Observation to Action: How geospatial data is used for the tracking and management of Invasive *Phragmites* in Minnesota

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Introduction

Throughout Minnesota and the Great Lakes region, invasive species are a concern for land managers, industrialists, and homeowners. Invasive species range from plants, animals, and insects to fungi and diseases. They are organisms who come from different geographic regions to negatively affect the local environment once introduced. Aquatic Invasive Species (AIS) are detrimental to the waters in and around Minnesota. A large part of the State's economy is based on the recreational use of these resources (Haight 2021). For those who own property on a body of water or wetland, AIS infections can degrade water quality, cause fish kills, alter riparian vegetation, and affect property values (Blanke 2019). AIS and their management are both economically and environmentally important for property owners to be informed about (Hazelton, 2014). While agencies such as the Minnesota Department of Natural Resources and the U.S. Fish and Wildlife Service work to defend the State's waters from invaders, some species have been able to establish in Minnesota (Reinhardt 2019).

Figure 1. Invasive *Phragmites* in wetland habitat in central Wisconsin. Wisconsin Wetland Association (https://www.wisconsinwetlands.org/updates/invasive-plant-profile-phragmites/)

One such species is invasive *Phragmites australis* (Cav.) Trin. Ex Steud. ssp. *australis*, also known as invasive common reed (Figure 1). Invasive *Phragmites* has established itself in the Great Lakes region, including Minnesota, Michigan, and Wisconsin (Kramer, 2017). This marshland and emergent plant can colonize land with varying levels of standing water such as roadway ditches, boat launches, and wetlands. Invasive *Phragmites* is a European variety that can grow in thick stands that restrict marshlands for native flora/fauna communities and physically alter the makeup of wetlands.

For many agencies, stopping the spread of invasives is a high priority. Different organizations use quarantine efforts to reduce spread, while others focus on surveying for new colonies as a preventative measure. Many governmental agencies and Non-Government Organizations (NGO's) must prioritize management efforts to have the most impact on the invasive species (Rohal 2018). Proactive management efforts therefore rely on cooperation with the public and landowners to observe new invasions and report them to the appropriate agencies. Once confirmed, confidence in this data allows scientists to then help fill databases of information on the species. EDDMaps and other tracking programs utilize the information to create different maps and analysis to plot populations. New reports in such databases are used by scientists to inform and create predictive computer models for the establishment and management of invasive species like *Phragmites*. Organizations are exploring the use of Geographic Information Systems (GIS) to determine where habitat may be suitable for invasive species such as *Phragmites* to establish (Allen 2017, Rout 2014). These powerful computer models rely on the data provided by people who report sightings of new invasive species to remain accurate and up-to-date.

Tracking of individuals and populations is vital to the success of any invasive species management program. As invasive species have multiple ways of colonizing new areas, analysis of those pathways can give insight as to the most vulnerable vectors for invasion (Britton 2013). Data reported by citizen scientists, land owners, lake associations, and surveyors is critical to the accuracy and precision of these models. Specifically, for *Phragmites*, the reporting of newly colonized sites is vital for the Early Detection/Rapid Response protocols (process for eradication of newly immigrated species before they become established) that the GIS models inform (Lovell 2006, Papes 2011). When invasions are in their infancy, they are more susceptible to management and eradication practices that keep an invasive species such as *Phragmites* from becoming established and sexually mature (Hazelton, 2014). Successful ED/RR programs decrease the cost and increase the success rate of invasive species management.

After populations are identified and treated, there is further work to ensure control of an invasive species is achieved. Monitoring of treatment areas and assessment of their success is analyzed and reported. Each successive season that an area is managed there are assessments to determine the best steps for moving forward (Vyn 2019). This ongoing process ensures that best practices are being used for the management of the area, and treatments are effective at controlling the invasive species. Informative reports determine costs and other long term analysis for the project. For *Phragmites*, these reports can advise future budget allocations for control of newly reported populations and determine which methods will be most effective to lead to control and potential eradication.

For the control of invasive species, having infrastructure in place to manage and report new populations is important to the success of eradication measures. Computer models and mapping programs are powerful tools for analysis of invasive populations and can increase their success rates while reducing costs. Scientists and government agencies are not the only parties who can benefit from these measures. The objectives of this paper are to educate the public about invasive Phragmites, how it is managed, how GIS can contribute to its control, and how individuals can contribute to the discovery, research, and management of invasive *Phragmites* in their area.

Life Cycle History and Biology

The Native Phragmites genotype has been part of the North American ecosystem for thousands of years. The hollow reeds were used for many years by Native Americans for basket weaving, brick mortar, and as a source of sugar (Kiviat and Hamilton 2001). In the natural environment, it provides a source of shelter for overwintering insects, nesting ducks, flood control, and a natural filtration of pollutants and nutrients from the water (Meyerson 2010). Native Phragmites grows in wetland, shoreline, and emergent areas, and can survive in environments of both brackish and freshwater (Saltonstall K. 2005). Native Phragmites tends to prefer the slow moving or stagnant water environments (Meadows 2007) that are common in many wetlands. As a perennial wetland grass, it is found along many of the shorelines of Minnesota's lakes, rivers, streams and wetlands.

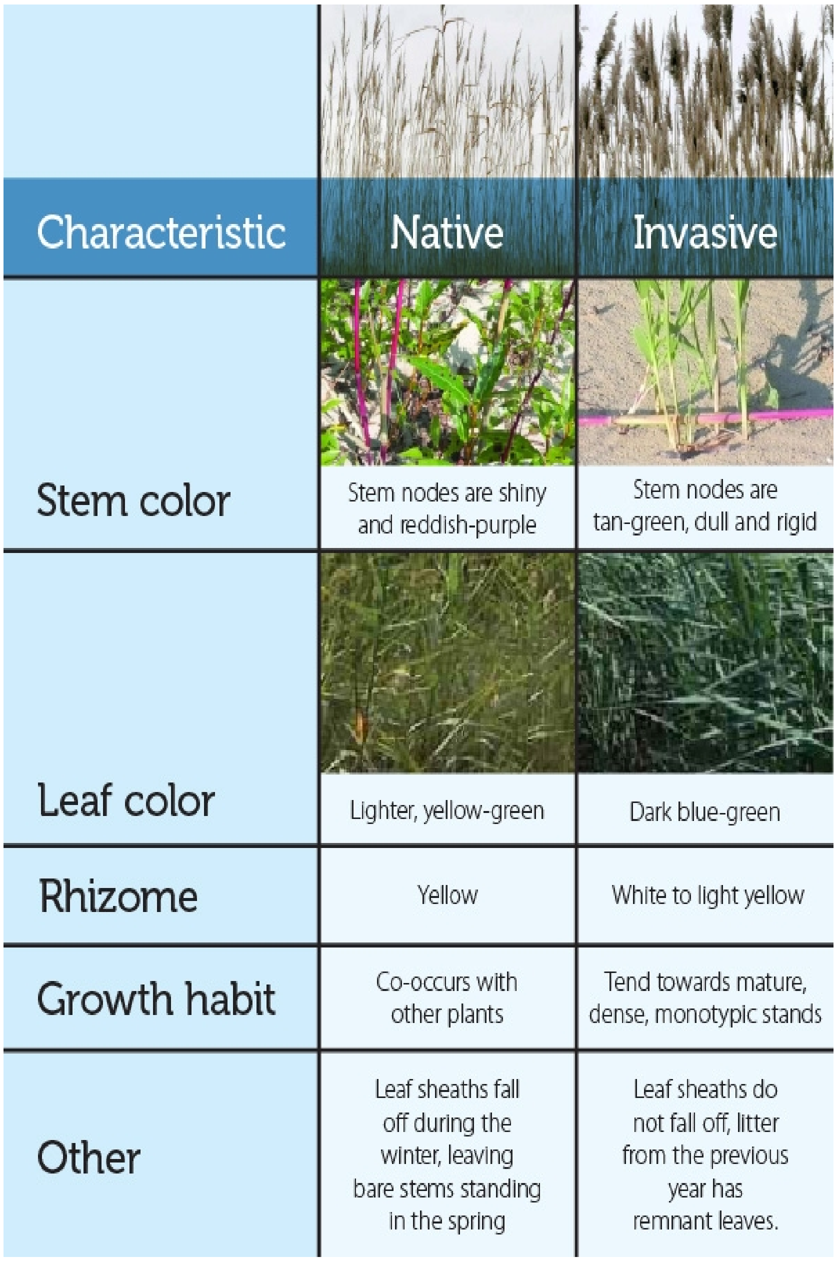
Figure 2. Contrast seed production of Invasive Phragmites

Native (left) seed heads are often less robust than non-native (right) seed heads. Photo: USGS Great Lakes Science Center.

The invasive strain of *Phragmites* is not native to the Great Lakes region. The genetic material of European *Phragmites* is thought to have come from Europe in the 1700-1800s in the ballast waters of cargo ships or in packing material (Meyerson 2009). It is theorized that the genetic strain from Europe hybridized with the native species, and it is the hybrid that has caused the aggressive shift in populations (Van der Putten, W.H., 1997, Tulbure et al. 2007). The hybrid is the modern day invasive plant. In Minnesota Invasive *Phragmites* holds to most of the same biological patterns as its predecessor, but with an increased range of salinity and pH. Invasive *Phragmites* can now be found in many wetlands in the continental US with suitable habitat and is out-competing its native counterpart. The vast biomass and hardy nature made some believe that it could be used for waste water treatment, and so it was intentionally introduced to Waste Water Treatment ponds in the 1950s and 1960s in Minnesota (Swearingen & Saltonstall, 2010). As of 2019, there were 16 Wastewater treatment sites that use Phragmites to dewatering biosolids following sewage treatment but the populations are closely monitored for the potential spread of the invasive.

A distinguishing characteristic of invasive plants is their ability to out-compete the native flora (Figure 2.). Sometimes this refers to developing in an otherwise open niche, such as having a higher tolerance for salt or acidity. Other invasives are known for their particularly robust sexual reproduction forming new plant colonies. *Phragmites* has multiple ecological advantages. It has a higher physical range for temperature, and salinity that allows it to establish in new areas (Colautti 2004). *Phragmites* can also thrive in varying anoxic conditions and a wide range of pH from 3.9-8.6 (Fofonoff et al. 2015). It can grow via rhizomes and stolons, and has larger seed production magnitudes higher than its native counterpart (figure 2). It is difficult to contain once established in an area (Brisson et al, 2010). Unless in physical proximity to each other, the native Phragmites, and the invasive *Phragmites* can be difficult to distinguish (Figure 3).

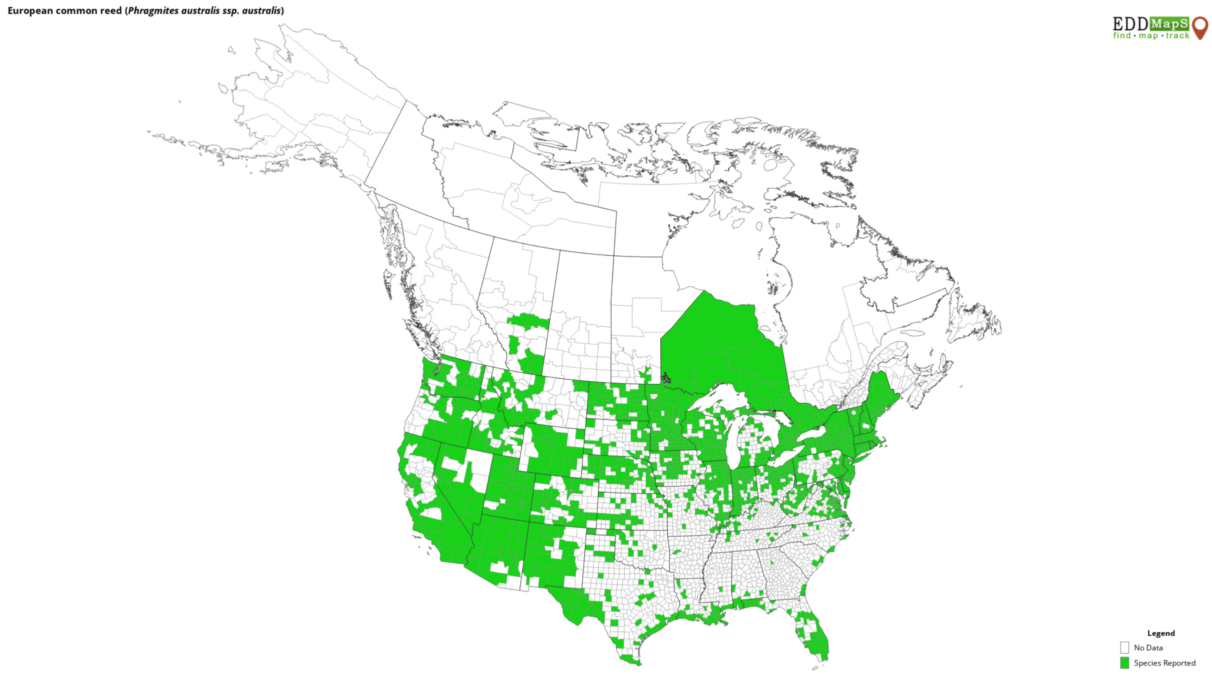
Figure 3. Comparison of Native and Invasive Phragmites. Image from Michigan Sea Grant



Characteristic	Native	Invasive
Stem color	Stem nodes are shiny and reddish-purple	Stem nodes are tan-green, dull and rigid
Leaf color	Lighter, yellow-green	Dark blue-green
Rhizome	Yellow	White to light yellow
Growth habit	Co-occurs with other plants	Tend towards mature, dense, monotypic stands
Other	Leaf sheaths fall off during the winter, leaving bare stems standing in the spring	Leaf sheaths do not fall off, litter from the previous year has remnant leaves.

Invasive *Phragmites* is found in many shorelines and wetlands across the US, particularly in the Great Lakes region (Figure 4, Jakubowski 2010). Its dense stands can grow 2-6 meters high. With thin blade-like leaves, hollow stems, and tall bushy flower bunches, these stands can quickly out-compete native species for space and resources. *Phragmites* also can grow and clone from deep rhizomatic structures. These can grow up to 3m per season and continually spread to put up new shoots (Amesberry et al. 2000). "As a biological invasion, the introduction of *Phragmites* could lead to detrimental consequences in North American tidal wetland ecosystems through alteration of resource utilization, modification of trophic structure, or change in disturbance regime (Vitousek, 1990; D'Antonio and Dudley, 1995; Mack, 1996)." (Chamber, et al 1999) Compared to the native species, it has dense community stands that prevent nearly all other vegetation from establishing, becoming a monocrop.

Figure 4. Distribution of verified Phragmites populations by county across North America. EDDmaps 2023



Experts theorize that the recent expansion of *Phragmites* populations is not just due to the introduction of European varieties, but the degradation of the physical environment (Chambers, 1999, McCormick 2010). Changes in nutrients levels, varying water levels, random disturbance regimes, and urban pollution may have assisted the growth of invasive *Phragmites* (Tulbure, 2007). The expansion of *Phragmites* into new areas is of concern. The damage it can cause to the environment and the difficulty and cost of management makes it imperative that the public can recognize and report the plant early.

Invasion Pathways

Invasive species are partially classified as such because of their ability to negatively affect their surrounding environment. For AIS this can be changes in soil structure, light or nutrient availability, choking out native species, and other detrimental consequences from their establishment (Figure 5). Once an invasive species becomes established, it changes the environment in a way that makes it easier for other species to invade, leading to even more native fauna and flora decline (Pimentel 2005). *Phragmites'* introduction and subsequent establishment have affected the environment enough to cause habitat degradation and be declared invasive. Negative ecological cascades are common with invasive introductions and can cause huge ecological, physical, and economic harm (Heimpel 2010).

Figure 5. *Phragmites* stand growing densely along the shore line forming a monocrop. Michigan SeaGrant

Many new stands of *Phragmites* require multiple introductions of new material (propagule pressure) before establishment is successful and reaches sexual maturity (Reaser 2007, Gertzen 2008). New stands as a result of propagule pressure can be partially linked to the movement of people and of biological material they may unintentionally harbor (Sobek-Swant 2014). States including Minnesota have laws specifically to target *Phragmites* and other invasive species that may move from one area to another that wouldn't make the journey otherwise without the assistance of people (Vitt 2010). This is often referred to as Human Assisted Migration. Reduction of human assisted migration is one of a few effective techniques to slow the spread of invasive populations. This holds particularly true with aquatic invasive species. Many aquatic plants or animals can't travel from one source of water to another without human assisted migration. The presence of AIS in Minnesota lakes are attributed to the fishing and recreation industries where people move boats or other equipment from one body of water to another carrying infected biological material such as water, mud, vegetative scraps, or animals such as fish and bait (Hansen 2005). This is why AIS inspection programs at boat launches are important to stopping or at least slowing the spread of invaders. They are stop-gap measures to quarantine those infested waters, and to keep people from unintentionally spreading AIS such as *Phragmites* to other water bodies (Bailey 2005, Christen 2009).

There are many examples of species being specifically introduced to a new environment by humans. *Phragmites* was purposely brought into Wastewater Treatment Facilities (WWTF) for its ability to produce large amounts of biomass and filter out contaminants (Blanke 2019). Outside of specific WWTF established before 2021, Phragmites is a listed Prohibited-control species through the state of Minnesota Noxious Weed Law (Kinsley 2022 Minnesota

Department of Agriculture). At a minimum, *Phragmites* must be controlled in a way that prevents spread of these species by seed or vegetative means in Minnesota in accordance with the DNR Noxious Weeds Laws. This means for Homeowners and Municipalities who have susceptible landscapes, being able to recognize and control *Phragmites* is essential.

Prevention

Preventing the establishment of *Phragmites* in new areas is dependent upon a number of factors. *Phragmites* is documented to move into areas of recent environmental disturbance (Catling 2011). This could be from construction, development, fire, flooding, or any number of other factors that would cause the area to have a shift in available resources (Von der Lippe 2007) . Changes in nutrient availability from disturbance then opens up new niches for invasive plants such as *Phragmites*. Anthropogenic disturbances on invasive species spread are documented to be most relevant in areas of dense human populations and high traffic volumes (Gelbrad 2003, Zwaenepoel 2006). These can be pathways for *Phragmites* to move to new areas and environments that wouldn't be able to access otherwise (Bellavance 2010, Leung 2007). Once we include how many people, or how often they come to certain areas, that might indicate high propagule pressure, and therefore higher risk of invasion (Wonham 2013, Kettering 2016). This can be inferred by human population density, city population totals, roadway usage, or hunting permits assigned to an area (Taylor 2004). Statistically, this number is linked to the instances of introductions for an area and used as a point of reference for anthropogenic-mediated disturbance and propagule pressure (LaBlanc 2010, Lockwood 2005). Monitoring of recently disturbed areas would then help identify early introductions of *Phragmites* for Early Detection and Rapid Response.

Preventing the spread of *Phragmites* is difficult to accomplish. To keep *Phragmites* out of pristine areas, it is recommended that no contaminated biological material be transported away from known infection areas. Weeds, seeds, water, or soil, from an affected area may harbor remnant material and could jump locations with assisted movement (Mueller 2008, Leprieur 2008). While humans cannot prevent the spread of material via natural seed dispersion, education and recognition of Phragmites is one of the more effective ways to keep *Phragmites* from spreading via human assisted migration (Simler 2019).

Treatments

Chemical treatments of *Phragmites* have had success. Due to its location in shorelines and wetlands, special care must be taken in selecting chemicals that will not be detrimental in aquatic environments (Sturtevant 2018). This often eliminates chemicals such as glyphosate which is the standard for many terrestrial invasive plant controls (Derr 2008). Aquatic-safe versions are available to the public but have additional requirements for use. Applications need to be made to affect rhizomatic roots and not just the above ground tissues, or they will be ineffectual. Aquatic approved chemicals such as *Imazapyr* are registered as treatments for *Phragmites*. Application of such chemicals in a fragile environment requires certifications and training, since they are not often host species specific (Holdrege 2011, Kettenring 2011). Special permits are required for the treatment of invasive species in wetlands in Minnesota. Chemical controls are best used in conjunction with a larger Integrated Pest Management (IPM) plan and may require multiple treatments over time.

It is difficult to quantify the cost per acre of *Phragmites* for management purposes (Pimentel 2000). In MN, there are 50-100 acres of verified *Phragmites* populations. Small sites that are recently established would have a lower management cost than large sexually mature stands (Pimentel 2005, Teal 2005). For chemical applications specifically, a single site can run from $500-2000 per year depending on the application protocol (Martin 2013, Lodge 2016). Hiring companies with the appropriate permits to use chemical controls can increase this to as much as 5000$ per acre/year if multiple sites are being treated or are difficult to access (Gilbert 2014, Bonello 2020). Chemical control is also shown to require multiple treatments in successive years to achieve control, increasing the overall cost of management (Lombard 2012, Knezevic 2013). Herbicide control of *Phragmites* is an important step in control of the invasive but there are other options (Derr 2008, Epanchin-Niell 2017).

Biological controls are often considered effective for invasive plants because the organisms can seek out and attack pocket populations (small isolated sections) that may be spreading past the leading edge (Albright 2004). There is always a risk that a bio-agent may become another invasive species. Agencies such as USDA APHIS use rigorous host-specific testing to determine the suitability of a biocontrol agent (Blossey, 2003) before it is released into the environment. The Technical Advisory Group for Biological Control Agents of Weeds had a proposal in 2019 to release *Phragmites* biocontrol agents (*Archanara gemipunca*, *A. neurica* both Lepidoptera, Noctuidae), but neither has yet been approved for field release. The proposed biocontrol agents are still being evaluated under the Endangered Species Act section 7 (ESA sec7) and the National Environmental Policy Act (NEPA) review. Today, there are no government approved biological controls for invasive *Phragmites* (Blossey 2020).

Other methods of control are less practical for large populations. Experimentation has been done by treating areas with black plastic called Solarization. The plastic heats and burns the shoots and clones to largely reduce the size of the stand over the course of the season (Stalonstall, 2002). This is only effective in small stands, as the plastic can be expensive to maintain as it can take months to be effective. Flooding of rhizomes has shown progress in limiting clonal propagation. However, seasonal draw down of the water actually creates more habitat for *Phragmites,* so water levels must be carefully controlled and monitored (Wilcox, 2004). Grazing, burning, mowing, and tilling have also been attempted, but with little consistent success (Quirion 2018).

Most alternative control methods are only cost effective for small newly colonized stands of *Phragmites* (Martin 2013, Turner 2003). As the population stands mature, the roots and rhizomes grow deeper, and the plants produce flowers with viable seed that can spread to new areas. Sexual maturity leads to a greater likelihood of spread via seed dispersion to even further areas that either the stolons or rhizomes would be able to reach. The larger more established populations have fewer feasible quarantine controls either economically or environmentally once maturity is reached (Quirion 2018). Observation and reporting of new populations increases the success rate of management in comparison to attempting to control and treat mature stands of *Phragmites*.

Prediction and Modeling

The analysis and prediction of new population stands is critical to stopping the spread of invasive species. Geographic Information Systems (GIS) models have become powerful tools for land managers and researchers for the management of invasive species (Holcombe 2007). The ability to input data into a spatial environment and create visual and accurate maps with high confidence has changed the way we allocate resources for research and present findings to the public (Joshi 2004). Visual GIS data has been particularly useful in implementing 'Early Detection/Rapid Response' protocols. In invasive management, ED/RR is one of the protocols used most to combat the leading edge of invasive populations (Herms 2014). If properly monitored, an area at risk of invasion can be continually evaluated for introductions. Then, when caught in the early stages before establishment, a quick and decisive treatment can keep the invasion from sexual maturity (Westbrooks R. 1998, 2004). While this can require higher amounts of manpower in the initial stage, it is much less costly and more effective than attempts to control an invasive population after it has become established and is reproducing.

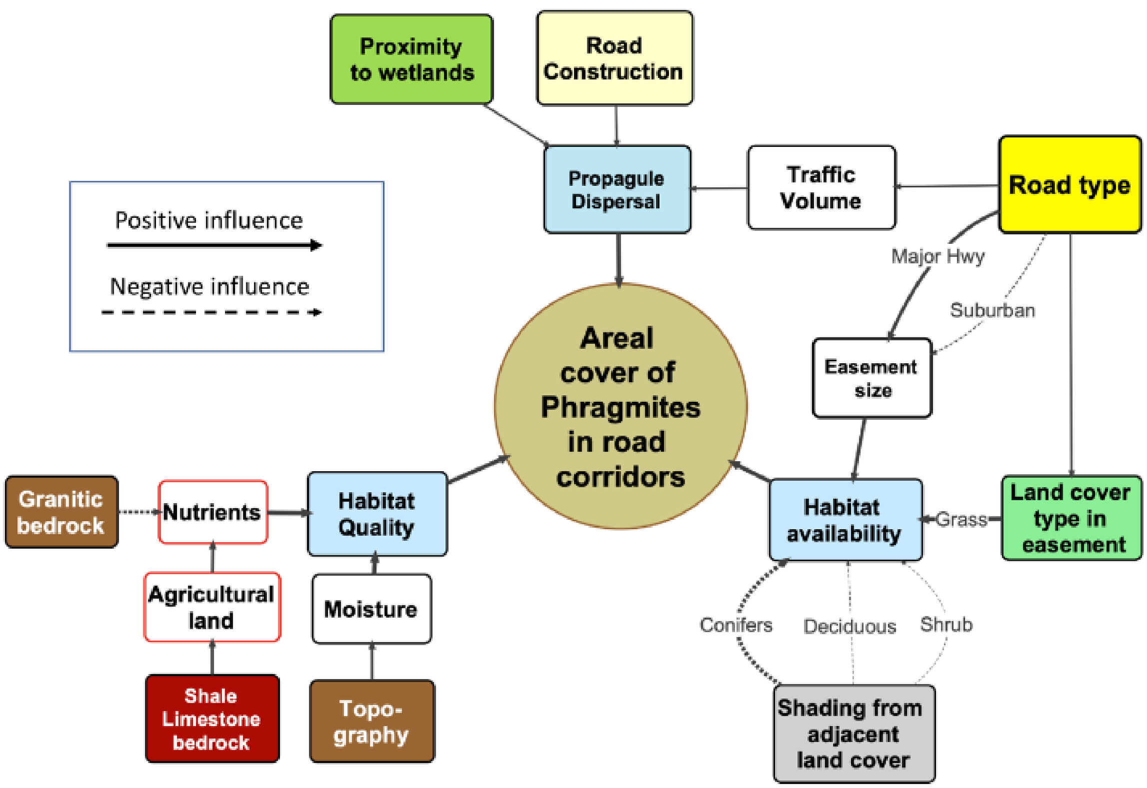


Figure 6. Conceptual model to show the relationship among main factors and associated variables that influence the distribution of invasive *Phragmites* within corridors of road networks. (Marccio 2019)

Many agencies use these models for informing policy decisions and allocating resources. Using GIS modeling to track the leading edge of the population as it crosses state lines is imperative as it is a federally important pest. (Sobek-Swant 2014). This allows managers to monitor those areas that may be at higher risk for introduction, and prevent the leading edge of the population from expanding into new areas (Figure 6).

Data inputs into a model for *Phragmites* can vary (Figure 7). With the progression of climate change, its geographic range is rapidly changing and opening up new niches for introduction (Briscoe 2019). Use of the modeling tools that are found in GIS programs can help predict these new ecological ranges to aid in prevention efforts (Reinhardt 2019, Addison 2013).

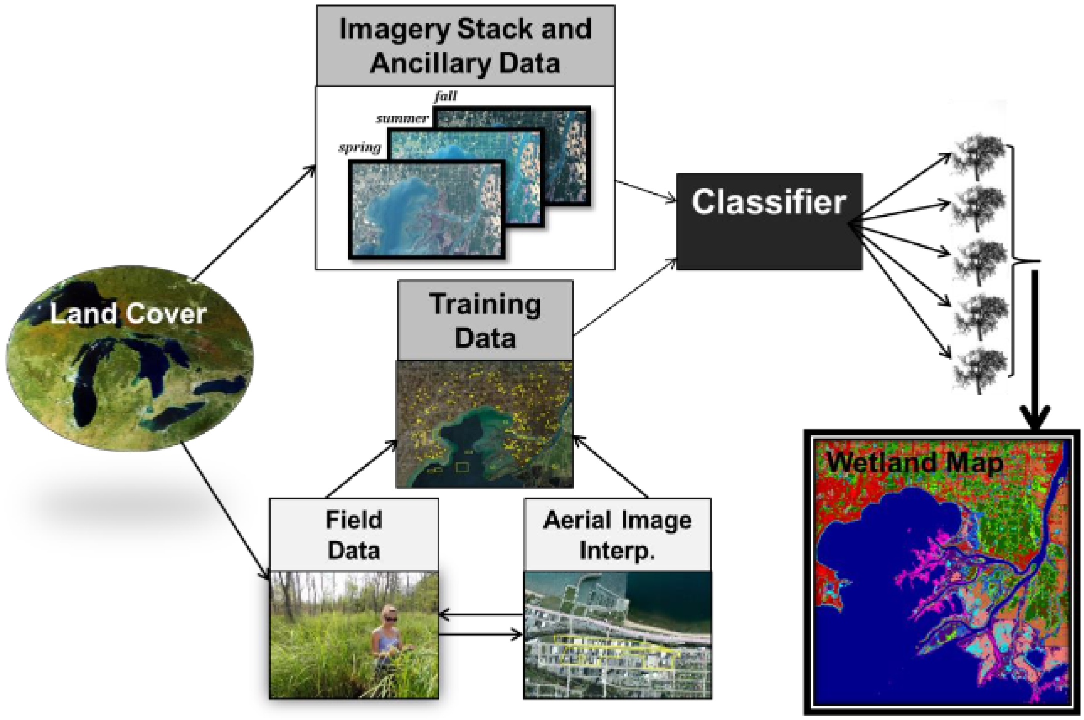


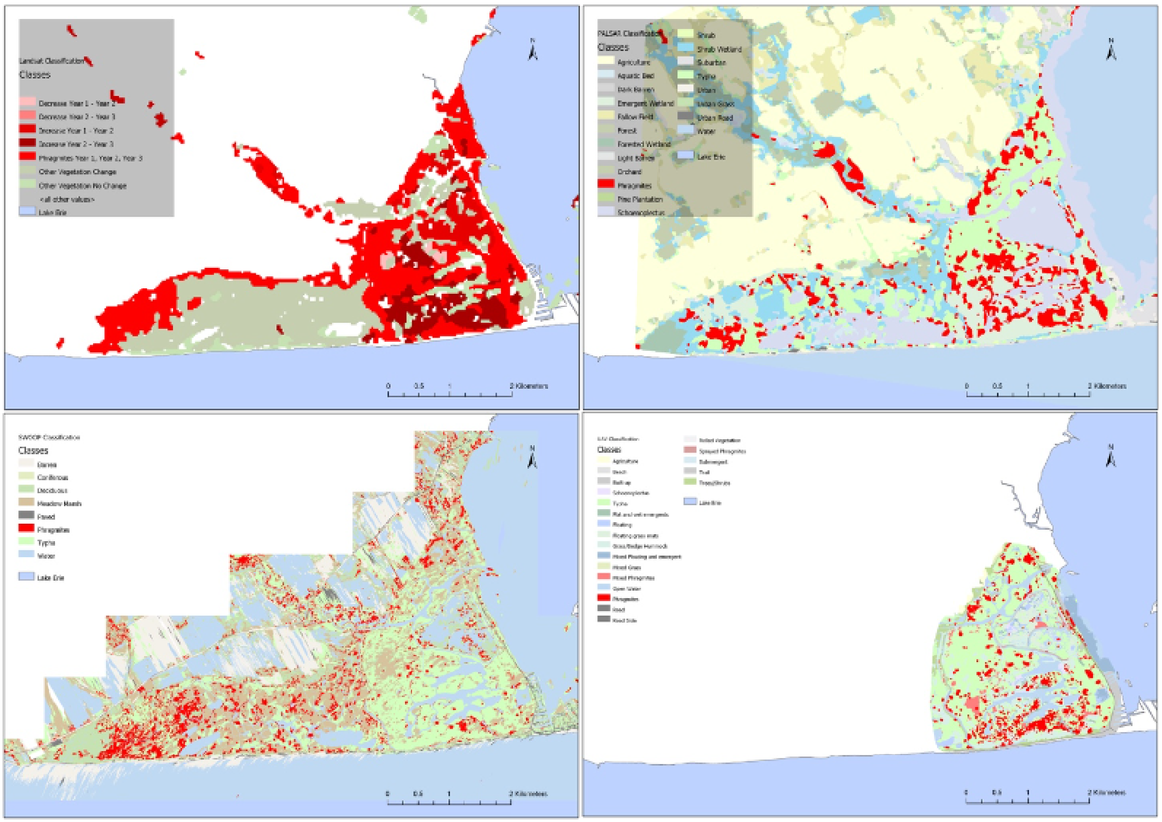
Figure 7 . Schematic showing the mapping methodology from field data, aerial image interpretation, and imagery to classified map.

For *Phragmites*, analysis of ecological range shifts are also useful to determine areas that may be available for invasion that previously were not. New environmental niches from climate change, human assisted migration, and ecological degradation are all factors which contribute to the establishment and spread of invasive *Phragmites* populations. Future research of *Phragmites* management may utilize similar prediction models using these factors to determine where ED/RR may be most effective.

Data Mapping

GIS model programs require the use of multiple sets of data to create an accurate prediction model. For the modeling parameters of a *Phragmites* invasion, the components can be broken down into a few categories. Some of the necessary differentiations include; physical, chemical, and biological requirements to become successfully established in an area (i.e., Suitability), and its proximity to known established populations, recently disturbed areas, or high traffic areas (i.e.Risk). This method is often used by modeling programs such as Invasive Species Distribution Models (iSDM)(Briscoe Runquist 2021, Srivastava 2019). By overlaying these individual components, we can create a theorized model showing areas with the highest risk for introduction or spread.

Figure 8. Remote sensing classification outputs. Initial Phragmites reporting in the first map upper left is classified by pink and gradients of red indicating which areas have shown a decrease in population. In comparison to subsequent years of assessment, a large portion of the population has been treated and controlled (Marcaccio 2019)



Phragmites has a wide tolerance range of environmental conditions (Tulbure 2010). It grows on most soil textures from fine clay to sandy loams and is somewhat tolerant of saline or alkaline conditions (ISSG 2011). It can often be found on recently disturbed sites with altered hydrology, sedimentation, and nutrient enrichment, most indicative of wetlands or emergent areas (Sturtevant et al 2018). This gives it a very large potential geographic range in MN and across the US. Temperature range is not limiting for *Phragmites*, though deep frost can affect the above ground shoots. Many wetlands, ditches, roadways, and areas with even varying degrees of stagnant water could support a *Phragmites* population (Figure 8). This makes it difficult for scientists to track populations just based on the physical characteristics and natural drivers of the landscape.

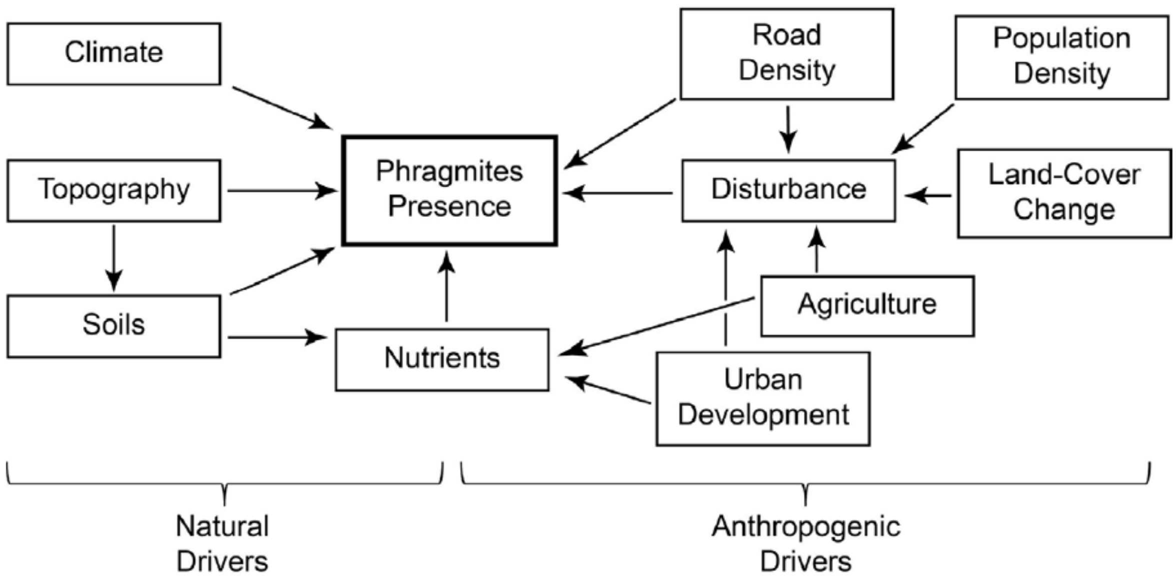


Figure 9. Simplified flow chart of causal influences of phragmites populations. (Carlson 2014)

Instead of using only the physical parameters of *Phragmites* which are not limiting, scientists additionally use other indicators of possible introduction and spread for mapping populations. One such indicator is how an invasive population may move from place to place (Figure 9). Divided into the categories of Natural Drivers and Anthropogenic Divers, it is only the second category of which scientists may be able to affect change. These introduction pathways are critical to invasive management to analyze where management resources should be allocated for prevention efforts (Figure 9). Expansion into new areas is likely due to some sort of assisted migration and/or an environmental disturbance (Meyerson 2013). For lakeshore owners or other land managers, this means areas that may have become disturbed by construction, flooding, or other development will be at a higher risk for invasion and should be monitored closely.

AIS spread in Minnesota is often related to trade, shipping, tourism, hunting, fishing, and other recreational travel (Sturtevant et al 2018). In relation to *Phragmites* specifically, fishing and recreation are of the most concern to local governing agencies. Organizations such as the DNR are able to track through permits where hunters and fisherman are traveling or using their licenses. This in turn with information from the MN Department of Transportation (MDOT) can provide at least cursory information for the roads and highways used by people for travel to and from lakes or marshlands (Caitling 2006). For the purposes of modeling and research, this means that areas of high anthropogenic influence should be closely monitored for introduction to implement ED/RR protocols (Dullinger 2009, Hulme 2008).

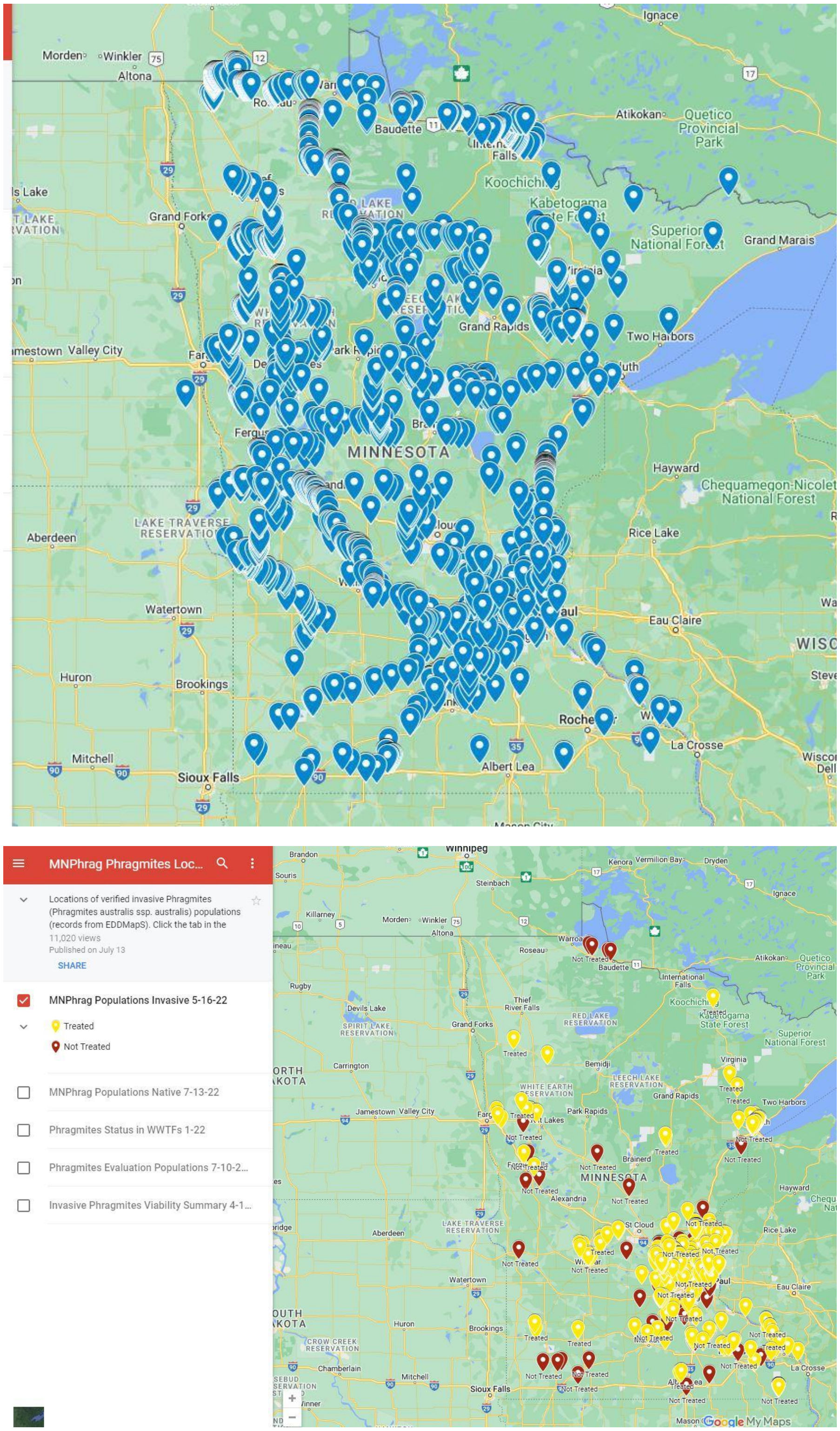


Figure 10. A direct comparison of the current distribution of invasive *Phragmites* to the native species (blue) shows the invasive (yellow and red) is focused in areas of greater human population, and not those of greater ecological opportunity (Blanke 2019).

For the most accurate mapping results on a large scale such as the state of Minnesota, researchers use large models such as the iSDM listed above. The parameters mentioned here are not the only factors that are indicative of *Phragmites* introduction. However, as they are used often as the initial predictors in many other invasion models and are easily accessible, they are some of the popular choices (Uden 2015). Other analysis programs may include derivation of Risk from proximity to known locations of *Phragmites*, higher weights or values to areas of increased human activity, environmental degradation such as recent construction or areas of drought, or the connectivity of suitable habitat from watershed basins.

Scientists rely on the constant influx of updated observations, using both Suitability and inferred Risks to help make accurate predictions (Rohal 2018). Citizen scientists and other observers in the public are key to analyzing real time data. By overlaying both the environmental conditions and Risk datasets, we get a better sense of what the natural predicted trend may be compared to the actual observed trends. That gap between the observed and predicted is then where scientists fill in different data, tweak the parameters, and adjust their predictions to try and align the model with observed reality. The closer they get, the better the model will be at predicting new areas of invasion for prevention and management efforts.

For *Phragmites* specifically, after the initial analysis, each of the above datasets would need to be separately analyzed and categorized for their influence on *Phragmites*. How scientists use the information to create predictions can vary greatly depending on scale, resources, available data, time, and computing power (Brummer 2013). Some scientists are able to use iSDM to create a model that layers the different types of data on top of each other. This could work for the tracking of *Phragmites*, but the exact method for the prediction model is typically decided by the needs of the client or land manager who would use the information. The scientist would have to decide which methods will work best for the provided data and the client's needs, but this general outline shows how observed data in the field can then be put to use for larger analysis and inform management decisions.

Assessment and Monitoring

Even with the powerful prediction tools of GIS mapping for prevention efforts, new populations still need to be physically treated and managed once confirmed. Field management of invasive populations requires similar analysis to the prediction tools. Different techniques need to be evaluated for each site to determine what methods may be most effective for the area. Then once a protocol is established, the site needs to be measured in a way that determines if the treatments were successful to be able to report back to any stakeholders. Each successive season the site is reevaluated and treatments adapted to any changes. This cycle of monitoring, assessment, and evaluation can be referred to as Adaptive Management Strategies.

Monitoring of an invasive species site uses physical parameters to determine any change in the plant population. For *Phragmites*, monitoring is measured in a few different ways. Above-ground biomass and sexual maturity are ways to determine what individual plants are still viable for creating new propagules for invasion (Rohal 2019). Another parameter is measuring the density of the population. This is done usually by creating transects or lines within a plot and measuring the number of plants per square meter in the area. GIS uses data from in field measurements of GPS coordinates to create a polygon of the population that can then be put on a map and measured for changes as control methods take effect. Then Pre- and Post- treatments areas can be compared to determine if the treatment method was successful (Figure 11).

Each site of *Phragmites* depending on size, age, sexual maturity, ease of access and other parameters will need to be evaluated differently (Haight 2021). Assessment of field data depends on the goals for the invasive population and who it will affect. Control and eradication require different methods and varied field monitoring techniques. Once the field data is collected, if parameters such as biomass or square meter density are reduced from the initial assessment, this would indicate that the treatment methods are working to reduce the population size. That change helps to inform future management decisions as to what treatment methods may be best for each site. Comparative analysis of the field data can also reveal which protocols may be most efficient and cost effective for the goal of the project and all parties involved.

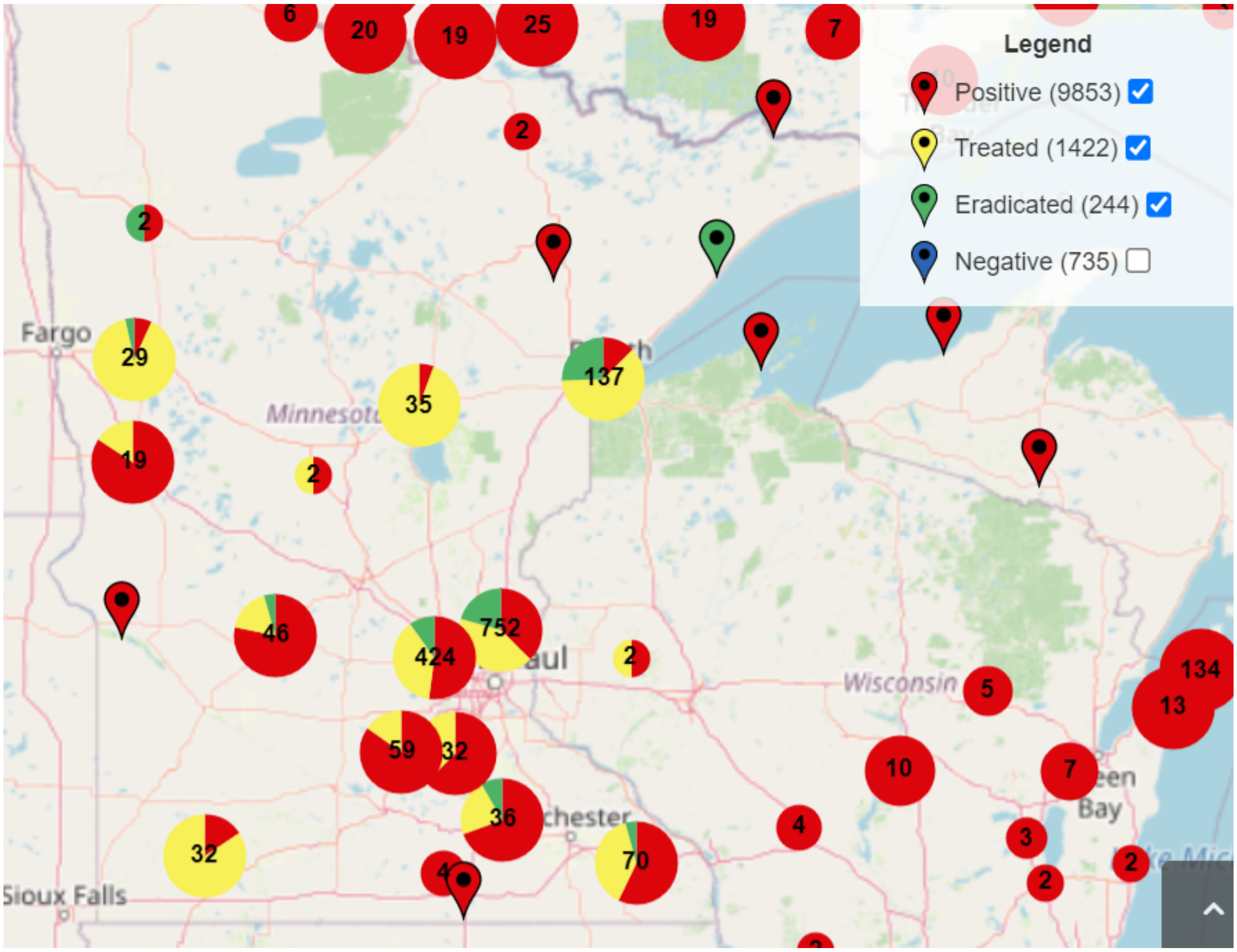


Figure 11. Current verified populations of invasive *Phragmites* in Minnesota as reported by EDDMaps 2023.Treatment and eradication points are indicated by yellow and green respectively.

Conclusions

In Minnesota, the fight against the spread of invasive *Phragmites* is just beginning. Most of the populations that have been identified so far are small and/or newly established. In total, there are less than 100 acres of invasive *Phragmites* confirmed in the state. These small isolated pockets are most vulnerable to the aggressive management strategies listed above because they have been identified early. This is thus far keeping the cost of management relatively low. However, the Minnesota landscape is vulnerable to invasion from these populations due to its vast wetland habitat. The lakes, streams, and ponds that Minnesota is famous for are all perfect environments for the introduction and invasion of *Phragmites.* Constant monitoring of the known populations of *Phragmites* is imperative to act as quarantine and establish management of the leading edge of the invasion. The man-power required for this even in small areas is costly. Larger organizations such as the MN DNR, 1854 Treaty Authority, Minnesota Aquatic Invasive Species Research Center (MAISRC), Minnesota Invasive Terrestrial Plants and Pest Center (MITPPC) and others choose to rely on GIS to determine where the highest likelihood of invasion may be.

As previously discussed, the cost of management and treatment of a site is far greater than that of regular monitoring and prevention. Early Detection and Rapid Response protocols are still more cost effective than attempted quarantine of an established invasive population. GIS models help to inform decisions about where active monitoring and labor efforts should be made to best allocate limited resources. Efficiency is key to keeping invasive management programs successful, and modeling is a powerful tool in accomplishing that.

GIS tools can be very powerful in analyzing the areas of habitat most vulnerable for invasion. They can evaluate large portions of land quickly and effectively for the areas that are susceptible to *Phragmites*. There are many variables that can be taken into account and adjust the models for environmental suitability or ecological risk. The physical needs of the plant and the degree of anthropogenic drivers are both important factors for modeling in GIS. The precision and accuracy of these programs is dependent on a constant influx of field observations of both these and other parameters. Citizen scientists, land owners, volunteers and other observers are essential to providing the data that these programs rely on. Without their help, scientists would struggle to keep their models accurate and up to date.

Public engagement related to invasive species management is key to identifying, preventing and responding to new invasions. With early identification, scientists can reduce the overall cost of management relative to quarantine and control. As more people are educated on the invasive species in their area, more support in the form of funding and/or resources becomes available to the use of the land managers and policy advocates. Having publicly accessible information and portals for observation reporting makes it more likely that any model predictions will be accurate. Without the help and support of the public whose lands are affected by *Phragmites*, management costs increase and the success rate of invasive management drops.

With the integration of GIS tools, scientists are able to quickly and accurately analyze large plots of land for different variables that indicate where the highest risk of *Phragmites* is and react swiftly to combat the invasion, decreasing costs and increasing the effectiveness of control. There is a long process from the first point of observation of an invasive species until action can be taken to control a population. The methods described above, and the steps used to ensure accuracy and efficiency, detail how reported data is used and why. It is imperative for the implementation of ED/RR that the public is able to recognize *Phragmites* in their area and understand how their reports are used in the fight against invasive species.

To report a sighting of Invasive *Phragmites* or other AIS, please go to https://www.mda.state.mn.us/reportapest or download the app

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