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A review of aquatic plant monitoring and assessment methods

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ABSTRACT

Aquatic plant management has become increasingly scrutinized by federal and state regulatory agencies, including the recent implementation of a National Pollutant Discharge Elimination System permitting program in each state. Many states require documentation of nuisance acres, and an evaluation of management success. Despite this need, no widely accepted "standard methods" for quantifying nuisance plants has been published. We review the most commonly used quantitative methods for monitoring plant distribution, species composition, and abundance, and make general recommendations to support management activities in monitoring plant populations and assessing management efficacy. It is important to choose an appropriate method to meet the goals and objectives of a given program, and to be willing to change methods as the needs and objectives of the program change. It is unlikely that the same monitoring and assessment method will be used throughout a program, especially a long-term program. We recommend choosing methods that are 1) quantifiable, that is, data can be statistically analyzed, 2) follow an appropriate sampling design, and 3) are repeatable and flexible enough to change on the basis of needs and personnel. Ideally, monitoring and assessment methods need to incorporate both target and nontarget impacts, collect data that are objective and can be quantified, and are labor and cost effective.

Key words: distribution, mapping, plant abundance, quantification, survey.

INTRODUCTION

Understanding the dynamics of aquatic plant populations in a given water body has become increasingly important because of the introduction and spread of numerous nonnative species. These plants are generally introduced from other parts of the world, some for seemingly beneficial or horticultural uses; however, the majority have escaped cultivation and now cause widespread problems (Madsen 2004). Nonnative plants affect aesthetics, drainage, fishing, water quality, fish and wildlife habitat, flood control, human and animal health, hydropower generation, irrigation, navigation, recreation, and ultimately land values (Pimentel et al. 2000, Rockwell 2003). For example, the estimated total cost of invasive aquatic plants, including management and losses, in the United States is approximately $110 million/yr (Pimentel et al. 2005). The cost of aquatic weed control in irrigation districts in 17 western states was estimated to be greater than $50 million/yr (Anderson 1993). Florida state agencies have spent nearly $250 million to manage hydrilla (*Hydrilla verticillata* [L.F.] Royle) in Florida waters over the past 30 yr; if one accounts for local government and local water management districts, this total approaches $750 million in management costs associated with hydrilla alone (Schardt, pers. comm.).

The direct economic impacts, such as those listed above, are easy to quantify; however, there are other impacts of aquatic plants that are much more difficult to ascertain. These impacts include the intrinsic benefits of aquatic habitats and the ecosystem services these habitats provide (Charles and Dukes 2007). Ecosystem services provide an important portion of the total contribution to human health and welfare on this planet (Costanza et al. 1997). Globally, it is estimated that marine systems provide $21 trillion in ecosystem services, followed by freshwater habitats at $4.9 trillion (Costanza et al. 1997). These estimates highlight the importance of conserving aquatic habitats and the services they provide to human welfare (Costanza et al. 1997). By any measure, the cost of invasion is significant, and the investment in management and research has not kept pace to minimize the costs associated with invasions (Sytsma 2008).

As the threat of nonnative plant species increases, the development and refining of methods to detect, monitor, and ultimately assess management of these species is critical. However, the use of quantitative methods to monitor and assess aquatic plants has not become as standardized as other components in aquatic systems, such as the biotic or physical components (Lind 1979, Madsen 1999). Pursuant to this, millions of dollars are spent every year in managing aquatic vegetation in waters throughout North America; however, only a small fraction is allocated to acquiring reliable quantitative data regarding plant populations or in assessing management techniques (Madsen and Bloomfield 1993). In many cases, quantitative assessments are left out completely because of budget constraints, untrained personnel, or a lack of understanding with respect to what methods are available and how to implement them effectively.

There is a growing consensus among researchers and managers from all aspects of aquatic ecology and management that effective and quantitative methods should be utilized or standardized to maximize management efforts

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and monitor nontarget impacts. With respect to assessing management techniques, effective monitoring is needed to evaluate new biological control projects to determine which agents are effective and what factors limit or enhance their success (Blossey 2004). Oftentimes monitoring programs are underfunded or inadequate in scope and do not identify where and why control is or is not successful (Blossey 2004). The development or improvement on methods for evaluating nontarget impacts of herbicides is also critical, especially with respect to native species of concern or threatened and endangered species (Getsinger et al. 2008).

Environmental factors can also have an impact on plant growth and function to structure aquatic plant communities both spatially and temporally. For submersed and emergent plant communities, zonation along a depth gradient is often observed as a function of light availability (Middelboe and Markager 1997). Sediment composition also influences submersed plant colonization and distribution (Doyle 1999, Madsen et al. 2001, Case and Madsen 2004, Madsen et al. 2006). Floating aquatic plant growth is often limited by available nutrients in the water column, with nuisance growth following temporal changes in nutrient loading. For example, water hyacinth (*Eichhornia crassipes*) responds to flooding events in large riverine systems where during flood cycles, water moves out into adjacent lands and upon receding brings with it an increase in nutrients to support water hyacinth growth (Kobayashi et al. 2008). In general, there are several factors that affect plant growth across spatial and temporal scales, and effective management requires an understanding of aquatic plant biology and the response of plants (both target and nontarget) to management actions (Sytsma 2008). The only way to effectively achieve this is to utilize methods that can document the distribution, growth, and abundance of aquatic plants over time (Sytsma 2008).

Assessment and monitoring of aquatic plants has become more important over the last year as the National Pollutant Discharge Elimination System (NPDES) permit program has been implemented to regulate aquatic plant management activities, most notably the use of herbicides. One of the requirements included in the federal NPDES pesticide general permit is for the quantitative assessment of nuisance plant coverage to document that the target species exceed a nuisance threshold. Quantitative methods are also required to assess the impacts of management activities on target and nontarget plant species. Therefore, the objectives of this paper are to 1) offer a broad overview of available methods that can be utilized for aquatic plant monitoring and assessment, and 2) provide guidelines regarding the use of these methods for assessing aquatic plants, as well as pointing out methods that are not effective for this purpose. These guidelines will cover submersed, floating, and emergent plant species for lakes and flowing waters. The goal is to equip professionals in aquatic plant management with the tools and justifications to address questions and concerns related to management activities such as nontarget and habitat impacts, management implementation in the correct areas, regulatory compliance (NPDES), public relations (including competing uses for water resources), and professional credibility to people outside of the aquatic plant management field.

OVERVIEW OF AQUATIC PLANT MONITORING AND ASSESSMENT METHODS

Before undertaking any sort of monitoring or assessment program, one must correctly identify the species of interest. Often, when incorrect identifications occur, the process used to document species identifications is poor, including the lack of herbarium specimens (Hellquist 1993) or digital photography adequate to correct these misidentifications. Correct identification of both target and nontarget plants is crucial in identifying rare or threatened species, as well as aiding in delineating areas with species of special concern (Hellquist 1993). Devoting time and resources to construct a proper species list for a given water body can be invaluable in developing a management plan; furthermore, species lists are often required in the preparation of environmental impact statements and permitting requirements (Hellquist 1993).

Several methods exist for sampling aquatic plants to develop a species list, determine distributions, and to estimate abundance in a given water body. These methods range from low-cost visual estimations of plant occurrence and cover to high-cost remote sensing that can sample a water body or an entire landscape. An important factor to remember when selecting a method is to choose the method that will meet the desired objectives for the project, but, more important, to choose a method that is quantifiable and can be subjected to statistical analyses (Madsen and Bloomfield 1993, Spencer and Whitehand 1993). Madsen and Bloomfield point out the following justifications for using quantitative methods:

- Quantitative data are objective measurements, and relying on subjective measurements leads to opinion, which is not a sound basis for management decisions.
- Quantitative data can be subjected to rigorous statistical analyses that can lead to the development of scientifically based management guidelines.
- Quantitative data can identify management techniques that were ineffective and thereby reduce the cost of a management program.
- Quantitative data can be utilized by different users other than the observer.

To ensure that monitoring and assessment data are collected in a manner that is suitable for quantifiable analyses, it is important to collect data using an appropriate sampling design. The four most common sampling designs are the completely random, stratified random, random–systematic, and systematic designs. A conceptual representation of these sampling designs is depicted in Figure 1. In general, the completely random design removes biases associated with the selection of sampling locations; however, Barbour et al. (1999) points out several limitations to this design in larger areas:

- A random selection of points may place points in

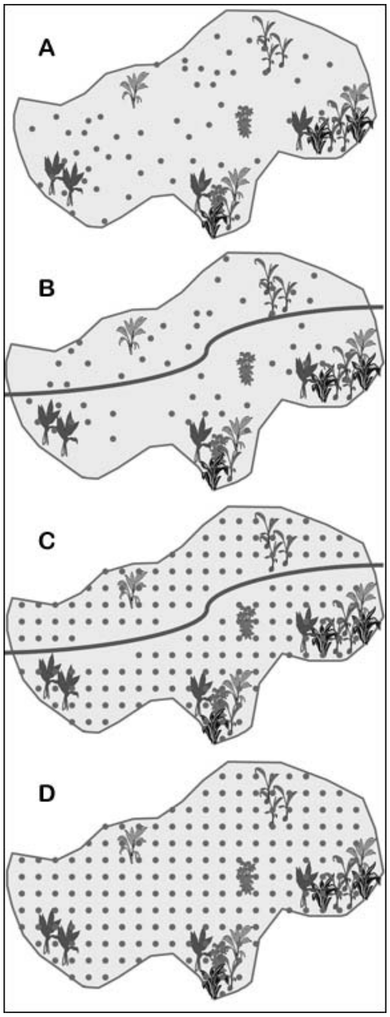

Figure 1. A conceptual representation of plant community sampling designs (A) completely random, (B) stratified random, (C) random–systematic, and (D) systematic.

difficult-to-access or inaccessible areas, and the little information these points would provide does not compensate for the added time it would take to sample them. The field time required to sample random points is large and would likely be an inappropriate choice for large surveys.

- A random selection of points may result in the location of some points being clumped, leaving large areas undersampled.
- A completely random design would undersample rare yet important species that would be sampled using other designs.
- A completely random design may make it difficult to conduct any sort of time-series comparisons, or detect spatial changes as new random sites are visited during each sampling event.

A stratified random design is typically utilized if a gradient exists in the survey location; for aquatic surveys this could include a river or stream channel running through a reservoir. The area can be divided into homogenous sections with sampling points randomly distributed within each section. The systematic sampling design places sample locations within an area on the basis of grid with a predetermined spacing. The systematic design works well for an initial survey as it will cover the entire water body and the observer is more apt to find most species depending upon the distance between points. If the distance between sample points is small the probability of detection increases; if the distance between sampling points is large then the probability of detection decreases and rare species are missed. Also, if data such as water depth or Secchi depth are collected at sampling locations, the maximum depth of plant colonization can be determined and the littoral zone delineated for future surveys. A random–systematic design selects areas either by random or using a stratified approach. The survey is then initiated by selecting the starting point either at random or in a stratified fashion, and then conducted using a systematic sampling approach (Barbour et al. 1999). The random–systematic design works well if a gradient is present, or if the littoral zone is well defined, thereby allowing sampling locations to be stratified within the littoral zone.

A summary of the more common aquatic plant sampling methods (including nonquantifiable) are listed in Table 1, with specific guidelines discussed in later sections. The simplest estimates of plant cover and abundance can be achieved using visual observations while on a water body. Generally, total acreage is estimated for each species on the basis of the total area of the water body. Visual estimations are highly subjective, are not repeatable, and are highly variable among observers, thereby making them nonamendable to statistical treatment. Also, it is very difficult to estimate abundance of submersed aquatic plants, and as such species are missed or underestimated.

A compromise between subjective estimates and quantitative methods would be a semiquantitative survey in which preselected areas are surveyed using a presence/absence approach to establish the frequency of occurrence for species (Madsen and Bloomfield 1993). Divers or a plant rake can be utilized to sample submersed species. This method would be useful to establish basic plant community composition if several sites were surveyed, and would capture more species than subjective estimates. Though again, similar to subjective estimates, these data cannot be readily analyzed and may not be adequate in establishing thresholds to meet permitting requirements.

Quantitative methods that can be utilized to rapidly collect information regarding plant occurrence, species richness, and distribution include the point-intercept and line-transect methods. These methods can be used in both small plots and in multiple locations within a water body to establish plant community characteristics or assess management efficacy. Point-intercept surveys are typically conducted using a preselected grid of points at a user-specified interval (Madsen 1999). By preselecting points, it removes the subjectivity with respect to sample locations. Once on the lake a global positioning system (GPS) is then used to navigate to each point where a plant rake is deployed to sample submersed vegetation. Emergent and floating vegetation can also be recorded at each point as well. The

Table 1. Summary of vascular aquatic plant monitoring and assessment methods (adapted from Madsen and Bloomfield 1993).

Method	Techniques	Effort	Variability	Recom-mendation[1]	Applications
Point intercept	Presence/absence	Low	Low, can be spatially variable	S, E, F	Small-plot assessments, baseline surveys, whole-lake monitoring, and long-term assessments
Line transect	Points, quadrats	Moderate	Moderate, can be spatially variable	S, E, F	Small-plot assessments, monitoring species distribution
Subjective estimates	Visual	Low	Low-high, depends on how many people are making estimates	S, E, F	Initial survey though this method is highly subjective and not quantifiable
Semiquantitative	Visual	Low	Low, can be spatially variable	S, E, F	Initial surveys
	Rake fullness or spinning rake methods	Moderate	High	S	Small-plot assessments, will over- or underestimate species depending on composition
Biomass	Coring, quadrats, box sampler, ponar dredge	High	High, can be spatially and temporally variable	S, F	Small-plot assessments
Nondestructive	Hydroacoustics	Moderate	Moderate, can be temporally and spatially variable	S	Small-plot assessments, whole-lake long-term monitoring
	Plant morphological measurements	Moderate-high	Moderate, can be temporally variable	E, F	Small-plot assessments
	Geographic information system, remote sensing	Moderate	Low-high, will depend on the resolution of images	E, F	Visualization of data, whole-lake long-term monitoring, not species specific
	Mathematical models	Low-high	Low-high, will depend on data underlying the models	S, E, F	Potential predictability, estimations of future invasions and plant growth, evaluate effects of alternative approaches

[1]S = submersed, E = emergent, F = floating.

point-intercept method is very adaptable to meet the desired objectives of a management program. More important, surveys are developed on the basis of a given sampling design (random, stratified random, random–systematic, and systematic), which allows data to be statistically analyzed to compare changes in species occurrence over time and to assess the effectiveness of management techniques (Wersal et al. 2010). With advances in GPS and geographic information systems (GIS) technologies, point-intercept survey protocols can be developed, implemented, and results analyzed while still on the water. Point intercept is a robust sampling method that is less sensitive to differences in abundance or season. However, this method may not detect the differences in abundance or seasonal effects that are often the focus of management assessments. Point-intercept surveys also may miss species that occur in nearshore areas that are too shallow for a boat to navigate to and thus underestimate these species in the survey.

Line-transect methods are similar to the point-intercept method; however, with transects one can collect presence/absence data, cover data, or use quadrats along transects to collect density and abundance measurements (Grieg-Smith 1983, Titus 1993, Madsen et al. 1996, Getsinger et al. 1997). In general, the line-transect method requires less technology than point-intercept surveys, as transects can be established and sampled without the use of a computer or GPS technology (Madsen 1999), though these technologies are more readily available and more cost effective than in previous years and are routinely used for transect establishment. Permanent transects can be delineated using nonmovable markers or through the use of GIS to spatially mark transects. Transects can be arranged in any number of sampling designs to capture variability within the water body as long as an appropriate number of transects is sampled (Titus 1993). Transect lengths can be any length from large field-based projects (Titus 1993) to small-scale (3-cm) intervals to estimate foliage coverage of submersed plants (Sidorkewecj and Fernández 2000). The line-transect method is particularly useful in determining aquatic plant community characteristics in small study sites over time and to assess management efficacy in small plots (Figure 2).

In addition to constructing a species list through presence/absence information, oftentimes it is of interest to collect plant abundance data to assess changes in the plant community due to management activities. Plant abundance can be characterized using a biomass harvesting technique such as a coring device, quadrats with and without divers, ponar dredge, or the semiquantitative rake fullness method. Biomass harvesting is labor intensive and can be subject to spatial and temporal variability depending upon plant densities, plant community composition, and life-history traits. However, biomass techniques provide the

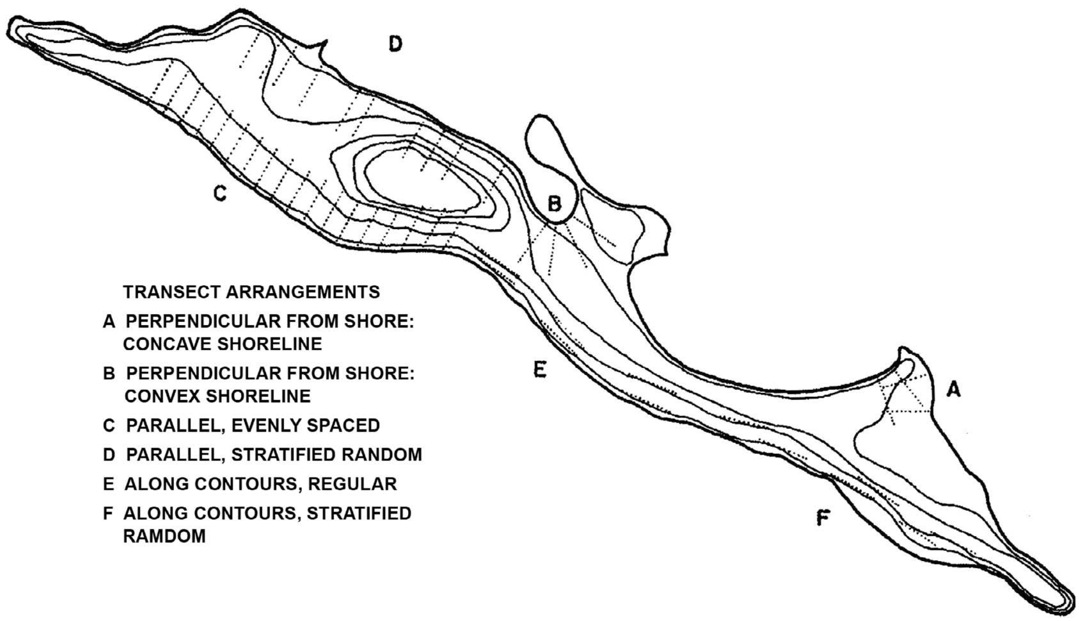

Figure 2. Line-transect sampling designs for aquatic plant monitoring and assessment in riverine habitats.

best information on species abundance as long as an adequate number of samples is collected to overcome issues with variability (Madsen 1993, Madsen and Bloomfield 1993). Pursuant to this, biomass techniques such as coring devices, box corers, and dredges are the only techniques that can adequately sample belowground plant biomass such as root crowns, rhizomes, tubers, and turions (Madsen et al. 2007, Owens et al. 2010). However, emergent vegetation is often difficult to harvest with corers and dredges.

Before undertaking a biomass sampling program, it is necessary to understand the trade-offs between the labor involved in using the sampling device, the area of the sampling device, and the number of samples needed to adequately assess the target plant population (Madsen 1993). For example, box corers generally have an area of 0.1 m^2 and polyvinyl chloride (PVC) coring devices an area of 0.018 m^2; therefore, fewer samples are needed with the larger sampling device to overcome issues with variability and collect a statistically-relevant number of samples (Downing and Anderson 1985). However, larger samplers require more processing time, and therefore it may be beneficial to use a smaller sampling device and collect more samples (Downing and Anderson 1985). For instance, a corer of 0.018 m^2 (Madsen et al. 2007) may require 30 samples in a given community to get a statistically-significant sample, but may actually require less time to collect and sort than the 10 samples needed for a statistically adequate sample with a 0.1-m^2 quadrat.

The spinning rake method is conducted by lowering a plant rake on a fixed pole to the bottom of the water body (Skogerboe et al. 2004, Skogerboe and Getsinger 2006, Owens et al. 2010). The plant rake is then turned once 360° to harvest aboveground plant material. The rake head has a known length, and when turned, serves as a circular quadrat in which an area can be calculated. Although this method is easy and low intensity, it is less precise than other biomass methods, especially in dense vegetation (Johnson and Newman 2011), where it tends to overestimate abundance and will not sample belowground plant structures. As with any quantitative method, biomass techniques should be used following a sampling design, and in doing so, will allow for statistical analysis of collected data. To determine if a statistically-adequate number of samples has been collected, a power analysis should be performed on an initial set of data from the site (Downing and Anderson 1985, Madsen 1993, Spencer and Whitehand 1993).

To overcome the labor intensity associated with biomass techniques, some researchers have developed plant rake methods such as the rake fullness method (Indiana Department of Natural Resources 2007, Hauxwell et al. 2010). The rake fullness method divides the rake (and sometimes tines) into discrete increments and when plants are harvested an abundance ranking is given for each species. This method, although easy and low intensity, relies on subjective ratings by an observer. Visual ratings tend not to be consistent between observers and should not be relied upon as a stand-alone measurement. Pursuant to this, Yin and Kreiling (2011) also reported potential issues with using rake methods to estimate density, and concluded that cross-species comparisons are not encouraged unless the efficiency of the rake method has been determined for each species being compared. This would increase survey time and the overall cost of a management program.

In some instances it may not be desirable to harvest biomass or use a method that may damage existing aquatic plants, especially in the presence of rare or threatened species in the area. In these cases, nondestructive methods could be used to estimate plant abundance, though some methods like hydroacoustics and remote sensing cannot differentiate plant species. Hydroacoustic sampling targets submersed aquatic plants by using an echo sounder or

TABLE 2. DECISION MATRIX TO GUIDE SELECTION FOR AQUATIC PLANT MONITORING AND ASSESSMENT METHODS.

	Desired Application						
Methods	Initial Survey	Small-Plot Assessment	Whole-Lake Assessment	Long-Term Monitoring	Quantifiable	Cost	Satisfies NPDES Requirements[1]
Point intercept	X	X	X	X	X	Low	Yes
Line transect	X	X		X	X	Low	Yes
Subjective estimate	X	X				Low	No
Semiquantitative (visual)	X	X				Low	No
Semiquantitative (rake fullness or spinning rake)	X	X		X	Marginal	Moderate	Yes
Biomass		X		X	X	High	Yes
Plant measurements		X		X	X	Moderate	Yes
Geographic information system				X	X	Moderate	No
Remote sensing			X	X	X	High	Yes
Mathematical modeling				X	X	Low	No

[1]NPDES = National Pollutant Discharge Elimination System.

fathometer (depth finders) that can record information from the transducer onto flash memory devices (Sabol et al. 2002, Hohausová et al. 2008, Sabol et al. 2009). The equipment needed to perform hydroacoustic surveys has become much simpler to use and more cost efficient. Shallow-range (0 to 7 m) chart recorders are standard on many low-cost commercial echo sounders (Thomas et al. 1990). Natural resource agencies that use these systems regularly could map submersed vegetation for approximately \$2.06/ac (Sabol et al. 2009). Maceina and Shireman (1980) reported that the principle advantage of utilizing a recording fathometer for vegetation surveys is that savings in time and manpower can be accomplished; for example, in Lake Baldwin, FL, 14 transects covering a total distance of 11.3 km were completed in 3 h. Hohausová et al. (2008) reported a positive relationship between the hydroacoustic signal and dry biomass, though the relationship could not differentiate species and results would likely be influenced by the dominant species present. With respect to monitoring and assessment, hydroacoustic surveys allow for the estimation of total biovolume of plants in a given area, which could be used to quantify seasonal changes in the whole plant community over time. Species-specific information cannot be determined unless another sampling method like point-intercept surveys are utilized to construct a species list.

Unlike hydroacoustic surveys, remote sensing is most effective in targeting riparian, emergent, and floating vegetation (Everitt et al. 2007, Liira et al. 2010, Midwood and Chow-Fraser 2010, Robles et al. 2010). Remote sensing is often expensive as satellite images of the target area have to be purchased, specialized software is needed to analyze images, and trained personnel are needed to complete the analyses. However, remote sensing is useful in long-term quantification of vegetation in a given area without having to actually use survey crews year after year. It also allows for the monitoring of larger areas than what are feasible using survey crews alone, though it is recommended to implement some sort of ground-truthing survey to verify plant species composition and the spatial accuracy of remotely sensed data. Remote sensing can also be used to assess herbicide injury, as the sensors can detect changes in light reflectance due to herbicide exposure before the human eye can see the plant damage (Robles et al. 2010). Other nondestructive sampling can also be done at smaller scales to estimate abundance based on plant morphology measurements (Daoust and Childers 1998, Thursby et al. 2002); however, this is typically only used on emergent or floating vegetation as these species are readily accessible and measurements can be taken easily.

GUIDELINES FOR SAMPLING AQUATIC PLANTS

When considering which method or methods to choose for a monitoring or assessment program it is essential to consider the target species, co-occurring nontarget species, the growth form of the target species, species life-history traits, and the scale at which the program will be implemented. Ultimately, a method should be chosen to meet the objectives of the management plan. We have offered a decision matrix to assist in choosing a monitoring or assessment method (Table 2), and have developed guidelines for the three growth forms of aquatic vascular plants along with planktonic and filamentous algae. These guidelines are not meant be exhaustive or definitive, but are effective methods that have been verified by scientific evaluations or are recommended in the Standards Methods for the Examination of Water and Wastewater (Rice et al. 2012) to estimate plant coverage or abundance.

Submersed species

Estimating cover and distribution in lakes. The simplest quantitative approach to estimating submersed aquatic plant cover and distribution in a monitoring program is to perform a point-intercept survey. The point-intercept survey works well to characterize the aquatic plant community (Mikulyuk et al. 2010) and monitor trends in community composition through time within a water body or system (Case and Madsen 2004, Madsen et al. 2006, Wersal et al. 2006, Madsen et al. 2008). The point-intercept method (or variations of rake methods) has become standard sampling protocol in the states of Washington (Parsons 2001), Idaho, Montana, Minnesota (Beck et al. 2010, Valley and Heiskary 2012), and Wisconsin (Mikulyuk et al. 2010) to collect initial plant community information and to establish management areas.

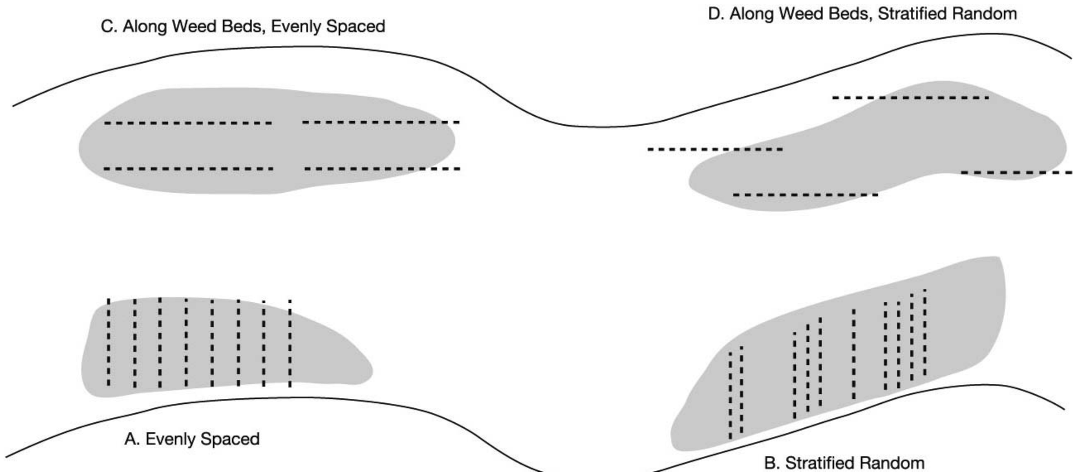

Figure 3. Line-transect sampling designs for aquatic plant monitoring and assessment in lakes, adapted from Titus (1993).

The point-intercept survey works well in assessing field-scale studies and operational management programs. Points can be generated in any treatment area and rapidly sampled to assess several small plots or effects throughout a water body in the case of a whole-lake treatment (Parsons et al. 2001, Madsen et al. 2002, Parsons et al. 2004, Parsons et al. 2007, Parsons et al. 2009, Wersal et al. 2010, Robles et al. 2011, Getsinger et al. 2013, Getsinger et al. 2014, Cox et al. 2014, Madsen et al. 2015). This method offers a more strict assessment compared with abundance method as plants are either present or absent and will be influenced by spatial variability in plant beds. It is also important to note that survey resolution will affect detection rates and it is advisable to set one grid interval and maintain that interval in successive years to make comparisons easier and more meaningful. Also, a common misconception with this method is that data can be interpreted as abundance; however, sample points are a dimensionless unit so abundance estimates are not possible.

Estimating cover and distribution in rivers. In riverine habitats it is much harder to quantify submersed plant species characteristics because of flowing water and inaccessibility in many areas. Submersed aquatic plants often grow in bands along the shoreline of rivers with depth distribution limited by high flows and unsuitable substrate. However, in larger rivers transects have been effective in quantifying plant species cover and assessing management operations (Getsinger et al. 1997). In smaller rivers, line transects could be established perpendicular to the shoreline to run through the vegetation band toward the middle of the river channel, or, line transects could be established parallel to the shoreline to follow the contour of the vegetation bands, with transects evenly spaced or in a stratified random design (Figure 3). In very small rivers or creeks, a line transect could be established across the entire width of the channel, if flows permit, and space transects in an appropriate sampling design.

Estimating abundance in lakes. When plant abundance is important, biomass collection techniques offer data that are species specific. There are several biomass collection techniques and devices, and the appropriate technique should be chosen to meet the objectives of the project, but also to adequately sample the target species. The PVC coring device as developed by Madsen et al. (2007) works very well in sampling submersed aquatic plants, especially belowground reproductive structures. The PVC corer can be utilized in monitoring the abundance of native aquatic plants over time (Case and Madsen 2004, Madsen et al. 2006, Wersal et al. 2006) or nonnative plant abundance in small plots (Woolf and Madsen 2003, Wersal et al. 2011). When using the PVC corer it is important to collect an adequate number of samples; we typically recommend 20 to 30 core samples per site. The PVC corer does not sample emergent aboveground biomass very well, especially tall plant species. Also, in dense beds of Eurasian watermilfoil (*Myriophyllum spicatum* L.) and curly-leaf pondweed (*Potamogeton crispus* L.), care must be taken to ensure that the coring device has cut through the vegetation and root crowns and has been pushed deep enough into bottom sediments. Failure to do this will result in a lost sample and extra expenditures in labor. Owens et al. (2010) suggested that a box corer (similar to an Eckman or ponar dredge) may sample some species of submersed aquatic plants more effectively than the PVC coring device. However, the box corer is large and cumbersome to operate and any benefit from using it can generally be overcome by collecting more samples using a smaller area sampler such as the PVC corer.

Another abundance technique is for divers to set quadrats on the bottom of the lake. Sampling in this manner will allow for the collection of species-specific presence/absence, species density, and biomass data. Research suggests that the diver quadrat method results in greater accuracy and precision with respect to abundance estimates than boat-based methods (Capers 2000, Johnson and Newman 2011). In particular, small species and less frequent species are often underestimated using boat methods (Capers 2000). However, in-water methods (diver quadrat) incur more risk to perform, require special training (i.e., scuba), and are more time consuming than other methods, and thus limit the spatial extent of this type of sampling compared with other methods.

The spinning rake method (Skogerboe et al. 2004, Skogerboe and Getsinger 2006, Owens et al. 2010) has been used to measure aboveground plant abundance. The spinning rake method was found to be a suitable alternative to the diver quadrat method, especially in large-scale studies requiring a high sampling intensity (Johnson and Newman 2011). It was concluded that the increased sampling efficiency that the spinning rake method offered offset its inherent lower precision (Johnson and Newman 2011). The spinning rake method will also be influenced by dense vegetation and overestimate biomass of the dominant species present (Johnson and Newman 2011). Furthermore, rake methods are not as effective in sampling species with basal growth forms such as wild celery; or in sampling belowground structures (Owens et al. 2010). To adequately sample belowground structures, one should use the PVC coring device (Madsen et al. 2007).

Recently, there has been a great deal of attention to adapting plant rake methods to collect plant biomass instead of using coring devices and divers. The aforementioned rake fullness method (Indiana Department of Natural Resources 2007, Hauxwell et al. 2010) has been utilized to rapidly assess plant communities. In Florida, it was determined that a rake-based fullness method was a suitable alternative to a ponar dredge and diver-harvested quadrats in estimating submersed plant abundance (Rodusky et al. 2005).

If species-specific abundance data are not required for a given project, then remote sensing (including hydroacoustic sampling) can be used to estimate abundance (biovolume) of aquatic plant species (Rice et al. 2012). In general the larger the area, the greater the advantage of using remotely sensed data especially if sampling is required over long timescales (Rice et al. 2012). Some studies have reported that remote sensing could be used to monitor canopy-forming submersed aquatic plants (Everitt et al. 2003, Fitzgerald et al. 2006, Nelson et al. 2006, Everitt et al. 2011). Remote sensing was used under mesocosm conditions to differentiate submersed species such as curly-leaf pondweed, hydrilla, Eurasian watermilfoil, northern milfoil (*Myriophyllum sibiricum* Kom.), hybrid milfoil (*Myriophyllum spicatum* × *Myriophyllum sibiricum*), and parrotfeather [*Myriophyllum aquaticum* (Vell) Verdc.] using hyperspectral reflectance data (Everitt et al. 2011). The authors determined by using stepwise discriminant analysis on reflectance data that 9 bands for May 11 and 10 bands for May 30 in the blue to near-infrared (NIR) spectral regions had the highest power to discriminate between species of submersed aquatic plants. During the July sampling period only seven bands in the red–NIR edge and NIR regions were useful for discriminating among species (Everitt et al. 2011). The change in the reflectance bands used for species separation is likely due to phenology and changes in the plants over the course of the growing season. Although species separation was achievable under experimental conditions, it is much more difficult to achieve at the landscape level because of larger expanses of open water, which serves as a sink for light energy. Using satellite imagery and aerial photography can work well as long as plants are at or near the water surface, though it is still recommended to conduct some ground-truthing surveys.

Large-scale management programs in Texas have utilized aerial photography to successfully assess the efficacy of grass carp (*Ctenopharyngodon idella*) herbivory on hydrilla in Lake Conroe (Martyn et al. 1986). Similarly, hyperspectral imagery was used to evaluate the efficacy of herbicide applications in the Sacramento–San Joaquin River delta in California (Santos et al. 2009). In regard to submersed plants, an underestimation is likely to occur depending upon the reflectance bands used in the analysis, water clarity, and the depth to which submersed plants are growing. It may be more cost effective to utilize hydroacoustic surveys for submersed aquatic plants, especially since many consumer sonar units are less expensive and record transect data to portable memory (Maceina et al. 1984, Sabol et al. 2009). Hydroacoustic surveys can give a very precise estimate of total plant volume in a given water body and are relatively rapid to perform (Sabol et al. 2009).

Estimating abundance in rivers. Line transects and diver-harvested quadrats were used to assess herbicide efficacy and nontarget impact in the Pend Oreille River, WA (Getsinger et al. 1997). Core samplers could also be utilized to randomly collect biomass samples within plots, or to collect samples along a line transect or grid instead of using divers. In fact, the PVC coring device was used in Lake Pend Oreille, ID (in both the lake and riverine portion) to assess plant abundance before and after herbicide treatments and diver-operated suction dredging (Madsen and Wersal 2008). In larger deeper rivers it may be possible to use hydroacoustic surveys to delineate plant beds and estimate cover. Satellite and aerial imagery can also be used to monitor and assess submersed species such as hydrilla and egeria (*Egeria densa*) in large rivers as long as they are at or near the water surface (Everitt et al. 1999, Everitt et al. 2003, Santos et al. 2009). Submersed aquatic plant biomass can be harvested in small rivers and shallow creeks using quadrats following an appropriate sampling design (Madsen and Adams 1988, Madsen and Adams 1989).

Emergent and floating species

Estimating cover and distribution in Lakes. For whole-lake monitoring, a point-intercept survey could be used to collect basic information regarding emergent and floating species composition, cover, and distribution (Robles et al. 2011). However, the line-transect method may be a better choice to effectively monitor and assess emergent and floating aquatic plant communities in small plots within lakes as their distributions are typically more concentrated in smaller areas than with submersed species. The line-transect method is likely a better choice than the point-intercept method as transects typically start along the shoreline and move out into deeper water. The point-intercept method may underestimate emergent and floating species in small plots because the dispersion of points may limit detection. Titus (1993) offers a detailed description regarding the use of the line-transect method, sampling designs, sample number, and data that can be collected. To properly implement a line-transect protocol we recommend using a sampling design that will meet the desired objectives for the project. Effective transect sampling designs are depicted in Figure 2 and are adapted from Titus (1993). Line transects have been used to characterize the plant communities in wetlands of South Carolina and also allowed for the development of a landscape model to predict changes in the vegetation type on the basis of hydrologic and environmental factors (De Steven and Toner 2004).

For emergent vegetation, Radomski et al. (2011) describe the reproducibility of using GIS to delineate field popluations of bulrushes (*Schoenoplectus* spp.) by using three different surveyors to conduct repeated surveys in five Minnesota lakes. The authors concluded that coverage mapping could be completed in a timely manner and with reasonable precision (Radomski et al. 2011). They did not detect any differences among surveyor estimates or the whole-lake stand coverage. For lakes that had a monospecific bulrush stand, the method could detect a whole-lake change of 10% (Radomski et al. 2011).

Estimating cover and distribution in rivers. When sampling rivers for emergent and floating plant species, the same factors that limit sampling of submersed vegetation still apply. Therefore, it is recommended to follow a similar sampling protocol as outlined in the aforementioned section on estimating cover and distribution of submersed aquatic plants in rivers.

Estimating abundance in lakes. If the objective is to monitor or assess small plots as part of a management program, establishing permanent quadrats in these plots would allow for repeated sampling over longer periods of time to assess impacts on both target and nontarget species. Welling et al. (1988) utilized permanent quadrats to assess the recruitment and zonation of emergent vegetation in response to drawdown events in prairie wetlands. Overall, quadrats are better for sampling taller emergent species (Wersal et al. 2013) and floating species as these growth forms do not lend themselves well to sampling with box corers or the PVC corer.

In addition to biomass sampling, remote sensing can be used to delineate emergent and floating plant beds, assess large-scale changes in area in response to management techniques and the cumulative effects of lakeshore development (Radomski 2006), and, unlike with submersed aquatic plants, emergent and floating plants can often be classified using spectral signatures (Marshall and Lee 1994, Hanlon and Brady 2005, Midwood and Chow-Fraser 2010). Pursuant to this, remote sensing has the potential to predict herbicide injury to aquatic plants before the human eye can detect any effect (Robles et al. 2010). If a remote-sensing approach is implemented, it may be necessary to periodically ground-truth data to ensure the accuracy of the imagery and algorithms used to monitor and assess plant communities.

Nondestructive measurements of emergent plants such as plant height, stem densities, leaf length, stem diameter, number of leaves, leaf thickness, number of axillary stems, and number of nodes can be used to construct mathematical models to estimate aboveground biomass of plant species (Daoust and Childers 1998, Thursby et al. 2002, Spencer et al. 2006, Gourard et al. 2008). Additionally, a combined approach using both remote-sensing data and plant morphometric data can be used to estimate biomass of floating aquatic plants without the need for destructive sampling (Robles et al. 2015). The development of models based on nondestructive measurements to estimate plant biomass may be beneficial in cases where sampling of rare or threatened species is necessary.

However, it may be necessary to harvest a subsample of individuals to assess which types of measurements could be useful in developing a predictive model. For example, Van et al. (2000) harvested 138 melaleuca trees (*Melaleuca quinquenervia*) in South Florida to determine relationships between dry-weight biomass and stem diameter measurements. Their resulting model based on inside-bark diameter measurements explained 97% of the total variation in dry-weight biomass. It was concluded that this model would be useful in assessing the impacts of biological control agents by allowing estimation of biomass from measurements made in melaleuca stands where destructive sampling was not possible (Van et al. 2000).

Estimating abundance in rivers. Many of the same methods used to estimate abundance of submersed vegetation could be used for emergent and floating vegetation including line transects and quadrats. However, remote sensing may be a good choice, especially if large areas of a river basin or drainage are being monitored or assessed. Remote sensing has been utilized in the Rio Grande system to monitor changes in wild taro (*Colacasia esculenta*), giant reed (*Arundo donax*), and water hyacinth populations (Everitt et al. 2003, Everitt et al. 2007, Everitt et al. 2008). Herbicide effects on the aquatic plant community in the Sacramento–San Joaquin River delta were assessed from 2003 to 2007 using hyperspectral remote sensing in Santos et al. (2009).

CONCLUSIONS

We have offered several aquatic plant community sampling methods that can be used for large-scale long-term monitoring and for small scale assessments of management techniques. It is important to choose an appropriate method to meet the goals and objectives of a given program, and to be willing to change methods as the needs and objectives of the program change. It is unlikely that the same monitoring and assessment method will be used throughout a program, especially a long-term program. We recommend choosing methods that are 1) quantifiable, that is, data can be statistically analyzed, 2) follow an appropriate sampling design, and 3) are repeatable and flexible enough to change on the basis of needs and personnel. Ideally, monitoring and assessment methods need to incorporate both target and nontarget impacts, collect data that are objective and can be quantified, and are labor and cost effective.

Monitoring and assessment are critical in documenting the success or failures of a particular management technique, and will allow for the evaluation of different techniques if needed, thereby preventing costly mistakes. A long-term management plan should be developed and incorporate not only year-of-treatment management evaluations, but also long-term monitoring of the aquatic plant community. Intensive monitoring has been cited as the only effective way to determine a program's success and when to terminate a management program (Simberloff 2003). However, all too often, monitoring and assessment protocols are the first items to be removed from management programs when funding is limited.

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