Implementing practical field and remote sensing methods to inform adaptive management of non-native *Phragmites australis* in the Midwest

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www.mtri.org and http://www.mtri.org/treatment_effects_phragmites.html

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Aerial view of a Saginaw Bay study site

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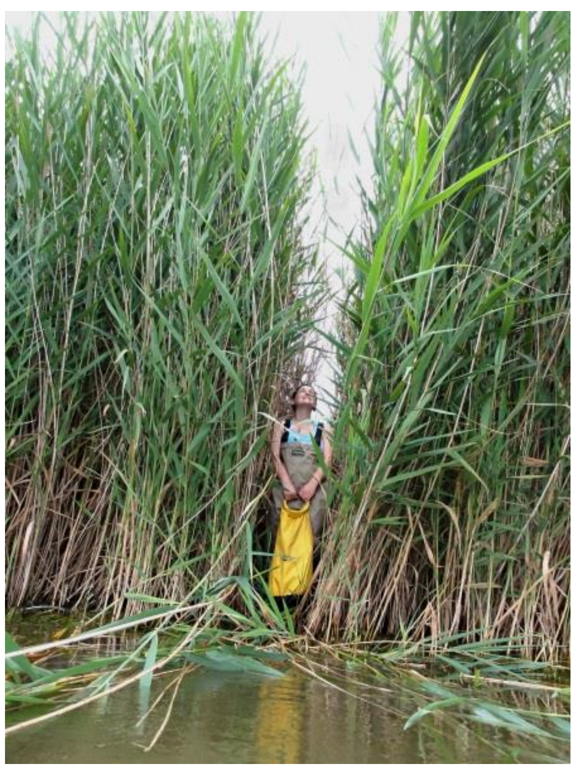
i) Overview

*Phragmites australis (*Cav.*) (*Haplotype M*)* is an invasive wetland reed found widely throughout the world which can greatly decrease wetland function and value. Despite large efforts for herbicide and/or mechanical removal of this invader, it remains a detriment to wetland ecosystems throughout its native range. The purpose of this report is to: (1) review the literature on *Phragmites* control; (2) summarize the results of a recent project on the biodiversity implications of *Phragmites* control completed by the authors in 2015; and (3) understand this information for use in an adaptive management context. This can then help to inform more effective *Phragmites* control efforts in the region through optimized monitoring to inform adaptive management, especially in light of limited budgets.

This report begins with a background section providing information on the invader, *Phragmites australis*; a brief discussion of natural systems and ecosystem management vs. adaptive management; a review of some of the variables linked to spread of this invasive plant; decision support tools, fact sheets and guides to *Phragmites* treatment; and a summary of some of the work on biological control efforts. In Sections 1g and h, the need for monitoring is discussed and the reality that the idea of "novel ecosystems" that include some level of invasive *Phragmites* coexisting with native wetland plants may have to be accepted. In section 2, adaptive management recommendations are reviewed.   Section 3 presents in detail the field and remote sensing research results and findings conducted by the authors in Green and Saginaw Bays. Section 4 synthesizes the information from the literature and research of Section 3 to provide implications for adaptive management. This synthesis underlines the importance of long term, adaptive management which takes full advantage of currently understood best practices, monitoring, and remote sensing opportunities. By combining these perspectives, management efforts can become more efficent and successful with respect to their individual goals.



1.) Background

1a) The Invader

Phragmites australis, the common reed, is one of the world's most widely distributed flowering plants, occurring on every continent except Antarctica (Holm et al., 1977). In North America, the invasive, non-native variety *P. australis* var. *australis* has expanded its range in recent decades, becoming prevalent in many wetland areas of the Midwest since the mid-20th century (Galatowitsch et al., 1999). Though the native variety of *Phragmites* (*Phragmites australis* var. *americanus*) has long been recognized as a key part of wetland ecosystems, *P. australis* var. *australis,* native to Europe and also referred to as "haplotype M", has become a cosmopolitan invader in much of the world. Haplotype M (henceforth *Phragmites*, in reference to the non-native variety) is a far more robust plant than var. *americanus*, with taller stems, larger seed heads, and a far denser stand growth pattern (Guo et al., 2013).

Invasive *Phragmites* crowds out native wetland plants and creates tall, dense monocultures that alter wildlife habitat suitability and ecosystem services, reducing biodiversity and access to lakes and rivers. Many efforts to treat and control this invasive plant have been undertaken, with millions of dollars being spent. However, the effectiveness of these treatment efforts is not well understood and improved strategies of action for control require an interdisciplinary effort between scientists, managers and policy makers.

1b) Ecosystem Management *vs*. Adaptive Management for Wetland Restoration

Uncertainty is inherent in all predictions and models of natural systems due to incomplete knowledge, various sources of error and the sheer scale, complexity, and variation that is possible in natural communities (Policanski, 1991). Recent interpretations of ecosystem processes and functions have challenged the idea that the goal of ecosystem management and restoration should be a return to some historic "reference condition", instead showing the considerable flexibility of ecosystems in response to change, especially with respect to species composition (O'Neill, 2001). Planning under the assumptions of a historically closed ecosystem to which one can return is problematic. Particularly in light of current trends of change and the increasing pressure of human land use and modification, it is not possible for managers to completely predict the response of ecosystems to intervention. Because of this, current theory holds that management should be an ongoing process which informs and modifies itself (Walters, 1986). Traditional management, Walters argues, will not succeed because it does not allow for the idea of failure and is therefore unwilling to synthesize new and old information. In many ways, forward-looking management policies work to make choices based upon what will optimize the future understanding of uncertainty in the system and outlook to compensate for future responses (Walters, 1986).

Adaptive management, in contrast, is an active form of management that selects from among specific available treatments and administration methods in response to a site's condition relative to the management goals (B. K. Williams et al., 2007). In doing so, management efforts are able to respond and conform to shifting environmental and social climates. While traditional management executes a specific set of activities in an attempt to reach a defined end stage, an adaptive management plan changes over time to achieve a specific function, often by changing the management activities in use. Adaptive management consistently aligns itself with best management practices and modifies plans in response to advances in knowledge (Walters, 1986). Under an adaptive management approach, managers must periodically select from a list of management options rather than continuing to follow an initial plan without further consideration (Moore et al., 2013). Lastly, all adaptive management requires monitoring of the site's responses to treatment with respect to management objectives, which in turn allows for new, iterative decisions to be made (Moore et al., 2013).

The U.S. Department of Interior (US DOI) has been dealing with this and related issues by implementing adaptive management on a practical basis for *Phragmites* control as part of its integrated waterbird management and monitoring program (Moore et al., 2014). Important adaptive management principles listed include the following:

- Dealing with uncertainty in *Phragmites* management as areas transition from one state to another
- Proper timing of active practices
- Understanding constraints that exist in certain areas
- Collecting observations of results to inform decision making
- Providing a decision support tool to help refuge managers in their efforts to deal with *Phragmites*
- Comparing observed outcomes with predicted outcomes.

This enables a gain in knowledge that can improve the performance of decision making over time. These efforts fit into the larger US DOI efforts to implement adaptive management in the field, described in Williams et al. (2012) ("Adaptive Management: the U.S. Department of the Interior Applications Guide", available through http://www.usgs.gov/sdc/adaptive_mgmt.html). The guide describes a framework for managing responsive natural resources where uncertainty is present about the impacts of interventions, such as invasive species control.

Within this paradigm, the management plan for a given site or problem is continually evaluated and revised based on treatment response so as to best use the available resources (Walters et al., 1990). Because of its flexibility, adaptive management is well suited to the treatment of areas dominated by invasive *Phragmites*. As of now, there is no agreed-upon "one best method" for treating *Phragmites*, nor does it seem likely that a single approach could optimally address every patch of *Phragmites*. Therefore, an adaptive management approach, one that works to address the issue with the best available knowledge but changes in response to future knowledge, will most effectively respond to the issue of *Phragmites* invasion. **The central thesis of this report is that appropriate, active monitoring of the results of *Phragmites* control efforts, with pre-control monitoring to establish a baseline for evaluating change, is necessary for successful control of this invader through adaptive management.**

Adaptive management can take a number of forms depending on funding and the circumstances of implementation. Typically, adaptive management is regarded as either "active" or "passive" (Fischman et al., 2015). Examples of true "active" adaptive management are rare due to cost constraints. Active adaptive management consists of constantly testing a series of hypothesis and treatments in an attempt to gain information on system dynamics. "Passive" adaptive management works using the principles of adaptive management, with a preformed set of possible treatments, a defined end goal, and consistent monitoring, but is not formulated in such a way as to actively test treatments and gain scientific data. In passive adaptive management, information on the "best" treatment is a side-effect of management, instead of a goal, as in active adaptive management.

The recent scientific literature has reported several conclusions on *Phragmites* expansion and control that are relevant to adaptive management. Included are advancements in knowledge on the importance of nutrients (especially nitrogen), changing climate, management methods and results, agency-recommended guidelines, and potential biological control agents that relate to *Phragmites* management efforts. The following sections review examples of this literature, with full references for those desiring further reading.

1c) Nutrients

The relationships between nutrient levels and *Phragmites* have been described in detail in recent scientific literature. High N levels make it easier for *Phragmites* to invade native wetland ecosystems, and provide significant explanation of higher *Phragmites* cover, as can be seen in Figure 1.1 (Silliman et al., 2004). As seen in Figure 1.2, where nitrogen (N) levels are high, *Phragmites* has far higher biomass accumulation (Rickey et al., 2004). Efforts in the Great Lakes to reduce N inputs, currently focused on reducing harmful algal blooms, have the potential to reduce the spread of *Phragmites* and increase the effectiveness of management efforts.

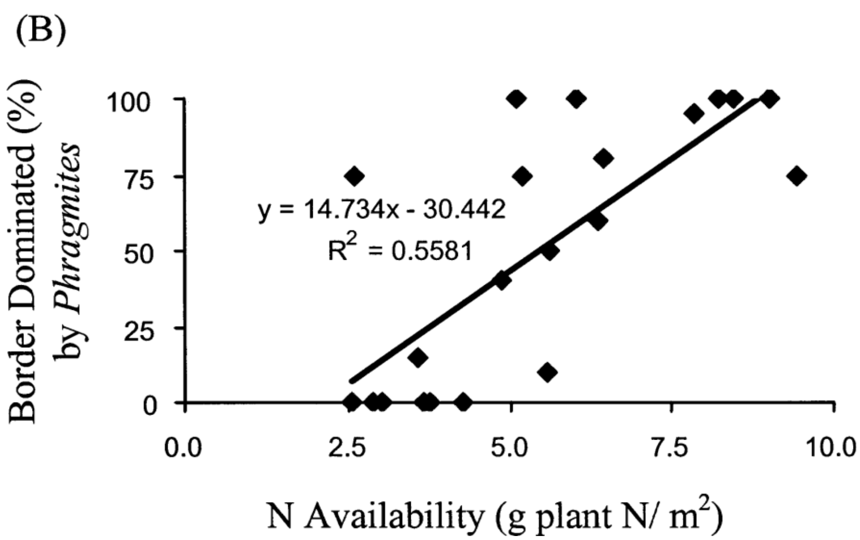


Figure 1.1: Nitrogen Availability in New England coastal marshes given border cover of *Phragmites* (Silliman et al., 2004)

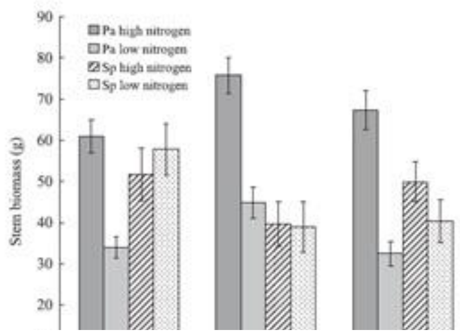


Figure 1.2: In areas of high nitrogen (dark grey), *Phragmites* (solid bars) is able to out greatly outcompete native species *Spartina pectinata* (textured bars). (Rickey et al., 2004)

N appears to be the more limiting nutrient (vs. phosphorous, P) (Romero et al., 1999), so N-focused management efforts are likely to be more beneficial. *Phragmites* can also impact the N cycle, in addition to benefitting from higher levels. It can lower the processing of N-rich fertilizers through denitrification, changing the N-cycle, while taking advantage of high N levels (Arce et al., 2009). Projects and Best Management Practices (BMPs) such as enhanced and new stream buffers between agriculture and waterways could help reduce *Phragmites* invasion risk by reducing the nutrient load in vulnerable areas.

1b.) Climate Change

Species that become invasive are frequently characterized by a capacity to take advantage of and adapt to sudden changes in local climates and environments (Figure 1.3). Therefore, it is widely expected that climate change will favor invasive species, as many factors associated with climate change, including changing water levels, removal of climatic barriers, increased nutrient deposition, and impacted native vegetation, are also those factors typically directly associated with *Phragmites* invasions (Dukes et al., 1999; Hellmann et al., 2008). All of these changes are projected to increase both the potential and realized ranges of invasive *Phragmites* in the Great Lakes Region.

For example, the invasive version of *Phragmites* has rarely been seen in northern Michigan (Bourgeau-Chavez et al., 2013). Invasive *Phragmites* is highly plastic in growth and form, displaying a wide range of suitable temperatures and lengthy growing seasons throughout its worldwide distribution (Guo et al., 2013). This, paired with its preference for lower water and exposed substrate (Pagter et al., 2005; Tulbure et al., 2010), will most likely increase the possible maximum range of *Phragmites* given current climate change predictions. With increasing temperatures and projected potential long terms changes in water level, areas currently free of invasive *Phragmites* stands could soon become susceptible to

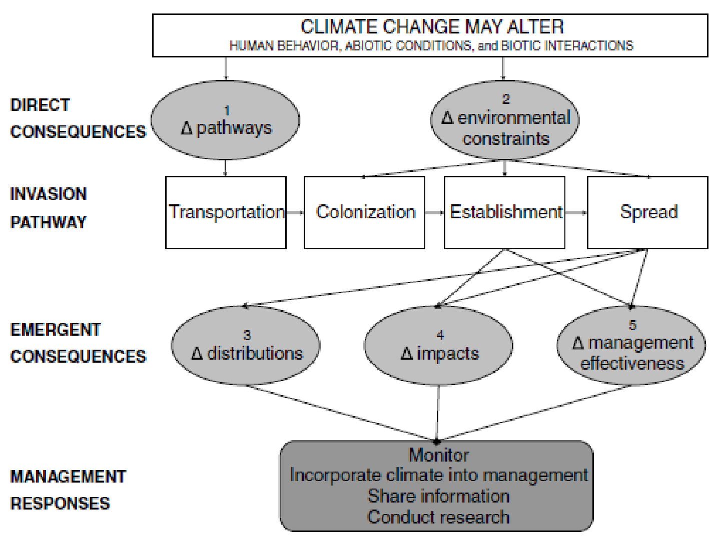


Figure 1.3: Possible changes and consequences of climate change on invasive species (from Hellmann et al., 2008)

invasion.

The USGS Great Lakes Science Center (GLSC) has created an online tool ("The GLRI *Phragmites* Decision Support Tool Mapper", Figure 1.4) that geographically displays *Phragmites* invasion risk related to changing water levels in the Great Lakes ([http://cida.usgs.gov/glri/*Phragmites*/](http://cida.usgs.gov/glri/Phragmites/)). This mapping tool allows managers to not only understand which habitats and areas are under the greatest threat of *Phragmites* invasion, but also the most likely sources of *Phragmites* spread (Carlson Mazur et al., 2014). This tool can be used to investigate what some of these low-water scenarios could mean for *Phragmites* invasion risk. With recent water trends, a "high-water" version may also be needed.

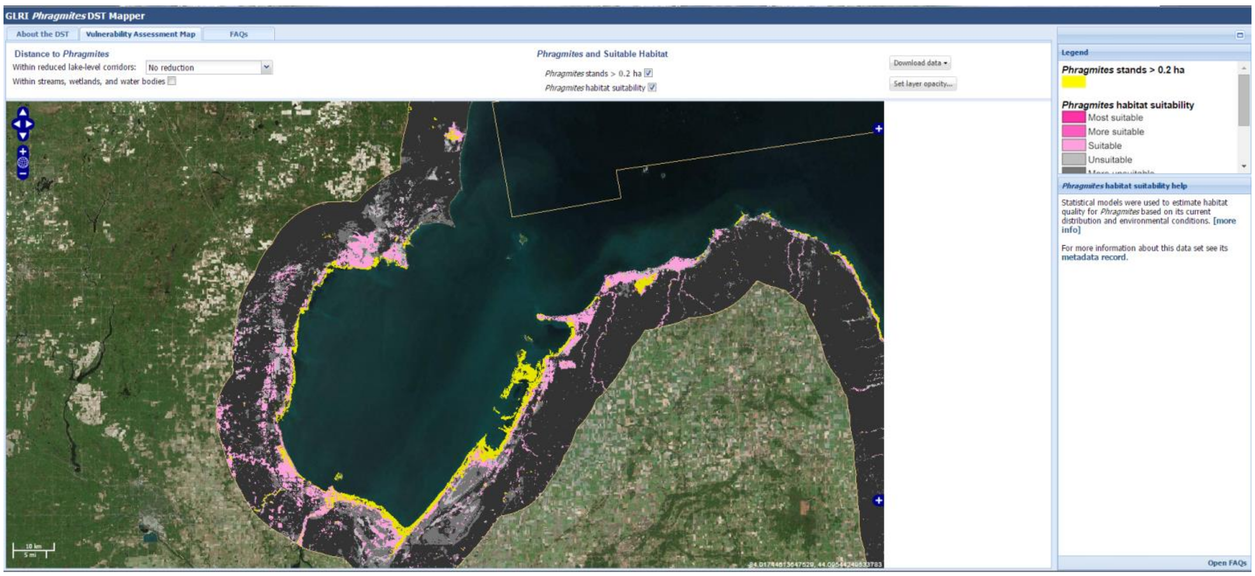


Figure 1.4: The USGS GLRI *Phragmites* Decision Support Tool Mapper includes layers of current *Phragmites* extent (yellow) and the suitability of surrounding wetland areas (pink), as well as projections given changing lake levels.

Also, the rate of *Phragmites* spread may increase, as current evidence shows that higher temperatures allow for long-distance sexual reproduction rather than only local vegetative reproduction (Brisson et al., 2008). Because of this shift, monitoring efforts focused only on wetlands neighboring current *Phragmites* stands are unlikely to be effective. Management of invasive *Phragmites* will require significant change to keep pace with the difficulties posed by climate change. Areas currently without *Phragmites* will need monitoring efforts, while areas already undergoing treatment will be forced to deal with expansion, denser production, and lower probabilities of native plant revegetation.

1d) Management – Lessons, the present, and the future

Current management efforts are typically focused on full-scale removal of *Phragmites* from invaded wetlands using a variety of methods, including mechanical treatments, such as mowing and disking, and chemical treatments, using Glyphosate and/or Imazapyr, or combinations thereof. A single "best treatment" does not exist over regional areas, as treatment has to be specified based on the stand to be treated, taking into account variables such as size, nutrient loading, and *Phragmites* density (Currie et al., 2014).

Meta-analysis of current studies and research shows that long term, multiyear dedication to both treatment and monitoring are key to success (Hazelton et al., 2014). Hazelton et al. (2014) found that the highest rates of success were found in cases where large scale treatments, be they broadcast spraying, hand wicking of herbicide, or mowing, were only effective when followed by yearly spot treating. If not, the remaining patches of *Phragmites* were able to reestablish and spread to regain hold over entire wetlands.

Dr. Kenneth Elgersma's (2014) work has shown that there can be an optimal number of years of treatment to control dense invasive plants such as non-native *Typha* and *Phragmites*, and this is related to available nutrient loads (Figure 1.5). Too few (only one) or too many (more than three) years of treatment lead to higher non-native biomass in areas with low N; about three years of treatment appears ideal. This optimal time period can be seen through active monitoring efforts; monitoring *Phragmites* control results for a three year period is strongly recommended to understand if efforts have been successful (Currie et al., 2014).

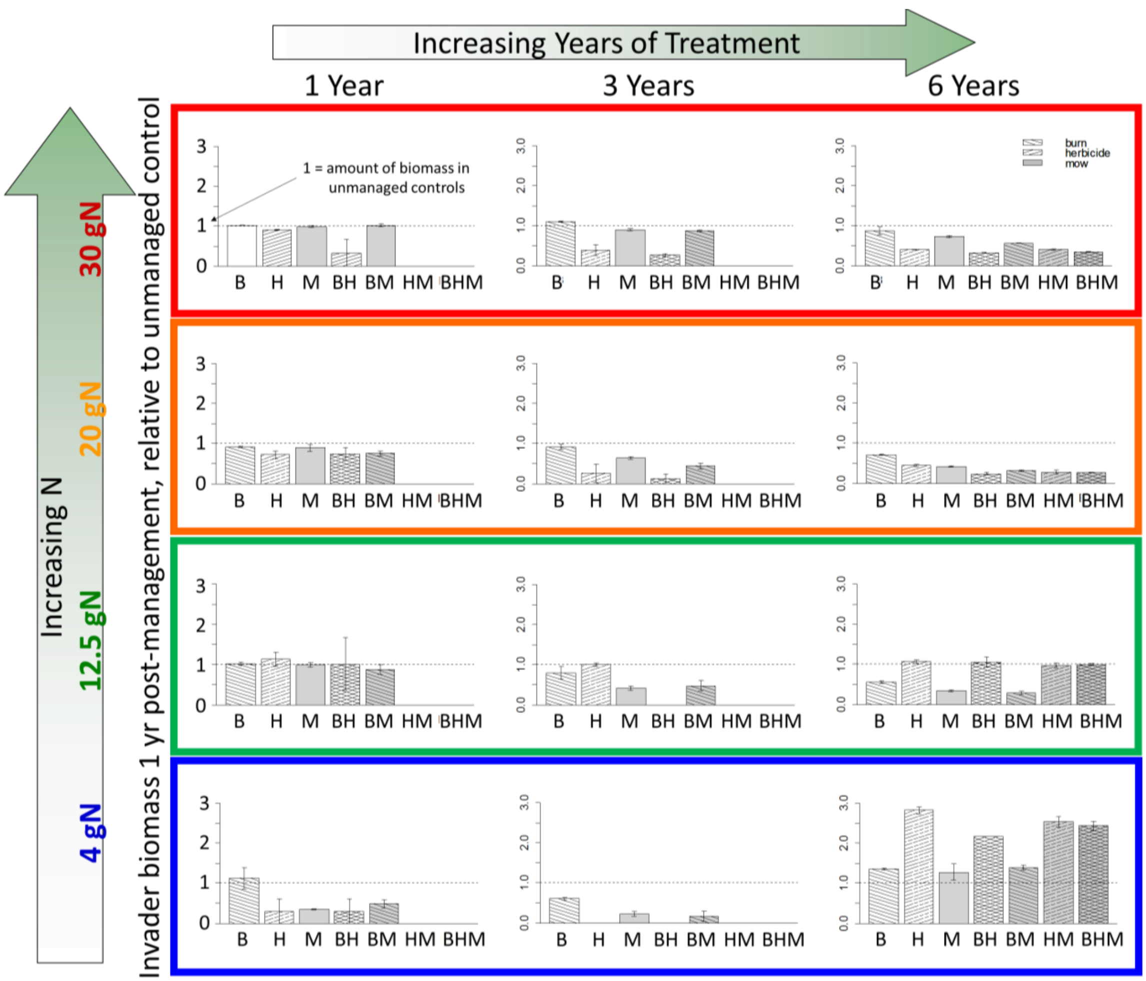


Figure 1.5: Current modeling by Elgersma projects the effectiveness of treating invasive *Typha* over various time periods, given varying Nitrogen input. (Elgersma et al., 2014)

One success story often cited is that of treatment on the Beaver Island archipelago in Lake Michigan. The township addressed the issue as a whole community rather than leaving treatment efforts in the hands of individual landowners. A local ordinance requires that all *Phragmites* within the area be treated, and forms are sent out annually by the local government, creating an "opt out" system for land owners that do not want their property treated. The remainder of the island is treated as a single parcel by commercial herbicide applicators using backpack sprayers or hand-wicking of glyphosate and imazapyr starting in 2007 (McDonough, 2007). Annual efforts have greatly reduced *Phragmites* cover from 27 acres to three acres, reopening beaches and greatly limiting reed spread (Grassmick, 2011).

1e) Agency Guides

Currently, a number of distinct agency and governmental guidelines exist for *Phragmites* treatment (see Table 1.1). Most are on a local scale, ranging from state Department of Environmental Quality (DEQ) publications to township ordinances. Many states, including Michigan (Figure 1.7), have published their own guides with suggestions for land owners (*A guide to the control and management of invasive Phragmites*, 2014; Hiland, 2013). The Michigan DEQ has also recently made available a tool for groups and individuals looking to treat *Phragmites* (Figure 1.6), which helps to prioritize treatment based on a number of factors, including patch size, treatment history, and location (available at http://www.michigan.gov/deq/0,4561,7-135-3313_71151_71481_8314-178183--,00.html) (*Phragmites Treatment/Managment Prioritization Tool* 2013). This, in turn, allows managers to optimize funding use. After deciding on treatment areas, most agency guides suggest long term chemical treatment, while also discussing the use of mechanical treatments, such as mowing or burning .

***Phragmites* Treatment/Management Prioritization Tool**

January 2014

Criteria

Ecological Criteria

1. *Region:* In what region of Michigan is your site located?

	Value	Score
Upper Peninsula	*(5 pts.)*	
Northern Lower Peninsula (north of vegetation tension zone)	*(3 pts.)*	
Southern Lower Peninsula	*(1 pts.)*	

2. *Local abundance:* Is invasive *Phragmites australis* locally abundant in similar habitat in the general area*?

**General area is approximately 2 miles from the site*

	Value	Score
Very Abundant (>50% of similar habitat is infested)	*(-5 pts.)*	
Moderate to low abundance (10-50% infested)	*(0 pts.)*	
Virtually absent locally (<10% infested)	*(5 pts.)*	

3. *Infestation size:* How large is the *Phragmites* infestation (approximate patch size)?

	Value	Score
Less than 1000 square feet	*(9 pts.)*	
1000 square feet - 1 acre	*(7 pts.)*	
1 acre - 20 acres	*(5 pts.)*	
Greater than 20 acres	*(3 pts.)*	

4. *Linear feature:* Is the infestation in a linear feature, such as a roadside ditch, drain, utility corridor, etc.?

	Value	Score
Yes, the infestation is in a linear feature	*(5 pts.)*	
No, the infestation is not in a linear feature	*(0 pts.)*	

5. *Seed source:* Is the area acting as a potential seed source to non-infested areas?

	Value	Score
The patch size is less than 1 acre AND the entire area will be treated	*(5 pts.)*	
The patch size is less than 1 acre AND the entire area will NOT be treated	*(1 pts.)*	
The patch size is more than 1 acre AND the treatment is on the edge of the in-festation OR the entire area will be treated	*(3 pts.)*	
The patch size is more than 1 acre AND the treatment is NOT on the edge of the infestation OR the entire area will not be treated	*(-5 pts.)*	

Figure 1.6: A sample of the MDEQ *Phragmites* Treatment/Management Prioritization Tool, which helps land owners and managers choose which patches of *Phragmites* to treat first, given a number of factors, including patch size, treatment history, and location.

Other local municipalities have created programs that either incentivize or require treatment. The state of Delaware, for instance, offers funding assistance for aerial spraying of *Phragmites* through a statewide cost share program which treated 2,374 acres in 2012 (Wilson, 2012). Smaller governmental bodies, such as Clay Township, Michigan, have created management plans which define focus areas, and allows the local government to file township-wide permits (Board, 2010). This strategy has shown considerable effect, as annual treatments remove existing stands, as well as removing propagule sources (Grassmick, 2011; B. Williams, 2011).

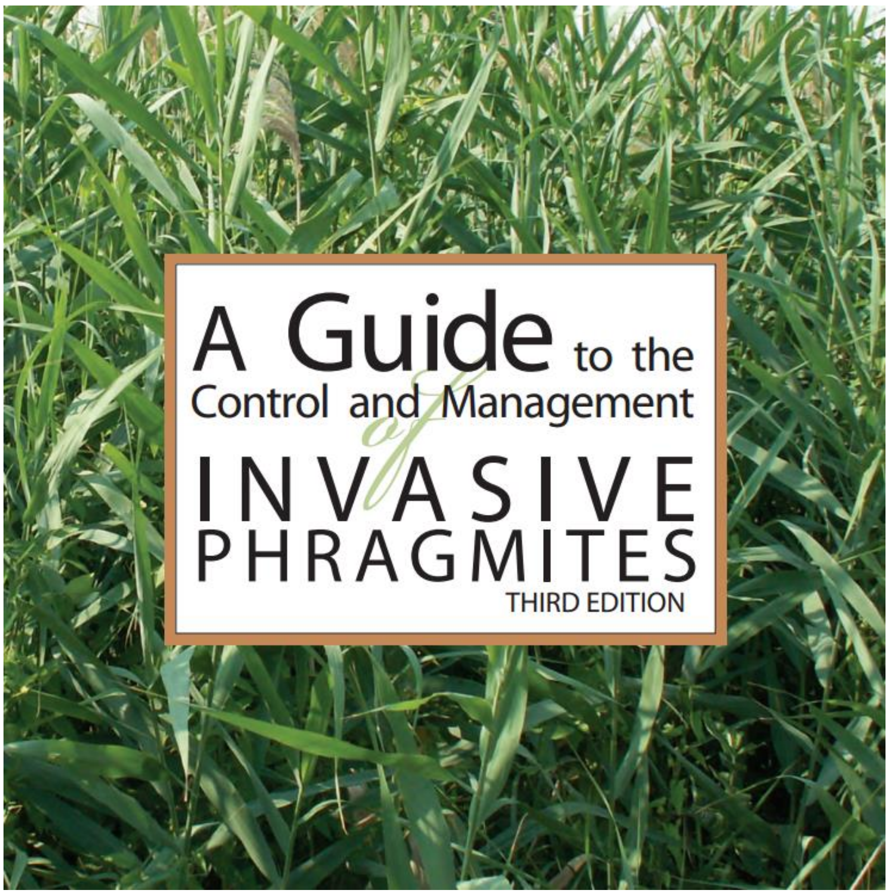


Figure 1.7: The MDEQ "Green Guide" is one of the most cited governmental publications on the treatment and management of *Phragmites*.

Table 1.1: A summary of some governmental and NGO publications on *Phragmites*

Guide	Publishing Agency	Year Published	Link	Comments
Marsh Invader! How to Identify and Combat one of Virginia's most Invasive Plants	Virginia Department of Conservation and Recreation	2007	http://www.deq.virginia.gov/portals/0/deq/coastalzonemanagement/task10-03-07.pdf	12 pg guide for land owners on what *Phragmites* is, and general management
Invasive Plants of Ohio: Common Reed Grass (Hiland, 2013)	Ohio Invasive Plants Council	2010	http://www.oipc.info/uploads/5/8/6/5/58652481/5factsheetcommonreedgrass.pdf	2 pg Fact Sheet on how *Phragmites* grows and 3 main control methods
A Guide to the Control and Management of Invasive *Phragmites*	Michigan Department of Environmental Quality	2014	https://www.michigan.gov/documents/deq/deq-ogl-ais-guide-PhragBook-Email_212418_7.pdf	46 pg guide on what *Phragmites* is, how it grows, how it can be treated, and various outcomes. A widely cited guide.
Summary of Common Questions Concerning *Phragmites* Control (Ailstock, 2006)	Anne Arundel Community College	2006	http://home.comcast.net/~herringbay/pdfs/PhragQandA.pdf	8 pg FQA for the general public on the keys of *Phragmites* growth and treatment, including herbicide alternatives
Plant Guide: Common Reed (Tilley et al., 2012)	United States Department of Agriculture	2012	http://plants.usda.gov/plantguide/pdf/pg_phau7.pdf	5 pg "Plant Guide" including uses, identification, and growth, not including management
Phragmites Treatment Herbicide Quick Guide	Great Lakes *Phragmites* Collaborative	2015	http://greatlakes*Phragmites*.net/files/HerbicideQuickGuide.pdf	2 pg Fact Sheet on various herbicides, pro/cons, application, and links to other resources
Invasive *Phragmites*-Best Management Practices	Ontario Ministry of Natural Resources	2011	http://www.nvca.on.ca/Shared%20Documents/*Phragmites*%20control%20-%20best%20practices.pdf	17 pg guide on *Phragmites* growth and treatment. Note that herbicide legislation in Canada changes recommendations

1f) Biological Control

Though biological control agents have not yet been released to deal with the issue of *Phragmites* in the United States, a number of different insects have been researched, to the point where release in the near future could occur. *Archanara geminipuncta,* a parasitic European moth, currently seems the most promising candidate, infecting nearly 2/3 of stands in its native range and parasitizing up to 90% of stems in any one stand (Blossey, 2014). Additionally, *A. germinipuncta* strongly prefers invasive/European *Phragmites* over the native genotype (Hinz et al., 2014). The release of bio-controls could drastically change the treatment of *Phragmites* and removal of invasive *Phragmites* stands. However, field testing of *A. germinipuncta* has not yet been completed. The status of bio-controls should be assessed periodically to determine if and when they can become a safe, practical part of the *Phragmites* control toolbox.

Table 1.2: Data on egg laying of *Archanara geminipuncta* in Hinz et al., 2014

	Mean			**# egg batches / # eggs**
	# stems per pot	stem length (cm)	stem diameter (mm)	
European	22.0	116.7	3.4	**16/194**
Introduced	18.2	98.4	3.5	**7/118**
Native	15.4	122.7	4.1	**1/14***

Other possible biological control agents have been investigated but appear to either be ineffective on a large scale or to negatively affect native *Phragmites.* In addition to the current leading moth species, *Archanara geminipuncta,* three other moth species were tested in a study: *Archanara dissoluta, Archanara neurica, and Arenostola phragmitidis.* Of these, only *Archanara neurica* was considered along with *A. geminipuncta* to display a capacity for effective control, though further testing has favored the latter. In addition to moth species, two fly species, *Lipara similis and Lipara rufitarsis,* which traditionally parasitize *Phragmites* in its native range, have been tested as potential biocontrol agents. However, both seemed to preferentially parasitize native *Phragmites*, making them ineffective as a control tool for non-native patches (Lambert et al., 2007). Reviewing the status of these bio-control efforts periodically is recommended to see if they become practical.

1g) Monitoring Methodology

Almost all authors and organizations agree that monitoring of treated and untreated *Phragmites* is necessary for long term management success. However, a number of various monitoring protocols exist, and what is measured can vary widely between projects (Figure 1.8). As with much of *Phragmites* management, there is no single, agreed upon best practice. It is generally accpeted that in order to manage effectively, however, that a quantitative measure of success must be available.

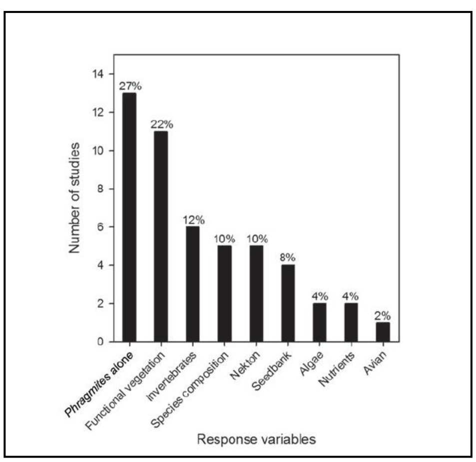


Figure 1.8: Response variables measured in various studies after the treatment of invasive *Phragmites*. (Hazelton et. al, 2014)

The methodology used in this specific study is derived from the Great Lakes Commission's Great Lakes Coastal Wetlands Monitoring Plan (Burton et al., 2008). This includes studies for anuran, bird, and vegetation biodiversity in a paired study. Studying biodiversity changes in relation to *Phragmites* treatment in this way is highly detailed, but very time consuming. This form of monitoring requires professional identification of birds, vegetation, and anurans. Though the data is exceptionally diverse and paints a wide picture of wetland health, it is not feasible in most circumstances.

On the other end of the spectrum would be the monitoring protocol created by the PhragNet project (Hunt, 2013). The "PhragNet" effort of the Chicago Botanic Garden is another vegetation monitoring protocol, focused on providing soil and leaf-tissue sampling data as part of identifying best practices for *Phragmites* control and helping re-establish a diverse native vegetation ecosystem. Each *Phragmites* patch is sampled in a series of transects, with the number of transects depending upon the size of the patch. Each transect consists of three points, one on the edge, one outside of the patch, and one 15 m inside (Figure 1.9). The PhragNet protocol does not require as much field sampling knowledge, and is feasible for individuals and groups dependent on volunteer labor. This provides baseline information for both the larger management community, as well as the land manager. While providing details on soil characteristics and whether *Phragmites* is the native form or not, it does not provide the species diversity data needed to understand if control efforts are improving vegetation biological integrity, so it should be used as part of adaptive management efforts with that caveat in mind.

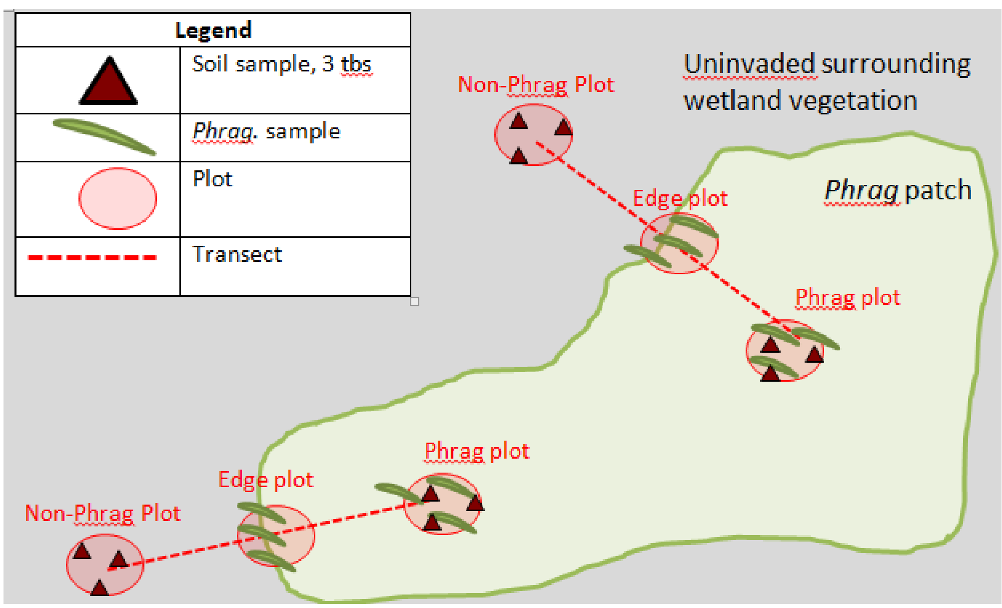


Figure 1.9: Monitoring protocol via PhragNet. Though the current protocol would not provide all of the necessary information, the 3-plot, multi transect method may be useful to collect other data.

Lastly, The United States Geological Service protocol seems to fall between the two, requiring some training, but allowing for wide range application without heavy resources investment. This protocol also works along transects, but qualifies landcover by category, rather than by species (Moore et al., 2014).

Using categories of vegetation cover simplifies sampling, and limits the necessary training, while allowing for similar statistical information as with the Burton et al. procedure (Moore, 2015).

Utilizing a Before/After/Control/Impact (BACI) study design produces more rigorous results than spatial-matched pairs or temporal baseline designs, but involves several assumptions that must be carefully considered in the process of establishing a monitoring protocol. This form of quantitative measure could easily be used to understand the information gained from a wide variety of sampling methodologies. Careful consideration should be given, however, to the assumptions made, particularly in small sample areas.

Key BACI Assumptions/Limitations are:

- Sampling design does not have to be balanced (number of surveys can vary among sites and years, not all sites need to be measured in all years)
- Assumes the system is in equilibrium before and after the impact (stable mean values) and that the change in the mean caused by the impact is immediate
- Assumes measurements and sites are independent of each other
- Assumes normality of residuals
- Assumes a step change in the mean difference between treated and untreated sites, less good at detecting gradual post-impact changes (Schwarts, 2015)

1h) Novel Ecosystems

Given the current state of *Phragmites* management and the projected spread of invasive species, the likelihood of complete eradication of the invasive form of *Phragmites* is not high. However, managing these areas as "novel ecosystems" is probably necessary to acknowledge that some level of coexistence of invasive *Phragmites* and native communities is likely in to the foreseeable future, and that systems that include invasive and native plants can still provide some levels of useful ecosystems services (Hobbs et al., 2009). Novel ecosystems look to work with non-native species as a part of a functional, healthy environment because it is not feasible to completely eradicate the non-native species (Figure 1.10). Rather than trying to consistently restore areas to "historic conditions" that were themselves dynamic, many professionals advise managing actively for function, rather than specific species compositions (Crowl et al., 2008; Davis et al., 2011). Particularly given uncertain future conditions due to climate change, attempting to manage systems to sustain current or recent historical conditions will not allow for ecosystems to adjust to new requirements. By attempting to create stable ecosystems, it would be likely that they would be too rigid to adjust to periods of extreme change.

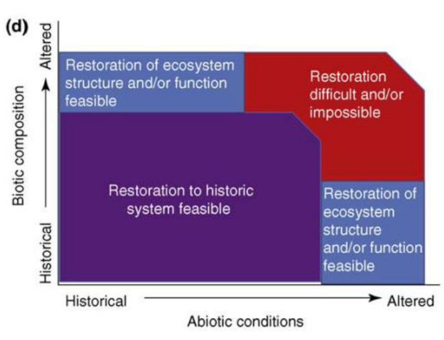


Figure 1.10: Highly altered ecosystems are far harder to restore to a historical system than those that have lower interference.

Looking forward to a shifting and heretofore unseen future condition, management efforts may not be able to create stability in composition, but instead focus on character and function as part of an adaptive management framework.

Phragmites, in part, can be useful in creating this function, providing bank stabilization, water filtration, and some amount of habitat, meaning that complete removal of established *Phragmites* could, in certain situations, negatively affect the function of wetlands (Hershner et al., 2008; Kiviat, 2013). Integrating *Phragmites* into ecosystems, rather than either unrealistic complete removal or allowing undesirable complete domination, could be managed as a "Novel Ecosystem" (Lugo, 2013). As a Great Lakes community, we will have to learn to live with invasive *Phragmites* in at least some situations. Understanding which areas of invasive *Phragmites* are more likely to respond to treatment, which will need effective monitoring, is part of this learning effort.

1i) Summary

In many ways, invasive *Phragmites* is here to stay. Not only has it become an entrenched part of many Great Lakes wetlands, the likelihood of its future expansion is very high. *Phragmites* similarly has a high possibility of serving at least some role in maintaining "novel" wetland ecosystems as impacts from climate change progress (Chambers et al., 2012; Kiviat, 2013). Therefore, management which focuses primarily on the overall health of an area in an adaptive management context, rather than solely on its composition, may best serve the health of Great Lakes wetlands.

Current management strategies focus primarily on removal and remediation, either through long term application of glyphosate or imazapyr, or mechanical treatments (mowing, burning), and sometimes in combination (*A guide to the control and management of invasive Phragmites*, 2014). Long term, "unending" treatment, however, may do more harm than good in controlling *Phragmites* growth (Currie et al., 2014). Currently, the likelihood of functional bio-controls seems limited, particularly in the near future (Hinz et al., 2014). In the face of continued pressures from climate change and shifting lake levels, the best management practices currently advised by state and nonprofit agencies may not achieve the goals of land owners and stakeholders. Pairing this flexibility with monitoring efforts to understand how the ecosystem is responding to control efforts will allow managers to gauge effectiveness and needs, and apply resources accordingly.

2) Implications of current literature for adaptive management recommendations

Because of the challenges described in Section 1, and an increased understanding of the place of non-native species in larger ecosystems, future efforts with concern to *Phragmites* will require an adaptive management approach (Davis et al., 2011). Working towards specific goals with respect to ecosystem services and health, rather than a search for a "historic" state that was itself dynamic, is not only more likely to be successful, but will save agencies and managers time, money, and effort. Adaptive management efforts will work using the knowledge gained by past and ongoing management efforts. Namely, this would identify the types of stands where *Phragmites* containment can be successful and the most effective methods given the area, while changing in future years as more information is gained. This form of fluid management will create more resilient, healthy, functional ecosystems in the face of future *Phragmites* invasion and environmental change.

2a) Management Changes Under Changing Conditions

Adaptive management is well suited to the biotic and abiotic changes which are currently applying pressures to systems strained by *Phragmites*. Current literature provides a number of examples of how to manage for limiting further growth in relation to these changes, including increases in nutrient input and deposition and shifting water levels. Working with this information, land managers can work to counteract any advantages that *Phragmites* may gain in the future. Whether efforts include nutrient catchment and retention or from controlling water levels when possible, countermeasures can, and in many cases should, be taken.

In particular, higher nutrient inputs may be having significant impact on the increasing distribution of *Phragmites*. Currently proposed research would look at the regrowth of *Phragmites* after treatment in paired areas of nutrient retention and those with unimpeded runoff. Looking at past publications for Currie et al. (2014) and Elgersma et al. (2014), the input and control of nitrogen runoff should inform the treatment of *Phragmites*, particularly in areas of long term treatment. Understanding the landscape scale inputs of Nitrogen can greatly influence treatment, in turn increasing success over a longer time scale. Making proactive efforts to reduce inputs of nitrogen, therefore, may be an effective way of both preventing *Phragmites* spread and increasing the effectiveness of treatment.

Lastly, the importance of climate change in the patterns of *Phragmites* distribution should be closely examined and understood to instruct future preventative management and monitoring. Tools such as the USGS GLRI *Phragmites* Decision Support Tool Mapper can allow land owners and managers to pinpoint areas that are theoretically susceptible to *Phragmites* particularly given changing water levels (Mazur et al., 2014). If water levels drop, as was seen throughout the early 2000s, *Phragmites* will be able to expand out from shorelines. If water levels continue to rise, as they have more recently, *Phragmites* will be able to expand into areas that are currently dominated by wet meadow species, encroach more closely on housing, increasing fire hazard, and increase distribution in lateral features and inland wetland and lakes. Land managers can therefore look to predications of distribution to understand the threat to their own areas, as well as to investigate areas which are currently outside the reach of *Phragmites,* but which soon might be susceptible and defenseless.

2b) Interpretation of Current Government and Related Management Suggestions

Investigating management suggestions throughout the nation suggests a strong preference for herbicide treatment (Figure 2.1). Herbicide application times and rates are dependent on stand density and location, though it is generally agreed that glyphosate and/or imazapyr should be applied in early fall to maximize effectiveness. Herbicide use can be challenging, particularly given public opinion or sensitive ecosystems. However, the use of broad scale herbicides, particularly the less aggressive glyphosate, have generally been the most widely suggested main form of treatment (*A guide to the control and management of invasive Phragmites*, 2014).

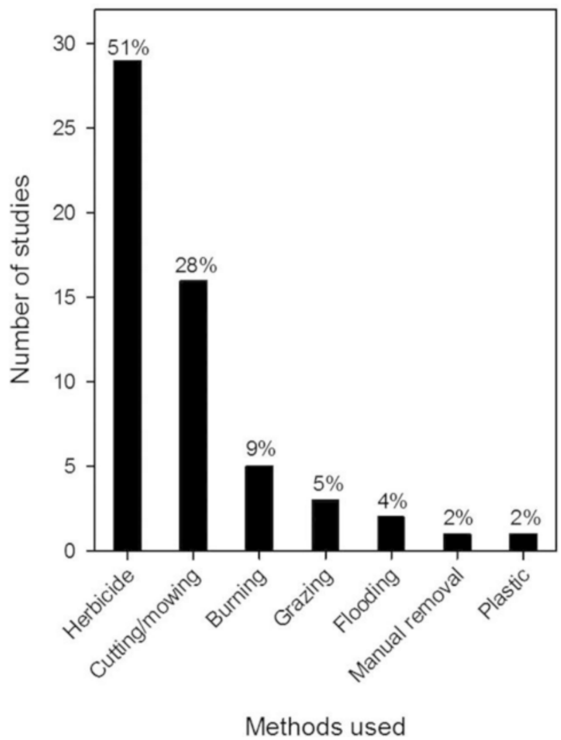


Figure 2.1: The types of treatment used in 34 scientific *Phragmites* studies over the last forty years. (Hazelton et. al, 2014)

While carrying out such treatments, recent research by Currie et al. (2014) should help inform managers when planning long term, multiyear approaches to *Phragmites* management. Especially in areas with high nutrient inputs, such as anthropogenic runoff, treatment for more than a few years with herbicide may increase the density and dominance of non-native species. Therefore, it is likely that managers, in addition to doing enough years of treatment, also need to limit treatment duration. Essentially, there is a point at which further treatment may simply be a waste of resources and do more harm than good.

Specific management practices should be localized both in strategy and application. For instance, many coastal areas must consider the impacts of salinity gradients on *Phragmites* management and growth, though this factor is moot among inland Great Lakes populations. Similarly, some areas are more likely able to effect water level change, which can help reduce and stunt regrowth of invasive *Phragmites (Ailstock et al., 2001; Marsh Invader! , 2008).* The scale of treatment, as well, will change the method of application. Hand wicking and backpack spraying of herbicide can be used in small, shallow water populations to minimize non-target effects, while larger, denser patches often require application from amphibious vehicles, such as a “marsh master”, or via aerial application. In particular, resources such as the Michigan DNR’s Prioritization Tool (2014) are advised to select locations of highest priority. Selecting plots where treatment has the highest chance of being successful will not only prove to be the best use of funds, but provide test cases to continue funding in the future.

Frequently stressed, if not evenly applied, is the importance of monitoring and continued treatment. Particularly in larger, denser, and older stands, several years of treatment are needed to make an impact on *Phragmites*, especially to make a lasting difference. However, repeating treatment without quantifying the effects of earlier work may be ineffective, and can increase non-target plant mortality. Monitoring, therefore, should be used to understand the current distribution and biological indicators of *Phragmites* and treatment efforts should continue in reference to the post-treatment distribution. By focusing on remaining patches of *Phragmites*, treatment resources can be concentrated.

An alternative method of community based treatment involves local ordinance and law. Large scale policy efforts (such as statewide ones) are uncommon, though some smaller municipalities have instigated change through highly effective local policy. When possible, "opt out" systems, which require owners who do not want their land to be treated to contact local authorities, seem to greatly increase treatment coverage, and greatly lower the possibility of small residual source populations. Examples, including Beaver Island and Harsens Island, are generally limited, including small, tight-knit communities where strong conservation and land ethics values already dominate. However, modeling change and legislation after such successful programs while increasing scale may allow for more effective and comprehensive *Phragmites* removal, effectively lowering cost and developing community commitment.

Working over a larger spatial scales with commitment to interorganizational cooperation allows adaptive management to find prime treatments more quickly, by allowing for replication (Moore et al., 2013). In this way, the problem of *Phragmites* may be perfect for such an application, particularly in areas inundated, independent of ownership. Working with multiple land owners and stakeholders, larger scale inventory, treatment, and monitoring can be completed without straining resources. Particularly when treating replicates with separate treatment types, however, distinct end goals and monitoring protocols must be set forward. Multiple types of vegetative monitoring in particular have been used in varying studies (Moore et al., 2014). Independent of the intensity of the monitoring, a quantitative system to grade success is necessary.

2c) Implications of Novel Ecosystems for Adaptive Management

The realization of the necessity of integrating longstanding invasive *Phragmites* populations is an important suggestion to be drawn from recent literature and publications. Invasive *Phragmites* is well known to have considerable negative impacts on the form and function of some wetland areas. However, more recent research consistently suggests that non-native species, and *Phragmites,* can contribute to the total function of an ecosystem (Carlson et al., 2009; Kiviat, 2013). In many circumstances, *Phragmites* can be utilized by at least some plants and animals as habitat (Figure 2.2). In particular, *Phragmites* has been shown to be valuable in nutrient uptake and sediment retention. With increases in nutrient deposition and on the anthropogenic stresses on native wetlands, *Phragmites* might be necessary to retain the health of wetlands where it is currently considered a pest and sufficient resources to eradicate it are not available on a practical basis.

Figure 2.2: Many species of birds can successfully nest in even Phragmites, and a number of plants can coexist in thin Phragmites stands.

Novel ecosystems reflect a comprehensive, long term approach to management. The idea that full removal of *Phragmites* is likely is probably not possible. Therefore, it is best that the management community looks to areas where *Phragmites* treatment can be productive vs. areas where *Phragmites* could be left to help spend available resources optimally. In some areas, *Phragmites* can serve as a filter between upland runoff of soil and fertilizer and the water. Particularly in the Great Lakes, this sequestration may very well assist in the management of nuisance algae and eutrophication.

Where *Phragmites* creates dense, nonproductive stands, or where it negatively interacts with human economic or aesthetic values, limiting or removing the population will most likely continue to the best management option. The impacts of *Phragmites* on diversity, particularly in areas with threatened or endangered populations, cannot be ignored. Dense, monotypic areas of *Phragmites* limit the regeneration and growth of many native plant species, as well as often being less productive for both bird and frog species. However, thinner, smaller stands may serve well as habitat for some birds, providing necessary cover. In areas where aesthetic values of the bay, such as on private property or those with high economic value from tourism, removal will continue to be a priority.

Removal of *Phragmites* should not necessarily be considered the default management, but instead a response to a specific negative effect. Communities of managers, land owners, and stakeholders should select those populations of *Phragmites* which pose the greatest threats, such as popular parks or valuable wetlands, and those which benefit from its growth. In this way, not only can treatment spending and resources be optimized, but healthier, more functional wetlands can better serve both the biotic and abiotic community.

2d) Summary

It is important to note that within current literature and management guidelines, no one best policy for removal of *Phragmites* exists. There is no panacea to the problems presented by *Phragmites* and, as such, land managers must synthesize the lessons learned by others to create a specific management regime. This may combine knowledge from public and private sources, nongovernmental recommendations, and governmental tools or opportunities. When, where, and how to treat

Phragmites is a case by case decision, calculated from a number of factors, including those defining the patch itself, the ability to do necessary monitoring, as well as the limits of control resources available.

Secondarily, it should be realized that the bulk of knowledge for *Phragmites* growth and expansion would suggest that managing *Phragmites* in the future will most likely include integrating it at least at some level into ecosystems and wetlands, rather than focusing only on eradication. Projections factoring for climate change paint a picture for the likely expansion of *Phragmites*, and similarly of the possible role it can play in the changing environment. Paired with research showing that excessive treatment can increase the growth of invasive species, long term management may need to aim for higher wetland function, whether or not they include *Phragmites*.

3) Project

Project Title: A Baseline and Standardized Method for Monitoring the Treatment of Invasive *Phragmites*

PI Name: Laura L. Bourgeau-Chavez, PhD, Michigan Tech Research Institute

Project Period: September 2013 to November 2015

The purpose of the study was to develop scientific methods for monitoring the effectiveness of herbicide spraying as a management technique for controlling the invasive species, *Phragmites australis*. Focus was on the evaluation of effectiveness of past herbicide treatments (including areas treated additionally with burning or cutting) on *Phragmites*, and post-treatment restoration response of vegetation and faunal biodiversity. Through field sampling we assessed paired treated and non-treated *Phragmites* dominant sites in Green and Saginaw Bays for biodiversity of birds, amphibians and vegetation. In addition, at scales of 15 cm to 30 m, aerial and satellite images were used to map treatment success. Treatment effectiveness was thus assessed in a nested scaling design, from field surveys to high resolution aerial imagery to moderate resolution satellite imagery.

A comparison was made of pre-treatment *Phragmites* distribution maps of the U.S. coastal Great Lakes (circa 2008-2010, Bourgeau-Chavez *et al*. 2013), with post-treatment imagery and field surveys collected by our project team (AES and MTRI). In addition, the Wisconsin DNR provided locations and dates of previous *Phragmites* treatments within the Green Bay study area and under this grant information was gathered on the treatment areas in Saginaw Bay. This information was obtained from multiple sources but primarily from DEQ herbicide permitting records. Distribution of *Phragmites* and treatment area maps were created in a GIS and were of key importance to locating sites for sampling in our paired treated/non-treated field sampling.

3a) Field Survey Methods and Statistical Design

i) Study Design and Field Data Collection

Data on breeding bird, anuran (frog and toad), and wetland plant communities collected in coastal wetlands along Saginaw Bay (Lake Huron) and western Green Bay (Lake Michigan) were used to indicate the ecological response of Great Lakes coastal wetlands to 1) *Phragmites* invasion and 2) treatment of invasive *Phragmites.* The dataset consists primarily of data collected after chemical (and sometimes mechanical) treatment of non-native *Phragmites* at individual sites, with pre-treatment survey data available for a subset of sites.

Sites were selected following a Before/After/Control/Impact (BACI) study design (area-by-time factorial), which is frequently used to assess the success of management activities. BACI design allows for comparisons of similar systems over time to determine change in relation to the management activity. The BACI design produces statistically robust characterization of the investigated systems, but the results are generally not transferable to wetland systems not included in the study (Parker, 2002).

Sites where *Phragmites* was treated were identified based on MDEQ herbicide application permits and landowner interviews, then paired with similar sites (nearby, same major coastal wetland type, and same hydrogeomorphic classification) where such treatment did not occur (Figure 3.1). Sites were defined as contiguous wetland areas of the same treatment status and hydrogeomorphic class. At some sites, pre-treatment data were available from the coastal wetlands monitoring program of the Great Lakes Coastal Wetland Consortium (GLCWC). Pre-treatment data were only available for the handful of sites where GLCWC monitoring fortuitously coincided with later *Phragmites* treatment. Pre-treatment data was sometimes available for both sites in a pair and other times only for one site. We took advantage of this variation in data availability to compare three statistical designs (see subsection ii., Statistical analysis).

In Saginaw Bay, post-treatment anuran, bird and macrophyte field data were collected for eight pairs of sites in 2014 and nine pairs in 2015. Pre-treatment data availability varied by taxa. For anurans, pre-treatment monitoring was conducted in 2011 or 2012 at five of the nine treated sites, and data was also collected at the paired control site for three of those five sites. For birds, pre-treatment monitoring was also conducted in 2011 or 2012 at five of the nine treated sites, though not exactly the same subset that was surveyed for anurans, and paired control pre-treatment data were available for three of those five sites. Finally, for macrophytes, pre-treatment monitoring was conducted at four sites and paired control site data was available for two of those.

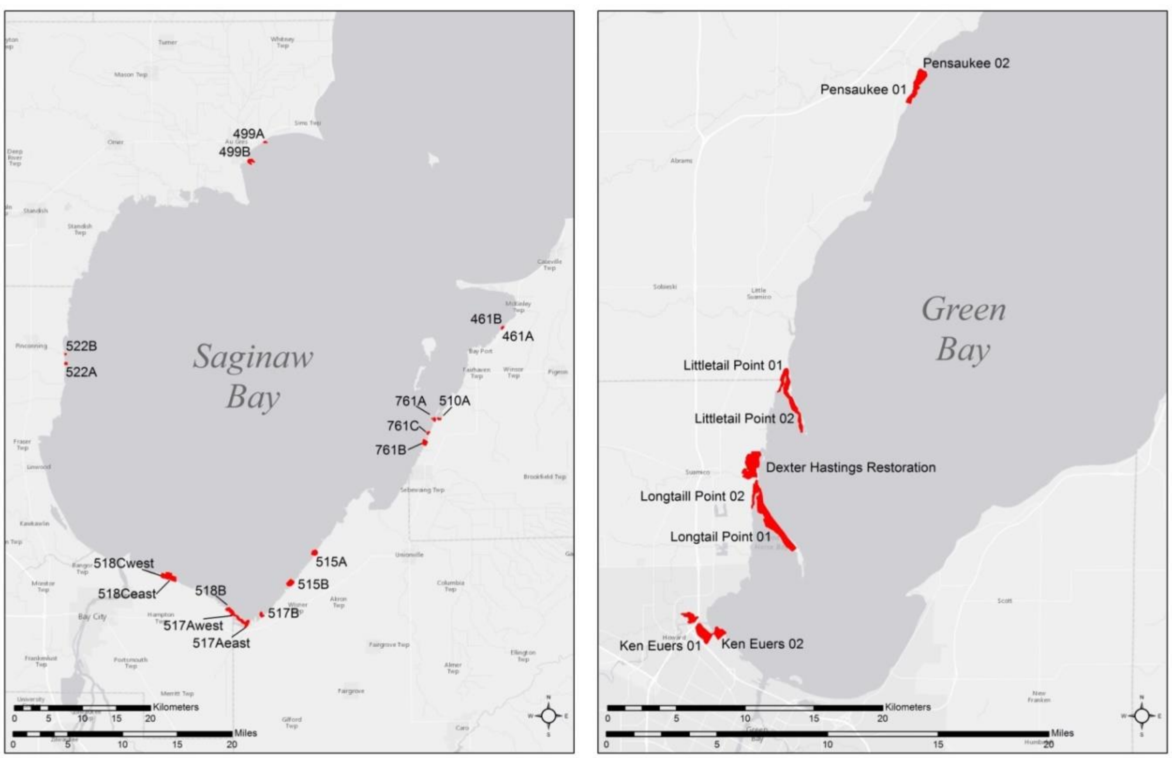


Figure 3.1: Map of the sites surveyed in Green Bay (Lake Michigan) and Saginaw Bay (Lake Huron) for bird, anuran, and vegetation diversity

In Green Bay, anuran, bird and macrophyte data were collected in 2014, and only bird data were collected in 2015. Post-treatment monitoring was conducted in Green Bay at five pairs of sites (two of which share a single control site) and one unpaired site (10 total sites). Because most of western Green Bay was aerially sprayed in 2011, it was difficult to locate suitable untreated control sites. Pre-treatment data were available from GLCWC for three of the treated sites for anurans with no available paired control data. Similarly, for birds, pre-treatment data were available for three treated sites but not their paired controls. Pre-treatment macrophyte data were available for two of the treated sites. The availability of monitoring data across all sites is summarized in Table 3.1.

Table 3.1: Years of available pre- and post-treatment data for each site treated for invasive *Phragmites*. Starred years indicate data was only collected for the treated site and not the paired control. Unstarred years represent paired data.

Site Name	Anurans		Birds			Macrophytes
	Pre-treatment	Post-Treatment	Pre-treatment	Post-Treatment	Pre-treatment	Post-Treatment
Saginaw Bay						
499A	---	2014, 2015	---	2014, 2015	---	2014, 2015
761C	2011*	2014, 2015	---	2014, 2015	---	2014, 2015
517Awest	2012*	2014, 2015	2012*	2014, 2015	2012*	2014, 2015
517Aeast	2012	2014, 2015	2012	2014, 2015	2012*	2015
522A	2011	2014, 2015	2011	2014, 2015	2011	2014, 2015
518Ceast	---	2014, 2015	---	2014, 2015	---	2014, 2015
461A	2012	2014, 2015	2012	2014, 2015	2012	2014, 2015
761A	---	2014, 2015	2011*	2014, 2015	---	2014, 2015
515A	---	2015	---	2015	---	2015
Green Bay						
KE	---	2013, 2014	---	2013, 2014, 2015	---	2014
PE	---	2013, 2014	---	2013, 2014, 2015	---	2014
LO01	2011*	2014	2011*	2014, 2015	---	2014
LO02	2011*	2014	2011*	2014, 2015	2011*	2014
LI01	---	2014	---	2014, 2015	---	2014
DXT	2011*	2013, 2014, 2015	2011*	2013, 2014, 2015	2011*	2014

Field data were collected and anuran, bird and vegetation community indicator metrics calculated following the methods outlined in the Great Lakes Coastal Wetlands Monitoring Plan (GLCWMP), in collaboration with and with training provided by the Great Lakes Coastal Wetland Consortium (Burton et al., 2008). In brief, anuran and bird communities were surveyed using a point count framework. For anurans in 2015, both digital recorders within Phragmites stands and in person surveys (in wet meadow next to dense Phragmites via protocol) were collected. The digital recorders were placed in the center of the dense Phragmites, which would be too difficult to safely traverse in the night when surveys are collected, to determine if there were differences due to where sampling occurred. Marsh recorders consisted of a digital recorder with programmable timer and an external, weatherproof omnidirectional microphone mounted on a tripod at a microphone height of approx. 5 feet. Recorder design was based on recommendations published by the Natural Sounds and Night Skies Division, National Park Service (Fristrup et al., 2012).

Point count data were converted to indices of biotic integrity (IBIs) based on community attributes that respond significantly to disturbance (for anurans, species richness, woodland-associated species richness, and presence/absence of woodland species; for birds, abundance of non-aerial foragers, abundance of marsh nesting obligates, and species richness of area-sensitive marsh nesting obligates).

Vegetation communities were sampled along transects, with transect quadrats evenly divided among the major plant zones at each site. The vegetation IBI was calculated following the GLCWMP based on the frequency and cover of invasive species and the mean conservatism scores in each plant zone. Selected metrics used in the calculation of the vegetation IBI (sitewide invasive species cover, native species richness, mean conservatism index, mean conservatism ratio) as well as percent *Phragmites* cover (sitewide and within the emergent zone) were also compared among sites. The independent and biodiversity variables included in the statistical analysis are summarized in Table 3.2.

Table 3.2: Description of biodiversity variables.

Independent Variables	***Description***
Site	Unique identifier for each site
SiteClass	Treatment status - whether site was a treated wetland or an untreated paired control
Herbicide	For treated sites, the herbicide(s) used (glyphosate, imazapyr, glyphosate+imazapyr, unknown)
Mowed	For treated sites, whether the site was mowed
FirstTreated	First year that *Phragmites* was treated at the site
TreatYears	Number of years of treatment applied at that site
Period	Whether data was collected before or after first treatment
Bay	Green Bay or Saginaw Bay
SumRel	Metric that sums multiple anthropogenic watershed stressor gradient variables (agricultural and urban land use, population density, road density, pollutant point sources from NPDES and NPRI permits). Represents ca. 2000. Scaled from 0 to 1 (negligible to maximum stress). See Host et al. (2011). Used to represent stressors other than invasive species.
HGM	Hydrogeomorphic coastal wetland classification (Albert et al., 2005).
Biodiversity Variables	
Anuran IBI	Provides a standardized, quantitative measure of the condition of the anuran community at a site, focused on woodland species
Anuran Diversity	Simple anuran species diversity
Bird IBI	Provides a standardized, quantitative measure of the condition of the wetland bird community at a site, focused on marsh nesting obligates
Vegetation IBI	Provides a standardized, quantitative measure of the condition of the vegetation community at a site based on invasive species cover and conservatism scores
Sitewide *Phragmites* cover	Mean *Phragmites* cover across all quadrats
Emergent *Phragmites* cover	Mean *Phragmites* cover across the quadrats collected in the emergent zone
Wet meadow *Phragmites* cover	Mean *Phragmites* cover across the quadrats collected in the wet meadow zone
Mean conservatism index	Mean conservatism score of all plant species present at a site. Ranges from 0 to 10, where higher scores indicate greater specificity of the species assemblage to a restricted habitat and lower scores indicate greater presence of generalist species

	(Reznicek et al., 2014). Used by the GLCWC to evaluate the intactness of coastal wetlands, where a score ≥ 3 is fair and one ≥ 6 is good.
Mean conservatism ratio	The mean conservatism score of all plant species present at a site divided by the mean conservatism score of only the native species present. Low scores (< 0.80) reflect large numbers of exotic species and degraded conditions (GLCWMP).
Native species richness	Number of native plant species recorded across all quadrats

ii) Statistical analysis

We took advantage of the variation in pre-treatment data availability to conduct a multi-level analysis of 1) post-treatment only data for paired treated and untreated sites, 2) pre- and post-treatment data for treated sites only, and 3) a full before-after-control impact (BACI) analysis of paired sites with pre- and post-treatment data. These three analyses represent tradeoffs in terms of statistical power, monitoring costs, site selection criteria, and potentially treatment timing. By comparing the results of these different analytical approaches, we can make recommendations about best practices and factors to take into consideration when establishing a biodiversity monitoring plan for *Phragmites* treatment projects.

a.) Spatial-matched Pairs

Spatial-match pairs, which compare post-treatment ecological condition between matched pairs of treated and control sites, are best used when pre-treatment data are unavailable (which is often the case) or when delaying treatment in order to collect pre-treatment data is inadvisable (Figure 3.2). This uses a regression model to test for a significant difference between treated and control sites. In doing so, it can be stratified by treatment type and include a stressor gradient as covariate to reduce the effects of other stressors that vary among sites.

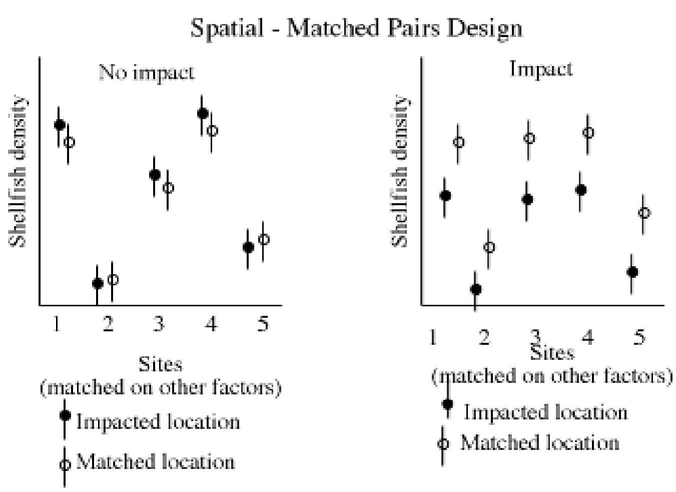


Figure 3.2: Example of a spatial-matched pairs study design to evaluate the effect of an environmental impact on shellfish density. From Schwarts (2015).

b.) Temporal Baseline

Temporal Baseline designs compares pre-treatment and post-treatment conditions at the same sites (Figure 3.3). This is best used in situations where control sites are unavailable. For instance, this would be applicable when a large area receives the same treatment, as with aerial spraying.

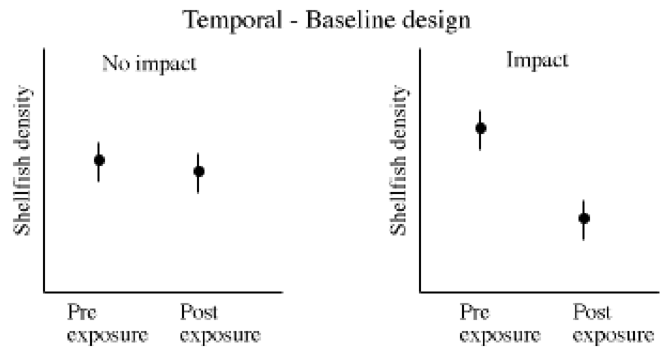


Figure 3.3: Example of a temporal-baseline study design to evaluate the effect of an environmental impact on shellfish density. From Schwarts (2015).

c.) Before/After/Control/Impact (BACI) Analysis

BACI allows for comparisons of similar systems over time to determine changes in relation to the management activity (Figure 3.4). The BACI design produces a statistically robust characterization of the investigated systems, and enables the calculation of the effect size and significance resulting from treatment by disentangling the effect size from interannual variation.

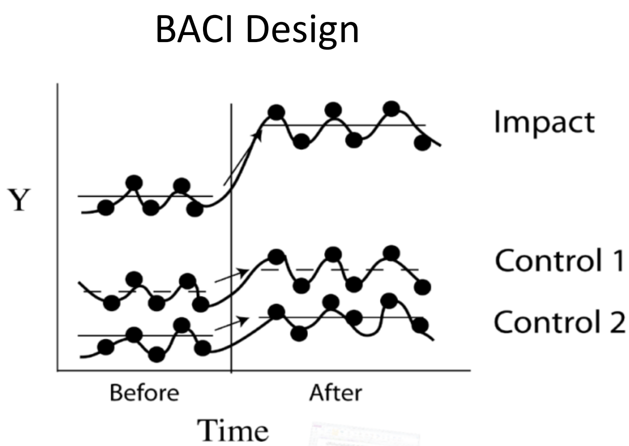


Figure 3.4: Example of a BACI Analysis study design key hidden assumption. From Schwarts (2015).

3b) Results

i)Treatment Effectiveness at Reducing *Phragmites* cover

Because treatment methods and efficacies varied among our study sites, it makes sense to look first at the direct effect of treatment activities on live *Phragmites* percent cover as estimated from the vegetation transect surveys. We can use the same three impact analysis statistical designs to look at the patterns of *Phragmites* cover across space and time. Because, due to the definition of the submergent zone, *Phragmites* was not found in that zone, we took the mean percent cover of live *Phragmites* in the quadrats collected in the wet meadow and emergent zones as a site's mean *Phragmites* cover for this analysis.

Looking first at the post-treatment data collected in 2014 (Saginaw and Green Bays) and 2015 (Saginaw Bay only), a three-way ANOVA including bay, year and site class (treated vs. untreated) showed significant effects of site class as well as the interaction between site class and bay ($F = 30.25$, $P < 0.001$ and $F = 18.40$, $P < 0.001$, respectively). For Green Bay, mean live *Phragmites* cover was 7.0% in treated sites vs. 55.2% in untreated sites. For Saginaw Bay, in 2014, mean live *Phragmites* cover was virtually the same in treated as in untreated sites (21.2 vs. 20.0%). Similarly, in 2015, mean live *Phragmites* cover was 29.6% for both treated and untreated sites in Saginaw Bay. A pairwise t-test with Bonferroni correction confirmed that site classes were significantly different in Green Bay but not in Saginaw Bay (Figure 3.5).

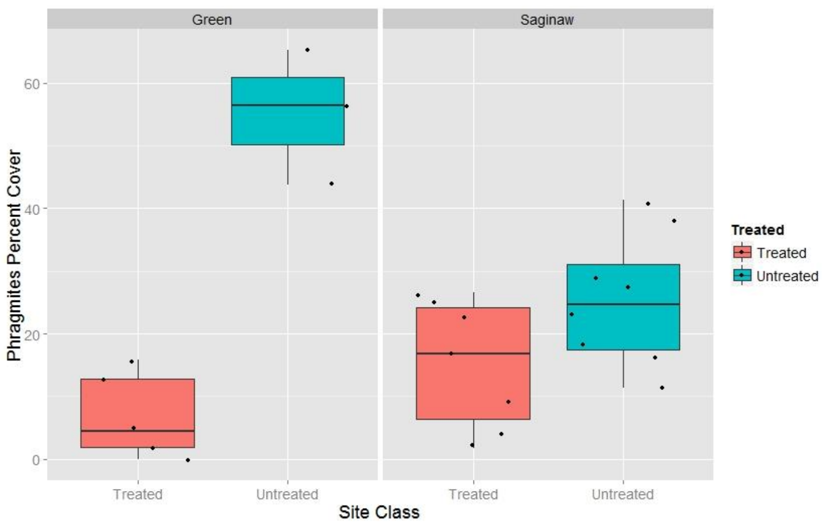


Figure 3.5: Box plot of post-treatment percent cover of live *Phragmites* in 2014, by region and treatment class.

For four treated sites in Saginaw Bay and two treated sites in Green Bay, pre-treatment data were available, so *Phragmites* cover could be compared before and after the initiation of treatment. These results indicate a pattern similar to that just observed in the spatial-matched pairs analysis. In Green Bay, live *Phragmites* cover decreased at both of the sites with pre-treatment data (from 4.6 and 18.4% in 2011 to 0.0 and 3.7% in 2013, respectively). In Saginaw Bay, live *Phragmites* cover increased at three sites and decreased at the fourth, for a net increase in mean *Phragmites* cover from 17.4% before treatment to 18.4% after treatment.

The site where *Phragmites* cover decreased was treated with glyphosate and imazapyr and was not mowed. Of the sites where cover increased, one was treated with glyphosate and not mowed, one treated with glyphosate/imazapyr and not mowed, and one treated with an unknown herbicide formulation and mowed. Due to the absence of a clear shift in *Phragmites* cover with treatment at Saginaw Bay and the small number of sites with pre-treatment data at Green Bay, no statistically significant pattern was observed (Figure 3.6). However, the lack of decrease in treated vs. untreated sites in Saginaw Bay is of concern, as the management efforts at our sites may not have been sufficient to reach the desire goal of effective *Phragmites* control.

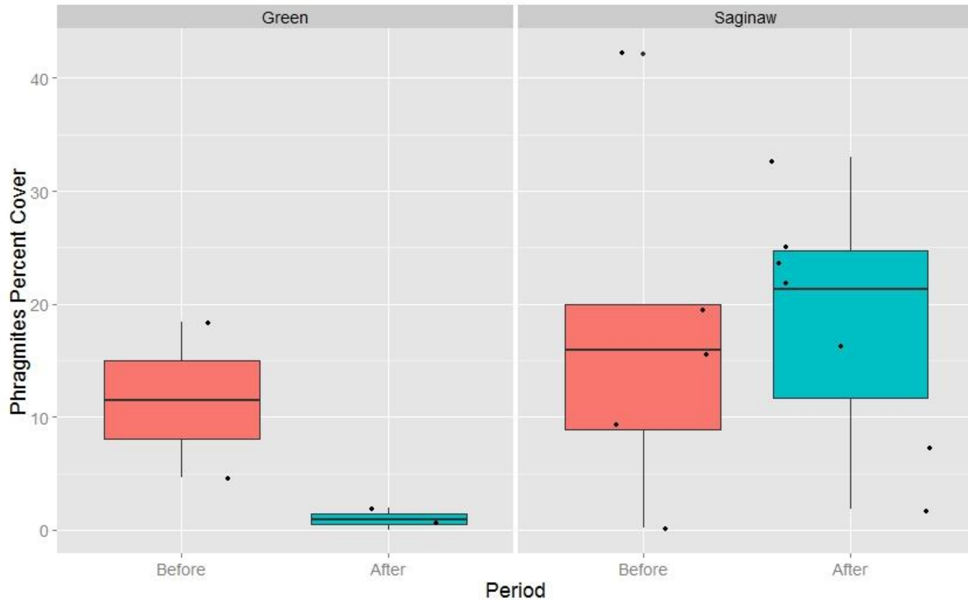


Figure 3.6: Box plot of post-treatment percent cover of live *Phragmites* in 2014 in areas with pre-treatment data, by region and treatment class.

Narrowing the dataset again to cases where pre- and post-treatment data are available for both sites of a pair, we are left with two pairs in Saginaw Bay: 461A/B, treated in 2012, and 522A/B, treated in 2013. Site 461A was treated with herbicide in 2012, then mowed in 2013. *Phragmites* cover at this site was approximately the same in 2014 as it was just before treatment, then increased approximately 7% from 2014 to 2015. In contrast, live *Phragmites* cover at the control site 461B increased a large amount from 2012 to 2014, then declined nearly 20% in 2015. Ice scour at this site during the harsh winter of 2014-15 disturbed much of the emergent zone, possibly accounting for this large decrease. Site 522A was treated with glyphosate and not mowed. Live *Phragmites* cover declined from 2011 (pre-treatment) to 2014 (post-treatment) at this site, but it also declined at the paired control site. Both treated and control sites then experienced similar increases in *Phragmites* cover from 2014 to 2015. Unsurprisingly, these two pairs of sites and their varying results did not produce a statistically significant pattern (Figure 3.7).

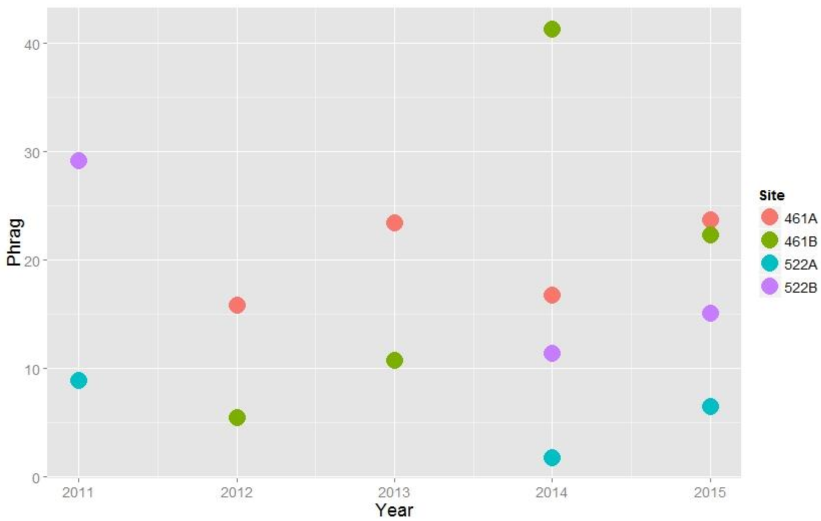


Figure 3.7: Change in percent cover of live *Phragmites* over time at two pairs of treated/untreated AOIs in Saginaw Bay. Sites ending in A were treated, those ending in B were untreated.

ii) Anuran Diversity

Because 1/3 of the amphibian IBI developed by the GLCWC is based on the presence/absence of woodland amphibian species and most of our sites were small enough that they fit only one point count station, sites tended to score 100 for that third of the IBI, leading to IBI distributions clustered toward the high end of the range of possible scores. Density plots of anuran IBI, divided by bay and time period, show no clear patterns of difference between treated and untreated sites before or after treatment (Figure 3.8).

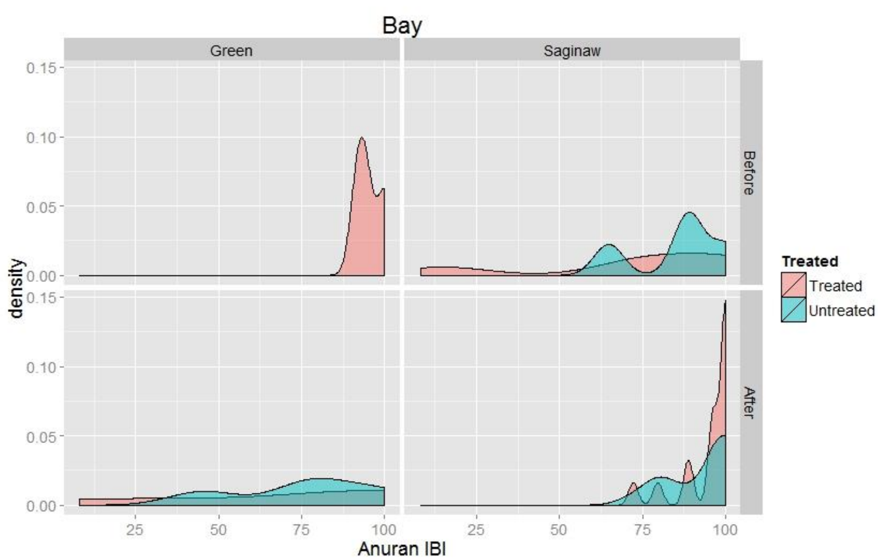


Figure 3.8: Density curves of calculated Anuran IBI values for the surveyed sites in Saginaw and Green Bays.

Because the calculated anuran IBI scores showed limited variation among sites, we also analyzed relative species diversity (number of species present divided by the number of species possible for that location). Looked at this way, we see a broader range of anuran community conditions across sites, though the limited number of possible values results in density plots with distinct peaks (Figure 3.9).

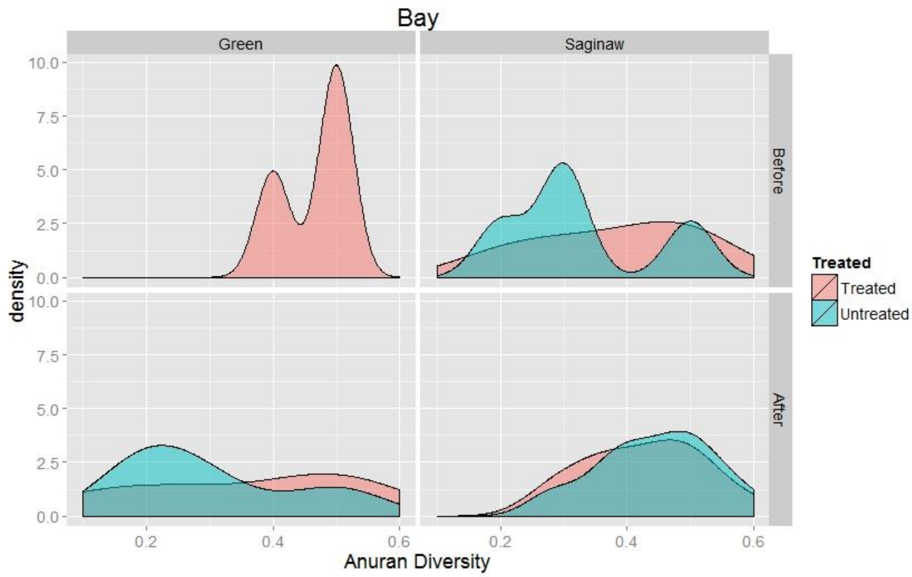


Figure 3.9: Density curves of calculated anuran species diversity values for the surveyed sites in Saginaw and Green Bays.

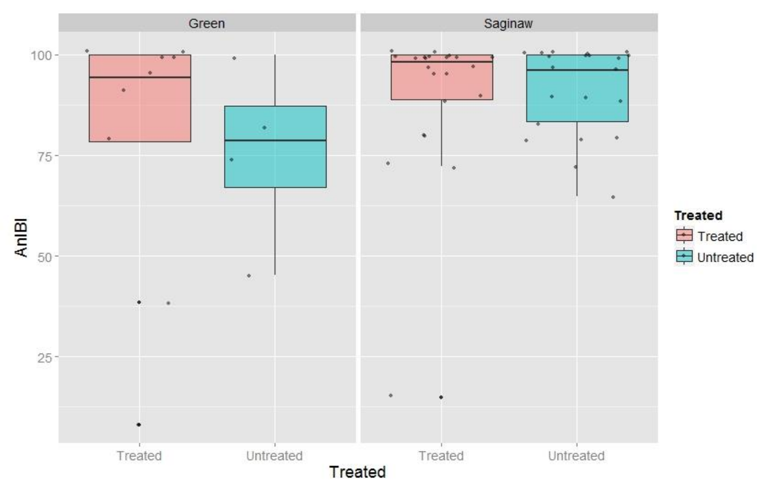


Figure 3.10: Anuran IBI values by treatment class in Green and Saginaw Bays.

The results of the spatial-matched pairs analysis of post-treatment data from paired control and treated sites indicated no significant differences in either anuran IBI or anuran relative diversity between control and treated sites ($p > 0.05$), regardless of whether a stressor gradient was included as a covariate, whether treatment was stratified by treatment type, or whether all pairs were considered together or separated by bay (Figure 3.10). For four of the pairs in Saginaw Bay and one pair in Green Bay, both sites in the pair scored IBIs of 100. An additional pair in Saginaw Bay both scored 96.2. Of the pairs that differed, the treated site scored higher in 4 pairs and the control site in 3 pairs. All three mowed sites scored IBIs of 100, but all three of their paired control sites also scored 100. The mean difference between pairs was smaller in Saginaw Bay (mean difference = 3.5) than in Green Bay (33.9), but there was a large amount of variation in the magnitude and direction of the difference for the Green

Bay pairs. This might suggest that Green Bay pairs were not as similar as Saginaw Bay pairs, which would not be surprising, as the amount of untreated wetland along western Green Bay was very limited, which in turn limited options for potential control sites.

Similarly, no differences in relative anuran diversity were observed between control and treated sites regardless of whether a stressor gradient was included as a covariate, whether treatment was stratified by treatment type, or whether all pairs were considered together or separated by bay (Figure 3.11). For this variable, only two pairs in Saginaw Bay and one site in Green Bay scored identically. Of the remaining sites, the treated site scored higher in four pairs and the control site scored higher in six pairs. Pairs differed in diversity by only one species, except for one pair in Green Bay, which differed by two species.

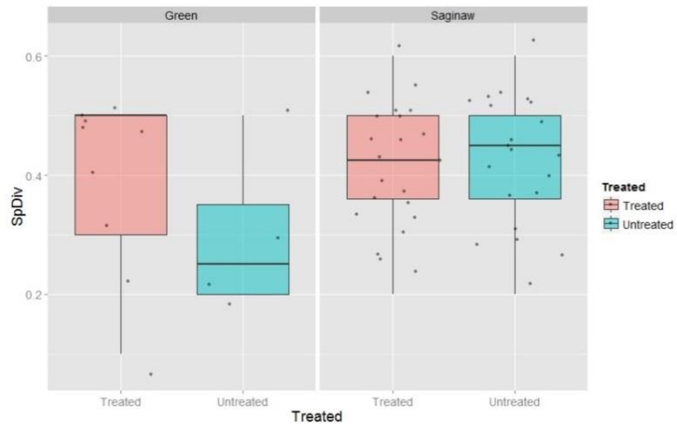


Figure 3.11: Anuran species diversity by treatment class in Green and Saginaw

Overall, across both treated and control post-treatment sites, both anuran IBI and relative species diversity tended to decrease with increasing cover of *Phragmites* as well as increasing cover of all invasive plants, but these correlations were not statistically significant. Finally, at the species level, It has been suggested that in the Great Lakes, spring peepers may provide a geographically consistent environmental signal over a wide range of stresses and can serve as an indicator of wetland health (Knutson et al., 1999; Price et al., 2007). Comparing the spring peeper abundance to percent *Phragmites* cover for our sites in 2014 and 2015, sites where spring peepers were present had a lower mean percent *Phragmites* cover, but this difference was very slight (14.0 vs. 16.5%), and in fact, the two sites with the highest percentages of live *Phragmites* cover also had abundant spring peepers, indicating that this species does not respond strongly to *Phragmites* invasion.

Moving to treated sites where baseline data collected before treatment were available, one site in Green Bay and two sites in Saginaw Bay (points overlap in Figure 3.12) scored anuran IBIs of 100 both before and after treatment. A third site in Saginaw Bay scored 80 before and after treatment. Of the remaining sites, IBI scores of two sites in Green Bay decreased following treatment and those of two in Saginaw Bay increased following treatment. Differences between pre- and post-treatment anuran IBIs were not significant in either bay ($p > 0.05$).

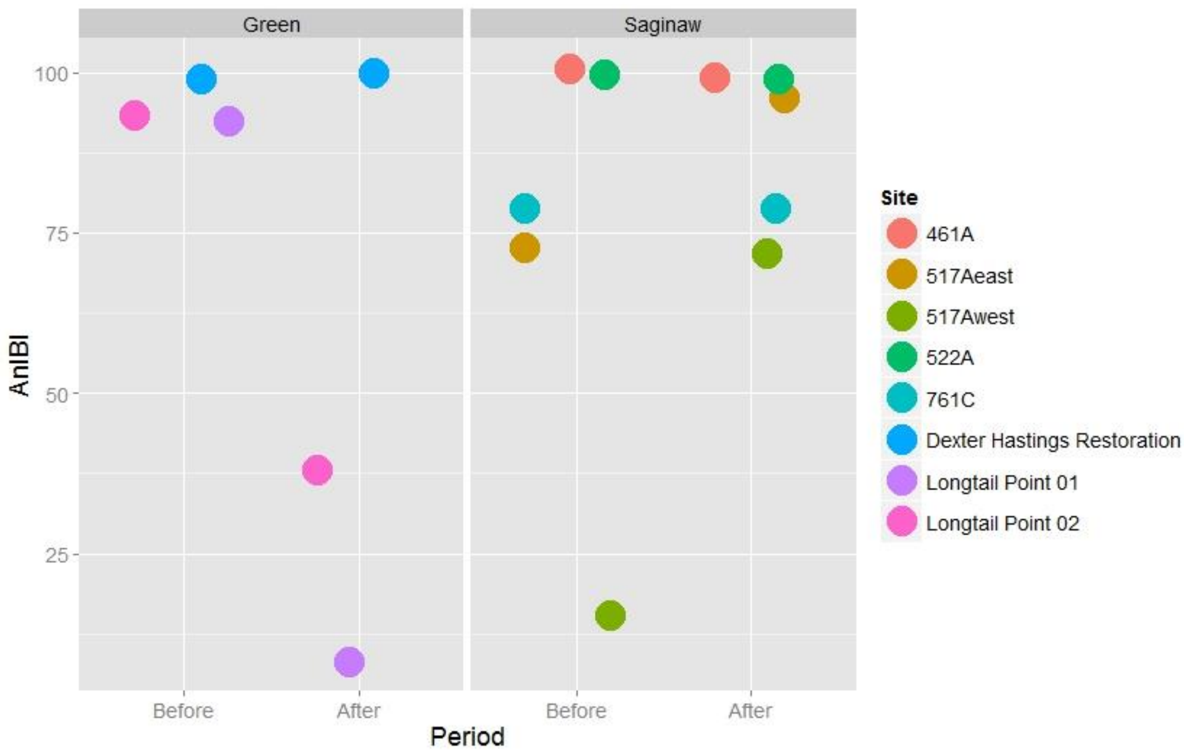


Figure 3.12: Anuran IBI values before and after *Phragmites* treatment at treated sites in Green and Saginaw Bays.

Looking at anuran relative species diversity, all sites varied over time, but still with differing patterns. In Green Bay, all three sites decreased in diversity following treatment, and in Saginaw Bay, three sites decreased and two increased. The two sites where diversity increased were both part of polygon 517 and were subjected to ground-based spraying with glyphosate/imazapyr with no follow-up mowing. The remaining sites, where diversity decreased, varied in the herbicide applied, mode of application, and mowing status (Figure 3.13). Across all sites, post-treatment species diversity was significantly lower than pre-treatment species diversity (paired t-test, $t = -6.1196$, $df=7$, $p < 0.001$).

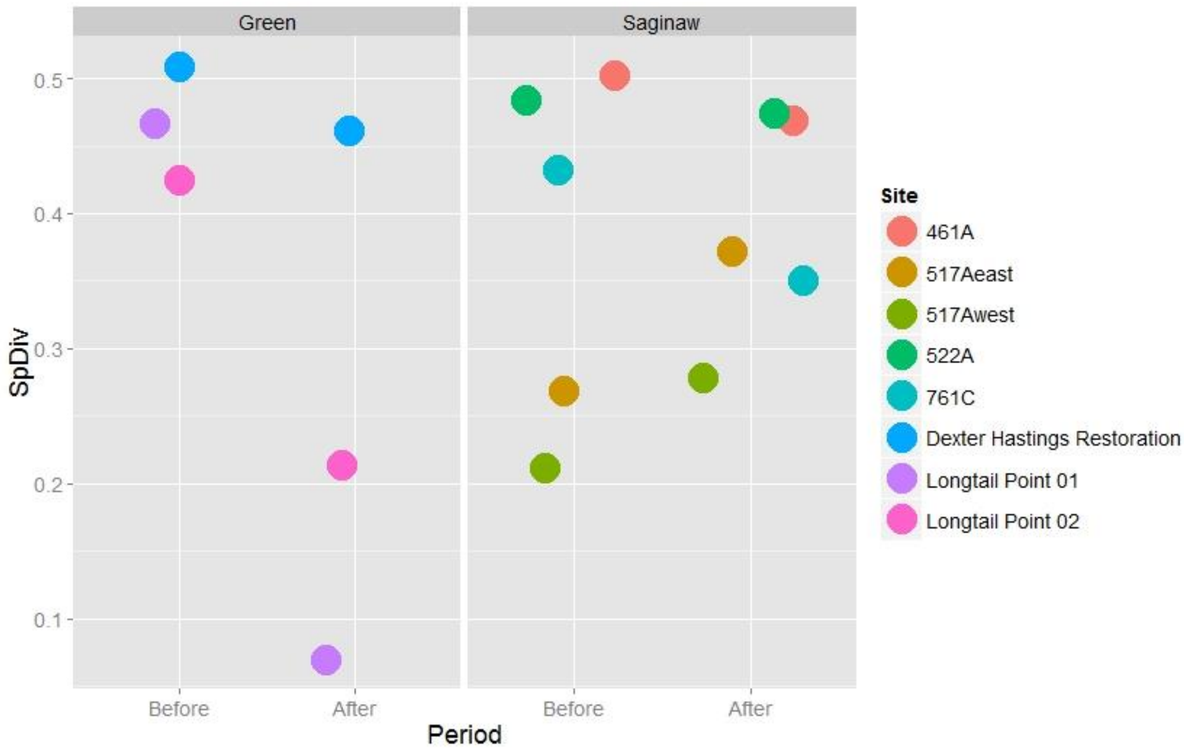


Figure 3.13: Anuran species diversity before and after treatment at treated sites in Green and Saginaw Bays.

Finally, complete anuran data (before and after treatment for a treated site and its paired control) were available for three pairs of sites, all in Saginaw Bay (Figure 3.14). Both the treated and control sites in pair 522 scored IBIs of 100 in all years. For pair 461, the IBI of the treated site remained 100 in all years and that of the control site varied by more than 30 from year to year. Finally, the IBI increased over time at the treated site in pair 517, while the IBI of its paired control varied with no clear trend. *Phragmites* cover at the treated site in pair 517 increased from 20 to 33% following treatment, possibly meaning that the increase in anuran IBI was not the result of successful *Phragmites* treatment.

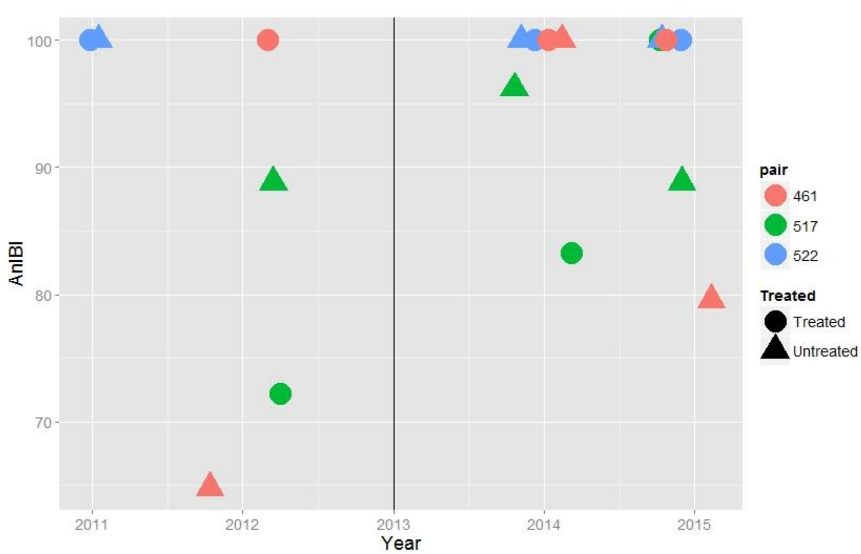


Figure 3.14: Anuran IBIs for full treatment pairs

The results for relative species diversity show a rather different pattern (Figure 3.15). Before treatment, pairs 522 and 517 had very similar diversity, and for pair 461, diversity was much higher at the treated site. Following treatment, diversity increased at the treated site relative to the control for pairs 522 and 517. The gap narrowed for pair 461, but due to an increase in diversity at the control site, not a large change in the anuran assemblage at the treated site (the only treated site of the three to be mowed).

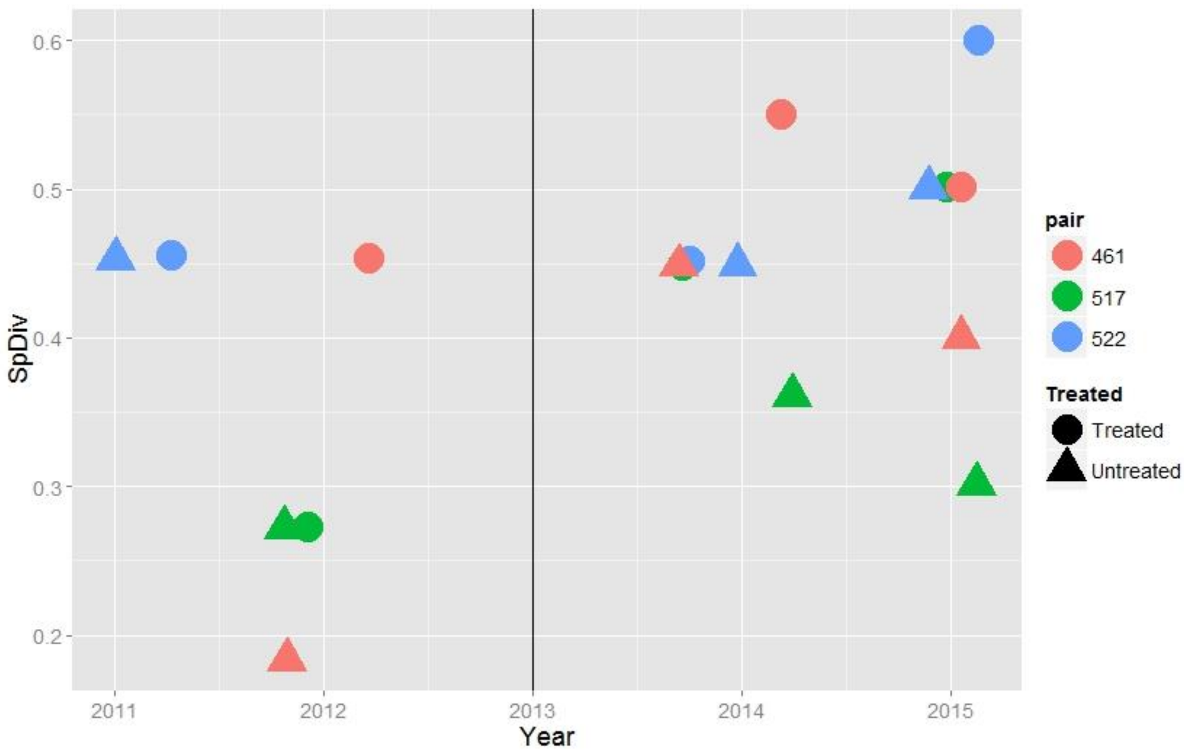


Figure 3.15: Anuran species diversity for full treatment pairs

The results of comparing the 2015 Saginaw Bay data gained both by in person surveys and recordings showed that in-person call surveys tended to pick up additional species that were inaudible in the recordings. Across the 18 stations in Saginaw Bay where both in-person and recorder-based frog/toad surveys were conducted, the average species richness was 4.67 species based on in-person records versus 3.61 species based on the digital recordings. Species richness was the same for both methods at 4 stations, was higher in the in-person data at 10 stations, and was higher in the recorder data at 4 stations. The species most frequently inaudible in recordings but present in point count data were Northern Leopard Frogs and Wood Frogs (5 stations each). Western Chorus Frogs and Green Frogs were also “missed” multiple times by the recorders. At higher wind speeds, the sound of dry Phragmites stalks brushing against each other was prominent in the recordings and made it difficult to hear calls at many stations.

On the other hand, the only Bullfrog call documented for the Saginaw Bay stations in 2015 was picked up by a recorder, and the recorders picked up species that were not heard during point counts at 8 out of 18 stations. The species present in the digital recordings but not the point count lists were most frequently American Toad (3 stations) and Western Chorus Frog (4 stations).

Overall, *Phragmites* treatment has not appeared to have a significant positive or negative impact on anuran community condition in Green Bay or Saginaw Bay.

iii) Bird Diversity

Density plots of bird IBI, separated by bay and time period, do not reveal any obvious patterns (Figure 3.16).

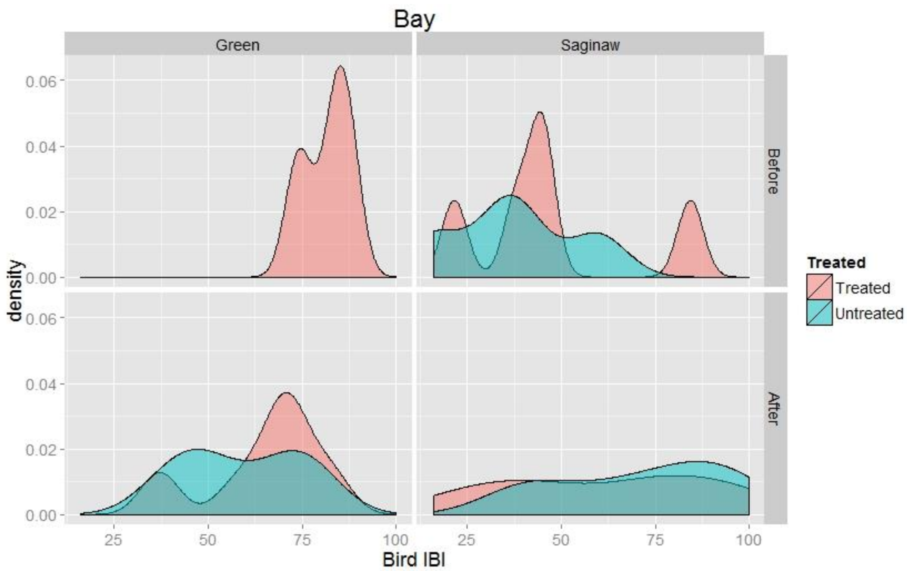


Figure 3.16: Density plot of calculated bird IBIs before and after treatment in Saginaw and Green Bays.

Analyzing just the post-treatment data (spatial-matched pairs design), paired treated and control sites did not differ significantly in bird IBI values, regardless of whether a stressor gradient was included as a covariate, whether treatment was stratified by treatment type, or whether all pairs were considered together or separated by bay ($p>0.05$) (Figure 3.17).

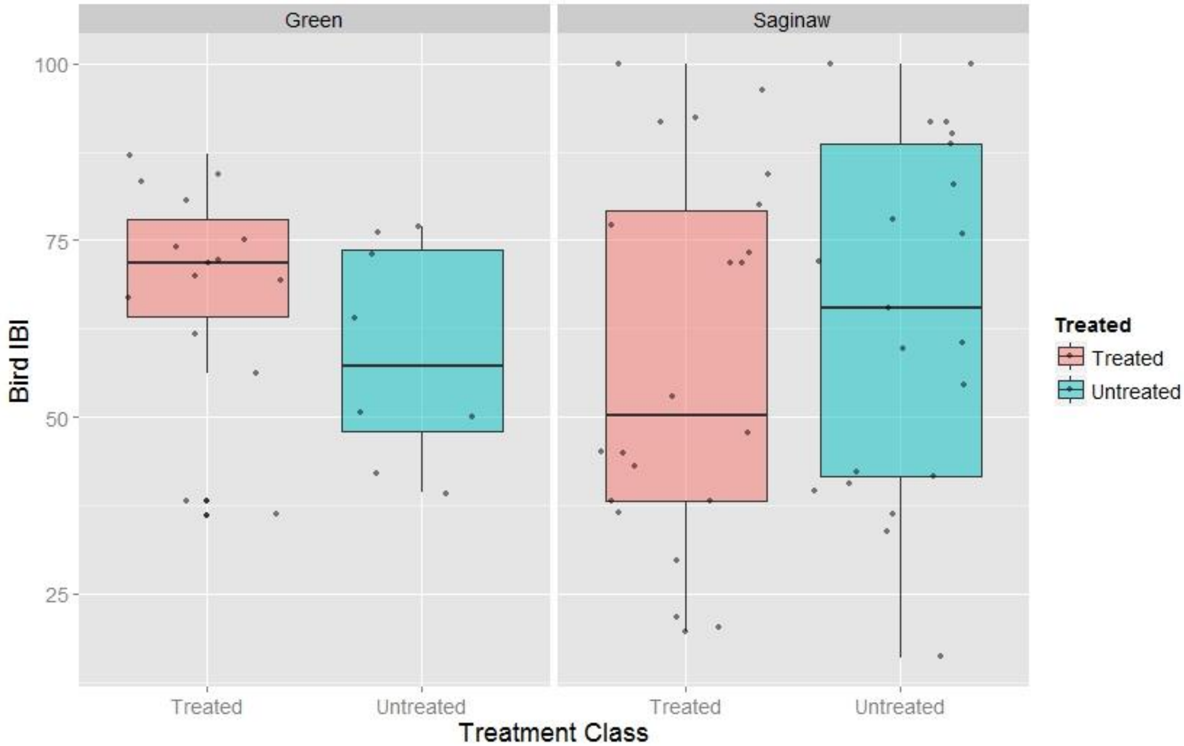


Figure 3.17: Post-treatment bird IBIs by treatment class in Green and Saginaw Bays.

One significant pattern that was noted was that treated sites that had been mowed were associated with significantly lower bird IBI values than untreated sites and near-significantly lower than treated, unmowed sites (one-way ANOVA, $F = 3.78$, $df = 2$, $p = 0.03$; pairwise t-test, $p=0.049$ and $p=0.062$, respectively with Bonferroni correction) (Figure 3.18). Thus, the major change in vegetation structure caused by mowing negatively affects marsh bird species in a way that herbicide treatment of *Phragmites* and leaving the dead stalks standing does not.

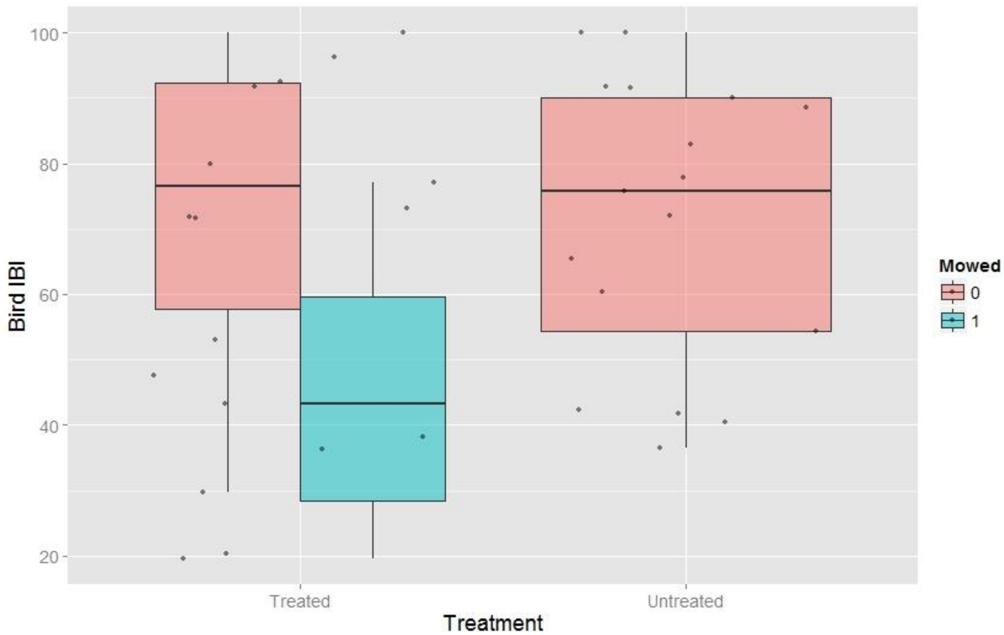


Figure 3.18: Post-treatment bird IBIs of survey sites by treatment class and mowing presence/absence; Mowed status: 0 = unmowed, 1 = mowed.

For all treated sites with pre-treatment bird survey data (8 sites), bird species diversity values before treatment and after treatment (2014 and 2015) were compared using a one-way ANOVA. Bird IBI values did not vary significantly among time periods, though there was a non-significant increasing trend in Saginaw Bay (F=1.02, df=2, p>0.05) (Figure 3.19).

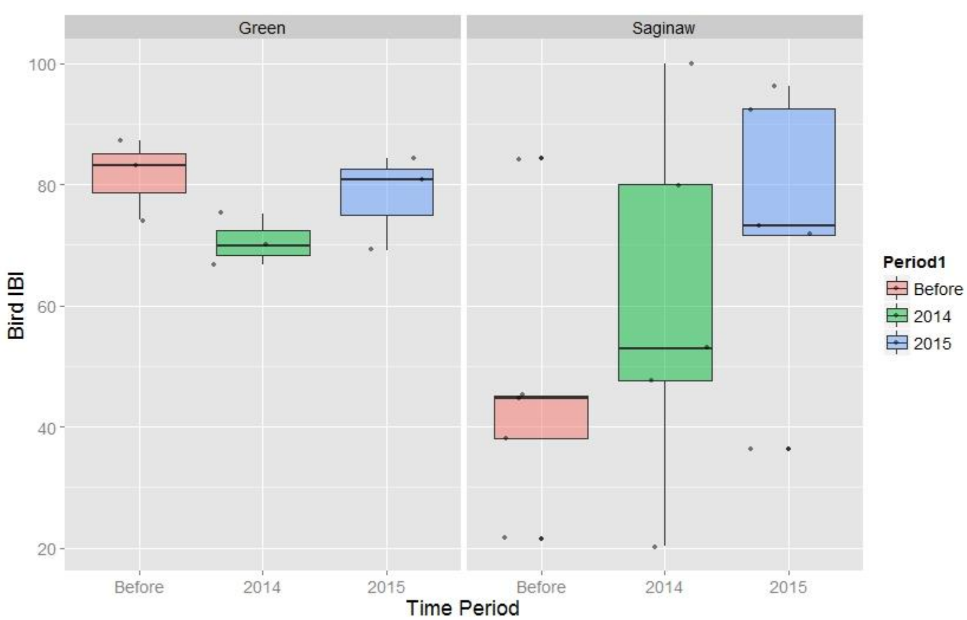


Figure 3.19: Bird IBIs at treated sites before and after treatment in Green and Saginaw Bays.

Finally, for the three pairs of sites (all in Saginaw Bay) with pre-treatment data for both sites in the pair, the change in bird IBI over time was compared between treated and control sites. The significance of the treatment effect was estimated by two-factor mixed-effect ANOVA. Because all three sites exhibited different patterns, there was no significant mean effect across sites (Figure 3.20). Both sites 517 and 461 (which was mowed) had similar IBI values to their paired control sites pre-treatment, and IBIs at both treated sites increased following treatment, but the treated site in pair 517 increased much more than the control, whereas the treated site in 461 increased less than its control. Within pair 522, the treated site's IBI was initially >20 greater than the control site's, but the pattern flipped after treatment. Across sites, both treated and untreated site IBIs increased similarly over time.

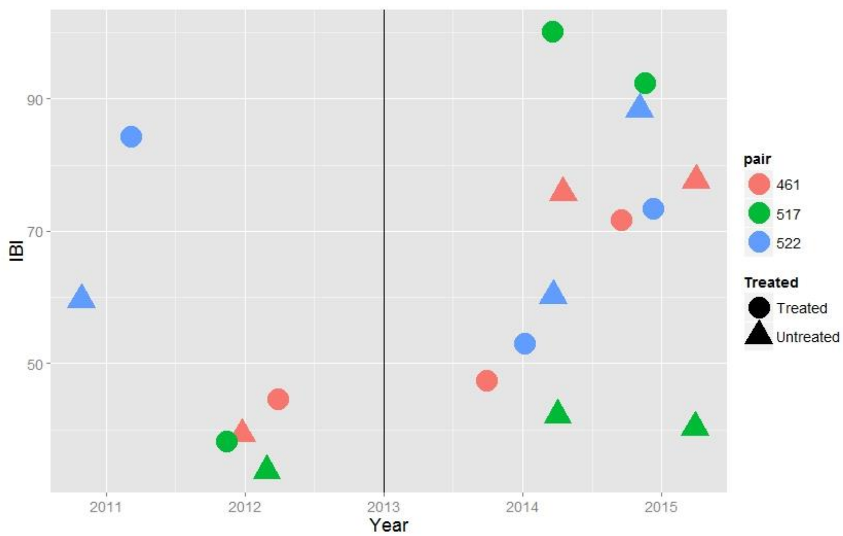


Figure 3.20: Bird IBIs for site pairs with multi-year pre- and post-treatment data in Saginaw Bay.

iv) Vegetation Diversity

To evaluate changes in vegetation condition, we calculated the GLCWC's IBI for vegetation, which relies on the frequency and cover of invasive species and the mean conservatism scores in each plant zone (Figure 3.21). Selected metrics used in the calculation of the vegetation IBI, native species richness (Figure 3.22) and "C" (C = mean native coefficient of conservatism) (Figure 3.23), were also analyzed to look more specifically at changes in native richness and the conservatism of a site's vegetation species assemblage. A higher mean native C indicates that the species present are less tolerant of disturbance and more restricted to high-quality natural areas, making mean native C a useful measure of habitat quality. Looking at these alternative metrics is also useful because the vegetation IBI cannot be calculated when a vegetation zone is missing at a site, which occurs several times in our dataset, leaving a smaller sample size when analyzing vegetation IBI.

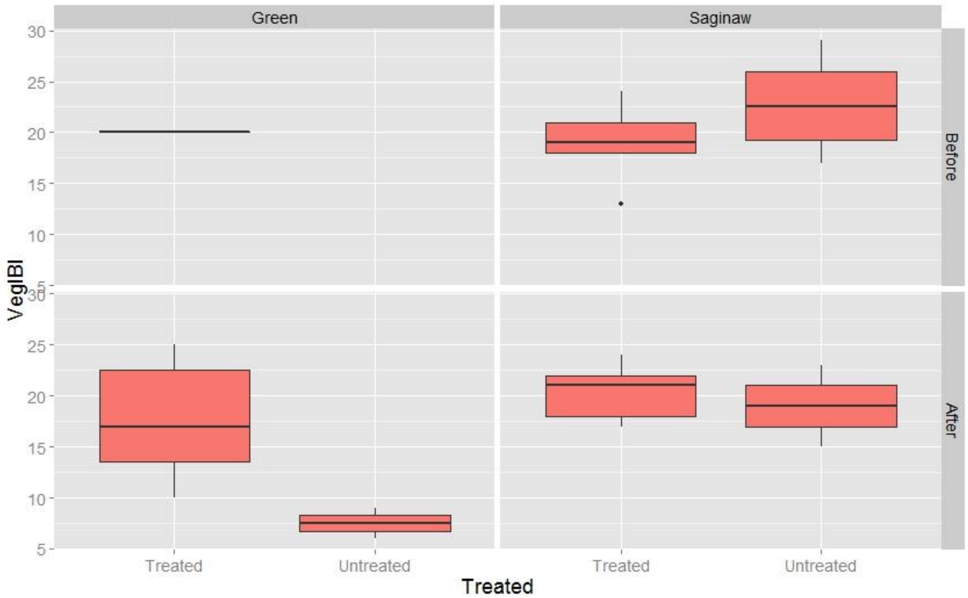


Figure 3.21: Box plots summarizing vegetation IBIs before and after treatment in Green and Saginaw Bays.

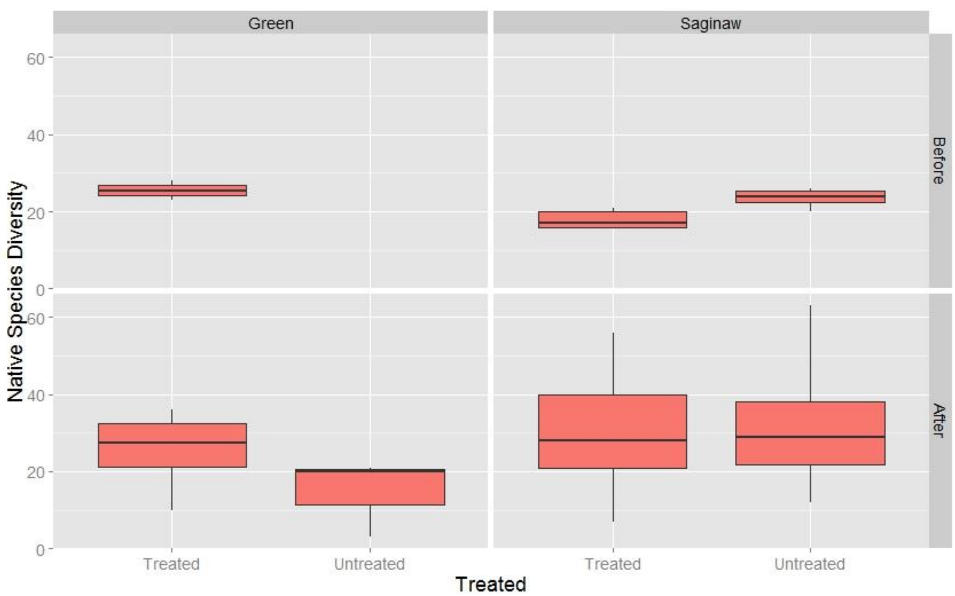


Figure 3.22: Box plots summarizing native macrophyte species diversity before and after treatment in Green and Saginaw Bays.

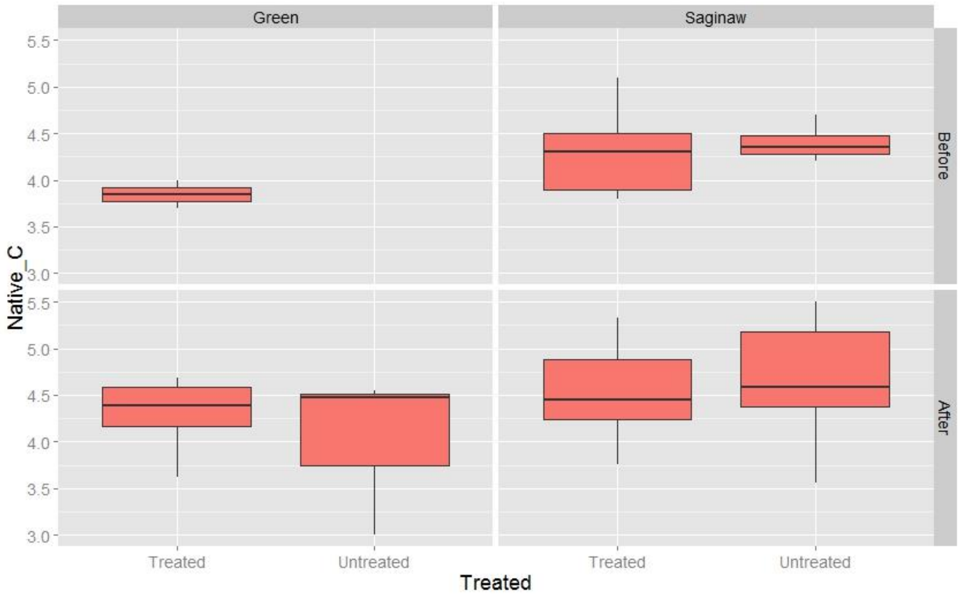


Figure 3.23: Box plots summarizing the mean conservatism coefficient of native species before and after treatment in Green and Saginaw Bays.

(a)Spatial-matched pairs

Post-treatment vegetation IBI varied significantly between bays (ANOVA, F = 8.56, df = 1, P = 0.005) and there was a significant interaction between the bay and site class factors (F = 11.46, df = 1, P = 0.001). Pairwise comparisons determined that treated and untreated sites were significantly different in Green Bay (p = 0.042) but not for Saginaw Bay (p = 0.13) (Figure 3.24).

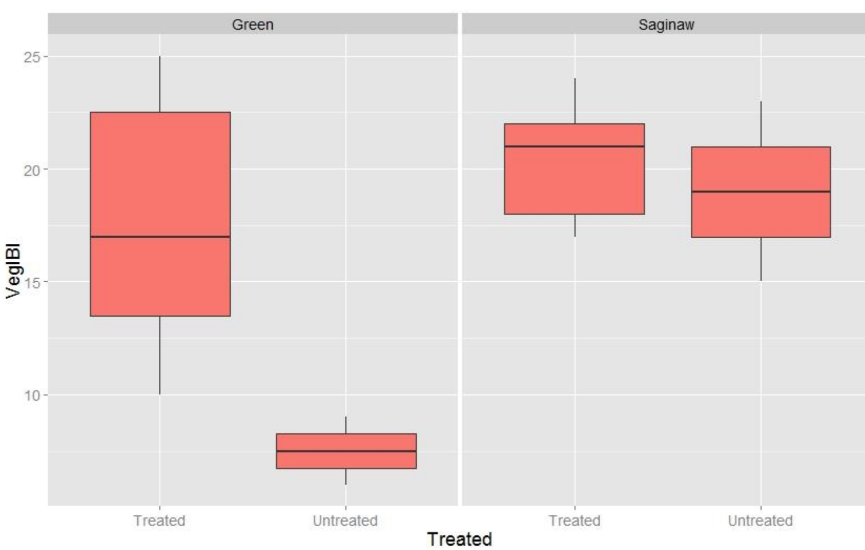


Figure 3.24: Vegetation IBIs in treated and untreated coastal wetlands of Green and Saginaw Bays during the post-treatment period.

In contrast, ANOVA identified no significant differences between bays or site classes for native vegetation diversity, and mean native C differed only between bays (significantly higher in Saginaw Bay, F = 6.0, df = 1, p = 0.017).

(b)Temporal baseline

For treated sites where vegetation surveys were conducted pre- and post-treatment, no differences were found between bays or periods for vegetation IBI or mean native C. Native species diversity was significantly higher after treatment than before treatment in both bays (Figure 3.25).

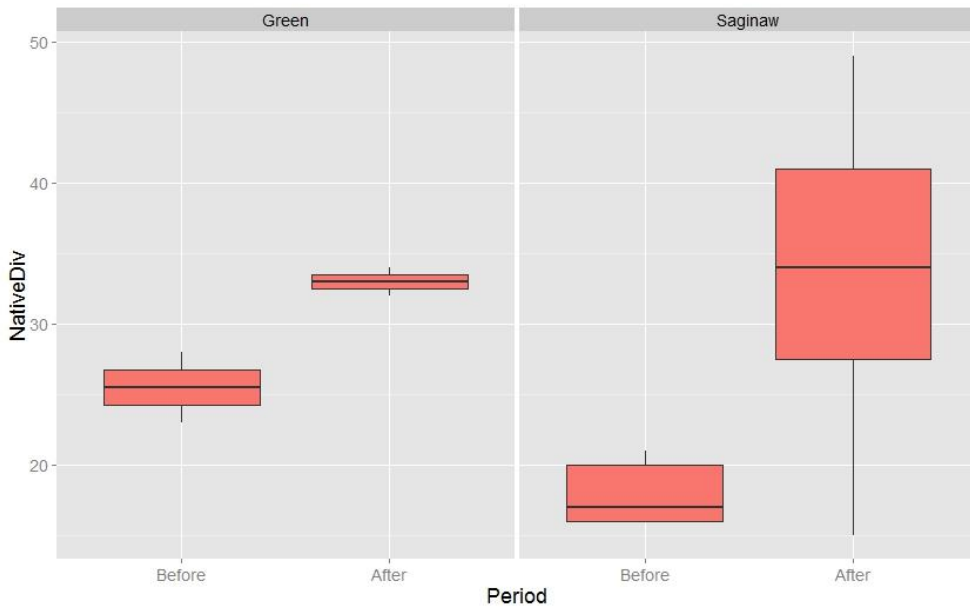


Figure 3.25: Native vegetation diversity in coastal wetlands of Green and Saginaw Bays treated for *Phragmites* invasion before and after treatment.

(c) BACI analysis

Because there were only two pairs of sites with complete data available for a BACI analysis and their patterns of change differed, the treatment effect was not statistically significant (Figure 3.26). For pair 522, the treated and control sites had similar vegetation IBI values across all years. For pair 461, both sites varied more from year to year than before vs. after treatment.

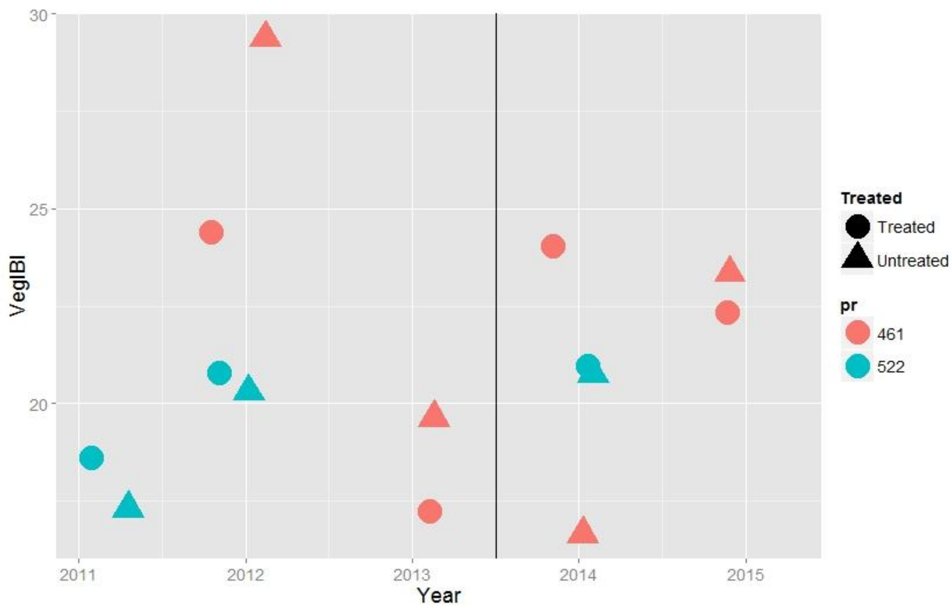


Figure 3.26: Change in native vegetation IBI over time in two treated/untreated pairs of AOIs in Saginaw Bay. Pairs are different colors; treated sites are represented with circles and untreated sites with triangles.

3c) Overview of remote sensing monitoring methods and results.

i) Review of remote sensing results

Aerial and satellite imagery can be very effective tools in mapping the extent of *Phragmites* invasion, identifying areas of standing dead and fallen stems, locating the leading edges, and mapping other vegetation and wetland cover. The resolution and data sources must fit the needs of the resource managers and researchers (Table 3.3). Monitoring methods need to be developed specifically for assessing treatment effects. Four different maps with varying resolutions were created to help determine the different uses in managing *Phragmites*.

Table 3.3. Comparison of Benefits/Limitations of Remote Sensing at various scales. Note that some Worldview-2 imagery is submeter, but 2m data were assessed for this report.

Source	Resolution	MMU	Capture Leading edges?	Cost of Imagery (High-Low)	Timeliness/ Limitations
Aerial Imaging	15 cm	15 cm	All	Medium	High
World-view 2	1.85 m	2 m	many	Free for Federal Agencies through NextView contract with Digital Globe	Cloud cover and satellite orbits
Rapid Eye/ Radarsat-2	5-8 m	0.05 ha	many	High	Cloud cover and satellite orbits
Landsat/ PALSAR-2	10-30 m	0.12 Ha	some	Landsat-free; PALSAR-2 (high)	Cloud cover for Landsat and satellite orbits/collection plans for both

(a) Landsat /PALSAR-2 Classification

Image fusion of multiple data sources allows an increase in spatial resolution and classification accuracy by gaining additional spectral information. Optical data (Landsat 8) are useful in differentiating features at the cellular level (e.g. chlorophyll, leaf moisture) as well as variations in surface or background reflectance (e.g. soil type, water). SAR data (PALSAR-2) are useful in differentiating wetland species based on inundation/water level patterns, vertical structure, and biomass. PALSAR-2 is an L-band (~24cm wavelength) SAR sensor which is able to penetrate the vegetation canopy and cloud cover. Multi season data also improves accuracy and helps in understanding phenological variations and water level cycles (Figure 3.27).

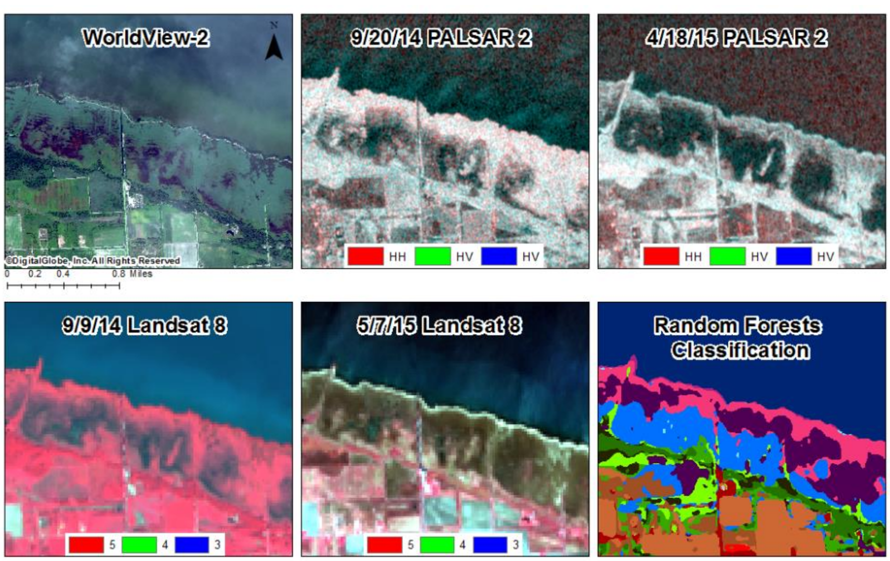


Figure 3.27. Multi-temporal and multi-sensor comparison of coastal Saginaw Bay, Michigan.

Random Forests was used to make the classification maps. Random Forests is a machine learning algorithm that uses a collection of decision trees that are grown from a random selection of user-supplied training data (field data and aerial image interpretation). Once the forest of decision trees is created, an individual pixel's classification is determined by which class receives the most "votes" from each decision tree. Random Forests generally produces higher classification accuracies than a single classifier and it is able to handle datasets with a small number of observations and a large number of attributes (Figure 3.28).

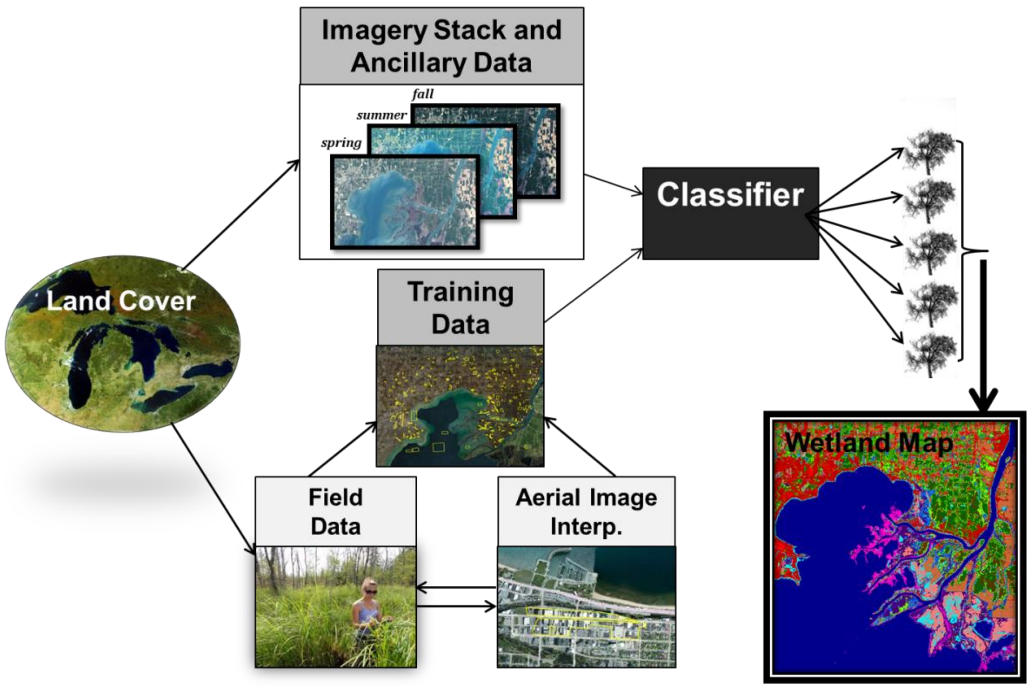


Figure 3.28. Schematic showing the mapping methodology from field data, aerial image interpretation, and imagery to classified map.

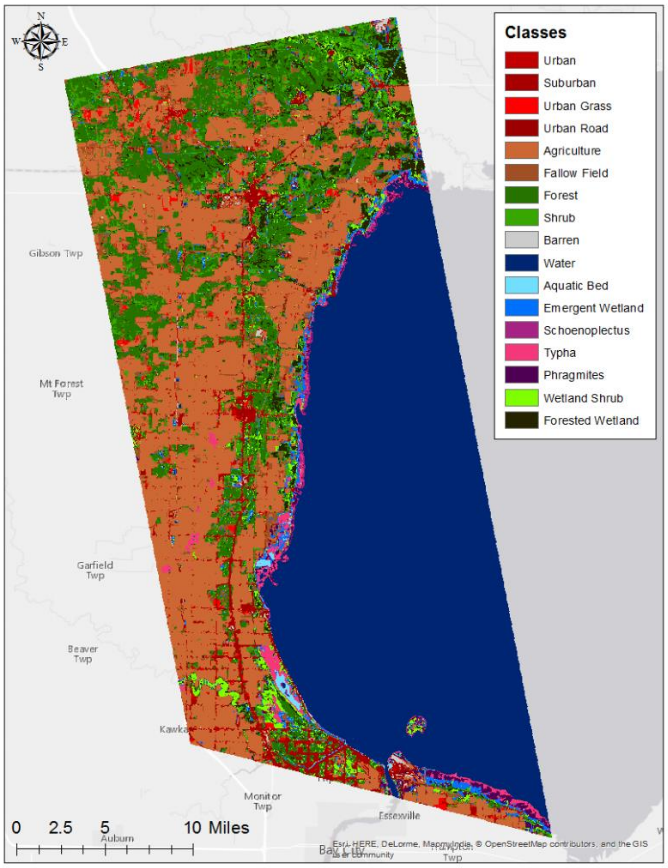


Figure 3.29. Landsat 8/PALSAR-2 moderate resolution classification of western Saginaw Bay.

Moderate resolution maps, such as the Landsat/PALSAR-2 map, are useful to detect larger stands of *Phragmites* (>0.12 Ha) over larger regional areas but some leading edges and isolated stands will be missed (Figure 3.29). While Landsat data are free, PALSAR-2 is expensive unless a data grant for research purposes has been awarded (http://www.eorc.jaxa.jp/ALOS/en/top/ra_top.htm), so cost is a factor to consider. Other limitations include cloud cover in Landsat and limited satellite orbits/collection paths.

(b) WorldView-2 Classification

WorldView-2 data has a panchromatic band and eight multispectral bands including: coastal, blue, green, yellow, red, red edge, near infrared (IR), and a second near IR band (IR2). A Random Forests classification was performed on a WorldView-2 scene from July 26, 2015. The high resolution classification of WorldView-2 will capture most leading edges and small isolated stands. WorldView-2 has a minimum mapping unit of 2 m which is much smaller than the 0.12 Ha of the Landsat/PALSAR-2 classification (Figure 3.30). WorldView-2 data has an average revisit time of 1.1 days, but availability can be limited by cloud cover. There may also be limited accessibility to WorldView-2 as it is only free for Federal Agencies.

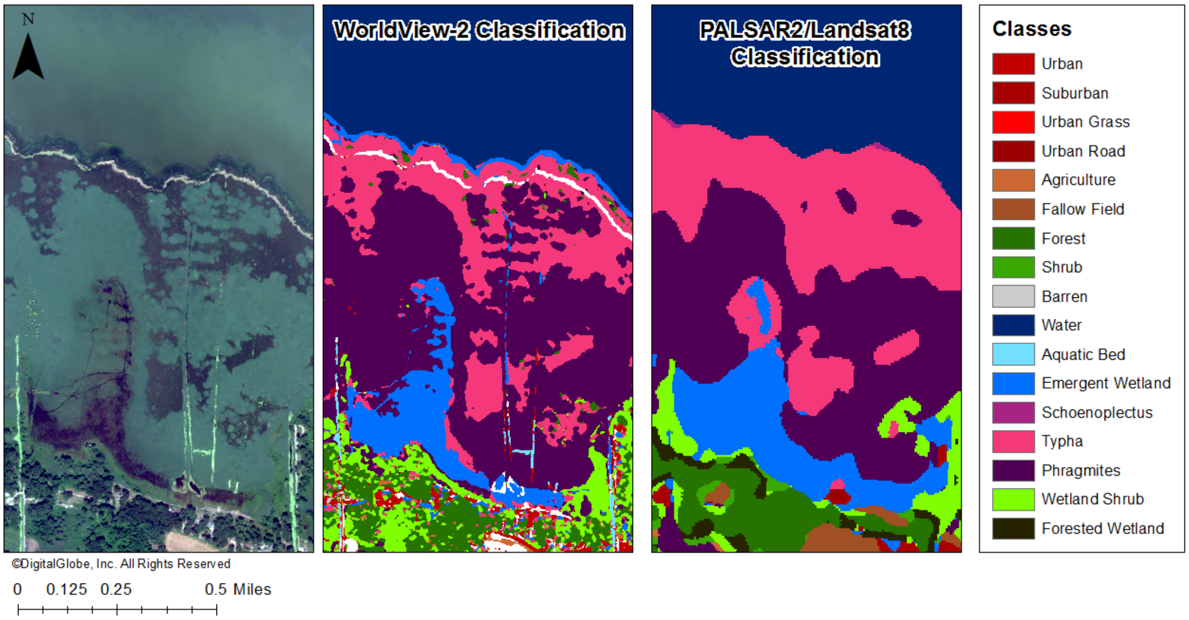


Figure 3.30. Comparison of WorldView-2 real color composite (left) to WorldView-2 classification (center) and Landsat /PALSAR-2 classification (right) of Saginaw Bay.

(c) Aerial Imagery Classification

AES collected aerial imagery in the July and September of 2014 with a resolution of 15 cm. In addition, AES incorporated NAIP images in the imagery classification for accuracy increment. Along with those image layers, a multi-temporal, object-based classification process using Random Forests was used to create high resolution maps of study areas in Saginaw Bay and Green Bay (Figure 3.31). To train Random Forest classifier we used sample/reference locations developed from field work, Google Earth, and oblique photos. This process relied heavily on the oblique images as they were acquired within days of the ortho photography, representing exact conditions (field to orthos) allowing the team to interpret and identify vegetation types and patterns over the landscape. These maps captured all the leading edges and small isolated stands with a minimum mapping unit of 15 cm. Multiple *Phragmites* map classes were included, such as dense *Phragmites*, mixed *Phragmites*, *Phragmites* detritus, and *Phragmites* dead stems. The level of invasion (density) as well as degree of regrowth in areas of post treatment is important in a successful site specific management plan. These maps are the highest resolution and provide the most detail on outliers, pathways, and sources of possible invasion as seen in Figure 3.32.

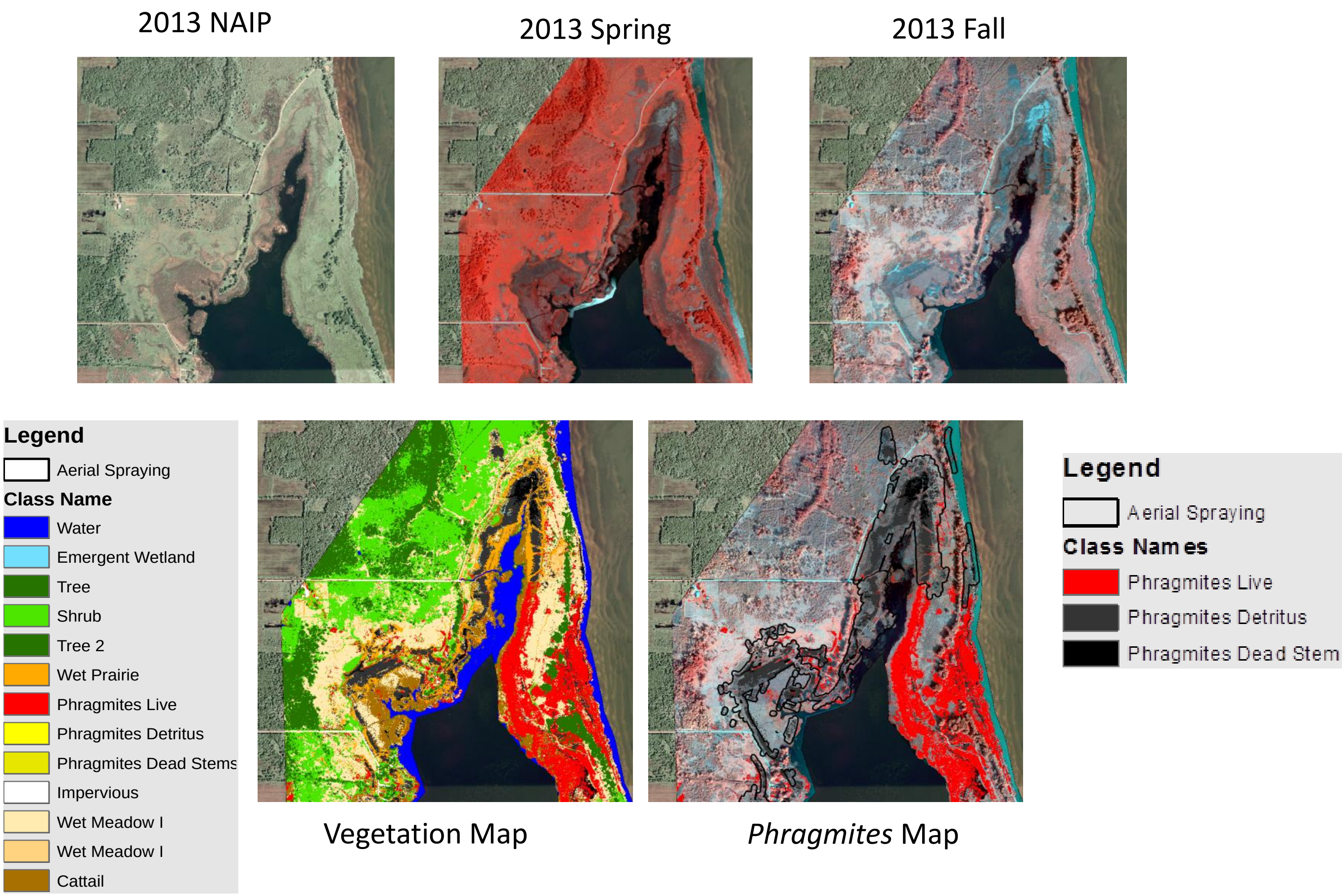


Figure 3.31. High resolution aerial image classification of a study site in Wisconsin with input data layers (top row) and output maps (bottom row).

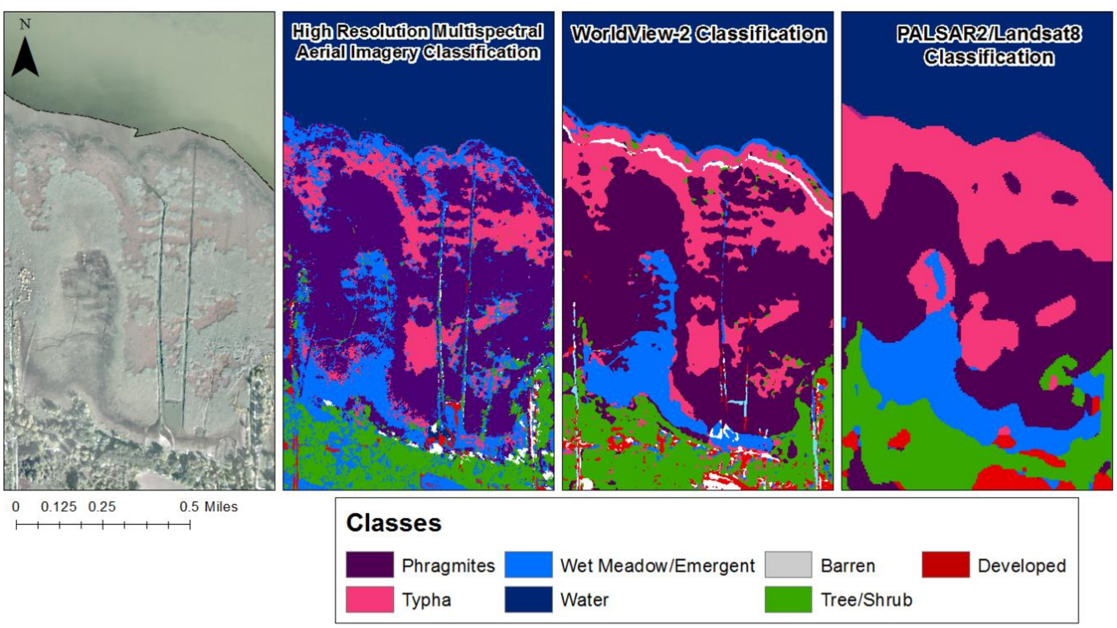


Figure 3.32. Comparison of Fall AES Aerial Imagery (left) to Aerial Imagery Classification (left center), WorldView-2 classification (right center) and Landsat /PALSAR-2 classification (right) of Saginaw Bay.

(d) Rapid Eye/Radarsat-2/LiDAR intensity/Landsat thermal Classification

In a previous study, Random Forests was used to create map identifying areas of living *Phragmites* and dead, treated *Phragmites* for Harsen's Island on the Lake St.Clair river delta. The map used multi-season, multi-sensor fusion of Radarsat-2 (7/17/2013, 9/3/2013, 9/27/2013, 5/25/2014, and 7/12/2014), RapidEye (9/8/2013), LiDAR intensity (3/22/2010-4/1/2010), and Landsat 8 thermal (5/26/2013, 7/13/2013, 9/8/2013). Radarsat-2 is a C-band SAR with a wavelength of ~5.6cm. RapidEye has resolution of 5m with five spectral bands including blue, green, red, red edge, and NIR. LiDAR data was collected by SEMCOG at a 2.5ft resolution and has been found useful in detecting inundation in leaf-off conditions. Landsat 8 thermal data (band 10 and 11) were collected at 100 meter resolution and resampled to a 30 meter product. The classified map had a total accuracy of 87.2% (Figure 3.33). The map identified most leading edges and successfully differentiated living *Phragmites* from treated *Phragmites*. Cost is a factor to consider as Radarsat-2 and RapidEye are expensive. Other limitations include satellite orbits and cloud cover in RapidEye and Landsat.

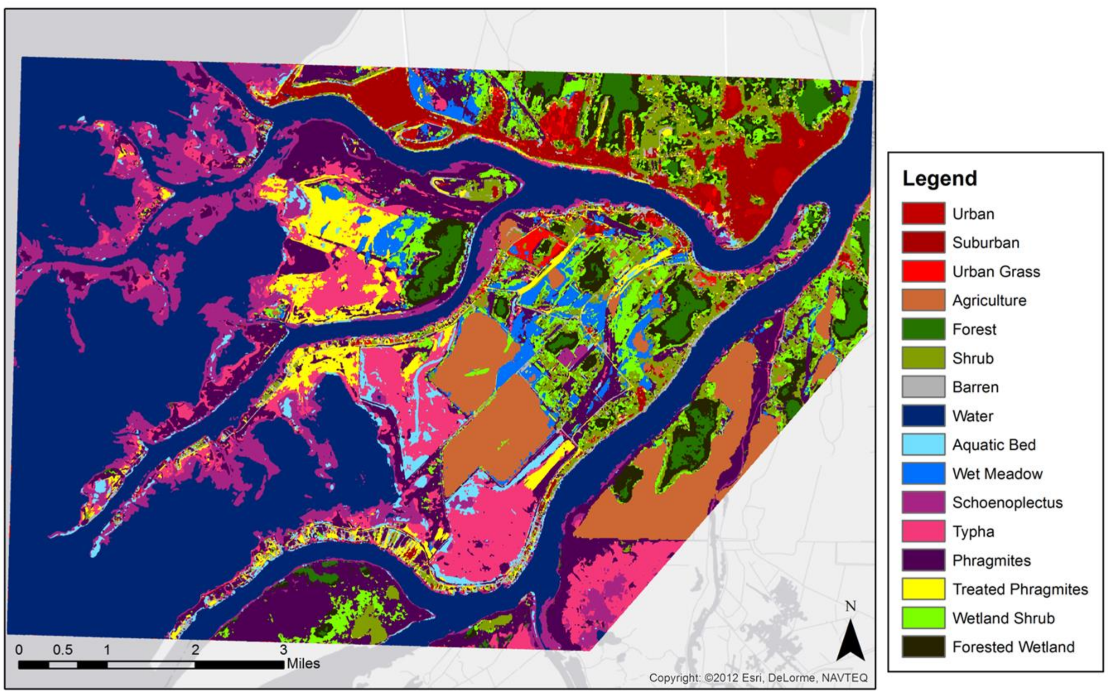


Figure 3.33. Classification of Harsen's Island identifying areas of *Phragmites* (purple) from treated *Phragmites* (yellow).

(e) Field data and map estimates of live Phragmites

Vegetation field data, collected in 2014 and 2015, were compared to remote sensing measurements of live *Phragmites* cover. For several treatment sites with map overlap, the % mean and max/min live *Phragmites* cover was estimated from field data and measured from the maps (Table 3.4). The field data consists of points representing 1m x 1m plots where vegetation stem density was recorded. The area of live *Phragmites* was also calculated within the treatment polygons for Landsat/PASLAR-2, WorldView-2 and the Aerial Imagery classification as available.

For site 518C, the field measurements vary significantly between years with a max percent of 15% in 2014 and 45% in 2015. The Aerial Imagery classification (2014) had the highest live *Phragmites* cover of 50%, followed by WorldView-2 (2015) at 19%, and then the Landsat/PALSAR-2 (2014-15) map at 7% (Figure 3.34). At site 517A, the mapping estimates were similar with the Aerial Imagery classification measuring 71% and WorldView-2 measuring 74% live *Phragmites* cover (Figure 3.35). The field measurements are much lower with a mean of 12-17% and a maximum percent cover of 30% in 2014 and 40% in 2015. For site 522A, there is very little live *Phragmites* present both in the field measurements (~1.2 to 1.5%) and the aerial imagery (5%) and this results in no live *Phragmites* detection in the coarser resolution mapping of Landsat/PALSAR-2 data (Table 3.4). These comparisons demonstrate the need for both field data collection to get species diversity and remote sensing monitoring to understand the distribution of living *Phragmites* invasion at site. The high resolution (15 cm) Aerial Imagery classification provides the best estimates of live *Phragmites* invasion and distribution across a site. For these maps (Figures 3.34 and 3.35) differences in the spatial resolution sometimes makes a big difference (Figure 3.34) and sometimes not (Figure 3.35, shows 15 cm and 2 m products only); this has to do with the density and distribution of live *Phragmites* at a site. The advantage of the 15 cm imagery is that it was able to capture not only the nearly pure stands of live *Phragmites* but also the "mixed" stands for an improved estimate of total live *Phragmites* cover at a site. In both cases (site 518C and 517A) using the mean of plot samples would greatly underestimate the percent live *Phragmites* cover and would not provide information on the distribution.

The moderate resolution maps (Landsat/PALSAR-2) underestimated live *Phragmites* cover as it missed small isolated stands and some leading edges (site 522A and 518B). The high resolution maps (Aerial Imagery and WorldView-2) typically measured more live *Phragmites* cover and were able to map areas with a lower density of living *Phragmites*. The WorldView-2 classification live *Phragmites* cover was similar to the Aerial Imagery classification for sites with dense *Phragmites* (517A) but it underestimated it in areas with more mixed *Phragmites* (site 518C). The moderate resolution map was unable to map *Phragmites* when it occurs in small, sparse stands (522A). The Aerial Imagery classification and field data measurements were similar for sites with small, mixed patches of *Phragmites* (522A). The WorldView-2 and Landsat/PALSAR-2 classifications only had one live *Phragmites* class (no mixed class) so this could account for some differences among the maps.

Table 3.4. Comparison of Field Statistics to remote sensing statistics for four field sites in Saginaw Bay.

		Field Sampled Estimates % Live *Phragmites* within treatment polygon				**Remote Sensing Estimates % Live *Phragmites* within treatment polygon**		
Site #	Treated Area Size (Acres)	2014 Mean % cover	2014 Max/min % cover	2015 Mean % cover	2015 Max/Min % cover	Aerial AES Multispectral 2014 (15 cm res)	Satellite WorldView-2 2015 (2 m res)	Satellite Landsat/ PALSAR 2014-2015 (30 m res)
499A	10.1	4.6%	22%/0%	1.5%	8%/0%	11%	NA	NA
522A	119.4	1.5%	10%/0%	1.2%	8%/0%	5%	NA	0%
518C	133.3	2.9%	15%/0%	13.7%	45%/0%	50%	19%	7%
517A	274.8	11.9%	30%/0%	16.6%	40%/5%	71%	74%	NA

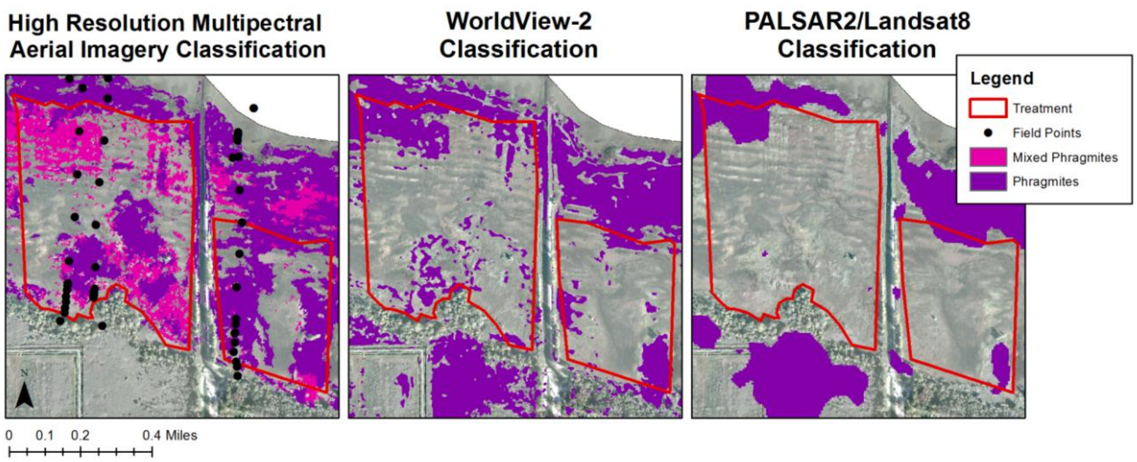


Figure 3.34. Maps of post-treatment live *Phragmites* distribution at site 518C, MDNR demonstration site treated in 2007-9. The Aerial image classification at 15 cm resolution shows the field points that were sampled in 2014 and 2015. Each point represents a 1m x 1 m plot.

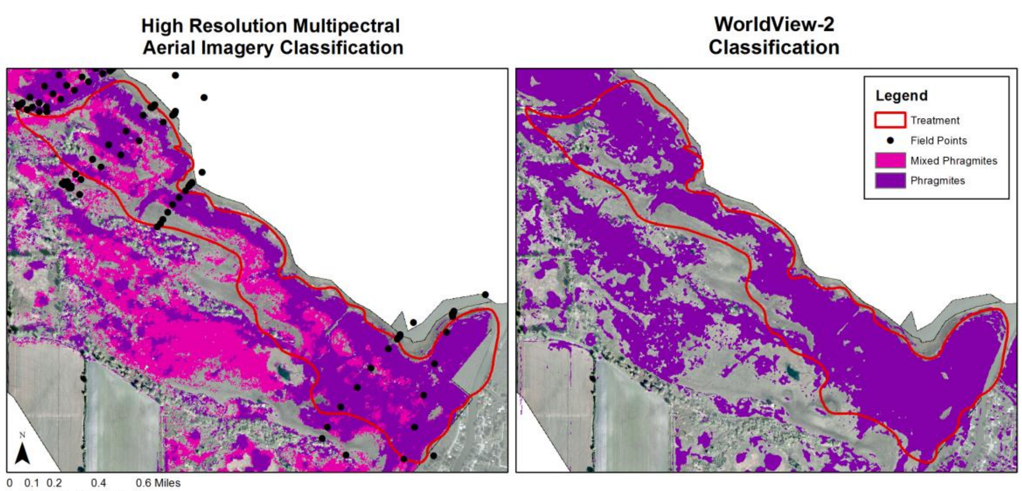


Figure 3.35. Maps of post-treatment live *Phragmites* distribution at site 517A, a site treated in 2012. The Aerial image classification at 15 cm resolution shows the field points that were sampled in 2014 and 2015. Each point represents a 1m x 1 m plot.

(f) Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAV; also unmanned aerial systems, UAS) can provide useful remote sensing data for mapping and monitoring ecosystems. Figure 3.36 shows examples from a paired set of study sites in Saginaw Bay (515A - untreated and 515B - treated). This type of rapid aerial imagery would usually require a manned aircraft to obtain. While manned aircraft have the advantage of being able to fly long distances to map and monitor multiple sites, small UAVs can be deployed quickly for at least local site characterization. These images were collected with a small DJI Phantom 2 Vision UAV that is currently available for about $600 (originally costing $1300 in 2013). Systems in the $600 to $1,000 range can fly with remote control and first-person viewer (FPV) capabilities in the 90 m to 760 range (approximately 300' to 2500') to help with local site imaging. Hobbyists can fly these devices now, within certain limits of the US Federal Aviation Administration (FAA) – below 122 meters (400'), not within five miles of airports unless explicit permission is granted by airport tower, within line-of-sight, and during daytime.

Figure 3.36: Images of Saginaw Bay untreated site 515A (left) and treated site 515B (right) showing how they can be useful for quickly understanding *Phragmites* extent and density at a location.

Commercial collection of UAV-based imagery is currently possible under the FAA's "Section 333" exemption program (https://www.faa.gov/uas/legislative_programs/section_333/) with the same rules as hobbyists, but requiring obtaining a commercial "333" exemption, including need for a licensed pilot. Companies working with agencies or groups that ask for UAV-based imagery should evaluate the Section 333 process. A newer set of FAA regulations for small UAV operations is due out in 2016 or 2017. Instead of requiring a pilot's license, the new proposed rules will only need a UAV operator's permit, which is projected to cost approximately $300. Public agencies typically operate UAVs under the older Certificate of Authorization (COA) process (see https://www.faa.gov/uas/public_operations/). Universities had typically operated under public agency COAs, but are now starting to get Section 333 permission to fly for a variety of purposes.

ii) Importance of Mapping in Management

Knowing the landscape context of where *Phragmites* stands are, including the leading edges and what is surrounding them, is a key input to an adaptive management strategy (Figure 3.37). Practitioners often emphasize early detection and treatment of outliers and prioritizing treatment in valued areas using well established techniques: however they often lack comprehensive distribution maps that clearly show outliers, pathways, and sources at a fine enough scale to be useful. This is a critical step to cost effective prioritization and successful long-term control.

Regular mapping updates are also necessary to successful management as the coastal zone is changing rapidly, particularly with efforts for control of *Phragmites* and in light of recent shifts in water levels from low to high in Lake Huron. Regular map updates can monitor treatment success and identify less successful areas needing additional treatment. Maps provide information on the level of invasion (density) as well as degree of regrowth of *Phragmites* in areas of past treatments.

Resolution is an important factor to consider as moderate resolution (~30m) maps do not provide enough detail on leading edges and small isolated stands. These maps are useful to detect large stands of *Phragmites* (>0.2 Ha) over regions but not ideal for adaptive management and monitoring at the site level. High resolution maps (~1m) are ideal for strategic planning of locations to treat and to determine the best treatment type. They can also identify small areas of *Phragmites* regrowth post treatment.

Cost is also important to consider, as well as the capability to map by the agency or group conducting the *Phragmites* management and control efforts. Satellite imagery can sometimes be obtained at little to no cost (e.g. Landsat is free, PALSAR-2 can be acquired free with a data grant, WorldView-2 is available to federal agencies through NextView at no cost, RapidEye data are ~$1.25/sq km with a minimum area) but requires knowledge of GIS/Remote Sensing to do the mapping. On the other hand, high spatial resolution aerial imagery costs a bit more but, the contractor collecting the imagery could also do the mapping (i.e. "one stop shopping"). Another benefit of using aerial imagery is that the timing of the collection can be set by the end user and flights below the clouds can be obtained. UAV-based imaging can help with some mapping and/or site evaluation needs. Cloud cover is a major impedance to timely collections by satellites (as well as the regular collection schedule). While cloud-cover is not an issue for the radar satellites (i.e. PALSAR-2) since it is such a long wavelength (~24 cm) it penetrates the clouds, the only factor restricting timely radar collections is the collection schedule for the sensor.

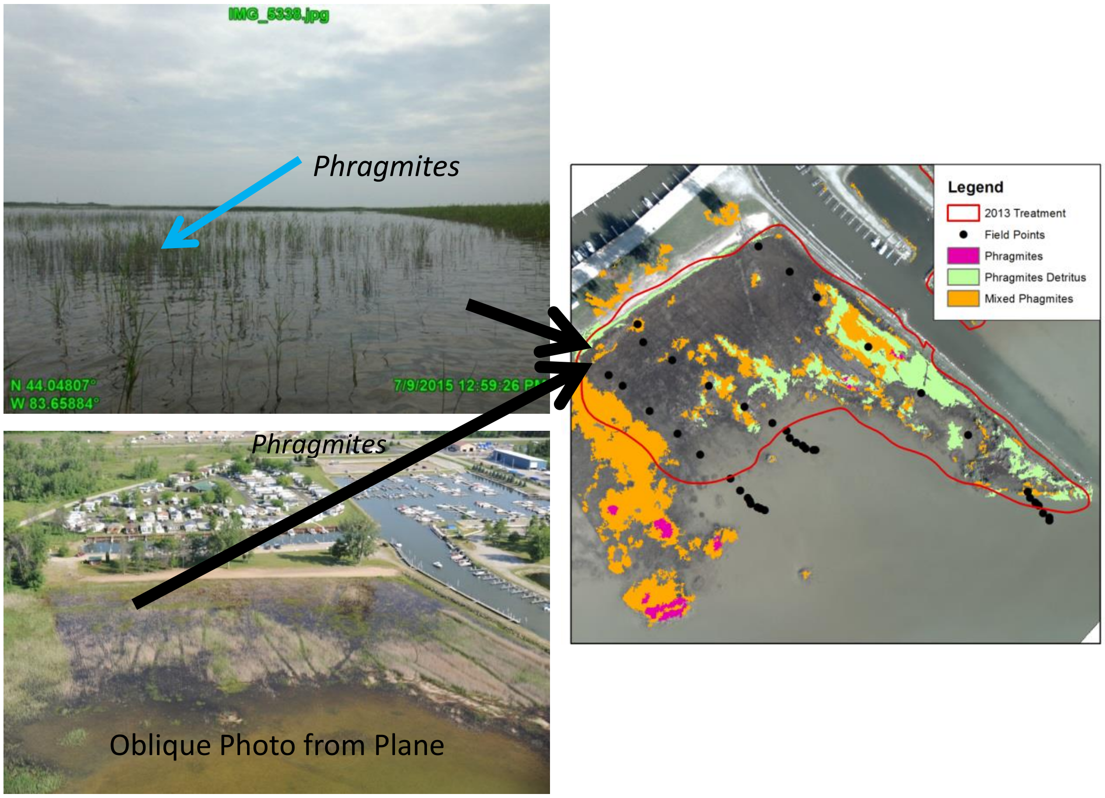


Figure 3.37: An example of how remote sensing results (from this project) can be integrated with field data to understand treatment sites, including identifying areas of *Phragmites* regrowth post-treatment.

4) Implications of Research for Adaptive Management

4a) *Phragmites*

In order to evaluate the effect of *Phragmites* management through the lens of adaptive management, a set of indicators needs to be established to measure and understand the success of the management efforts. Long-term monitoring, preferably beginning with pre-treatment measurements, documents the response of vegetation conditions and wildlife use to *Phragmites* treatment at the plot level to determine if the desired habitat conditions are obtained. Planning ahead to collect the data required for a BACI analysis or other statistical design to measure effect size provides a measure of the relative effect size of treatment and its statistical significance, which is important to understanding if treatment has had the desired effect. Monitoring also provides a quantitative measure of the effectiveness of treatment at reducing *Phragmites* cover itself as well as the “half-life” of treatments, as *Phragmites* tends to re-invade and often requires repeated control measures, especially without follow-up to initial chemical control. Finally, monitoring helps confirm that rare species are not adversely affected by treatments.

The vegetation survey revealed broad differences in the efficacy of *Phragmites* treatment between Green Bay and Saginaw Bay. While the pre-treatment data needed for BACI analysis was not available, both the spatial-matched pairs and temporal baseline results indicate that live *Phragmites* cover was reduced significantly by the 2011/2012 treatment activities along western Green Bay, compared to the condition of both untreated control sites and the treated sites themselves before herbicide application. By contrast, in Saginaw Bay, both analyses indicate that the patchwork of treatments applied to Saginaw Bay wetlands during the same period did not have a strong effect on the percent cover of live *Phragmites*. This suggests that the regional-scale, aerial spraying approach adopted in Green Bay was much more effective at controlling *Phragmites* than the property-scale management actions in Saginaw Bay.

Overall, year-to-year variations in estimated live *Phragmites* cover at a given site were sometimes large even in the absence of treatment. Change in *Phragmites* cover could likely be better monitored using a form of remote sensing-based mapping. Mapping *Phragmites* cover in this way also provides more complete information on where to target spot treatments. The poor success of the various one-time *Phragmites* control efforts in Saginaw Bay underlines the importance of these follow up spot treatments for successful, longer-term results. On the ground vegetation monitoring protocols used here did not optimize field time, because the submergent zone was included (where *Phragmites*, by definition, is not seen). Surveying vegetation in just the wet meadow and emergent plant zones would focus field efforts on the areas providing useful data for monitoring as part of a more streamlined more streamlined vegetation transect methods.

4b) Anurans

The impacts of *Phragmites* invasion on anurans are not yet clear. Multiple recent studies have identified a link between *Phragmites* cover and the probability of habitat desiccation (Mazerolle et al., 2014; Perez et al., 2013). However, Mazerolle et al. concluded that *Phragmites* invasion did not appear to be an important driver of population dynamics compared to the influence of the landscape matrix surrounding breeding wetlands. Similarly, the anuran data collected in Green Bay and Saginaw Bay between 2011 and 2015 revealed no strong impact of *Phragmites* invasion on anuran community condition. Herbicide treatment also appeared to have a neutral effect on species assemblages, despite the potential for direct effects of herbicide on anuran survival and reproduction (Helander et al., 2012). The coastal wetlands of Saginaw Bay and western Green Bay are moderately impacted by anthropogenic stressors (SumRel stressor gradient values ranging from 0.42 to 0.77), which likely accounts for the absence of rarer species (Pickerel Frog, Mink Frog, Fowler's Toad) from our dataset. This limits the possible range of variation among sites and makes the detection of differences more difficult. In a management context, anuran surveys could be used as a planning tool to identify the presence of rare amphibians and plan around their life cycle and habitat needs. At sites where anuran diversity is a management priority, aural surveys could be complemented by trapping to assess the use of the site by species at different life stage

The ability to capture additional species beyond those observed using the original field protocol indicates that acoustic sensors can be useful for producing more complete acoustical monitoring datasets and potentially for extending the spatial scope and temporal extent of monitoring programs. However, the differences between point count and recorder species lists for 2015 demonstrate that the device needs to be redesigned with the wet, windy, dense environment of Great Lakes wetlands in mind. Use of a microphone model with a lower noise floor and the development of more automated bioacoustical data processing methods for detecting calls within recordings would both contribute significantly to making recorders a useful tool for monitoring both anurans and marsh birds. Commercial recorders such as the FrogLogger (http://www.frogloggers.com/) and SongMeter (www.wildlifeacoustics.com), some of which include processing software, have been available for some time but are significantly more expensive than many DIY designs. Apart from data considerations, the development of standard Great Lakes wetland monitoring methods using automated recording devices is also desirable because it minimizes both, the hazard to monitoring staff posed by nighttime fieldwork and the disturbance to breeding anurans (tadpole, juvenile and adult) as well as reproductive output and recruitment.

The results of the anuran field surveys highlight two important considerations with relevance to adaptive management. First, indicator metrics are important, and should be selected based on management goals. Within the temporal baseline analysis, a significant change over time was observed for species diversity but not for anuran IBI. This is likely because, as discussed earlier, the GLCWC anuran IBI is not ideal for small, moderately disturbed wetland sites. Second, data from control sites is extremely valuable for distinguishing between treatment effects and change over time due to other factors. Looking at the temporal baseline results of a significant decrease in relative anuran diversity following treatment, one might conclude that the treatment negatively affected anurans, but the spatial-matched pairs and BACI results do not support this. In the absence of control site data, it is difficult to ascribe observed changes to a particular cause.

4c) Birds

Marsh nesting obligate species were negatively affected by mowing in the short- to medium-term, but pre-treatment surveys confirmed that no endangered or threatened species (e.g., King Rail, Yellow Rail, Common Moorhen, Least Bittern, Forster's Tern) were present at the mowed sites pre-treatment. In cases where endangered/threatened bird species are present, efforts to eradicate *Phragmites* may need to be tempered by the site-specific management goal of retaining those species. For example, the presence of rare breeding birds may necessitate moving mowing or burning activities from the generally ideal time of late summer to winter to avoid disturbing breeding birds, and treating large sites in sections to avoid making a substantial area unsuitable as habitat at once. Regardless of the presence of rare species, the MDEQ's Guide to the Control and Management of Invasive *Phragmites* states that no mowing should occur between March 1 and July 15 to avoid impacts to nesting birds.

While point count surveys provide information about the assemblage of bird species breeding at a site, they do not characterize breeding success. Particularly for highly vagile bird species, local variation in reproductive success can often be masked by recruitment from a wider region (George et al., 1992) or accentuated by lack of recruitment from a larger area (DeSante, 1990). Source-sink dynamics may thus make the density of a species in a given area a misleading indicator of population viability (Pulliam, 1988; Van Horne, 1983). In this context, point count surveys might best serve as a preliminary monitoring tool to screen for the presence of rare or special-concern species. When present, a protocol that monitors the demographic parameters of those species (i.e., nesting productivity, post-fledging productivity, recruitment, or survivorship) can then be put into place. As one example of such a monitoring effort, Lazaran et al. (2013) evaluated the effect of herbicide treatment of *Phragmites* on Marsh Wren nesting success by locating and monitoring nests, then comparing territory density, nest density, number of days to nest initiation, and nest height before and after herbicide treatment. Their results indicated that *Phragmites* treatment, particularly aerial spraying, reduced the availability of nesting habitat for Marsh Wrens, which require tall, emergent vegetation stalks. Mowing in sections could reduce this impact.

In summary, the responses of wildlife species to *Phragmites* invasion and control are individualistic and complex. For some species, dense *Phragmites* growth provides no habitat value, but for others, including some declining species, *Phragmites* serves as a food source, shelter, nest material, and/or buffer vegetation. In response to this complexity, and in view of the impossibility of the complete eradication of *Phragmites* everywhere, management of *Phragmites* should be done on a site-by-site basis that takes into account the biota occupying existing *Phragmites* stands. Management goals should be set only after an appropriate assessment of the ecosystem services provided by a particular stand of *Phragmites* has been completed in order to foster biodiversity in a region. Following treatment, monitoring is necessary in the short- to medium-term (three to five years) to identify targets for spot treatment and to confirm that special-concern species already using the site are not being negatively impacted. Longer-term monitoring, beyond the scale of a few years that was the focus of this study, is needed to capture the recolonization of the treated site by species that avoid both *Phragmites* and disturbance.

4d) Vegetation

The results of the vegetation surveys provided the strongest indication of a positive effect of *Phragmites* treatment on biodiversity, as the mean species diversity of native plants increased significantly in both bays following *Phragmites* treatment. Unlike anurans and birds, for which the positive or negative effects of *Phragmites* are more complex and vary among species, *Phragmites* invasion has been clearly demonstrated to reduce plant diversity (Ailstock et al., 2001; Silliman et al., 2004). Plant diversity and cover is one of the key metrics used to understand the health of ecosystems and wetlands. The link between *Phragmites* treatment and increased vegetative biodiversity may allow for a qualitative measure of treatment effect.

Working in a coastal wetland on Lake Erie, Carlson et al. (2009) found that secondary treatments, including spot-spraying or cutting and raking following site-wide treatment, can increase native plant diversity relative to sites treated only with aerial spraying. The same study argues that though total removal of *Phragmites* may be unlikely, increasing and maintaining vegetative biodiversity is possible, as long as the density remains low. Maintaining small diverse communities could fulfill a number of management goals, particularly where rare or sensitive species could coexist in an understory (Kiviat, 2013).

4e) Key questions for *Phragmites* managers

Managers involved with *Phragmites* removal projects must decide whether the potential negative impacts of herbicides are worth the risk, especially for biota indirectly impacted by the change in plant communities. This is closely related to the objectives set by land managers in order to reach stakeholder goals, a key process in utilizing adaptive management in *Phragmites* treatment (B. K. Williams et al., 2007). For many landowners in the Saginaw Bay area, for instance, shoreline utilization and views are often key, meaning that the stagnation of native plant regrowth would be considered fortunate, if not desirable. However, in other public land areas, rare flora and fauna or ecosystems are often of high importance, meaning large scale loss of plant cover from herbicide use would not achieve management goals. In this way, the application considered successful in one area could be a failure in another.

Secondarily, managers must understand and be willing to treat in the “long term”, particularly considering that single year treatments are often only effective for a few years, and rarely allow for the reestablishment of any native communities. Management programs should also reevaluate stand conditions and necessary treatments regularly. In this way, resources can be concentrated on the largest problems. For instance, large scale aerial treatment may make sense as a first year treatment, when large patches of *Phragmites* are dominant. However, as *Phragmites* becomes patchy and limited, aerial treatment becomes unnecessary, and cheaper localized treatments may become more effective. Remote sensing for site monitoring through updated vegetation mapping can help identify the local areas to treat. Most publications and managers suggest establishing a set group of alternatives at the beginning of treatment. This will stop management efforts from becoming “ad hoc”, allowing others to gain information for future management (Fischman et al., 2015).

Monitoring is possibly the most important key in ensuring success in reaching defined management goals. Quantitative, statistical, scientific monitoring is essential in informing recursive decision making. Choices cannot be made without up-to-date information on current standards. Too many managers either treat without any of the principles of adaptive management (AM), or in an impromptu method referred to as “AM-Lite” (Fischman et al., 2015). This problematic and patchy implementation of adaptive management uses no forward planning, and is much closer to trial and error than active decision making. Planning for future changes and contingencies is necessary, meaning that continuing AM-Lite principles will not effectively manage *Phragmites*.

Reducing uncertainty through the information provided through adaptive management, including monitoring, so that success can be measured and recognized is a key principle of the US DOI guide. This learning-based management of natural resources provides a flexible decision-making environment that enables decisions to be actively adapted based on careful monitoring of actual project responses and evolving project outcomes. As the US DOI Adaptive Management guide states,

> *"In contrast to trial and error, adaptive management involves the clear statement of objectives, the identification of management alternatives, predictions of management consequences, recognition of uncertainties, monitoring of resource responses, and learning". (B. K. Williams et al., 2012)*

This may seem like a potentially expensive "extra" that stretches limited funds that are more focused on the control efforts themselves. However, previous sections have shown that vegetation monitoring may be the most important component of practical monitoring to understanding the success of *Phragmites* control efforts. Remote sensing for mapping the impacts of control efforts, and locating remnant stands of *Phragmites*, does not have to be cost-prohibitive.

5) Implications of Current Research in Reference to Current Literature

5a) *Phragmites* Prioritization Tool

In an updated Michigan *Phragmites* Prioritization Tool (http://www.michigan.gov/deq/0,4561,7-135-3313_71151_71481_8314-178183--,00.html), we recommend that a new Criteria Category called "Planning and monitoring" should be added, with points awarded for:

1. Pre-control monitoring: Has monitoring taken place before control efforts, to establish a baseline for understanding control impacts:
   a. Yes, there was a pre-control monitoring program using an established protocol: +2 points
   b. Yes, there was pre-control monitoring, but using informal methods: +1 point
   c. No, pre-control monitoring did not take place : +0 points
2. Plans for monitoring: Do monitoring plans exist to evaluate impacts and success of control efforts:
   a. Yes, using identified methods for at least 5 years: +3 points
   b. Yes, using identified methods for at least 3 years: + 1 point
   c. No, monitoring plans do not exist: -1 point
3. Management plan: Has a formal management plan been created for the site undergoing *Phragmites* control:
   a. Yes, and it uses the principles of adaptive management: +3 points
   b. Yes, but it does not explicitly include adaptive management: +1 point
   c. No, a management plan does not exist: +0 points

The point scales used here are only representative examples and should be determined by MDEQ based on their priorities for the Prioritization Tool. However, we suggest that adding this Planning and Monitoring category will help tool users understand the importance of monitoring and management plans. Particularly given limited budgets and growing demands, it is necessary that managers recognize that monitoring and planning are an integral part of effective ecosystem management and *Phragmites* treatment.

5b) Implications and Suggestions for State Monitoring Recommendations

i) Levels and Intensity of Treatment

Based on work such as that of Elgersma (2014), we recommend that at least three years, but not more than six, are likely to be needed for effective *Phragmites* control, including collecting the data necessary to determine the success of treatment efforts. One year of treatment, or mechanical control only, are just not sufficient for controlling *Phragmites*, as shown in our own project data and other studies (Kettenring et al., 2011). It should be noted that no single treatment is universally endorsed as best. Secondarily, the community of managers and scientists working with *Phragmites* are not necessarily in agreement on the current goals or definition of treatment success. Understanding both the research and public needs inherent in *Phragmites* control is integral to ensure satisfaction with treatment and outcomes.

As described in this report, as well as current literature, the type of treatment that is best for a given stand of *Phragmites* will be dictated by multiple factors, which can most likely only be determined though the practical application of the principles of adaptive management. For instance, it is first and foremost important that treatment of *Phragmites*, in and of itself, cannot be the sole goal of treatment. A clear, determined, measureable goal, in line with the principles of managers and stakeholders, must be set before treatment. Beyond this, the type (or types) of treatment will change based upon these goals, and over time as more information becomes available. For instance, large scale aerial spraying of *Phragmites* may be necessary at one point, while back pack spraying would achieve the same goal within a few years. Managers should consistently revaluate not only the state of their area of interest, but also the information that influences their form of management.

ii) Implementing Adaptive Management

Key activities of adaptive management (stakeholder engagement, resource monitoring, and modeling) should be reviewed and described in state monitoring guidelines, with explicit reference to the well thought-out US DOI Adaptive Management Applications Guide (B. K. Williams et al., 2012). The "Implementing Adaptive Management for Control of *Phragmites australis* on National Wildlife Refuges in the Northeast Region and Model Development to Support the Integrated Waterbird Management and Monitoring Program" (Moore et al., 2014) is an example of a federal agency actively trying to integrate adaptive management into *Phragmites* control efforts, including using monitoring data and appropriate models to evaluate treatment outcomes.

State guides are a critical resource to informing land managers, the public, scientists, and other stakeholders in the most effective means of controlling invasive species such as *Phragmites*. The third edition of the Michigan guide explicitly states that:

> *"Monitoring and adaptive management are integral components of a successful Phragmites control plan. A detailed monitoring plan should be developed prior to implementation of control measures. Monitoring provides the data needed to determine the effectiveness of initial control efforts and the types of follow-up control methods that are necessary."*

This is a good start, but the language on the types of monitoring, including surveying vegetation biodiversity, collecting before-treatment control data (when and where possible), and including a mapping component should be strengthened.

We recommend that all state, local, and federal guidelines include at least a reference to adaptive management principles so that stakeholders are more likely to use them to inform and evaluate the success of their efforts.

iii) Monitoring Recommendations

Based on our results and the literature cited within this report, we recommend the following basic monitoring durations:

- At least three years, with five recommended after treatment is completed, realizing limitations on funding and there can be site-dependent issues.
- Monitoring should be completed for at least a year before treatment starts, to provide necessary information to evaluate the impacts and intended success of control effort, and to provide information on rare species that may be present and could be impacted.
- Inclusion of control sites in addition to before/after data collection, to distinguish treatment effects from other sources of variation.

An important component of our recommendations is to include appropriate scale remote sensing-based mapping as part of pre- and post-treatment monitoring. For example, the multi-spectral 15-cm imagery produced very useful results for informing adaptive management, including understanding where small areas of *Phragmites* had survived treatment efforts and could form a base for rapid re-invasion. Moderate resolution combined Landsat plus SAR satellite imagery could cover larger areas for rapid, relatively low-cost mapping. UAVs can provide a useful tool for evaluating and monitoring treatment sites.

We recognize the limitations on invasive species control funding, but success should be measured by more than the amount of a controlled area. Working solely with measurements such as "87 acres of *Phragmites* were controlled in 2013" give little understanding of the realistic success of resource use. Being able to measure if vegetation diversity is definitely improving, and continuing to improve more than a year or two after control, is important, as this reflects the true impacts of management. Monitoring efforts provide the key data to adaptively manage a resource based on informed decision making. Limited funding has the opportunity to be spent more wisely, and with greater effect, by following the principles of adaptive management.

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