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Case Study

Spatial and temporal variation of aquatic plant abundance: Quantifying change

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ABSTRACT

Significant resources are used each year to manage the abundance of invasive, submersed aquatic plants, mostly in disturbed systems. Only recently has low-cost, automated hydroacoustic methods been developed and used for mapping aquatic plant abundance and conducting "before–after" assessments of aquatic plant management (APM) activities. Recent studies suggest that macrophyte abundance is highly variable in disturbed systems even in the absence of management. Therefore, detecting an APM management "signal" through the background "noise" inherent in disturbed aquatic systems is a challenge. I repeated hydroacoustic and species surveys during the course of 5 yr (2011 to 2015) in one eutrophic Minnesota glacial lake that experienced minimal APM. Basic geographic information system raster comparison methods were used to compare aquatic plant biovolume (percentage of water column filled with vegetation) maps across years and created a benchmark map based on the time series average. Deviation maps displayed spatial and temporal variability, with average lakewide plant biovolume ranging from 53% in 2013 to 31% in 2015. There were no consistent interannual trends or correlations with other meteorological variables (e.g., ice-out, average temperature, or precipitation amount). Although aquatic plant biovolume was highly variable, percentage of cover and other indicators (dominance and index of biotic integrity) remained relatively similar during the course of the study. To be more confident in APM prescriptions and outcomes, my results suggest that greater investment into long-term aquatic plant abundance monitoring programs will be necessary to establish benchmarks and ranges of variability in different types of lakes.

Key words: acoustics, interannual, macrophyte, SAV, variability.

INTRODUCTION

Billions of dollars are spent each year in the United States to manage aquatic invasive species (NOAA, unpub. data), and significant resources are focused on invasive aquatic-plant management (APM). In north temperate glacial lakes, selectively removing nonnative invasive plants while minimally affecting native species and other nontarget organisms is often a goal of APM (Madsen et al. 2002, Valley et al. 2004, Bremigan et al. 2005). Given the dynamic nature of lakes and the myriad of other factors affecting plant dynamics (e.g., climate, eutrophication, benthivorous fish), achieving this goal has been a challenge for APM managers.

For instance, macrophyte communities can be highly variable in both disturbed and undisturbed systems (Macan 1977, Nichols and Lathrop 1994, Titus et al. 2004, Søndergaard et al. 2016). Aquatic plant management is just one of many factors that may affect aquatic plant species composition and abundance. In the absence of APM, large change can still occur in aquatic plant communities. For instance, a bloom of epiphytic algae likely collapsed a Eurasian watermilfoil (*Myriophyllum spicatum* L.) population and reduced biovolume in an unmanaged eutrophic lake studied by Valley and Drake (2007). Further, slower, chronic issues, such as eutrophication and climate change, in developed regions have ushered in shifting baseline conditions, impaired lake resilience, and increasing variability in macrophytes, regardless of APM activities (Nichols and Lathrop 1994, Valley and Drake 2007). Finally, spatial and temporal variability of measured variables and measurement error by investigators can affect conclusions (Søndergaard et al. 2016).

High natural variability in aquatic plant communities serves as a backdrop of current efforts to manage macrophytes and demonstrate the effectiveness of management interventions. For instance, many APM evaluations are often based on "before–after" treatment snapshots, often with 1 yr of pretreatment data, the year during, and perhaps 1 yr after without any reference monitoring. Studies demonstrate low power to detect effects for some aquatic plant indicators (Beck et al. 2014, Søndergaard et al. 2016), and often, several years of monitoring data are needed to be confident about the natural range of variables before any manipulation even takes place (Knowlton and Jones 2006, Søndergaard et al. 2016). Consequently, subtle effects of herbicides on invasive and native plants are difficult to measure without comprehensive pretreatment or reference data (Netherland and Jones 2015).

This study explores variability in whole-lake aquatic plant biovolume (percentage of the water column occupied

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with vegetation—also historically referred to as *percent volume inhabited* or *percent volume infested*—(PVI) and species dominance (Valley et al. 2015) across 5 years of repeated surveys (2011 to 2015) in one eutrophic Minnesota lake with minimal permitted APM activities and no new infestations of nonnative plant species. I demonstrate how the same technique used by NOAA to create 30-yr average climate and deviation-from-average maps (Daly et al. 2008) can be used as a benchmark for comparisons after any management activity or to document effects from other environmental disturbances. I also explore possible links of the variability in PVI and species dominance to temperature and precipitation trends.

MATERIALS AND METHODS

Study area

Orchard Lake is a 96-ha, 10-m-deep (3 m average depth), eutrophic (trophic state index = 51 [MN PCA 2016]) lake in a developed, suburban area of Minneapolis, MN (44°41′02.82″N; 93°18′36″W). Most APM activities on Orchard Lake during the study occurred only in small areas directly in front of lakeshore properties by homeowners for access (maximum of 0.02 ha or 232 m^2 allowed without a permit), and the Minnesota Department of Natural Resources (DNR) never permitted more than 0.8 ha of cumulative vegetation removal per year (both harvesting and chemical), except in 2011. In 2011, the DNR permitted the chemical treatment of 7.7 ha (8% of the lake area) for invasive curlyleaf pondweed (*Potamogeton crispus* L.). Still, this plant species typically senesces by midsummer in southern Minnesota, regardless of treatment, so the effect on plant growth during the mapping event in July 2011 was likely minimal. The lakeshore of Orchard Lake was extensively developed, with 91 residential homes (approximately one home per 53 m of shoreline).

Aquatic plant surveys

Aquatic plant biovolume was assessed using hydroacoustics and data processing with BioBase[1] cloud-based software (http://www.cibiobase.com; Radomski and Holbrook 2015, Valley et al. 2015). A Lowrance HDS[2] with a 20° beam transducer (model HST-WSBL), along with wide area augmentation system–corrected global positioning system (GPS), was used to log a 200-kHz broadband signal on a storage-media card while traveling 6.4 to 9.6 km h^{-1} along transects spaced 40-m apart. Surveys were conducted in mid to late July of each year.

Data were uploaded to BioBase, where algorithms evaluated each acoustic and GPS signal and created spatial data layers (point features) of depth, aquatic plant height, and percentage of the water column occupied by vegetation (biovolume). Data points predicted by BioBase exceeded 4,500 along transects for all surveys, and adjacent points were often spaced < 2 m apart. BioBase imports the plant and depth points into a kriging geostatistical algorithm to create a uniform map of predicted aquatic-plant biovolume. Grid cell sizes of 10 m were used for all kriging maps produced by BioBase.

In 2012 to 2015, point-intercept species surveys (Madsen 1999) were incorporated into the survey design and were conducted simultaneously at points spaced 80-m apart along every other hydroacoustic transect. This is consistent with the approach discussed by Porter et al. (2012) to integrate high-frequency sensor data with value-added observational data for strong ecological inference. Presence of all submerged species on a double-sided rake thrown from the boat was recorded at 75 to 89 sites throughout the depth range of the lake in which the plants grew. Aquatic plant species dominance, which is a measure of the degree to which one species dominates local richness and biovolume (Valley et al. 2015) was calculated for each species sampled at each site for each survey. Finally, an index of biotic integrity (IBI; Beck et al. 2010) was computed from all point-intercept surveys and compared across years.

Climate data

Climate significantly affects lake metabolism and nutrient loading (and thus may indirectly affect aquatic plant growth). Accordingly, data were acquired on two primary climate variables (average temperature and total precipitation) from the Minneapolis-St. Paul (MSP) airport, which is 20 km north of Orchard Lake. Data were retrieved from the DNR state climatology office (MN DNR 2016a) Data were summarized from ice-out to the survey date for each year. Water levels in Orchard Lake were regulated by an outlet structure that prevents high water conditions. Precipitation during all years of the study was greater than average (see "Results and Discussion"), and thus, water levels remained consistent at the outflow elevation (MN DNR 2016b). Other water quality information was not available during this study.

Geographic information system (GIS) raster analyses

Exported kriging grids were converted from X (latitude), Y (longitude), and Z (biovolume) grid-centroid text files in WGS84 decimal degrees (e.g., point features) to rasterized biovolume grids using spatial analyst for ArcMap 10.3 software[3] (Feature to Raster in the Arc Toolbox). Raster maps were projected into Universal Transverse Mercator using NAD83 zone 15 as the datum. Summary statistics were used from the biovolume grid data, with a sample size of $>$ 7,900 100 m^2 grid cells.

An average map across all 5 yr was created with the Raster Calculator in the Arc Toolbox (i.e., 2011 biovolume map + 2012 + 2013 + 2014 + 2015/5). This created a very detailed map of what the biovolume looked like, on average, at a 100-m^2 resolution. A difference map for each year was created by subtracting the biovolume map from the year of interest from the average map and creating a map of biovolume deviations. Values less than zero represented areas in which the biovolume was less than the average. Likewise, if values were greater than zero, the biovolume was more than the average in those areas. Significant deviations from average were determined if the 95%

Table 1. Frequency of occurrence for aquatic plant species at depths ≤ 4.6 m (± 95% confidence intervals) sampled via point-intercept in Orchard Lake (Dakota County, MN). Summaries of aquatic plant species dominance are expressed as the percentage included (Valley et al. 2015). The index of biotic integrity (IBI) was calculated using methods described by Beck et al. (2010).

Common Name	Species Name	2012	2013	2014	2015
Coontail	*Ceratophyllum demersum* L.	63 (10.9)	68 (9.9)	60 (10.5)	60 (10.2)
Northern watermilfoil	*Myriophyllum sibiricum* Komarov	38 (11)	68 (9.9)	45 (10.6)	29 (9.4)
Chara	*Chara* sp.	21 (9.2)	18 (8.2)	16 (7.8)	24 (8.9)
Waterstargrass	*Heteranthera dubia* (Jacq.) Small	14 (7.9)	7 (5.4)	6 (5.1)	9 (6)
Longbeak buttercup	*Ranunculus longirostris* Godr.	10 (6.8)	24 (5.1)	8 (5.8)	8 (5.6)
Largeleaf pondweed	*Potamogeton amplifolius* Tuckerman	9 (6.5)	11 (6.7)	11 (6.7)	1 (2.1)
Common elodea	*Elodea canadensis* Michx.	5 (4.9)	20 (8.5)	6 (2.9)	2 (2.9)
Richardson's pondweed	*Potamogeton richardsonii* (A. Bennett) Rydb.	4 (4.4)	12 (6.9)	12 (6.9)	6 (4.9)
American eelgrass	*Vallisneria americana* Michx.	1 (2.2)	1 (2.1)	4 (4.2)	2 (2.9)
Whitestem pondweed	*Potamogeton praelongus* Wulfen	0	2 (3)	1 (2.1)	6 (4.9)
Sago pondweed	*Stuckenia pectinata* (L.) Börner	0	2 (3)	1 (2.1)	2 (2.9)
Illinois pondweed	*Potamogeton illinoensis* Morong	0	1 (3)	1 (2.1)	0
Curlyleaf pondweed	*Potamogeton crispus* L.	0	29 (9.7)	0	1 (2.1)
All rooted		85 (8.1)	95 (4.6)	81 (8.4)	79 (8.4)
Average maximum site dominance		30 (10.4)	32 (9.9)	34 (10.1)	29 (9.4)
Plant IBI		48.9	55.3	46.0	47.5
n		75	85	84	89

confidence intervals (95% CI) around the deviations did not overlap with zero.

Because this study involved very large sample data points, but the focus the interpretation was on the magnitude of differences (Johnson 1999). Valley and Drake (2005) documented very high repeatability for hydroacoustic survey results in lakes geomorphically similar to Orchard Lake, thus increasing confidence that differences between surveys were due to environmental change and not to an artifact of sampling.

RESULTS AND DISCUSSION

Species composition and dominance

Across all years, coontail (*Ceratophyllum demersum* L.) and northern watermilfoil (*Myriophyllum sibiricum* Komarov) were the most common species (29% to 68% frequency of occurrence; Table 1). However, overall dominance was low, and rarely, did any species grow all the way to the surface in monocultures (e.g., maximum species dominance at any site > 50%; Table 1). The frequencies of most species remained stable from year to year with the exception of northern watermilfoil, longbeak buttercup (*Ranunculus longirostris* Godr.), and common elodea (*Elodea canadensis* Michx.), which were significantly more common in 2013 than in other years (Table 1). In 2015, largeleaf pondweed (*Potamogeton amplifolius* Tuckerman) largely disappeared but was stable at around 10% frequency in the previous 3 yr. Overall percentage of the frequency of vegetation, which correlates with the percentage of cover (Valley et al. 2015), was relatively stable from year to year, and only 2015 was significantly less than 2013 (Table 1). Confidence intervals from all other years and combinations overlapped. Furthermore, the overall status of the plant community in the lake, as determined by an IBI (Beck et al. 2010), was typical for a lake of Orchard Lake's productivity and was stable throughout the study (IBI scores ranged from 46 to 55; coefficient of variation = 0.08; Table 1). The maximum depth of vegetation growth, as determined by hydroacoustics, varied from 5.0 to 5.9 m (Table 2). Using Secchi clarity vs. maximum depth of plant growth regression published by Canfield et al. (1985), suggested seasonal water clarity ranged from 2.8 to 3.3 m. This result is within the historical range for Secchi clarity in Orchard Lake, as published by MN PCA (2016).

Patterns of biovolume and cover

The variability in total biovolume of plants across years in Orchard Lake was conspicuous (Figure 1). On average, plants occupied 43% more of the water column in 2013 than they did in 2015. By averaging maps across years and then subtracting each year from the average, we see where plant growth was greater and less than average for each year (Figure 2). In all years, 95% CIs around the biovolume differences never overlapped with zero, meaning that each year, biovolume deviated significantly from the average condition. Despite systematic differences compared with averages each year, we still observed considerable random spatial heterogeneity in differences in local areas. In other words, a local site could have seen variability in plant growth that was unlike any other area in the lake (Figure 2). Further, high variability was observed in plant canopy height as a function of depth (Figure 3). Growth patterns were qualitatively similar in 2011 to 2013 with many areas of the lake supporting plant canopies taller than 2 m, as indicated by medians and interquartile ranges. However, in 2014 and 2015, growth looked uniformly depressed, but interestingly, plants grew deeper in these years (Figure 3). Valley and Drake (2007) demonstrated considerable variability in macrophyte biovolume in eutrophic (unstable) lakes with productivity levels similar to Orchard Lake.

Despite large swings in plant abundance across years, the cover by plants remained virtually unchanged, with only a 3% difference in plant cover between 2013 and 2015 (Figure

Table 2. Meteorological data summarized for the area around Orchard Lake (Dakota County, MN). Data were retrieved from the Minnesota Climate Working Group database (MN DNR 2016a). Numbers in parentheses indicate the deviation from National Weather Service's 30-yr averages.

Survey Date	11 July 2011	17 July 2012	10 July 2013	29 July 2014	22 July 2015
Ice-out[1]	10 April 2011	18 March 2012	29 April 2013	14 April 2014	25 March 2015
Average temperature, C (departure)	16.4 (−0.1)	17.8 (+3.3)	18.6 (+0.3)	17.0 (−1.1)	15.8 (+0.2)
Total precipitation, cm (departure)	32.5 (+4.6)	47.0 (+12.9)	29.9 (+6.79)	59.7 (+26.7)	41.6 (+7.11)

[1]Ice-out was determined by citizen volunteers on Crystal Lake (Dakota County, MN; 5 km northeast of Orchard Lake) and reported to the Minnesota Department of Natural Resources climate office.

1). Valley and Heiskary (2012) documented large changes in the frequency percentage (cover) of curlyleaf pondweed as a response to winter snowfall patterns and noted that curlyleaf pondweed abundance (which was not recorded) likely responded much more strongly to winter snowfall. Dudley et al. (2013) also noted stronger correlations of macrophyte abundance metrics to environmental stressors than the presence–absence conditions that percentage of cover metrics reflect.

Maximum depth of vegetation growth (Z_{max}), surprisingly, did not correlate with biovolume (Pearson's product moment correlation, $P = 0.94$). Although clarity was not measured directly in Orchard Lake, Canfield et al. (1985) and Valley and Drake (2007) suggest a tight correlation between Z_{max} and Secchi clarity. Given the lack of a clear relationship between Z_{max} and biovolume, the water clarity was not likely a driver of the differences in biovolume across years.

Correlations with temperature and rainfall

Because I did not have access to measures of trophic condition (e.g., seasonal means of total phosphorus,

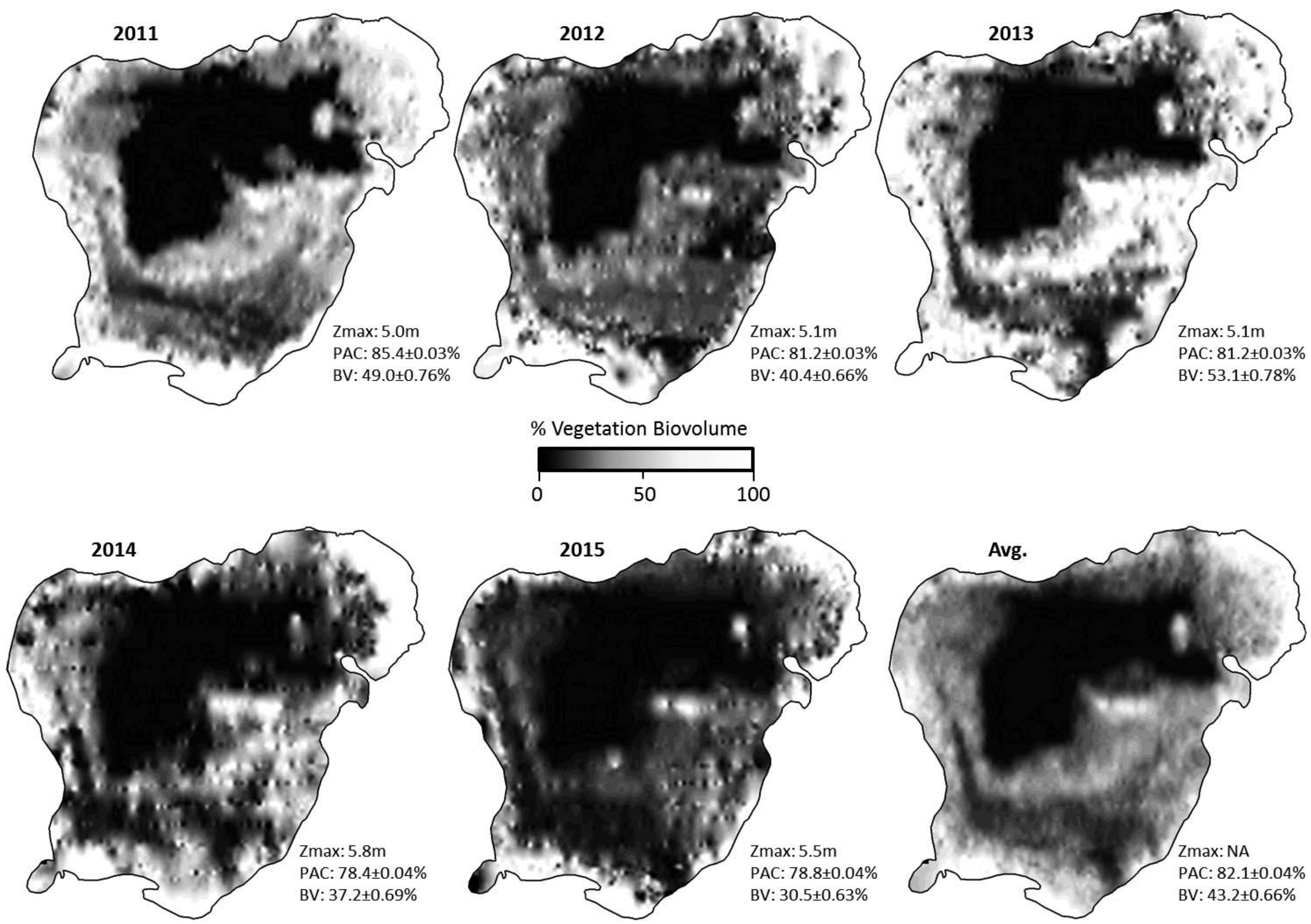

Figure 1. Aquatic plant biovolume maps of Orchard Lake (Dakota County, MN) created with Lowrance hydroacoustics and BioBase software. BV = the average percentage of water column occupied by submersed vegetation; PAC = percentage of the lake bottom that had biovolume values ≥ 5%; Z_{max} = depth of 98% of all vegetation occurrences (noninterpolated point data). Cover and biovolume are means estimated with 95% confidence intervals.

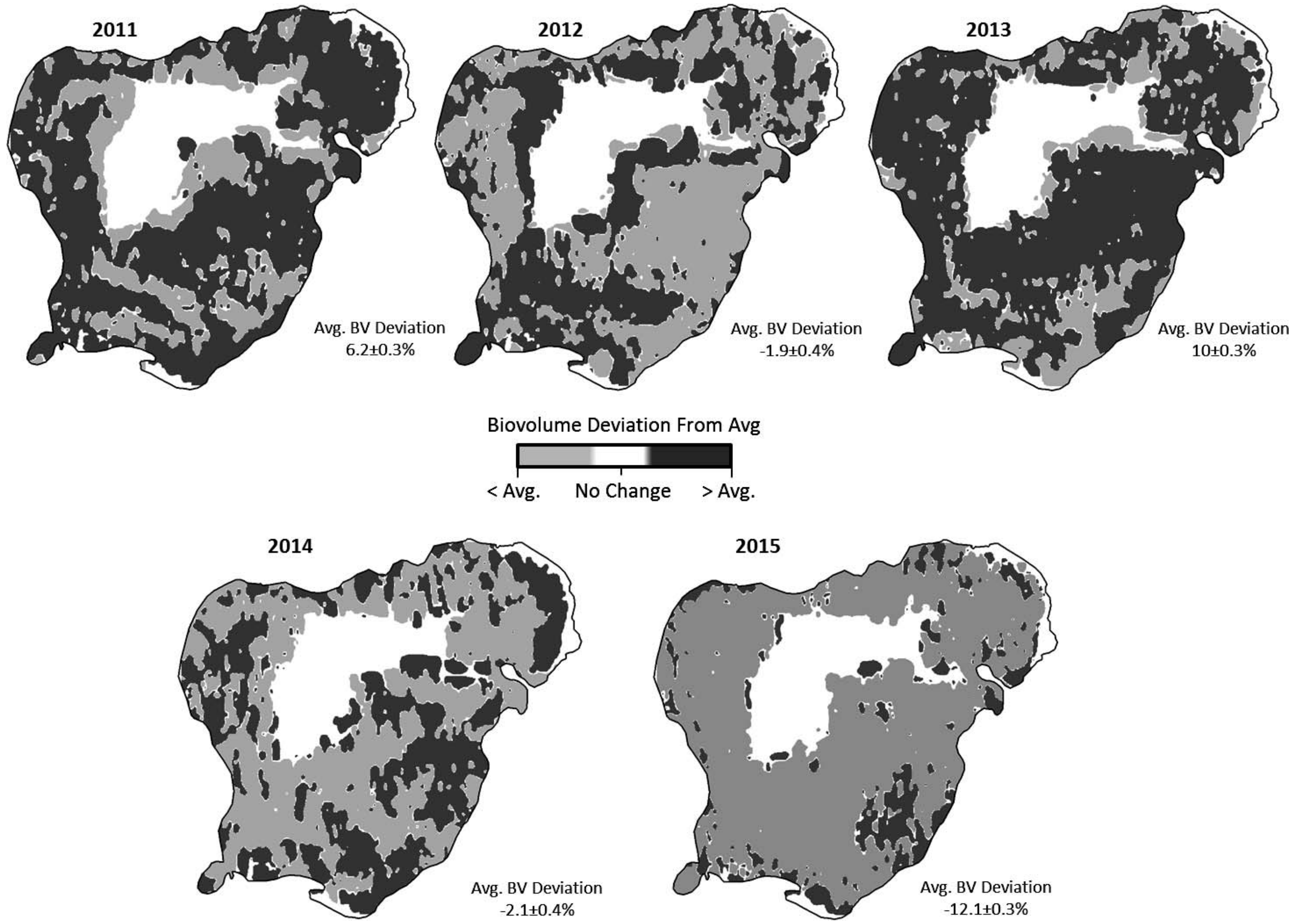

Figure 2. Maps of deviation from average biovolume. Maps of aquatic plant biovolume for Orchard Lake (Dakota County, MN) were created with Lowrance hydroacoustics and BioBase software. Raster biovolume maps from each year were subtracted from an average map of all years using the Raster Calculator in ArcMap 10.3. Blue colors represent areas in which biovolume was less than the average for that year. Green colors represent areas in which biovolume was greater than average. Mean deviation ± 95% confidence intervals are cited below each map.

chlorophyll-*a*, and Secchi), I collected the closest ancillary metrological information available. Growing season length and temperature may influence macrophyte growth patterns and status indicators (Rooney and Kalff 2000, Beck et al. 2014). Further, through its effects on external nutrient and sediment loading, rainfall may also affect macrophyte growth. Accordingly, Pearson's moment correlations were run with lakewide biovolume and average air temperature and total precipitation calculated from ice-out to the survey date of each year. We did not find a significant correlation of either variable on biovolume ($P > 0.20$). Although it is expected that aquatic plant abundance should respond to climate, effects from a large number of other co-occurring bottom–up and top–down drivers can dampen the effect of climate. As such, it is not surprising that effects may not be seen until more monitoring years accrue (Beck et al. 2014, Sondergaard et al. 2016).

In conclusion, a hypothetical observer would see different results for Orchard Lake, depending on his or her interests. The biologist concerned with overall biotic status would likely not have seen much change from 1 yr to the next in Orchard Lake. Although the frequencies of individual species changed modestly across years, the lake bottom covered by macrophytes was consistent from year to year, was always codominated by coontail and northern watermilfoil, and biotic integrity was consistent as well. However, the fisheries manager an angler interested in aquatic plants for largemouth bass production or the aquatic plant manager or lakeshore property owner concerned about recreational nuisances would see a very different picture of Orchard Lake. They would notice that the lake changed quite dramatically from one year to the next. Vegetation beds that grew to the surface in one location of the lake in 2013, were gone in 2014. In a different location, surface-growing beds unseen in 2013 were apparent in 2014.

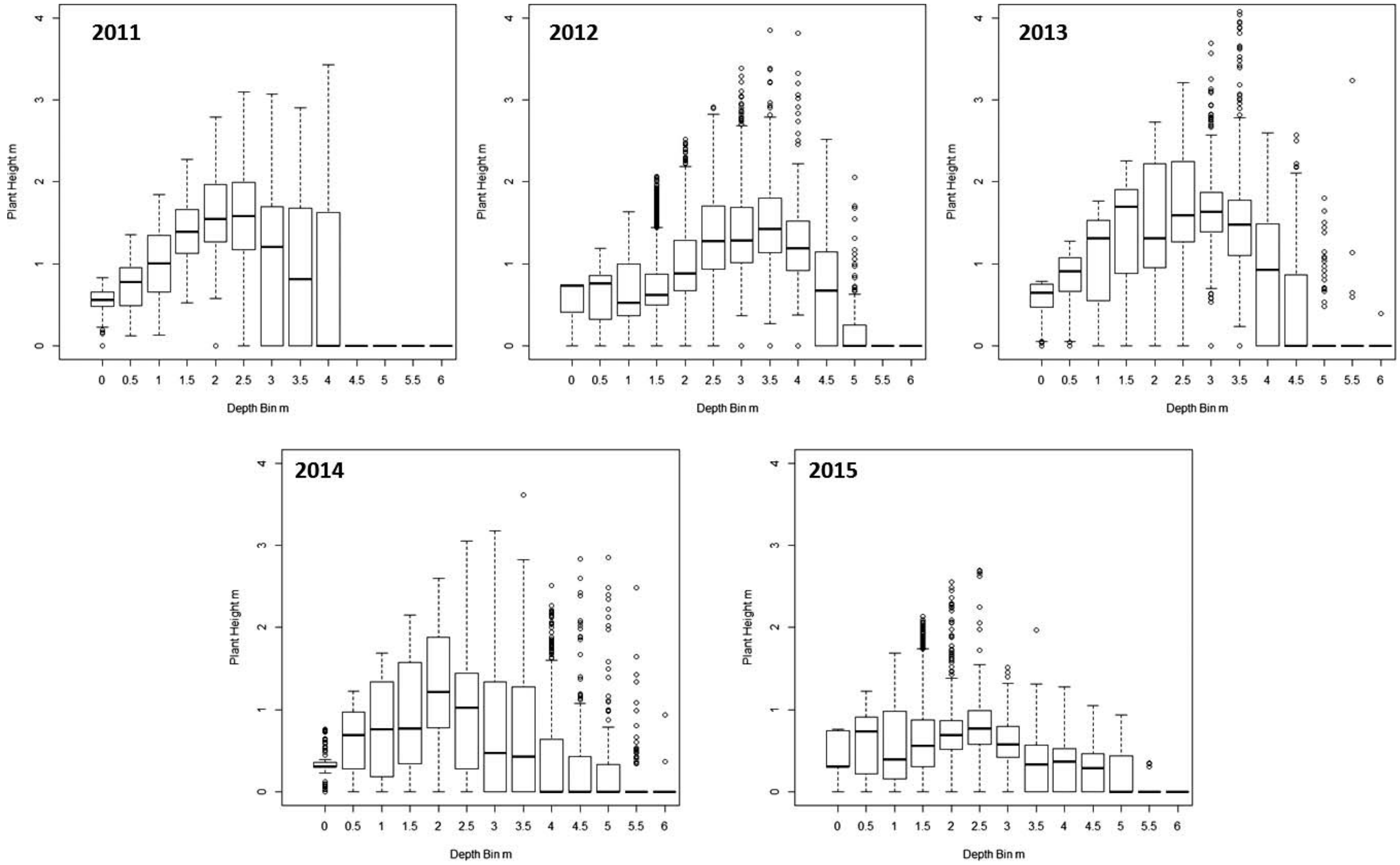

Figure 3. Tukey box and whisker plots of plant canopy height, binned at 0.5-m depth increments in Orchard Lake (Dakota County, MN) as measured by Lowrance hydroacoustics and BioBase software. Boxes represent the inner quartiles, and whiskers represent the outer quartiles. Dots above whiskers are outliers.

In eutrophic lakes such as Orchard Lake, variability in plant abundance may be the norm (Valley and Drake 2007). It is not a coincidence that eutrophic lakes are typically the most managed lakes as well. As such, confidently separating effects of management interventions from background variability *in situ* is a significant challenge for the APM field and industry. Results from this study and others cited suggest that only the pronounced "all or nothing" change after a management intervention can be confidently detected without multiple years and reference-area monitoring. For instance, if the percentage of Eurasian watermilfoil frequency went from 90% in year 0 to 10% in year 1 after an herbicide was applied, then it's very likely the herbicide was responsible for that reduction. However, these results and others suggest that one could not conclude a treatment regimen was responsible for reducing overall surface growth from year 0 to year 1 without benchmark biovolumes and analysis of the natural range of variability. This will require government agencies (typically states in the United States) to establish sentinel monitoring sites (e.g., MN DNR 2010, Beck et al. 2014) in which consistent monitoring can occur and benchmarks can be established. In this study, I was limited by sample size, but with a commitment to long-term monitoring, prior benchmarks can be established similar to those for climate (Daly et al. 2008) and lake water quality (Heiskary and Wilson 2008) and can be used to compare current conditions in similar lakes to determine changes in their status. Moving in this direction could greatly improve the confidence in APM outcomes and gain more public credibility.

SOURCE OF MATERIALS

[1]BioBase 5.2, Navico Inc., 4500 South 129th East Avenue, Suite 200, Tulsa, OK 74134.

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

[3]ArcGIS 10.3, Environmental Systems Research Institute, 380 New York Street, Redlands, CA 92373.

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