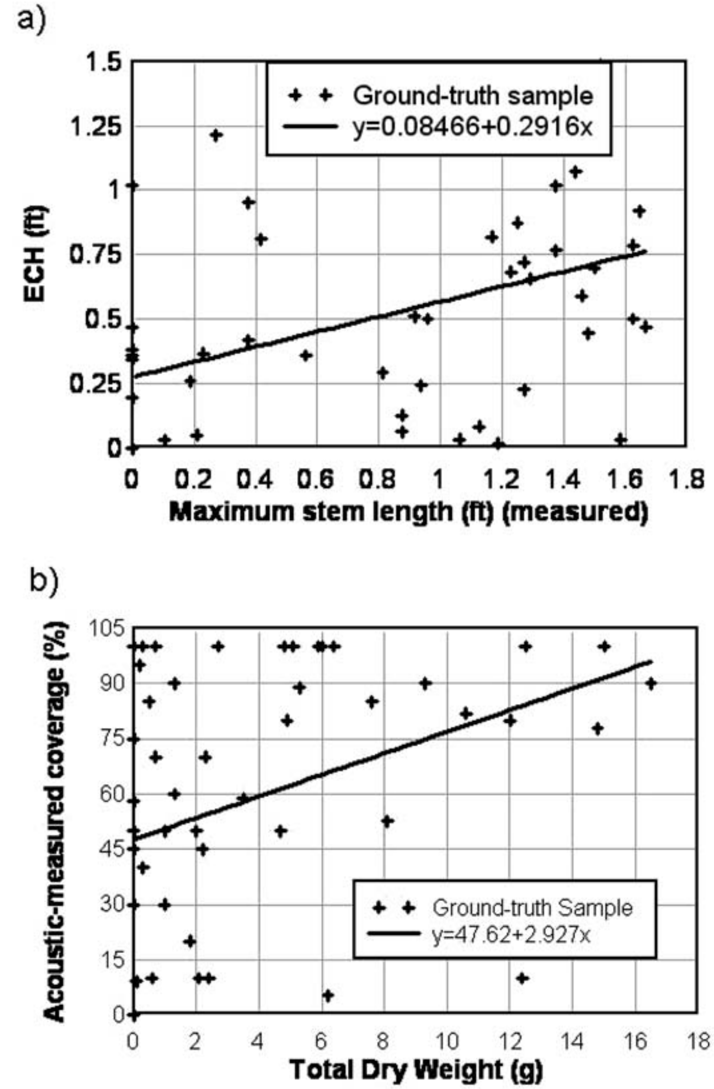

Figure 5. Scatter plot of ground truth height stem length vs. plant height (r^2 = 0.423, p = 0.0022) (a) and ground truth sample dry weight vs. coverage (r^2 = 0.3768, p = 0.007) (b).

pling using the point intercept method, conducted by Kathy Aron (Aron and Associates) in 2005, showed that the aquatic plant community was dominated by Eurasian watermilfoil and, to a lesser extent, by curly-leaf pondweed. Only trace amounts of native vegetation, Chara, sago pondweed (*Stukenia pectinata*), and coontail were found. Additional surveys (Kathy Aron) conducted in the weeks prior to the herbicide application showed that this tall vegetation was predominantly Eurasian watermilfoil. Four weeks after treatment only 40% of the lake area had plant coverage exceeding 50%, and ECH averaged <1 ft (0.30 m) between the 8-ft (2.44 m) and 10-ft (3.05 m) depth contours and averaged even shorter at other depths. Plant sampling during this survey showed that curly-leafed pondweed was found most frequently and that Eurasian watermilfoil was found least frequently. Eight weeks after treatment, only a quarter of the lake area exhibited plant coverage exceeding 50%, and ECH averaged <0.5 ft for all depths. The decline process is best illustrated in the change analysis maps (Figure 3b).

No obvious localized effect around the treatment areas was evident; the declines appeared to be lake-wide. The tall canopies formed by Eurasian watermilfoil simply collapsed. Coverage was reduced lake-wide, but plants were not eliminated from any areas that originally contained them. Lake-wide effects were not anticipated, and there is no valid study control in this sampling design, such as a bathymetrically isolated embayment or nearby untreated reference lake, to "prove" that the reduction is attributable to the chemical treatment. There are other uncontrolled factors which may potentially be at play. For instance, some mechanical harvesting was occurring in localized areas on the eastern shoreline. The phenology of Eurasian watermilfoil in this part of the country is such that vigorous growth typically occurs from spring through summer (Smith and Barko 1990); a natural dieback in late spring would not be expected. Further, surveys on other nearby lakes during 2006 indicated healthy and vigorous growth of Eurasian watermilfoil through late summer (Kathy Aron, Aron and Associates, pers. comm.), making it unlikely that either of these factors could have

Table 2. Labor time required for these surveys.

Task Description	Labor (person hours) Per Survey	All 3 Surveys
Equipment preparation (mob/demob)	4	12
Conduct acoustic survey	8	24
Process raw data	4	12
Ground truth sampling		
(field)	8	
(laboratory)	16	
Data analysis	6	16
TOTAL		
(without ground truth)	22	64
(with single ground truth)	46	88

played a major role in the lake-wide decline; therefore, we assume that the chemical treatment was the primary cause.

Several possible reasons are suggested for the control being lake-wide as opposed to localization as originally expected. The recommended application rate base on the 2,4- D herbicide label (DMA 4) was 2 mg/L; however, concentration exposure time data (Green and Westerdahl 1990) showed that Eurasian watermilfoil can be controlled by application rates as low as 0.5 mg/L active ingredient with exposure times ≥72 hrs. The herbicide application was applied in early spring when water temperatures were cold, resulting in slower degradation of the control agent, allowing for more contact time and more time to migrate to other areas. The lake is very shallow, thus the western side is not bathymetrically isolated from the other parts by a deep center that would act to dilute the agent migrating from the treatment area. Lastly, the treatment was early in the growing season when the plants were young and actively growing, and possibly more susceptible to the chemical control agent.

The acoustic system with all needed components (Table 1) is not inexpensive. The initial cost might be beyond the financial means of some resource agencies or small companies. However, when used efficiently and often, the total and per acre costs can be very modest ($2.06/ac-survey computed here). These estimates represent costs of an “in-house” effort as opposed to a contracted effort. However, these comparative costs suggest that the acoustic system could be economical for large resource agencies and private sector firms that frequently perform submersed vegetation mapping.

We tested a technique for rapid ground truth data collection to verify acoustical output generated in this study. Comparison between the rake samples and acoustical outputs did show a highly significant positive correlation, but was still considerably lower than measurements found using other more time-intensive techniques (Sabol et al. 2002, Valley and Drake 2005, Winfield et al. 2007). We attribute this to the fact that rake sampling is only a qualitative measurement, and that the acoustic and corresponding rake sampling positions were not sufficiently close to represent the small area sampled acoustically. Rake sampling is, of course, valuable for establishing the species list but is inadequate for quantitative comparison with acoustic data. All species on the list have been encountered in other acoustic studies, and, with the exception of Chara, all exhibit highly detectable acoustic signatures. Further, we believe the acoustic technique has been sufficiently validated in other studies. However, if it is deemed necessary to precisely tie acoustic measurements to physical plant characteristics, then we recommend using the techniques described in previous studies (Sabol et al. 2002, Valley and Drake 2005, Valley et al. 2005, Winfield et al. 2007). Some limited ground-truth sampling, to establish species list and spot check acoustic performance, is recommended at least once for each new site, but can be minimized on subsequent surveys.

We acknowledge that some “fine tuning” methodological issues associated with this acoustic technique still need to be addressed with future research. Among these are: refinement of study design guidance, including transect spacing and orientation; processing parameter selection; interpolation technique selection; and determination of level of intensity needed for ground truth analyses. However, using some common sense and methodological consistency, we believe that a great deal of valuable information can be generated to assist with operational aquatic plant management. The technique provides orders of magnitude more information on the canopy geometry of the submersed aquatic plants than available by other established techniques including physical sampling and aerial photography. Some physical “ground truth” sampling is required, primarily to establish a species present list. If species present exhibit easily distinguishable geometric attributes of their canopies, such as large differences in plant height, then acoustically measured plant height can be used to discriminate species (Sabol et al. 2008), however this is not often the case. Per acre cost of mapping can be modest if the system is used regularly and efficiently. Graphical and statistical analysis techniques shown here convert the voluminous raw data into usable information that generates a high-resolution picture of plant conditions before and after a plant management operation. Such information could be used to better plan and refine operations to achieve better control with less cost and chemicals applied.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Carlton Layne of the Aquatic Ecosystem Restoration Foundation for help in organizing this study, and Mr. Ray Valley of the Minnesota Department of Natural Resources for his insightful review comments. This research was supported by the U.S. Army Aquatic Plant Control Research Program and by Marine Biochemist.

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