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Developing Management Recommendations for Hydrilla (Hydrilla Verticillata L.F. Royle) in the Ross Barnett Reservoir: A Community Approach

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Developing management recommendations for Hydrilla (Hydrilla verticillata L.f. Royle)

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By

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In order to develop recommendations for management of hydrilla at Ross Barnett Reservoir, Mississippi a number of techniques were utilized. Point intercept surveys were conducted within known hydrilla sites at Ross Barnett Reservoir, Mississippi in order to quantitatively assess chemical management for hydrilla control. Hydrilla tuber data were also collected during the winter and spring of 2012 and 2013. Tuber data were compared between the Ross Barnett Reservoir and Tennessee-Tombigbee Waterway in order to see the effects of chemical management on hydrilla tuber bank dynamics. Water exchange data were collected using Rhodamine WT dye at Ross Barnett Reservoir, Mississippi to determine water exchange characteristics. Dye half-life varied between the eight plots, with a minimum estimated half-life of 2.0 hours and maximum estimated half-life of 30.9 hours. Herbicide evaluations showed that bispyribac-sodium, penoxsulam, and fluridone provide the best hydrilla control 12 weeks after treatment.

DEDICATION

I dedicate this thesis to my Lord and Savior Jesus Christ who has blessed me with many talents and kept me motivated during my studies. I also dedicate this to my parents Brian and Melanie; without your support this would have never been possible. Thank you so much for your encouraging words and your unselfishness as I continued my education. I also dedicate this to my friends and family, I am so thankful to be surrounded by wonderful friends and family who have encouraged me to follow my passion and do what I love.

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CHAPTER I

INTRODUCTION: HYDRILLA (*HYDRILLA VERTICILLATA* LF ROYLE) AND THE ROSS BARNETT RESERVOIR

In the past few decades, invasive non-indigenous aquatic plant species have become problematic across the state of Mississippi. Typically, these species are introduced from other parts of the globe, for horticulture and/or beneficial uses (Reichard and White 2001). Long growing seasons and warm temperatures combined with their ability to grow and spread quickly throughout many of the reservoirs and rivers found in the state has allowed successful establishment of these plant species. Increasing populations of nuisance aquatic plants can have negative impacts on the ecological services that Mississippi's water resources provide. Impacts can include, alterations in the interactions between fish and other aquatic species, disruption of nutrient cycling, constricting navigation canals, lowering property value, and declined recreational use of rivers and lakes (Madsen 2004, Pimentel et al. 1999).

One important water resource located in central Mississippi is the Ross Barnett Reservoir. The Ross Barnett Reservoir is a 13,400 hectare (33,000 acre) fresh water supply reservoir for the city of Jackson, MS. It is also the state's largest surface water impoundment and a popular recreational area for boaters, water skiers, anglers, campers, and other users. In addition to recreation, it also provides important wildlife habitat, as well as shoreline, commercial and residential land developments (Cox et al. 2010). In

2005, 19 aquatic and riparian plant species were observed during an aquatic plant survey at Ross Barnett Reservoir, including hydrilla (*Hydrilla* verticillata L.f. Royle) (Wersal et al. 2006). Since its discovery, the number of hydrilla sites has increased from four sites in 2005 to sixteen sites in 2010 (Cox et al. 2011). The rapid increase in the number of hydrilla locations has caused concerns, and the development of a reservoir management plan, including site specific hydrilla recommendations is imperative.

Biology and Ecology of *Hydrilla verticillata*

The submersed aquatic macrophyte hydrilla belongs to the family Hydrocharitaceae (Yeo et al. 1984). Hydrilla, which is native to Asia, was first discovered in a Florida canal in 1960 (Blackburn et al. 1969, Langeland 1996). Since its arrival in the United States it has spread rapidly to other states. By 1976, Georgia, Alabama, Mississippi, Louisiana, Texas, and Iowa all reported hydrilla populations (Yeo et al. 1984). It is a very versatile plant species and can grow in both static and flowing water, from a few centimeters (cm) to 15 meters (m) in depth (Yeo et al. 1984). The depth at which hydrilla can become established is often dependent on water turbidity, although it is a shade tolerant species. Hydrilla can be found in a variety of water chemistry situations and due to its growth and reproduction habits hydrilla has been referred to as “the perfect aquatic weed” (Langeland 1996).

Hydrilla’s ability to survive well in freshwater reservoirs and rivers has caused many problems. Reduced water flow, associated with clogged irrigation and/or water control structures, interferences with navigation, boating, swimming, and fishing are some of the negative impacts caused by extensive hydrilla growth (Yeo et al. 1984). Hydrilla populations have also been known to outcompete and displace native aquatic plants, such as pondweeds (*Potamogeton* spp.) (Langeland 1996). The dense canopy produced in an established hydrilla community makes it nearly impossible for other aquatic plants to flourish (Haller and Sutton 1975). According to Van et al. (1976), *Hydrilla verticillata* had the lowest light requirement for photosynthetic activity when compared to coontail (*Ceratophyllum demersum* L.) and Eurasian watermilfoil (*Myriophyllum spicatum* L.), thus giving hydrilla the photosynthetic advantage in comparison with other submersed species.

Hydrilla reproduction enables it to survive during less than optimal conditions. It utilizes four different reproductive methods, tubers, turions, seed, and fragmentation (Langeland 1996). Tubers and turions are asexual propagules that provide a method of reproduction year after year. Tubers are actually "subterranean turions" that are formed in the soil, whereas turions are formed above the soil and are typically found in the axils of leaves or branches (Yeo et al. 1984). Tubers are formed at the terminal nodes of underground stems (rhizomes) are 4 to 15 mm in length and colored off-white to black (Netherland 1997). Tubers can remain viable for several years; Van and Steward (1990) reported, monoecious tubers were able to survive over 4 years in undisturbed sediment during a study in south Florida. The ability of hydrilla tubers to remain viable for lengthy time periods enable it to form a tuber bank and re-establish annually although other plants have been removed.

Management of *Hydrilla verticillata*

Biological Control

Grass carp (*Ctenopharyngodon idella*) have been utilized as an effective hydrilla control option (Van Dyke et al. 1984). Although effective at controlling aquatic plants, grass carp are not species specific. According to Hanlon and others (2000), the stocking rate for grass carp to effectively suppress submersed aquatic plant species may impact all aquatic macrophytes in the system, which typically is not desired. Additionally, several snail species have been shown to control hydrilla, but only under simulated experimental conditions (Langeland 1996). In addition to grass carp and snails, many insects are also being considered as biological control options for hydrilla. An Indian leaf mining fly (*Hydrellia pakistanae* Deonier) and an aquatic moth (*Parapoynx diminutalis* Snellen) are insect species that have been researched as control options (Center et al. 1996, Langeland 1996). According to Center et al. (1996), populations of *Hydrellia pakistanae* were released in 1987 in an attempt to establish populations at hydrilla infested lakes; though fly population establishment was highly variable.

Chemical Control

Chemical control options are often used to suppress hydrilla populations, but as a monocotyledon species, auxin herbicides are not effective at labeled rates; and glyphosate and imazapyr are not effective as in water treatments. Herbicides that are effective for hydrilla control include: copper, diquat, endothall, and fluridone (Langeland 1996). Copper, diquat, and endothall are fast acting contact herbicides and are often used to treat small (< 2 ha) hydrilla populations (Langleland 1996). Fluridone is typically used in large scale herbicide applications (>2 hectares) (Langleland 1996), and according to

Netherland and Getsinger (1995), the exposure time of fluridone is the most important factor associated with controlling hydrilla, regardless of treatment rate. Limited exposure times due to wave action and current when using fluridone can reduce efficacy.

Herbicide resistance in aquatic plants is a relatively new phenomenon, although resistance has a longer history in terrestrial plants (Poovey et al. 2005). However, fluridone resistance was documented in 2004 in hydrilla populations in Florida (Michel et al. 2004). Hydrilla and wild radish (*Raphanus raphanistrum* L.) are currently the only vascular plants known to be resistant to PDS inhibiting herbicides (Poovey et al. 2005). Herbicide resistance is a major concern; in order to combat the problem new herbicides and modes of action are needed for controlling aquatic weeds.

Hydrilla Long Term Management

When developing long term management plans for invasive nuisance aquatic plants, such as hydrilla, an aquatic plant management plan is needed. A management plan should contain eight components: prevention, problem assessment, project management, monitoring, education, management goals, site specific management, and evaluation (Madsen 2005). By utilizing these components managers will be able to establish protocols to prevent new introductions of nuisance plant species and provide an early detection rapid response program (Madsen 2005).

Presence/absence sampling techniques can be used to quickly collect large amounts of data. Two techniques that use this approach are point intercept and line intercept sampling methods (Madsen 1999). The objective of point-intercept sampling is to collect data at regularly spaced pre-defined locations and to avoid subjectively selecting locations in the field (Madsen 1999). This sampling approach can be used for monitoring plant populations (Madsen et al. 1994), assessing the spread of exotic plant colonies (Madsen et al. 1991), and assessing the effectiveness of aquatic plant management techniques (Madsen 1999). The utilization of point-intercept surveying within hydrilla sites at the Ross Barnett Reservoir, before and after treatments will be able to show how efficient chemical control techniques are to reduce hydrilla occurrence, and will enable a species percentage to be calculated for each sampled area annually. Analyzing the percentage of plant occurrence will allow managers to see increases or decreases in plant presence based on management efforts for controlling certain plant species.

The ability of hydrilla to reproduce using special reproductive organs, tubers and turions, has thwarted management actions in infested areas (Sutton and Porter 1985). Tuber and turion production is assumed to be a major factor associated with re-growth of hydrilla after winter die-back and control strategies, such as herbicide application (Sutton and Porter 1985). Core sampling an area with established hydrilla populations can allow for the assessment of possible tubers in the sediment. Tuber sampling data is beneficial by allowing managers to see how chemical control not only effects above ground reproductive structures (turions and propagules), but below ground reproductive structures (tubers) as well.

Rapid dissipation of herbicide residues is commonly desired in aquatic systems, but may result in poor plant control due to short contact time with the target plant species (Netherland and Getsinger 1992). Within aquatic plant communities, water exchange characteristics can be subtle and site specific. Utilizing dye studies offers insight into bulk water-exchange which can enable herbicide half-lives to be determined prior to herbicide application (Wersal and Madsen 2011). Studies have shown significant relationships between the dissipation rates of rhodamine WT dye and aquatic herbicides (Turner et al. 1994, Fox et al. 1991). Herbicide concentration and exposure time (CET) is essential to achieving plant control and determining CET relationships should be able to improve and predict plant control in areas with varying water exchange (Netherland and Getsinger 1992).

Higher plants are unique in their ability to have natural tolerances toward certain herbicides that significantly affect other closely related plant species. This selective behavior of herbicides is widely exploited in row crop agriculture to control weeds in crops that are tolerant to the particular herbicide(s) being applied (Kreuz et al. 1996). In aquatic plant management, the use of aquatic herbicides for selective removal of invasive nuisance plant species is often desired to promote growth of native vegetation and improve the aesthetics of a water body (Netherland et al. 1997). Due to the negative impacts caused by introductions of exotic nuisance plant species, removal of nuisance vegetation with minimal damage to non-target plants (i.e. selectivity) is often desired when managing public and private waters (Netherland et al 1997). In order to effectively achieve selective control of nuisance invasive plants, information is needed regarding the potential effects of the test herbicide on non-target species, as well as its effectiveness towards the target species. Plant species, growth stage, plant phenology, translocation characteristics, herbicide treatment rates, and exposure times can all be factors affecting the selective characteristics of particular herbicides (Glomski and Mudge 2009).

In order to develop sound aquatic plant management recommendations for the Ross Barnett Reservoir a series of techniques were used to meet the following objectives:

Objectives of Research

- Compare hydrilla populations between managed and unmanaged systems using presence/absence surveys and hydrilla tuber sampling;
- Evaluate bulk water exchange characteristics in up to eight hydrilla sites using Rhodamine WT dye in order to evaluate water movement within different parts of the Ross Barnett Reservoir;
- Test the selectivity of several different herbicides for hydrilla control in the presence of submersed, emergent, and floating native aquatic plant species.

The utilization of point-intercept surveying within hydrilla sites at the Ross Barnett Reservoir, before and after treatments will be able to show how efficient chemical control techniques are to reduce hydrilla occurrence, and will enable a species percentage to be calculated for each sampled area annually. Analyzing the percentage of plant occurrence will allow managers to see increases or decreases in plant presence based on management efforts for controlling certain plant species. Hydrilla tuber sampling within sites that continually produce hydrilla plants will allow for more insight on whether herbicide treatments are actually reducing tuber production and if fragmentation is actually the cause for repeated hydrilla occurrence.

The utilization of rhodamine WT dye at the Ross Barnett will allow for more sound aquatic plant management recommendations and will result in site specific treatments where appropriate herbicides, application rates, and treatment techniques can be used to gain optimal control within a given area. In order to test the selectivity of several different herbicides for hydrilla management, a mesocosm herbicide selectivity study will allow for more insight into herbicide selection with regards to hydrilla control and its effects on native aquatic plant species

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CHAPTER II

IMPACT OF HYDRILLA (*HYDRILLA VERTICILLATA* L.F. ROYLE) MANAGEMENT ON CO-OCCURRING NATIVE PLANTS AND HYDRILLA TUBER BANK DYNAMICS BETWEEEN MANAGED AND NON-MANAGED SYSTEMS

Abstract

Hydrilla was first recorded in the Ross Barnett Reservoir in 2005. Since its discovery, chemical control options have been utilized to manage hydrilla stands within the reservoir. To ensure that current aquatic plant management techniques are effective, assessments and intensive surveying are imperative to ensure success of a long-term management program. In order to evaluate hydrilla management and native aquatic plant distribution within treatment areas a series of point intercept surveys were conducted within known hydrilla sites at the Ross Barnett Reservoir in order to compare changes in plant occurrence between years. Point intercept survey data were collected during September 2012 and September 2013. Data were then subjected to a McNemar's statistical test that tested for a statistical change in occurrence from one year to the next. In addition to testing for frequency of occurrence, native species richness was calculated and analyzed in order to see changes between months and between years. Species richness data were subjected to a general linear model and means were separated using a Fisher's protected LSD test. Hydrilla tuber surveys were also conducted during winter

and spring of 2012 and 2013. Four managed hydrilla sites were chosen in the Ross Barnett Reservoir, and core sampling data were compared to data collected during 2007 in the Tennessee-Tombigbee Waterway. Hydrilla tuber weight (g), tuber biomass (dry wt. m^{-2}), tuber density (number of tubers m^{-2}) and above ground biomass (dry wt. m^{-2}) were subjected to a general linear model to determine differences between a managed (Ross Barnett Reservoir) and unmanaged (Tennessee-Tombigbee Waterway) hydrilla site.

Introduction

The submersed aquatic plant hydrilla (*Hydrilla verticillata* L.f Royle), a native of Asia, was first discovered in the United States in a Florida canal in 1960 (Blackburn et al. 1969, Langeland 1996). Since its introduction into the United States, many management efforts have focused on controlling hydrilla populations. Hydrilla is a versatile plant species that can grow in a variety of water conditions (Yeo et al. 1984). Due to its adaptive ability, reproductive habits, and rapid growth it has been referred to as the "the perfect aquatic weed" (Langeland 1996).

Hydrilla management is an extremely expensive task and funding is often insufficient for adequate control (Langeland 1996). Mechanical, biological, and chemical control techniques have all been used to suppress and eradicate hydrilla populations. Mechanical control is generally an expensive temporary solution and used when immediate removal is necessary (Langeland 1996, Serafy et al. 1994). Biological control options are also available for hydrilla management. Grass carp (*Ctenopharyngodon idella*) have been documented as an effective control option, but selective plant management is difficult to obtain (Van Dyke et al. 1984). Several snail and insect species have also been considered as hydrilla management tools. Snail species have been shown to control hydrilla, but only under simulated experimental conditions (Langeland 1996). Insect species, such as the Indian leaf mining fly (*Hydrellia pakistanae* Deonier) and an aquatic moth (*Parapoynx dimutalis* Snellen) are also potential biological control options (Center et al. 1996, Langeland 1996). Given the expensive and/or unpredictable outcome of other control techniques, chemical control is most often implemented for hydrilla management due to its consistent effectiveness. Both contact and systemic herbicides are available for hydrilla control. Contact herbicides such as, copper, diquat, endothall, and flumioxazin, are typically only used to treat small areas (Langeland 1996). The systemic herbicide fluridone is most often used for large scale applications (>2 hectares) (Langeland 1996). In addition to fluridone, several new systemic herbicides, such as penoxsulam and bispyribac-sodium have recently been registered for aquatic use and claim to selectively control hydrilla (Netherland 2011).

Hydrilla has multiple means of reproduction and can proliferate through tuber and turion production, as well as, seed and fragmentation (Langeland 1996). Tubers and turions are asexual propagules that provide a means of reproduction annually. Tubers are actually "subterranean turions" that form in the sediment, whereas turions form in the axils or leaves and/or branches (Yeo et al. 1984). Tubers originate at the terminal nodes of rhizomes, range from 4 to 15 mm in length and can appear black to off white in color (Netherland 1997). Dioecious hydrilla tubers have been shown to form between October and April, and tuber formation is a response of the plant to shorter day lengths (Haller et al. 1976, Van et al. 1978). Tubers remain viable for several years. Monoecious hydrilla tubers have been reported to survive over 4 years in undisturbed sediment (Van and Steward 1990). The ability of hydrilla tubers to remain viable in the sediment for long periods of time enable it to form a tuber bank; which can lead to annual re-establishment of plants although other plants have been removed.

Hydrilla was first recorded in the Ross Barnett Reservoir in 2005 (Wersal et al. 2006). Since its discovery, chemical control options have been utilized to manage hydrilla stands within the reservoir. Since 2006, hydrilla has been managed with a combination of the contact herbicides copper [7-oxabicyclo(2.2.1) heptanes-2,3-dicarboxylic acid] and diquat [6,7-dihydrodipyrido(1, 2-a:2',1-c) pyrazinediium] and the systemic herbicide fluridone [1-methyl-3-phenyl-5-[3-trifluoromethylphenyl]-4(1*H*)-pyridinone]. Copper/diquat combinations and fluridone applications have proven successful, and have greatly reduced hydrilla in certain parts of the Ross Barnett. However, new sites are forming in other areas, most likely through hydrilla fragmentation, natural water dispersal, human activity, and waterfowl. To ensure that current aquatic plant management techniques are effective, assessments and intensive surveying are imperative to ensure success of a long-term management program (Madsen 2005). In order to gain insight on the success of the current hydrilla management procedures at the Ross Barnett Reservoir several objectives were formulated. The objectives of this research were to:

1. Conduct point-intercept surveys within hydrilla sites annually to document changes in hydrilla occurrence. Is chemical management significantly reducing hydrilla occurrence within sites? 2) Identify changes in the occurrence of native plant species within managed hydrilla sites. Is

chemical management negatively affecting non-target native plant species? 3) Provide an analysis of hydrilla tuber bank dynamics between managed and unmanaged systems. Does chemical hydrilla management have an impact on the establishment of a hydrilla tuber bank?

Materials and Methods

Hydrilla Site Surveys

A point intercept survey within known hydrilla sites at the Ross Barnett Reservoir was conducted during March, May, and September of 2012 and 2013 in order to evaluate hydrilla management and aquatic plant distribution. Surveys were conducted by overlaying known hydrilla sites with a grid of points, created in ArcMap10®, Arc GIS computer software, and surveying each point located within that site. Navigation between points and the display and collection of spatial and attribute data were recorded electronically with a Trimble Yuma™ (Sunnyvale, California) tablet computer utilizing templates and pick lists created in Farm Works® Farm Site Mate software version 11.4 (Hamilton, Indiana) (Cox et al. 2011). A weighted plant thatch rake with an attached rope and/or visual observations were used to determine presence or absence of a plant species. Plant presence and absence data were recorded into template pick lists by recording a "1" for presence and "0" for absence. Water depth at each point was also recorded using a Lowrance LCX-28 depth finder (Tulsa, Oklahoma) or a sounding rod. Total number of points sampled during each sampling trip varied due to water level fluctuations, overgrowth of plants that limited boat access, and the addition of newly discovered hydrilla sites. Because of inconsistencies between the numbers of points sampled within each site, nine of the thirty known hydrilla sites were selected for data analysis (Figure

2.1) In order to compare changes in plant occurrence between years, presence/absence data collected during September 2012 and September 2013 was subjected to a McNemar's statistical test that tested for a statistical change in occurrence of plant species in correlated data sets (i.e. sample the same point multiple times). Due to limited occurrence by many plant species only the most frequently occurring plant species were used in the analysis. These consisted of: alligatorweed (*Alternanthera philoxeroides* (Mart). Griseb), fanwort (*Cabomba caroliniana* A. Gray), coontail (*Ceratophyllum demersum* L), hydrilla, water primrose (*Ludwigia peploides* (Kunth) P.H. Raven), American lotus, (*Nelumbo lutea* Willd), and white water lily, (*Nymphaea odorata* Aiton). In addition to testing for frequency of occurrence, native species richness was also calculated and analyzed in order to detect changes between months and between years. Species richness data were subjected to a general linear model and means were separated with a Fisher's protected LSD. All statistical analysis was performed using SAS 9.3® (SAS Institute, Inc., Cary, NC).

Tuber Bank Analysis

In order to evaluate the effect of hydrilla management on hydrilla tuber production; tuber surveys were conducted during winter and spring of 2012 and 2013 at the Ross Barnett Reservoir and Tennessee-Tombigbee Waterway (Tenn-Tom Waterway). Four managed hydrilla sites were chosen in the Ross Barnett Reservoir that have a history of tuber sampling (Wersal et al. 2006) and have continually shown hydrilla growth after herbicide treatments (Figure 2.2). In addition to the managed hydrilla sites, data collected from the Tenn-Tom Waterway during 2007 were used to compare differences between the two lakes (Figure 2.3). The Tenn-Tom Waterway has received little if any hydrilla management activity, and good historical hydrilla population data exists (Robles 2009). A total of 20 sediment samples were collected from each site at the Ross Barnett Reservoir utilizing a PVC coring device (Madsen et al. 2007), similar methods were used during sampling at the Tenn-Tom waterway in 2006 and 2007 (Robles 2009). The sediment was collected and sieved through a pail with a wire mesh bottom to separate any plant material from sediment. Above ground hydrilla biomass and tubers found were collected and transported to Mississippi State University. Tubers and above ground biomass were sorted and placed in a plant dryer at 70º C in for several days. Once the material was dried and weighed, above ground biomass, tuber biomass, tuber weight, and tuber density were calculated. Data were subjected to a general linear model using SAS 9.3® statistical software to determine differences between variables. A Fisher's protected LSD test was then applied at a $p = 0.05$ level of significance to separate mean differences between the tested variables.

Results

Hydrilla Site Surveys

The results of the point-intercept surveys indicated that out of the seven major species present within each site, only three species: alligatorweed, fanwort, and hydrilla were significantly reduced. From September 2012 to September 2013 hydrilla frequency was significantly reduced by 50% in the sampled sites following June and August herbicide treatments (Table 1). Alligatorweed and fanwort were also significantly affected. The significant reduction in alligatorweed occurrence is most likely attributed to the intensive lake wide herbicide applications of 2,4-D [(2,4-dichlorophenoxy)acetic acid] and glyphosate[N-(phosphonomethyl)glycine] aimed at controlling alligatorweed and water hyacinth (*Eichhornia crassipes* [Mart.] Solms). The only adversely affected native plant species was fanwort. Fanwort is a native submersed plant species that is less competitive than other aquatic species and is sensitive to the herbicides diquat, copper sulphate, and fluridone (Parsons and Cuthbertson 2001) all of which most likely contributed to the significant reduction from 14.1 % in 2012 to 6.8 % in 2013. Water primrose (44% and 40.1%), American lotus (32% and 38%), and white water lily (38% and 31%) were the most frequently recorded species accounting for greater than 30% occurrence in September of 2012 and 2013. Native species richness within hydrilla sites did not differ between years and followed a similar trend each month, significantly increasing as the growing season progressed (Figure 2.4). New species, such as, watershield (*Brasenia schreberi* J.F. Gmel.), brittle naiad (*Najas minor* All.), American pondweed (*Potamogeton nodusus* Poir.), and bladderwort (*Utricularia gibba* L.) became established as the growing season progressed. Although native species richness appeared lower during 2013, differences were not significant between years.

Tuber Bank Analysis

Hydrilla tuber weight, biomass, density, and above ground biomass were all significant when compared between the Ross Barnett Reservoir and Tenn-Tom Waterway. The Tenn-Tom Waterway showed significantly higher above ground biomass, tuber biomass, tuber weight, and tuber density when compared to Ross Barnett. Above ground biomass (g DW m^{-2}) in the Tenn-Tom varied from >400 g DW m^{-2} the winter to between 100-200 g DW m^{-2} in the spring (Figure 2.5). The Ross Barnett Reservoir showed < 0.1 g DW m^{-2} of above ground biomass during winter and spring sampling periods combined. Tuber biomass and tuber weight varied among months on the Tenn-Tom. During the spring, tuber biomass and tuber weight was significantly higher than the winter sampling period (Figure 2.6 and 2.7). Tuber biomass and tuber weight did not significantly differ between the Tenn-Tom winter sampling period and the Ross Barnett spring sampling period. Hydrilla tuber density followed a similar trend. Spring sampling on the Tenn-Tom showed a significantly higher number of tubers being found (140.7 N m^{-2}) than the winter sampling period (31.5 N m^{-2}) (Figure 2.8). Both the winter and spring sampling on the Tenn-Tom showed significantly higher tuber density compared to winter (1.0 N m^{-2}) and spring (6.9 N m^{-2}) sampling on the Ross Barnett.

Discussion

Hydrilla Site Surveys

Since 2006, management techniques have been able to suppress and control hydrilla populations throughout the reservoir. Based on these data it is evident that intensive management and rigorous herbicide applications are reducing the occurrence of hydrilla within certain areas of the Ross Barnett Reservoir, as well as, having little impact on co-occurring native plant species. Increased native plant coverage is not atypical in herbicide treatment areas. In Lake Seminole, native submersed aquatic plants colonized most of the bottom after hydrilla was reduced following endothall and fluridone treatments (Maceina and Slipke 2004). Native plant species richness increased significantly within the selected hydrilla plots as the growing season progressed, and did not differ between years. The slight decrease in richness from 2012 to 2013 is most likely attributed to the wet spring where turbid water conditions and excess current limited plant growth early in the year.

These results are beneficial, showing that native plant richness is not declining due to invasion of hydrilla and/or application of herbicides. It is believed that increased plant species occupy more available niche space and thus limit the opportunity for additional species to establish (Elton 1958). Very high native plant densities are thought to be able to prevent the establishment of non-native propagules; therefore reducing the chances of non-native species establishment (Capers et al. 2007). However, it is also suggested that at increased spatial scales invasive species are more likely to be found in areas with the highest native species richness (Levine and D'Antonio 1999, Lonsdale 1999) and suggest that no matter how diverse a community is, it does not resist invasion (Capers et al. 2007).

The use of point intercept surveys within hydrilla sites allowed for the assessment of the current hydrilla control program for the Ross Barnett Reservoir. The use of chemical treatments has suppressed hydrilla growth with no significant impact to the native plant community. Although chemical treatments are showing success at particular locations, new areas are being found typically in close proximity to existing sites. This suggests that fragmentation and transport by boats and water currents are the primary method of hydrilla dispersal within the Ross Barnett. It is important to continue chemical treatments within hydrilla sites and to educate reservoir users on the potential impacts hydrilla can cause.

Tuber Bank Analysis

Herbicide treatments at the Ross Barnett Reservoir are limiting hydrilla tuber production. Dioecious hydrilla forms tubers from October through April in Florida (Haller et al. 1976), and subsequent hydrilla treatments between June and October at the

Ross Barnett may be limiting hydrilla tuber formation. It has been shown that fluridone applied at rates of 5 to 50 $\mu g\ L^{-1}$ could limit tuber formation (MacDonald et al. 1993). Due to fluridone having a long persistence, ability to accumulate in the sediment, and activity at low concentrations it has the potential to inhibit tuber sprouting (Netherland 1997). Intense herbicide management aimed at preventing hydrilla tuber formation for several years has been shown to substantially deplete tuber numbers (Sutton 1996). Miller et al. (1993) reported that turions were not produced significantly until October when day lengths were less than 12 hours, production then declined during December to February and increased again in March. Herbicide treatments during the summer and early fall at the Ross Barnett Reservoir may be preventing tuber production by reducing plants available for tuber production.

These data suggest from a management perspective, that management of the tuber bank will lead to a reduction in year to year recruitment of hydrilla, sustain native plant diversity, and new infestations within the Ross Barnett are most likely from plant fragmentation. In order to prevent the establishment of large hydrilla populations, early detection and rapid response coupled with intensive chemical management is essential. Eradication of small populations is much easier and much more likely than when managing a large population (Madsen 2005). Future research into some of the new chemistries recently registered for hydrilla control may provide additional tools that managers can use to limit hydrilla growth and tuber production

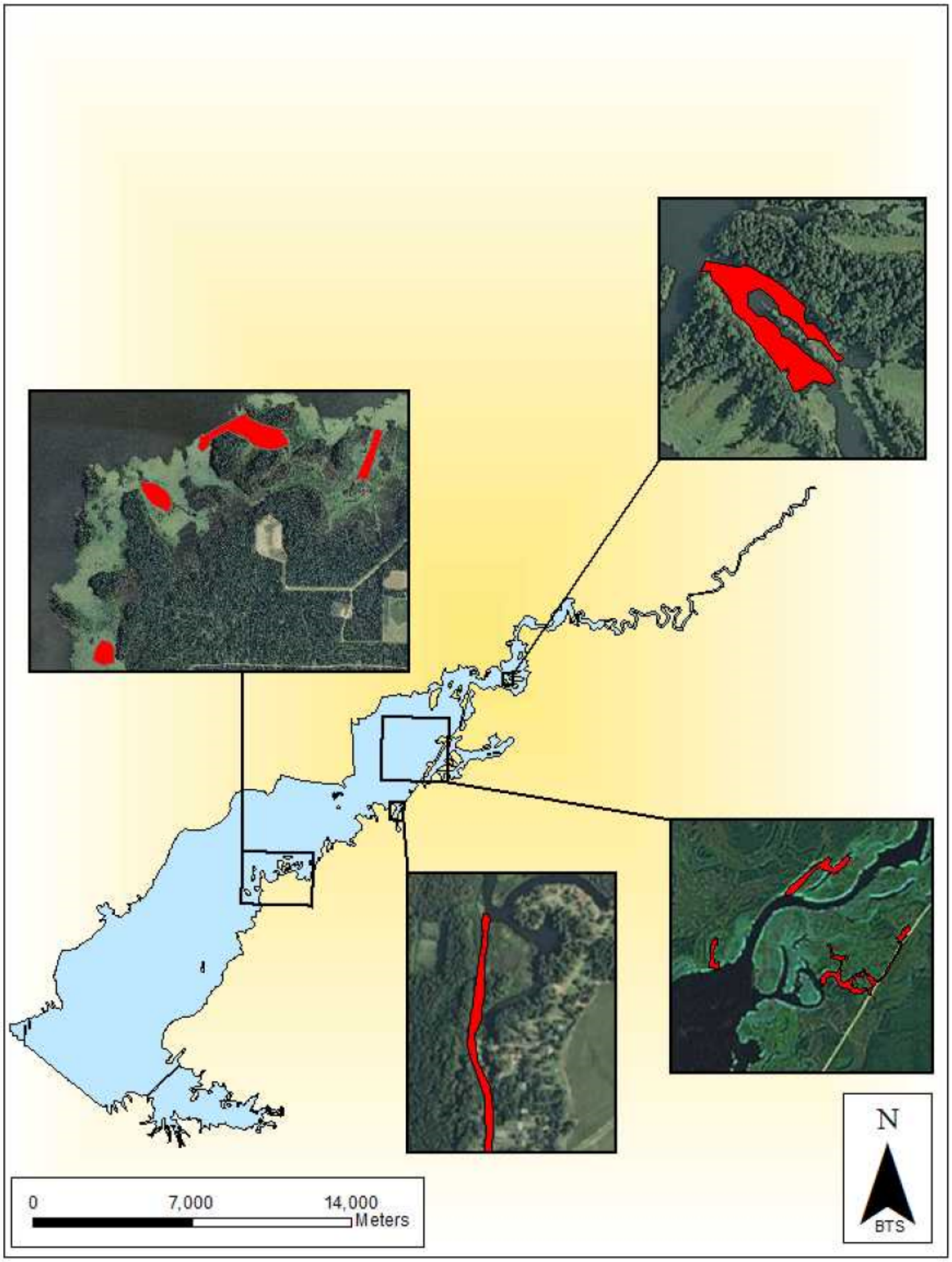

Figure 2.1 Selected hydrilla sites used for comparison of point intercept data within the Ross Barnett Reservoir, Mississippi.

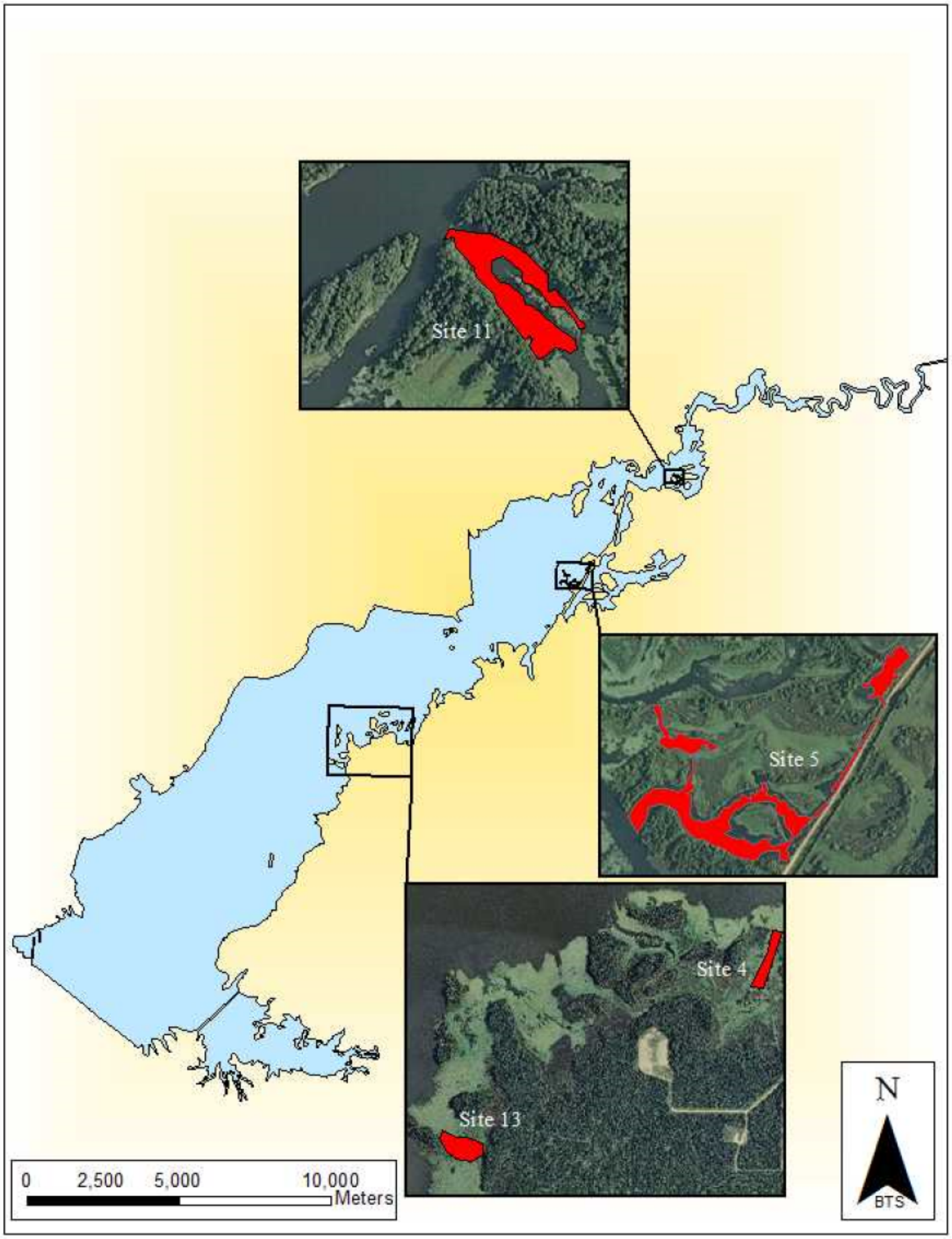

Figure 2.2 Hydrilla tuber sampling locations within the Ross Barnett Reservoir, Mississippi.

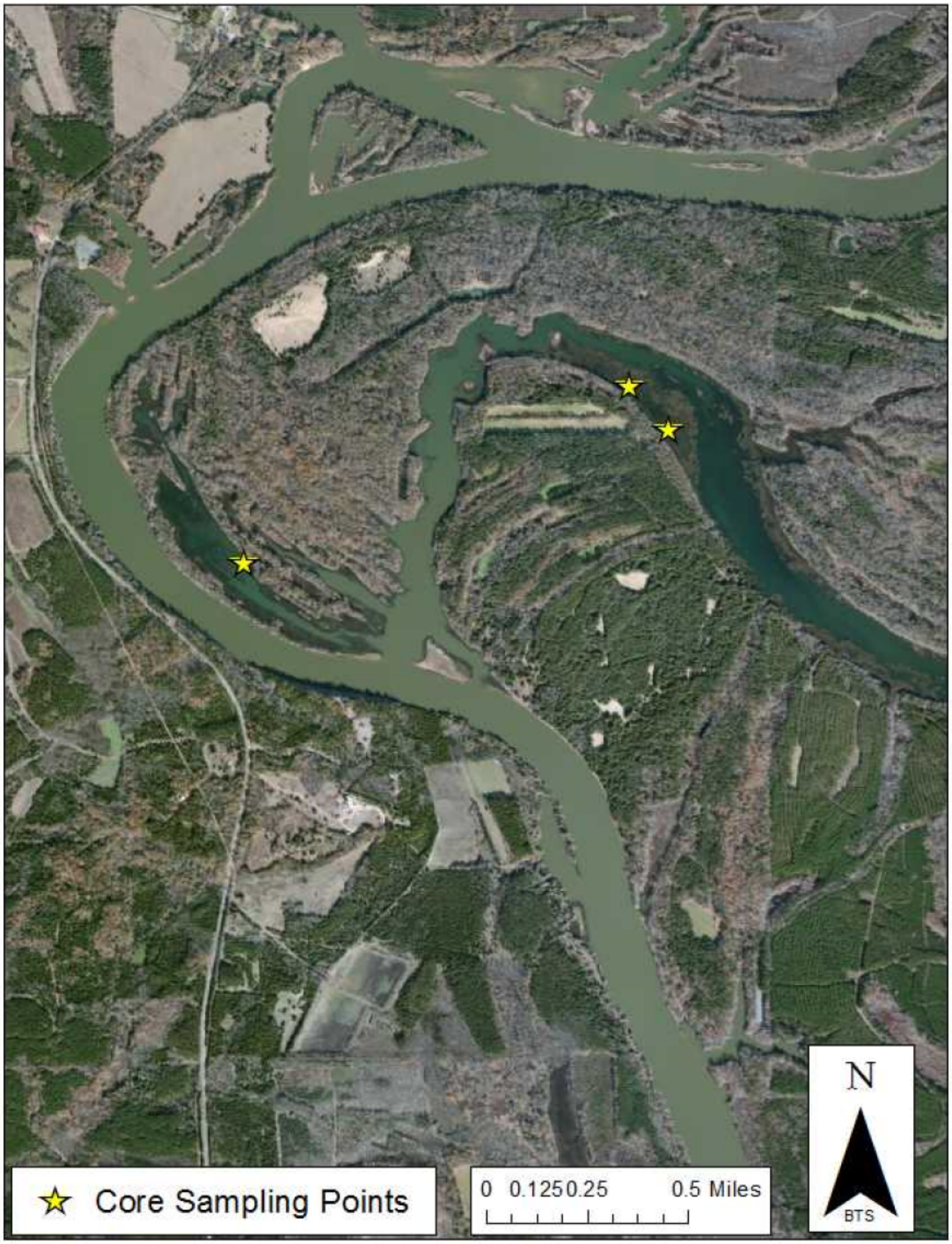

Figure 2.3 Hydrilla core sampling locations within the Tennessee-Tombigbee Waterway, Alabama in 2007 (Robles 2009).

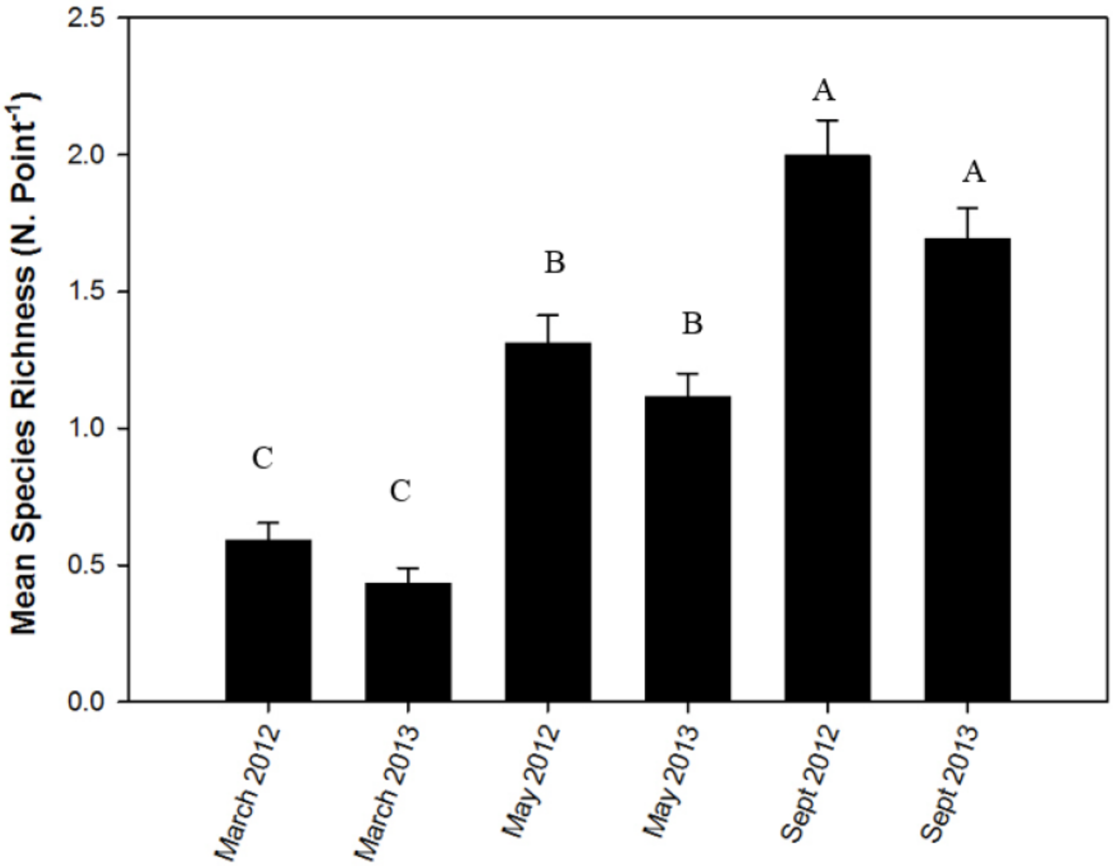

Figure 2.4 Mean native plant species (number of species observed at each point) at each sampled location on the Ross Barnett Reservoir from March 2012-September 2013.

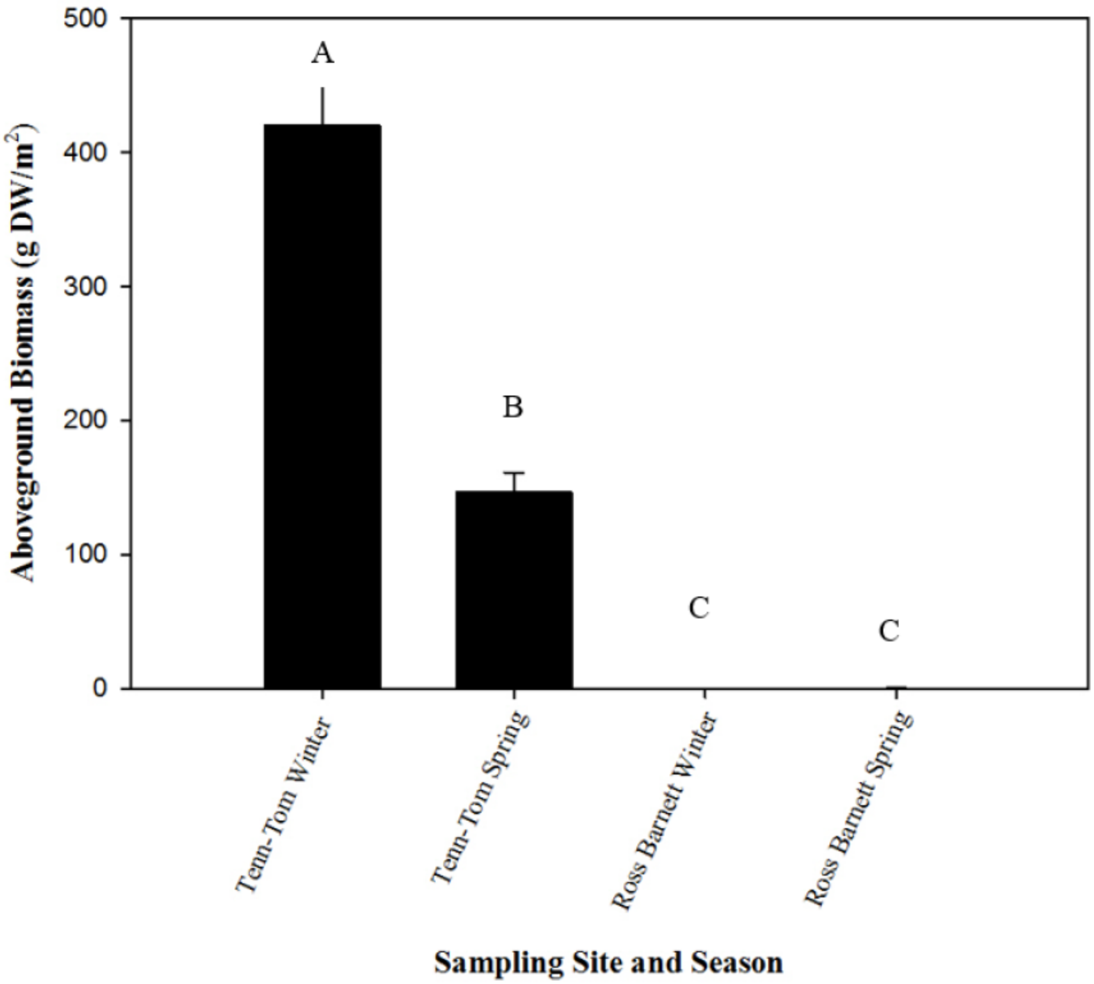

Figure 2.5 Above ground hydrilla biomass (g DW m^{-2}) from ANOVA of Ross Barnett Reservoir vs. Tennessee-Tombigbee Waterway within sampled hydrilla sites.

Means with the same letter are not significantly different at the p=0.5 level.

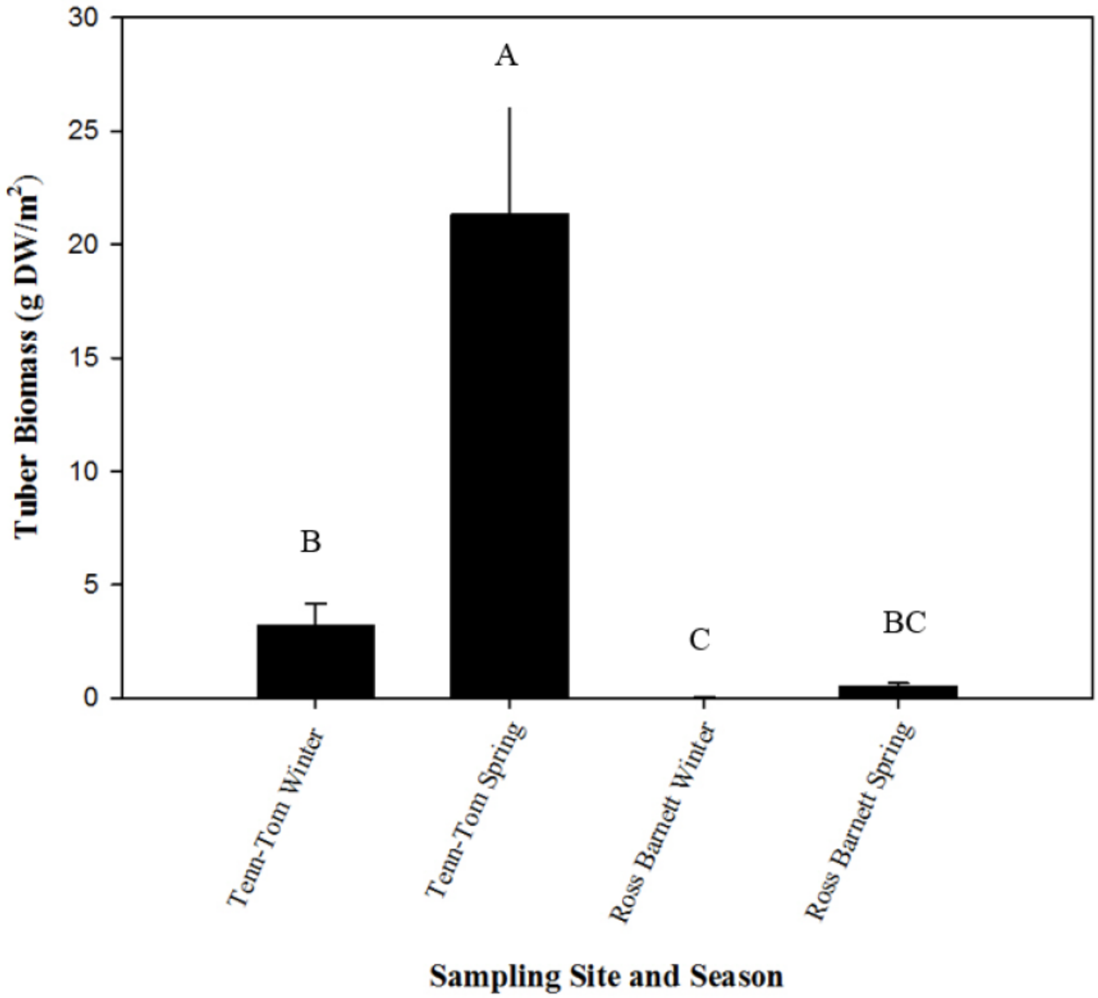

Figure 2.6 Hydrilla tuber biomass (g DW m^{-2}) from ANOVA of Ross Barnett Reservoir vs. Tennessee-Tombigbee Water within sampled hydrilla sites.

Means with the same letter are not significantly different at the p=0.05 level.

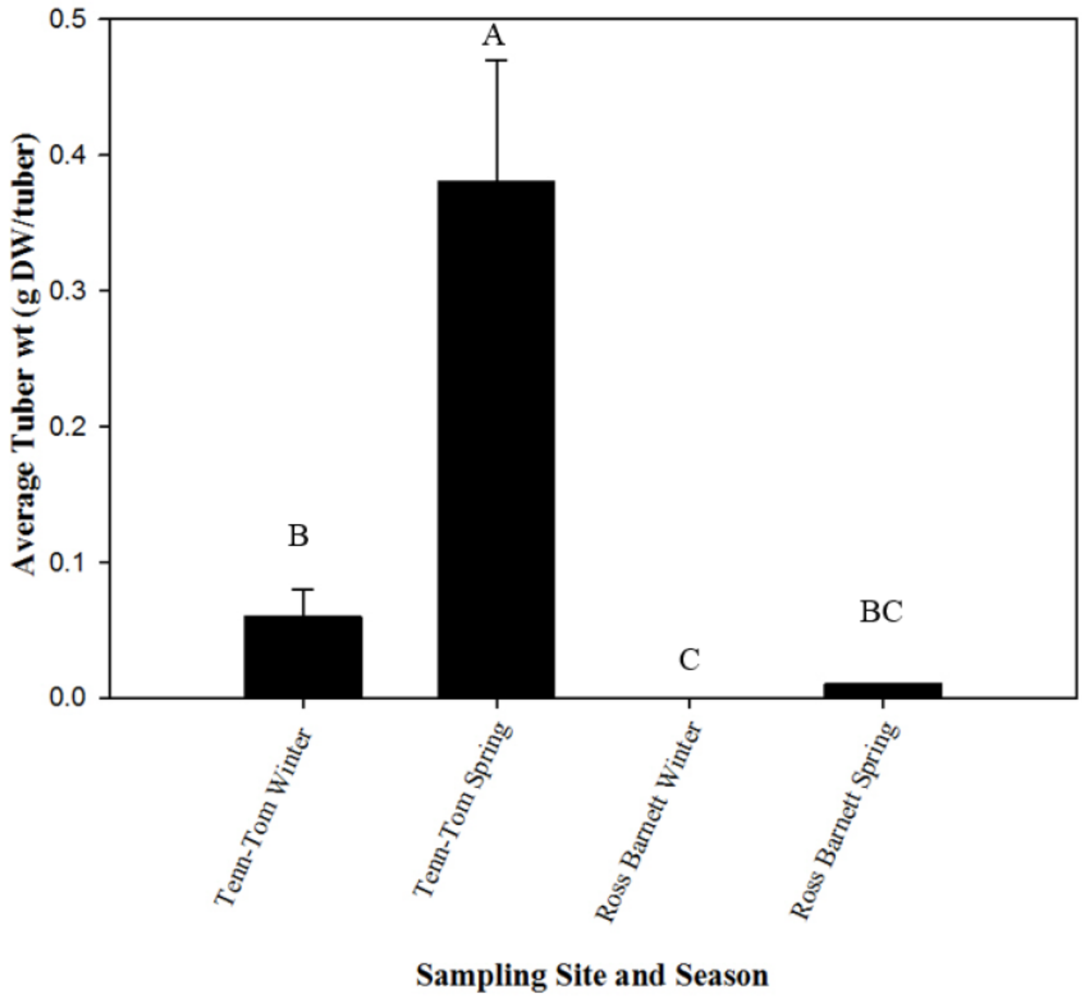

Figure 2.7 Average hydrilla tuber weights (g DW per tuber) from ANOVA of Ross Barnett Reservoir vs. Tennessee-Tombigbee Waterway sampled hydrilla sites.

Means with the same letter are not significantly different at the p=0.05 level.

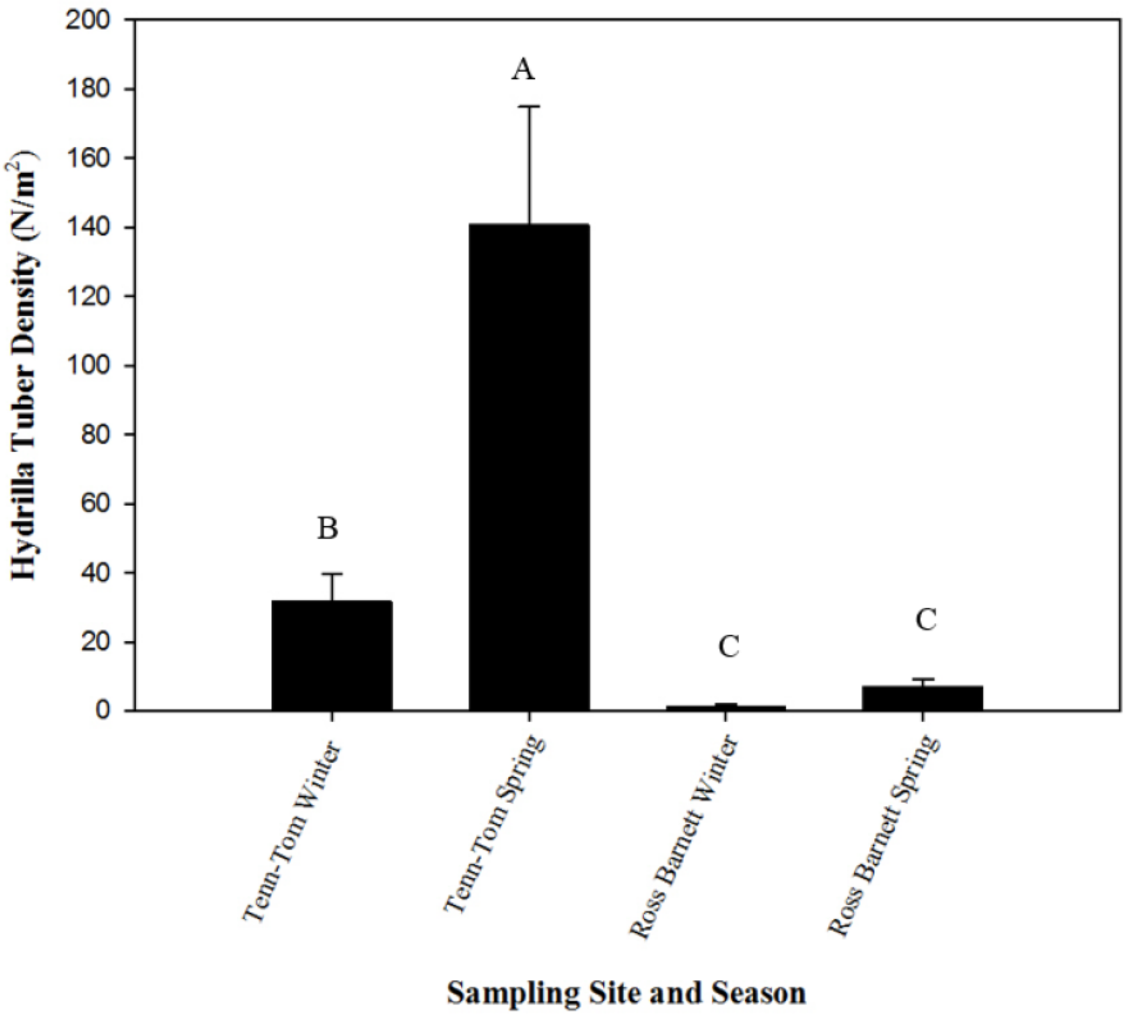

Figure 2.8 Hydrilla tuber density (N m^{-2}) from ANOVA of Ross Barnett Reservoir vs. Tennessee-Tombigbee Waterway within sampled hydrilla sites.

Means with the same letter are not significantly different at the p=0.05 level.

Table 2.1 Percent frequency of occurrence for seven frequently observed plant species within known hydrilla sites of the Ross Barnett Reservoir during September 2012 and September 2013.

Species Name	Common Name	September 2012 % Frequency (n=177)	September 2013 % Frequency (n=177)
Alternanthera philoxeroides	Alligatorweed	5.6	0.6a
Cabomba caroliniana	Fanwort	14.1	6.8a
Ceratophyllum demersum	Coontail	11.9	14.7
Hydrilla verticillata	Hydrilla	14.1	6.8a
Ludwigia peploides	Water Primrose	44.1	40.1
Nelumbo lutea	American Lotus	32.2	37.9
Nyphaea odorata	White Water Lily	37.9	30.5

The letter "n" refers to the total number of points sampled, an "a" indicates a statistically significant change in frequency of occurrence from the previous year for the indicated plant species

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CHAPTER III

AN ANALYSIS OF BULK WATER EXCHANGE CHARACTERISTICS WITHIN HYDRILLA STANDS IN THE ROSS BARNETT RESERVOIR

Abstract

The Ross Barnett Reservoir is home to a variety of both emergent and submersed aquatic plants, including hydrilla (*Hydrilla verticillata* L.f. Royle). Management and control efforts have been implemented since 2006 in order to prevent the spread of hydrilla populations within the reservoir and throughout the state of Mississippi. Using hydrilla management data from previous years, including herbicide selection and survey data, eight plots infested with hydrilla were chosen for water exchange studies. The eight plots have exhibited inadequate control in previous years; however, little information regarding site characteristics is known, including bulk water exchange. Four of the eight plots chosen were located above Mississippi highway 43 and sampled during June of 2011. The remaining four plots were located below Mississippi highway 43 and sampled during June of 2012. Rhodamine WT dye was applied to each of the eight plots at a target concentration of 10 parts per billion (ppb) and dye monitored right after treatment, 1 hour after treatment (HAT), and every 3 hours afterward until a dye half-life could be determined. Dye half-life varied between the eight plots, with a minimum estimated half-life of 2.0 hours and maximum estimated half-life of 30.9 hours. Water exchange information will be used to select herbicide active ingredients, treatment rates and

treatment methods based on anticipated contact time. Alternative strategies may be needed to gain adequate hydrilla control in areas with high water exchange.

Introduction

The Ross Barnett Reservoir is a 13,355 hectare (33,000 acre) water body located in Central Mississippi. It serves as the primary water supply for the state's capital city, as well as, many recreational water activities. The reservoir is home to a variety of both emergent and submersed aquatic plants, including hydrilla (*Hydrilla verticillata* L.f. Royle), which was first recorded in 2006.   Since its discovery, management and control efforts have been implemented in order to prevent the spread of hydrilla throughout the reservoir. Various herbicides have been used to control hydrilla within the Ross Barnett. The systemic herbicide fluridone {1-methyl-3-phenyl-5-[3-(trifluromethyl) phenyl]-4(1H)-pyridinone} , as well as, combinations of the contact herbicides copper chelate (7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid) and diquat (6, 7-dihydrodipyrido[1,2-α:2',1'-*c*]pyraxinediium dibromide) have been utilized to control hydrilla.

When applying submersed herbicide applications, concentration and exposure time relationships are important for successful treatment. Rapid dissipation of herbicide residues may result in poor plant control due to short contact time with the target plant species (Netherland and Getsinger 1992). The systemic herbicide fluridone is degraded primarily by photolysis (Mossler et al. 1989), but high water exchange rates have been shown to have an impact on fluridone half-lives within larger treatment areas (Fox et al. 1993, Getsinger et al. 1990, Getsinger et al. 1992). Laboratory and mesocosm studies have analyzed concentration and exposure time relationships on several submersed aquatic plants using fluridone at rates ranging from 0.05 to 1000 µg $^{-L}$ (maximum label rate = 150 µg^{-L}) with various exposure times, from one hour to several months (Anderson 1981, Hall et al. 1984, Van and Steward 1986, Van and Conant 1988, Spencer and Ksander 1989, Spencer et al. 1989, Macdonald et al. 1993, Netherland et al. 1993, Netherland and Getsinger 1995a). Results from these studies suggests that although increased treatment rates increase plant injury, injury symptoms among treatment rates are relatively similar over comparable exposure times (Netherland and Getsinger 1995b).

The contact herbicides copper and diquat are both frequently used to control nuisance aquatic plant species. Diquat has been a valuable tool for aquatic plant managers, particularly in situations where rapid removal of vegetation is desired, or when water exchange patterns limit herbicide exposure time towards target submersed species (Glomski et al. 2005). Tank mixes of copper and diquat have been shown to allow increased uptake of herbicide residues in target plant species. In herbicide trials assessing the effect of diquat on the uptake of copper and the effect of copper on the uptake of diquat when applied to hydrilla and southern naiad (*Najas guadalupensis* (Sprengel) Magnus), 77 and 38 percent more copper, respectively, was found in plant tissue when compared to using copper alone (Sutton et al. 1970, Sutton et al 1972).

Within aquatic plant communities, water exchange characteristics can be very subtle; utilizing dye studies offers insight into bulk water exchange which can enable herbicide half-lives to be determined prior to herbicide application (Wersal and Madsen 2011). Water exchange within plant stands can be characteristic of plant architecture and can vary from plant bed to plant bed (Wersal and Madsen 2011). Studies have shown significant relationships between the dissipation rates of Rhodamine WT dye and aquatic herbicides (Turner et al. 1994, Fox et al. 1991). Herbicide concentration and exposure time (CET) is essential to achieving plant control, and determining CET relationships should allow for improved plant control in areas with varying water exchange (Netherland and Getsinger 1992). The utilization of Rhodamine WT dye allows for more sound aquatic plant management by knowing water flow characteristics in particular sites, treatment techniques, such as, appropriate herbicide selection and application rates can be selected based off these characteristics and used to gain optimal control within a given area.

Materials and Methods

Using management and hydrilla control data from previous years, including herbicide selection and survey data, eight hydrilla plots were chosen for water exchange studies (Figure 3.1, 3.2). Rhodamine WT dye, a fluorescent dye, was applied to the water column of the eight hydrilla plots using a 25 gallon tank equipped with two weighted hoses to inject dye directly into the water column. Applications were made with a target concentration of 10 parts per billion (ppb), which is standard for water exchange evaluations (Wersal and Madsen 2011). The concentration of Rhodamine WT dye was measured throughout the water column using a Turner Designs field fluorometer (model: 8000-010). The field fluorometer is capable of detecting rhodamine dye at a concentration of 0.01 ppb (Wersal and Madsen 2011). Dye readings were conducted at equally spaced pre-determined points, created with ArcMap10© Arc GIS computer software, and navigation between each point was done using a Trimble Yuma tablet computer (Sunnyvale, California) using the Farm Works® Farm Site Mate software (Hamilton, Indiana). The dye concentration at each point were measured by lowering a weighted 12V bilge pump joined with a hose into the water column. Samples were collected at three depth intervals: surface, middle, and bottom depths. Samples were also collected outside of the plots in order to track movement of the dye. Dye concentration was monitored immediately after treatment (0 hour), one hour after treatment (HAT), and at three hour intervals until the dye concentration was no longer detected. Once the dye was no longer detected an exponential decay regression analysis was conducted to determine a whole plot dye half-life within each plot.

Results

Dye half-lives varied within each of the eight plots, with a maximum half-life of 30.9 hours and a minimum half-life of 2.0 hours. The plots located above Mississippi Highway 43 showed greater bulk water exchange (Figures 3.2 to 3.6) when compared to the plots below MS highway 43 (Figures 3.7 to 3.10). This may be due to the upriver plots close proximity to the river channel as opposed to the sites below Mississippi highway 43. Dye half-lives for the upriver plots varied from 2.0 hours (plot 1) to 14.3 hours (plot 3). Dye half-lives for the plots below highway 43 varied, with a maximum half-life of 30.9 hours (plot 6) and minimum of 10.1 hours (plot 7).

Discussion

Water flow within the Ross Barnett Reservoir is impacting water exchange within plant stands. The Ross Barnett Reservoir does contain a water control spillway on the southern end of the Reservoir, but water levels are typically stable during summer (full pool 297.50 feet). During both sampling periods water discharge rates were minimal, between 11.3 to 7.1 cubic meters per second (USGS 2013). The impacts are likely to be site specific; plots 1, 2, and 4 all had high rates of water exchange. Plot 1 exhibited the shortest dye half-life of 2.0 h. It is characterized as a shallow inlet, very close to the main river channel and connected to Fannegusha Creek; a small tributary that joins the Pearl River (Figure 3.1). Rapid water exchange in plot 1 is likely due to and dependent on the flow from Fannegusha creek. During sampling, several points were sampled outside of plot 1 to determine the direction of water movement. It was determined that the water flow was moving away from the river and back into Fannegusha creek. Plot 2 is located in close proximity to plot 1 and is situated at the mouth of Fannegusha Creek where it intersects the main river channel (Figure 3.1). Although plot 1 and 2 are no more than 100 meters apart; site characteristics differ considerably between the two. Extensive plant growth of emergent and floating plants in the back of plot 2 congests a large portion of the site which can directly impact water flow dynamics and lead to a reduction in flow velocity (Petticrew and Kalff 1992). These characteristics of plot 2 likely contributed to slower water exchange (half-life 8.8 h) when compared to nearby plot 1.

Plot 4 is located in Cane Creek, another small tributary that intersects the Pearl River (Figure 3.1). In conjunction with being located in a creek channel it is also in a residential area that receives frequent boat traffic. Boat traffic associated with varying flow regimes of Cane Creek likely influenced the rapid water exchange (4.0 h) observed within the site. Plot 3 exhibited the slowest water exchange of all the plots located above Mississippi highway 43. It is a small protected backwater located along Lake Harbor Road where it is subjected to minimal wind and boat traffic. It was once connected to the main river channel, but increased plant growth on the northern portion of the plot has since closed off access to the main channel. Minimal wind exposure, limited water movement, and excessive plant growth allowed the dye to maintain a half-life of 14.3 hours.

The four plots located below Mississippi highway 43 (Figure 3.2) all produced dye half-lives >10.1 hours. They were located on the Rankin County or Eastern shoreline of the Ross Barnett Reservoir, and all exhibited similar characteristics; small protected pockets subjected to north and northwest winds. Each of the four sites also contained extensive amounts of floating and emergent aquatic plants, most notably American lotus [*Nelumbo lutea* (Willd.)] and white water lily [*Nymphaea odorata* (Aiton)].

Plot 6 had the longest half-life of 30.9 h. It is a shallow narrow channel that is subjected to minimal wind and current which allowed dye concentrations to be maintained in the plot. During sampling of plot 6wind direction was from the southeast (9 to 10 mph), which in theory should have pushed dye out towards the main lake, though it had little influence on movement of dye out of the plot. This observation suggests that subsurface water flow may have actually been moving into the channel and away from the reservoir. Plots 5 and 8 had similar dye half-lives of 20.0 and 24.5 hours. Both plots are similar to site 6; small, shallow (average depth 1 m), protected pockets subjected to minimal wind and current. Plot 7 exhibited the fastest water exchange of all the sites below highway 43 (10.1 h). It is the least protected from wind and has a greater average depth (1.6 m) when compared to the other sampling plots below highway 43.

Based off of hydrilla treatment records and personal observations within herbicide treatment sites, water exchange is a critical factor affecting the success of herbicide treatments. During 2009, plot 6 was treated with a combination of quick release and precision release fluridone granules which provided successful control for over a year.

During 2011, the site was treated twice with contact herbicides copper and diquat, which also provided good control, but required multiple treatments the following year. Since its discovery in 2007, plot 2 received fluridone (formulation not available) treatments in 2007, 2008, and 2009, all of which resulted in little success, likely due to its estimated half-life of 2 hours. Since 2010, contact herbicide treatments have been implemented and have provided maintenance management, but multiple treatments have been needed annually. Plot 1 has also received multiple contact treatments annually since its discovery in 2010. Due to its close proximity to plot 2, which was discovered in 2007, it may have been present well before 2010. The sites that show repeated annual growth have most likely established a tuber bank and multiple herbicide treatments need to be implemented annually.

Results from this study indicate that herbicide half- lives > 10 h can be attained for fluridone applications under stable summertime lake conditions. Nawrocki (2011) showed that granular fluridone treatments in Lake Gaston, North Carolina were successful in areas with a whole plot dye half-life of 10.5 hours. Treatment plots with the least water exchange all had similar characteristics; shallow protected pockets with excessive plant growth. Due to the longer dye half-lives recorded in plots 3, 5, 6, 7, and 8 granular combinations of fluridone (quick release and slow release pellets) may be the best treatment option. Mossler et al. (1993) has shown that total granular fluridone release occurs in 10 to 16 days in mildly agitated water, thus adequate concentrations could be maintained in select sites of the Ross Barnett Reservoir. Slow release granular fluridone will allow for consistent and extended herbicide concentration in treatment areas (Netherland et al. 1998). Application timing is also important. MacDonald et al.

(1993) found that immature hydrilla plants are more susceptible to low fluridone concentrations as opposed to mature hydrilla plants. Extended granular fluridone exposure time during the phenological weak point of hydrilla growth resulted in excellent hydrilla control in Lake Gaston, North Caroline (Nawrocki 2011). Granular fluridone applications early in the growing season in areas with the least water exchange should improve hydrilla control in the Ross Barnett Reservoir.

Dye plots above Mississippi Highway 43 are likely to have increased bulk water exchange due to water flow associated to intermittent streams, the main river channel, and increased water depths. Due to the short half-lives of Rhodamine WT dye at plots 1, 2, and 4; contact herbicides may be needed in order to efficiently treat these areas. It is also important when applying diquat to cause minimal disturbance to the sediment. In several sites the hydrilla growth is along the shoreline in very shallow water. Drop hoses and boat movements can increase water turbidity causing diquat to bind to the sediment, thus becoming less efficient in the treatment areas. The unique characteristics of each hydrilla site in the Ross Barnett Reservoir calls for a management plant that is adaptive. Site specific techniques will need to be determined to address the areas where hydrilla is growing.

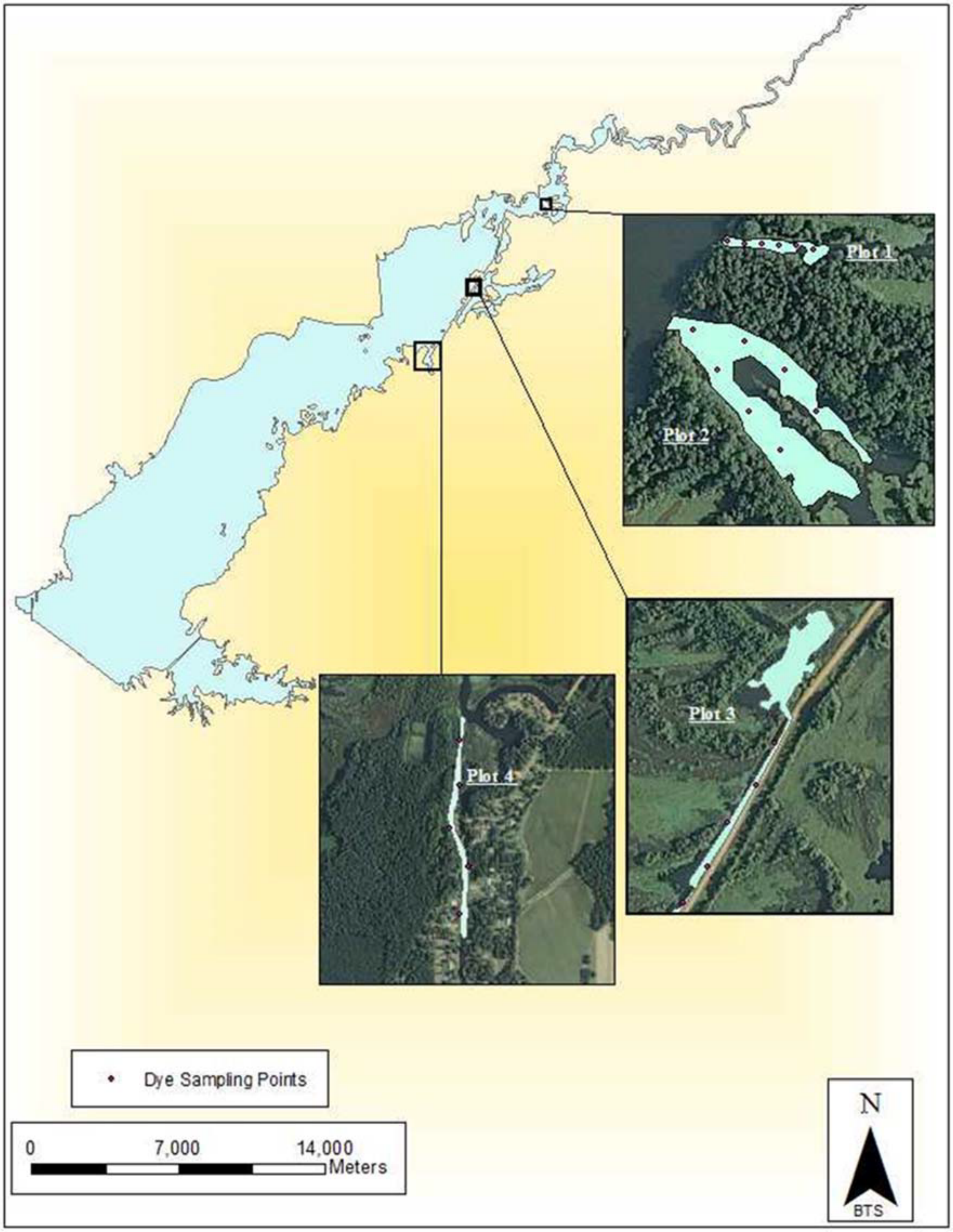

Figure 3.1 Rhodamine WT Dye sampling plots above Mississippi Highway 43 during June 2011 on the Ross Barnett Reservoir, Mississippi

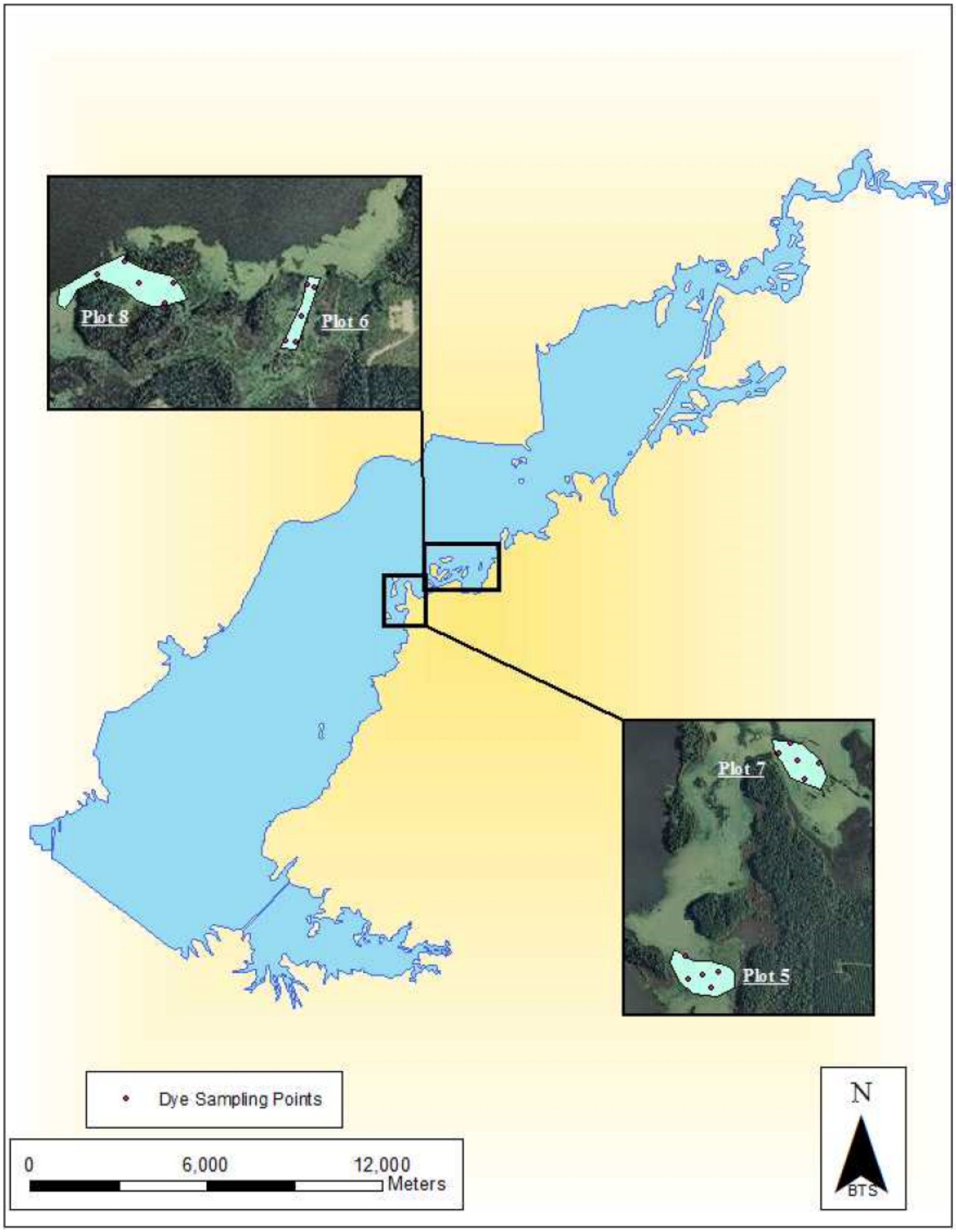

Figure 3.2 Rhodamine WT Dye sampling plots below Mississippi Highway 43 during June 2012 on Ross Barnett Reservoir, Mississippi

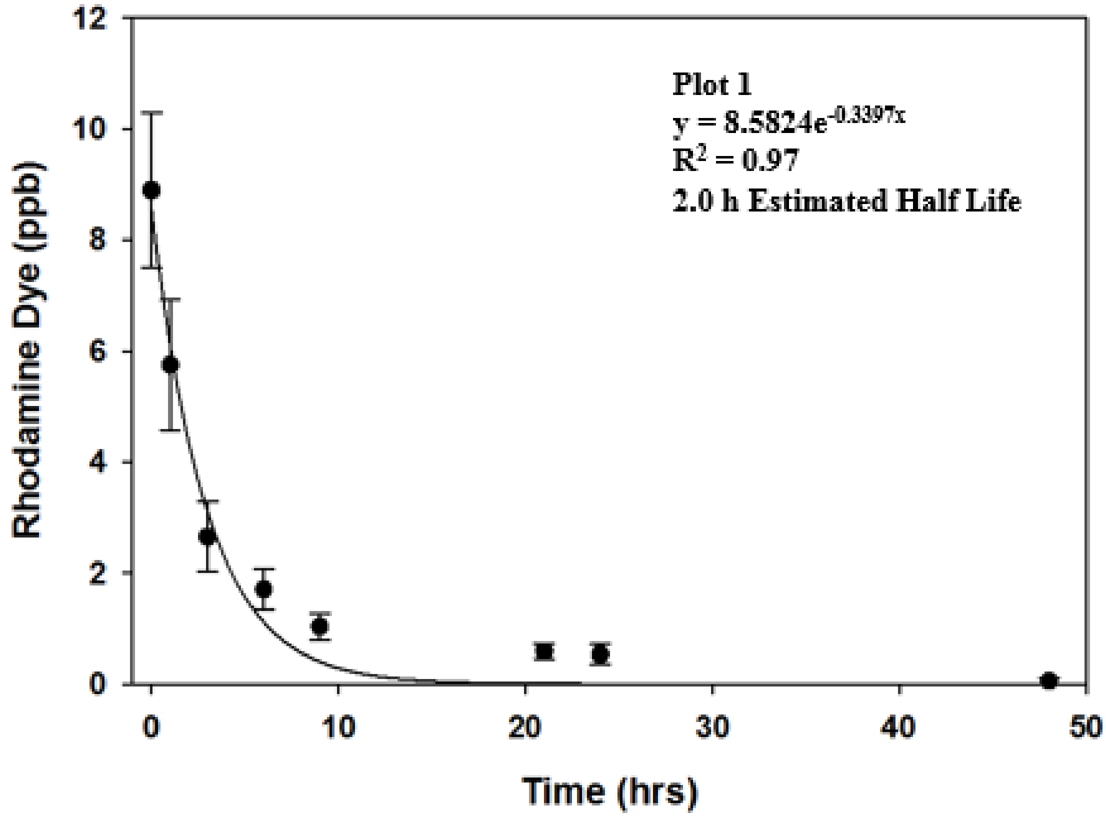

Figure 3.3 Rhodamine WT dye dissipation rate in hydrilla plot 1, Ross Barnett Reservoir, Mississippi June 27th to 29th 2011

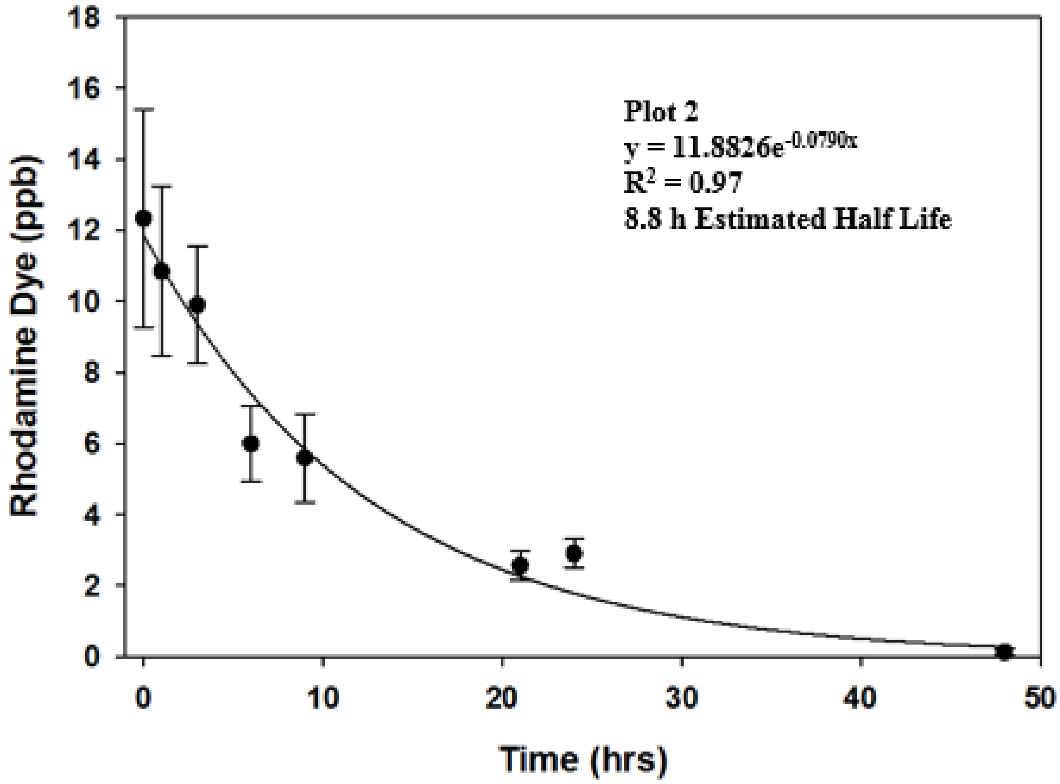

Figure 3.4 Rhodamine WT dye dissipation rate in hydrilla plot 2, Ross Barnett Reservoir Mississippi June 27th to 29th 2011

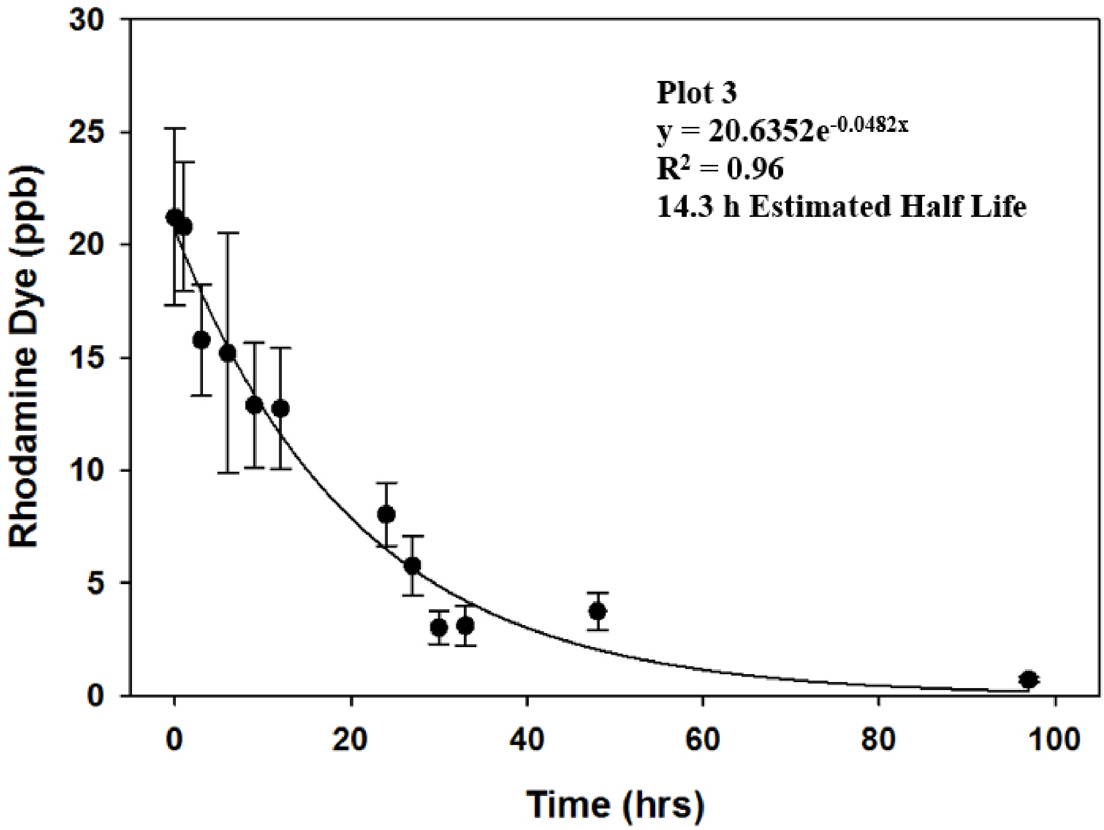

Figure 3.5 Rhodamine WT dye dissipation rate in hydrilla plot 3, Ross Barnett Reservoir, Mississippi June 29th to July 2nd 2011

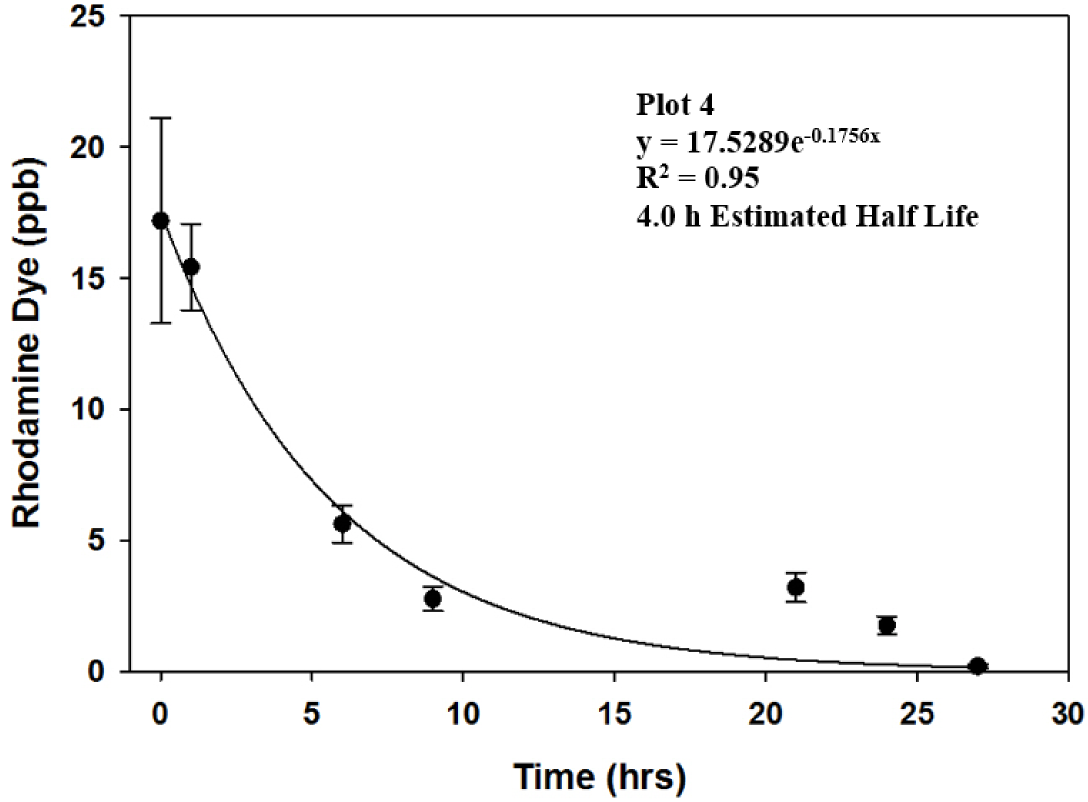

Figure 3.6 Rhodamine WT dye dissipation rate in hydrilla plot 4, Ross Barnett Reservoir, Mississippi June 29th to June 30th 2011

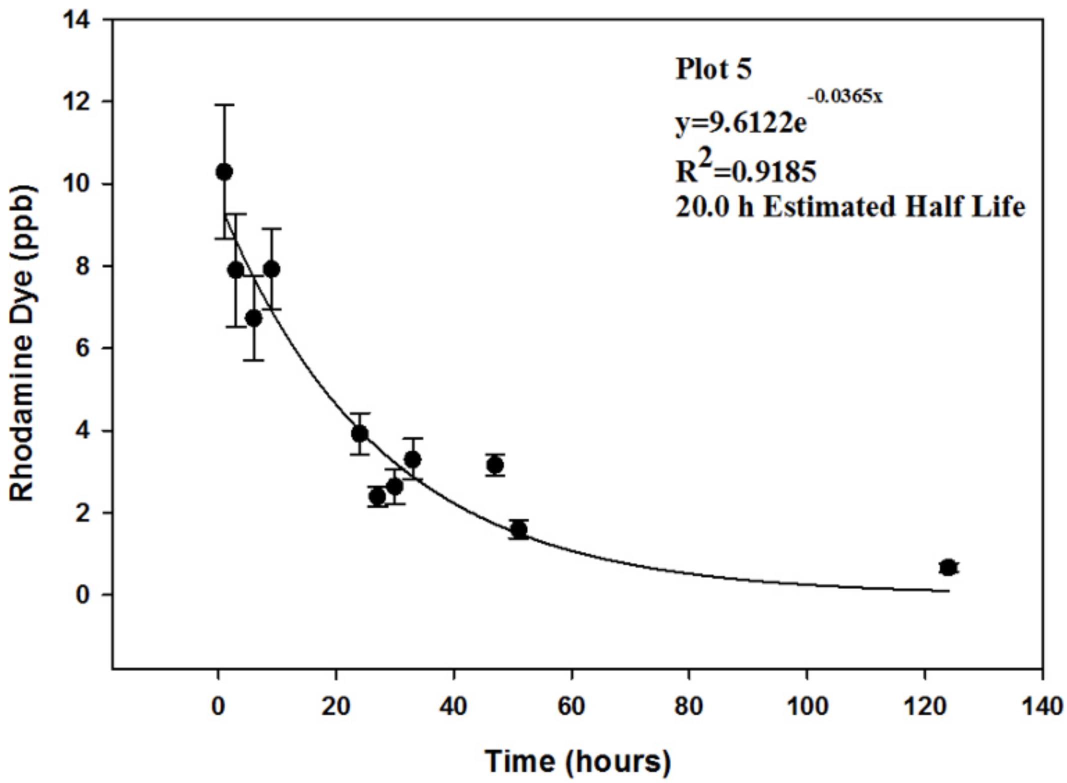

Figure 3.7 Rhodamine WT dye dissipation rate in hydrilla plot 5, Ross Barnett Reservoir, Mississippi June 19th to June 25th 2012

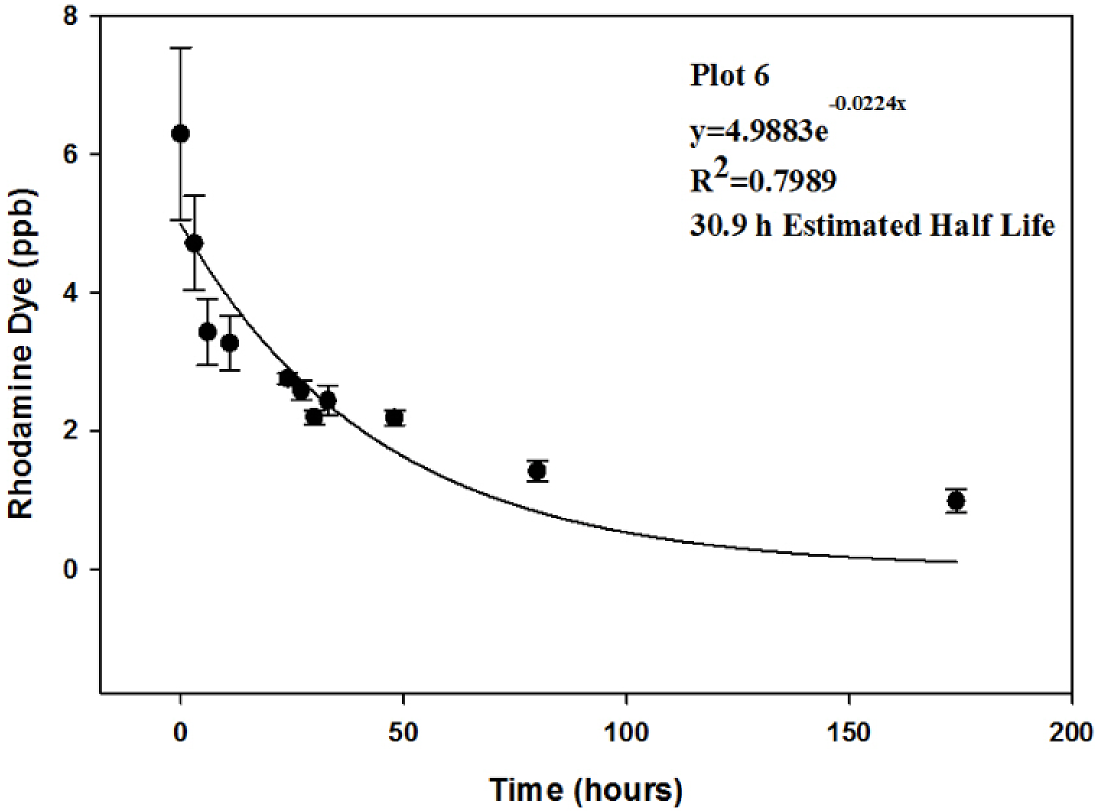

Figure 3.8 Rhodamine WT dye dissipation rate in hydrilla plot 6, Ross Barnett Reservoir, Mississippi June 18th to 25th 2012

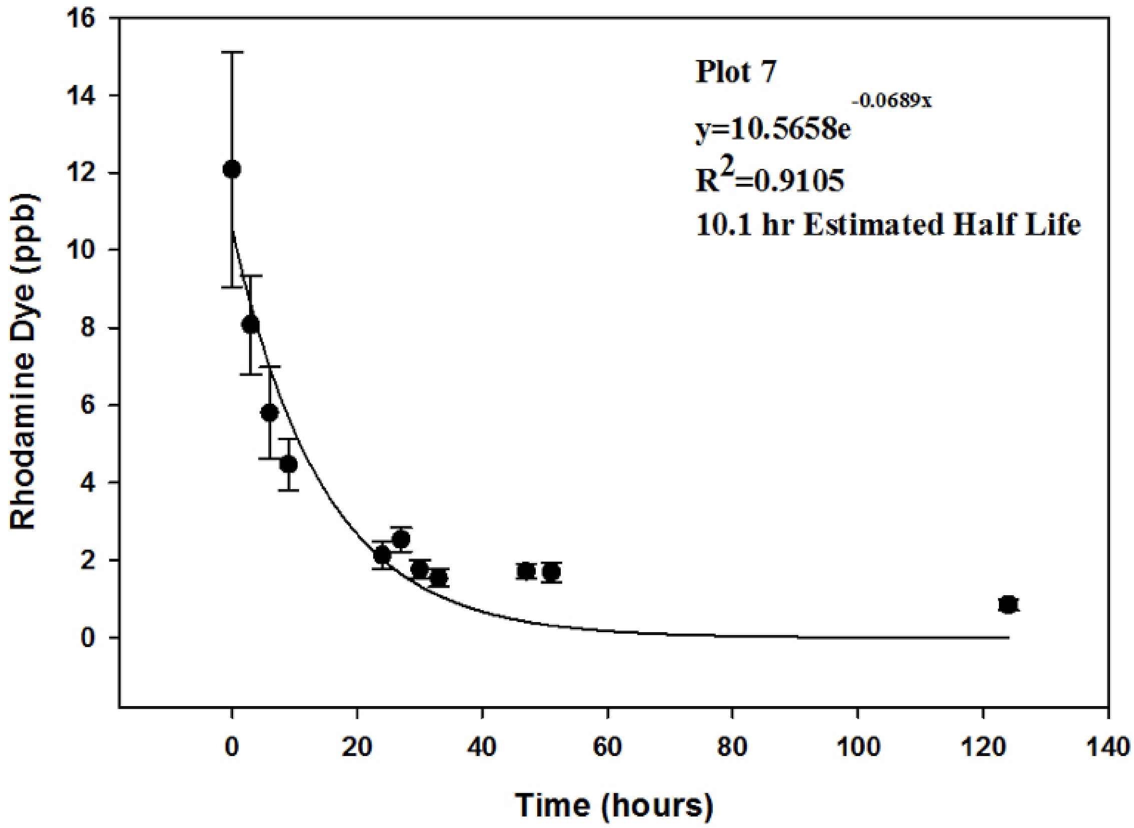

Figure 3.9 Rhodamine WT dye dissipation rate in hydrilla plot 7, Ross Barnett Reservoir, Mississippi June 19th to June 25th 2012

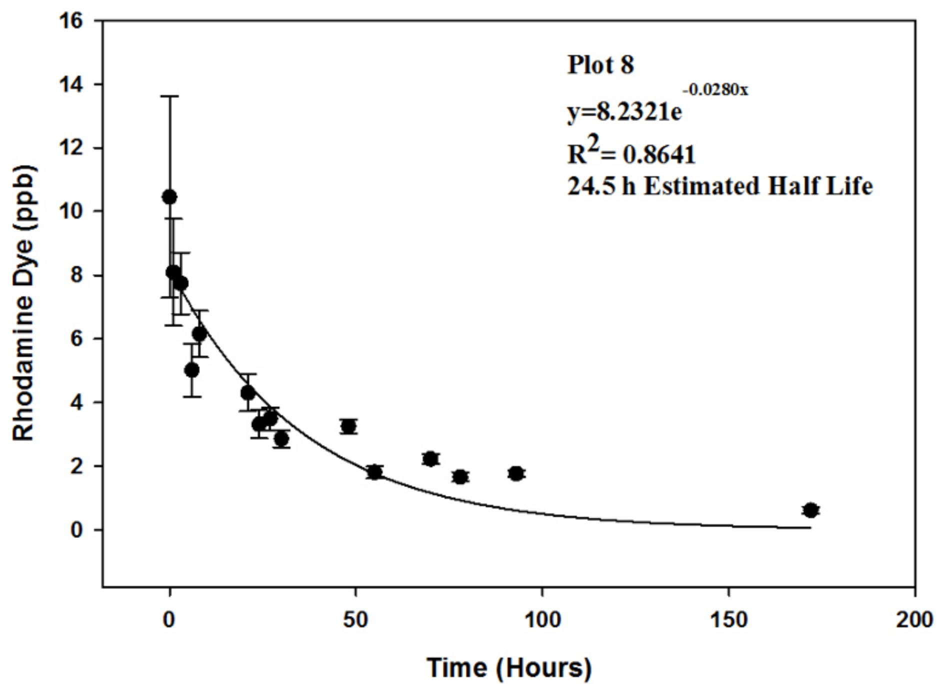

Figure 3.10 Rhodamine WT dye dissipation rate in hydrilla plot 8, Ross Barnett Reservoir, Mississippi June 18th to June 25th 2012

Table 3.1 Rhodamine WT dye half-lives within each plot; herbicide treatments since 2010, and treatment recommendations based on dye dissipation rate in each plot

Plot	Half-life (hours)	2010	2011	2012	Recommendation
1	2.0	Copper/Diquat	Copper/Diquat	Copper/Diquat	Contact
2	8.8	Copper/Diquat	Copper/Diquat	Copper/Diquat	Contact
3	14.3	No Treatment	Fluridone, Copper/Diquat	Copper/Diquat	Systemic
4	4.0	Copper/Diquat	Fluridone	Copper/Diquat	Contact
5	20.0	Fluridone	Fluridone, Copper/Diquat	Copper/Diquat	Systemic
6	30.9	No Treatment	Copper/Diquat	Copper/Diquat	Systemic
7	10.1	No Treatment	No Treatment	Copper/Diquat	Systemic/Contact
8	24.5	No Treatment	No Treatment	Copper/Diquat	Systemic

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CHAPTER IV

SELECTIVITY OF EIGHT HERBICIDES FOR MANAGEMENT OF HYDRILLA IN THE PRESENCE OF EIGHT CO-OCCURRING NATIVE PLANT SPECIES

Abstract

The effects four systemic (fluridone, imazamox, penoxsulam, and bispyribac-sodium) and four contact herbicides (diquat, endothall, flumioxazin, and copper) on hydrilla (*Hydrilla verticillata* (L.f.) Royle) and eight native aquatic plant species was observed over a 12 week period at the mesocosm facility located on the R.R. Foil Plant Science Research Center, Mississippi State University, Starkville, Mississippi. A series of treatments were applied to a set of emergent and floating plant species, as well as, a treatment for submersed plant species. Emergent and floating species consisted of American lotus (*Nelumbo lutea* Willd.), white water lily (*Nymphaea odorata* Aiton), water primrose (*Ludwigia peploides* (Kunth) P.H. Raven) and American pondweed (*Potamogeton nodosus* Poir.). Submersed species consisted of coontail (*Ceratophyllum demersum* L.), elodea (*Elodea canadensis* Michx), bladderwort (*Utricularia gibba* L.), sago pondweed (*Stuckenia pectinata* (L.) Börner), and hydrilla. All herbicides were applied to the water at recommended treatment rates for hydrilla control. Contact herbicides were allowed a 12 hour exposure time, after which the tanks were drained and replaced with pond water. Tanks treated with systemic herbicides had a static exposure over the duration of the experiment. Harvests for both systemic and contact herbicide

treatments were conducted at 4, 8, and 12 weeks post treatment to assess plant biomass and re-growth. Biomass data were subjected to a general linear model to determine treatment effect. If a significant treatment effect was observed, means were then separated using a Fisher's Protected LSD test. All analyses were conducted in SAS software at p=0.05 significance level. The systemic herbicides fluridone, bispyribac sodium, and penoxsulam significantly controlled hydrilla when compared to the reference 12 WAT. Penoxsulam and bispyribac sodium were more selective in controlling hydrilla. Contact herbicides copper, flumioxazin, and diquat provided significant control 4 WAT, but plant regrowth occurred soon after and there was no significant biomass reduction at the end of the 12 week study period.

Introduction

Hydrilla (*Hydrilla verticillata* L.f Royle) is an exotic invasive submersed aquatic plant that has the ability to form dense canopies and out-compete desirable native vegetation. . Impacts can include, alterations in the interactions between fish and other aquatic species, disruption of nutrient cycling, constricting navigation canals, lowering property value, and declined recreational use of rivers and lakes (Madsen 2004, Pimentel et al. 1999). The application of aquatic herbicides for selective control of invasive nuisance plant species, like hydrilla, can be beneficial for survival and growth of native vegetation. Because of the detrimental impacts caused by infestations of exotic species and the benefits of native vegetation, removal of nuisance plant species with minimal impact to native vegetation is a primary goal for managing public and private water bodies (Netherland et al. 1997).

The systemic herbicide fluridone has been the tool of choice for hydrilla control on large water bodies. Fluridone works by inhibiting the phytoene desaturase (PDS) enzyme in the carotenoid biosynthetic pathway. This disrupts the production of carotenoids, which play an important role in protecting against photooxidative damage (Bartely and Scolnik 1995). The absence of carotenoids causes new plant tissue to become bleached due to the photo-destruction of chlorophyll (Bartels and Watson 1978). Due to its low toxicological risk fluridone poses to the non-target aquatic community and low use rates, it has received widespread and frequent use to control hydrilla (Poovey et al. 2005). Though in recent years, fluridone resistant hydrilla has been confirmed in some populations in Florida (Michel et al. 2004).

The acetolactate synthase (ALS) inhibiting herbicides penoxsulam, imazamox, and bispyribac sodium have all been recently registered (in the past 10 years) by the US Environmental Protection Agency (EPA) for aquatic use. They represent the first new chemistries with hydrilla activity since fluridone was registered in 1986 (Netherland 2011). ALS herbicides inhibit the production of the branched chained amino acids valine, leucine, and isoleucine by binding to the ALS enzyme, leading to an inability of the target plant to synthesize proteins resulting in rapid cessation of new growth (Tranel and Wright 2002). Although different ALS inhibiting herbicides effect the same target enzyme, terrestrial use has shown that these compounds have different weed spectrums, use rates, use recommendations, selectivity towards non-target plants, and different potential for developing resistance by the target plant (Tranel and Wright 2002).

The contact herbicides copper ethylenediamine chelate and endothall are also frequently used for hydrilla control. Copper is effective at controlling several vascular plants including hydrilla (Madsen 2000). Its mechanism of action is not well understood, but may be involved in the disruption of photosystem II electron transport (Senseman 2007). Diquat is classified as a photosystem I inhibitor and works by disrupting electron movement in photosystem I of the photosynthetic reaction (Hess 2000). Diquat applications can act on a very short contact time and cause rapid die off of plant material it comes in contact with, but it is not effective on roots, rhizomes, or tubers, thus regrowth typically occurs and subsequent applications are needed (Madsen 2000). Endothall is often used to control hydrilla in both large-scale and spot treatment scenarios (Netherland et al. 1991). Although endothall is classified as a contact herbicide which implies rapid initial uptake by the target plant (Ashton and Crafts 1981), several studies have reported slow initial uptake of endothall by submersed weeds (Haller and Sutton 1973, Reinert and Rogers 1986; Van and Conant 1988).

The fast acting contact herbicide flumioxazin was recently registered for aquatic use in 2010 offering another possible tool for hydrilla management (Mudge et al. 2012). Flumioxazin is classified as a protoporphyrinogen oxidase inhibitor (PPO) and acts by reacting with light to form singlet oxygen radicals causing lipid peroxidation and cell membrane destruction (Duke et al. 1991). Flumioxazin has shown activity on hydrilla. Mudge and Haller (2006) reported hydrilla dry weight was reduced 63% and 99% in static tests when treated with 50 and 400 $\mu g\ L^{-1}$ rates of flumioxazin. It is also reported that flumioxazin is pH sensitive and alkaline pH causes rapid degradation in aqueous environments, ranging from minutes ($pH \geq 9$) to > 4 days ($pH \leq 5$; Katagi 2003, Senseman 2007).

In order to gain a better understanding of species-selective control of currently registered herbicides for hydrilla control, a study was conducted in which 4 systemic herbicides (fluridone, penoxsulam, bispyribac sodium, imazamox) and 4 contact herbicides (copper, diquat, endothall, flumioxazin) were applied to mesocosms containing hydrilla and the native species coontail (*Ceratophyllum demersum* L.), elodea (*Elodea canadensis* Michx), bladderwort (*Utricularia gibba* L.), sago pondweed (*Stuckenia pectinata* (L.) Börner), American lotus (*Nelumbo lutea* Willd.), white water lily (*Nymphaea odorata* Aiton), water primrose (*Ludwigia peploides* (Kunth) P.H. Raven) and American pondweed (*Potamogeton nodosus* Poir.). The objective of this study was to test the selectivity of several different herbicides for hydrilla control in the presence of submersed, emergent, and floating native aquatic plant species.

Materials and Methods

Planting

The study was conducted in 80 1,143-L tanks (300 gal) located in an outdoor mesocosm facility at the R. R. Foil Plant Science Research Center, Mississippi State University, Starkville, Mississippi. The study was conducted over a 12 week period beginning May to August 2012 and replicated in 2013. Tanks were separated based on plant type, 40 tanks being allocated to submersed plant species and 40 tanks allocated to floating and emergent species. Eight tanks, 4 for each plant type, were designated as pre-treatment tanks. Each plant species was planted in 4.2-L poly-cel pots which containted a soil and gravel mixture amended with Osmocote fertilizer (24-8-16) (Scotts-Sierra Horticultural Products Company, Marysville, OH) or 875 cm^2 submersible cages. Three pots or cages of each plant species was placed into each tank designated for that species type.

Hydrilla and elodea samples were collected from stock tanks located at the mesocosm facility. Two stems, approximately 20 cm in length were planted into each of 120 pots allocated for that species. Sago pondweed tubers were purchased from Kester's Wild Game Food Nurseries Inc. (Omro, Wisconsin) and floated in stock tanks until tubers sprouted. Once the tubers began to sprout two tubers were planted into each of the 120 sago pondweed pots. Coontail was collected locally from a pond in Starkville, Mississippi. A single 20 cm fragment was placed into each of the 120 submersible cages. Bladderwort was collected from stock tanks located at the mesocosm facility. During 2012, 10 g of wet weight bladderwort was placed into each of the 120 submersible bladderwort cages similar to coontail, but failed to establish. During 2013, 25 g of wet weight bladderwort was planted in efforts to increase probability of establishment, but survival of plants was minimal 8 weeks after planting.

Water lily rhizomes were purchased from Joe Snow Aquatic Plants (Argyle, Texas). One 5 - 8 cm rhizome segment was planted into each of the 120 designated water lily pots. American lotus seed pods were collected from the Ross Barnett Reservoir in Central Mississippi. Seeds were separated and scarified using a file or belt sander to weaken the seed coat. Seeds were then floated in water until sprouting was observed (Sayre 2004). Once seeds had sprouted, two lotus seeds were planted into each of the 120 American lotus pots. American pondweed samples were collected from stock tanks located at the mesocosm facility. A single 5 cm rhizome section with attached stem approximately 20 cm long was planted into each of the 120 American pondweed pots.

Water primrose was collected locally from a pond in Starkville, Mississippi. A single segment, approximately 20 cm in length was planted into each of the 120 designated water primrose pots. After planting, plants were given an acclimation time of 4 weeks to grow in their respective tanks prior to herbicide treatment. Eight pre-treatment tanks were established at the beginning of the study, 4 pre-treatment submersed plant tanks and 4 pre-treatment emergent/floating plant tanks. The day prior to treatment above ground pre-treatment biomass samples of each plant species was collected by cutting plant biomass at the sediment surface or by removing plant biomass from each submersible cage. All pre-treatment samples were dried for at least 7 days at 70 C and weighed for pre-treatment biomass.

Treatment Methods

Submersed applications of the following herbicides at rates typically recommended for hydrilla control were made: diquat (Reward®, Syngenta Professional Products, Greensboro, NC) at 370 ppb, endothall (Aquathol K® United Phosphorous Incorporated, King of Prussia, PA) at 3000 ppb, flumioxazin (Clipper® Valent U.S.A. Corporation, Walnut Creek, CA) at 400 ppb, copper ethylenediamine chelate (Komeen®, SePro Corporation, Carmel IN) at 1000 ppb, fluridone (Sonar Genesis, SePro Corporation, Carmel IN) at 10 ppb, imazamox (Clearcast®, BASF Corporation, Research Triangle Park, NC) at 100 ppb, penoxsulam (Galleon® SC, SePro Corporation, Carmel, IN) at 20 ppb, and bispyribac sodium (Tradewind®, Valent U.S.A Corporation, Walnut Creek, CA) 30 ppb. Contact herbicides were allowed a 12 hour contact time, after which the tanks were drained and replaced with pond water.

Data Analysis

Due to complications establishing plant species during 2012, only 2013 data is reported. After initial treatment plants were visually rated weekly with a scale from 0 to 100 % percent control (0 no control, 100 complete control). Although these data were collected they were not subjected to statistical analysis. Plant biomass was collected at 3 harvest periods; 4, 8, and 12 WAT. Biomass data were subjected to a general linear model to determine treatment effect. If a significant treatment effect was observed, means were then separated using a Fisher's Protected LSD test. All analyses were conducted in SAS software at p=0.05 significance level.

Results

The systemic herbicides fluridone, bispyribac sodium, and penoxsulam significantly controlled hydrilla when compared to the reference 12 WAT (Table 4.1). All three herbicides also significantly reduced sago pondweed biomass (Table 4.3). Penoxsulam and bispyribac sodium were more selective for controlling hydrilla; due to fluridone significantly reducing elodea when compared to the reference 12 WAT (Table 4.2). Contact herbicides copper, flumioxazin, and diquat provided significant hydrilla control 4 WAT, but plant regrowth occurred soon after and there was no significant biomass reduction at the end of the 12 week study period (Table 4.1). Due to problems with bladderwort establishment and survival prior to treatment only 4 WAT data is included for this species in this this report (Table 4.9).

Discussion

Although no treatments provided 100% control of hydrilla, fluridone, bispyribac sodium, and penoxsulam provided the best hydrilla control after the 12 week study period (Table 4.1). Penoxsulam and bispyribac sodium provided more selective control, as sago pondweed was the only native species impacted by this treatment12 WAT (Table 4.3). Fluridone also significantly reduced elodea when compared to the reference 12 WAT (Table 4.2). This suggests that the systemic herbicides fluridone, bispyribac sodium, and penoxsulam may provide the best long-term selective hydrilla control if they can be maintained at a sufficient concentration.

Bispyribac sodium and penoxsulam are both ALS inhibitors and performed similar in the reduction of hydrilla biomass. When compared to the reference only sago pondweed was significantly reduced following the 12 week study period (Table 4.3). Although no published reports are available for control of sago pondweed following in water applications of these systemic herbicides, Vassios (2010) reported that greater than 70% control was achieved following pre-emergence dry ground applications of penoxsulam in irrigation canals. Due to the high variability among water primrose treatments, penoxsulam did not significantly differ from the reference, but visually 100% control of primrose was documented 12 WAT (Table 4.7). Penoxsulam has been shown to have toxicity towards emergent plant species. Koschnick and others (2007) reported that soft-stem bulrush (*Scirpus validus* Vahl), pickerelweed (*Pontederia cordata* L.), and sagittaria (*Sagittaria lancifolia* L.) were all susceptible to penoxsulam treatments. Fluridone significantly reduced hydrilla biomass when compared to the reference 12 WAT (Table 4.1). It also significantly reduced sago pondweed and elodea when compared to the untreated reference (Table 4.2, 4.3). Similar results have been reported from species-selective fluridone herbicide trials. Netherland et al. (1997) reported that fluridone treatments at 10µg^{-L} significantly reduced elodea and sago pondweed 90 days after treatment.

The contact herbicides copper, flumioxazin, and diquat all significantly reduced hydrilla biomass when compared to the reference 4 WAT (Table 4.1). Diquat resulted in the best control 4 WAT, which conflicts data published by Glomski et. al. (2005), where diquat treatments of 370 ppb with a 12 hour contact time did not significantly control hydrilla 3 WAT. Flumioxazin provided a significant biomass reduction in hydrilla, but after the 4 WAT harvest regrowth was evident (Table 4.1). Mudge et al. (2010), reported regrowth from treated hydrilla tissue 5 to 13 days after treatment with flumioxazin applied at 50 to 1600 µg L^{-1}. Copper has been widely used to control noxious algae and has been shown to have activity on elodea (Mal et al. 2002). Typically copper is tank mixed with other herbicides such as diquat and dipotassium salt of endothall for hydrilla management. When evaluating the effect of diquat on the uptake of copper (Sutton et al. 1970) and the effect of copper on the uptake of diquat (Sutton et al. 1972) in hydrilla and southern naiad (*Najas guadalupensis* (Sprengel) Magnus), 77 % and 38 % more copper was present in plant tissue with the mixture compared to using copper alone. Mixing copper with endothall has also shown excellent control in managing hydrilla. Pennington and others (2001) reported a significant reduction in hydrilla biomass when compared to the reference 3 and 6 WAT using copper/endothall and diquat/endothall tank mixes. Although Pennington et al. (2001) reported a significant reduction in hydrilla biomass when applying rates of endothall as low as 1 mg L^{-1} active ingredient (ai), in this study that was not the case. Concentration and exposure time of endothall likely contributed to the unsuccessful control of hydrilla in the present study. Endothall concentrations at 3.0 mg $^{-L}$ need at least a 24 hour contact time to achieve >85% reduction of hydrilla (Netherland et al. 1991). The present study only allotted contact herbicides a 12 hour contact time in order to simulate water exchange in field situations.

Based on the results of this study, contact herbicides copper, diquat, and flumioxazin would provide short term non-selective hydrilla control in areas where CETs are limited. Tank mixes of diquat and copper would offer increased efficacy and provide better control than copper or diquat used alone (Sutton et al. 1970, Sutton et al. 1972). Multiple contact herbicide treatments annually will be needed due to regrowth of hydrilla plants < 4 WAT. Applications of fluridone, penoxsulam, or bispyribac-sodium provide the best long-term selective control of hydrilla. However, herbicide selection should be dependent on which native plant species are present within the target area. In areas containing both hydrilla and elodea, penoxsulam and bispyribac sodium would be the best option to minimize elodea damage. With the discovery of fluridone resistant hydrilla it is important to rotate chemistries when applying treatments. Based on these data, penoxsulam and bispyribac sodium can provide selective hydrilla control similar to fluridone and can be valuable tools for hydrilla management in the future. Future research should evaluate lower use rates and varying exposure times of penoxsulam and bispyribac sodium for hydrilla control.

Table 4.1 Mean aboveground biomass (g DW pot^{-1}) of hydrilla following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

Hydrilla[a,b]			
Herbicide	**4 WAT**	**8 WAT**	**12 WAT**
Reference	11.63 ab	15.15 a	16.21 a
Copper	5.22 c	10.47 a	13.18 ab
Flumioxazin	4.05 c	13.82 a	8.76 ab
Endothall	13.76 a	10.23 a	10.89 ab
Diquat	3.26 c	8.64 a	12.50 ab
Imazamox	14.04 a	12.29 a	9.85 ab
Fluridone	7.15 bc	6.76 a	6.09 b
Bispyribac Sodium	4.72 c	6.69 a	4.577 b
Penoxsulam	6.48 bc	8.98 a	6.40 b

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table 4.2 Mean aboveground biomass (g DW pot^{-1}) of elodea following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 Ltanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

	Elodea[a,b]		
Herbicide	**4 WAT**	**8 WAT**	**12 WAT**
Reference	11.69 bc	20.32 ab	27.99 ab
Copper	0.00 d	6.17 bc	11.17 bdc
Flumioxazin	8.20 bcd	6.54 abc	10.57 bdc
Endothall	25.07 a	21.27 a	21.30 abc
Diquat	0.00 d	0.00 c	0.00 d
Imazamox	4.95 cd	14.31 abc	16.34 abcd
Fluridone	10.03 bc	9.07 abc	8.71cd
Bispyribac Sodium	17.22 ab	15.12 ab	32.18 a
Penoxsulam	16.57 ab	10.97 abc	12.45bcd

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column

Table 4.3 Mean aboveground biomass (g DW pot^{-1}) of sago pondweed following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

Sago Pondweed[a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	5.91 a	6.16 a	10.38 a
Copper	1.28 cd	5.40 ab	6.70 ab
Flumioxazin	1.07 cd	0.89 cd	0.00 d
Endothall	0.00 d	0.20 d	0.00 d
Diquat	0.00 d	0.00 d	0.00 d
Imazamox	3.58 b	4.48 b	3.20 bcd
Fluridone	2.70 bc	1.62 c	2.70 cd
Bispyribac Sodium	1.50 bcd	0.54 cd	0.218 d
Penoxsulam	2.18 bc	1.80 c	5.15 bc

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column

Table 4.4 Mean aboveground biomass (g DW pot^{-1}) of coontail following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

Coontail[a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	0.24 a	0.06 ab	0.06 ab
Copper	0.00 b	0.00 b	0.00 b
Flumioxazin	0.02 b	0.00 b	0.03 b
Endothall	0.27 a	0.01 b	0.00 b
Diquat	0.00 b	0.00 b	0.00 b
Imazamox	0.06 b	0.11 ab	0.03 b
Fluridone	0.05 b	0.06 ab	0.04 b
Bispyribac Sodium	0.05 b	0.10 ab	0.06 ab
Penoxsulam	0.14 ab	0.19 a	0.16 a

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column

Table 4.5 Mean aboveground biomass (g DW pot^{-1}) of American lotus following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

American Lotus[a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	1.28 a	1.24 a	2.26 ab
Copper	2.64 a	0.97 a	2.90 ab
Flumioxazin	0.28 a	0.00 a	0.00 b
Endothall	1.97 a	3.43 a	3.10 ab
Diquat	0.00 a	0.00 a	0.00 b
Imazamox	3.74 a	0.32 a	5.94 a
Fluridone	3.36 a	2.14 a	2.32 ab
Bispyribac Sodium	4.29 a	1.49 a	2.84 ab
Penoxsulam	0.00 a	1.89 a	2.10 ab

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column

Table 4.6 Mean above ground biomass (g DW pot^{-1}) of white water lily following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

White Water Lily[a,b]

Herbicide	**4 WAT**	**8 WAT**	**12 WAT**
Reference	5.12 a	3.58 ab	3.41 a
Copper	4.97 a	4.33 a	2.59 a
Flumioxazin	0.69 d	0.79 b	2.57 a
Endothall	4.03 abc	3.36 ab	1.84 a
Diquat	4.62 ab	2.29 ab	2.87 a
Imazamox	2.31 bcd	2.77 ab	1.68 a
Fluridone	1.99 cd	0.62 b	2.40 a
Bispyribac Sodium	5.34 a	1.07 ab	1.62 a
Penoxsulam	3.13 abcd	1.98 ab	2.90 a

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table 4.7 Mean above ground biomass (g DW pot^{-1}) of water primrose following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

Water Primrose[a,b]

Herbicide	**4 WAT**	**8 WAT**	**12 WAT**
Reference	5.29 a	3.43 ab	1.74 ab
Copper	5.02 a	6.38 ab	5.84 ab
Flumioxazin	4.08 a	8.57 a	2.77 ab
Endothall	3.97 a	2.68 ab	7.44 a
Diquat	0.11 a	0.00 b	0.00 b
Imazamox	3.99 a	2.44 ab	0.91 ab
Fluridone	2.98 a	5.95 ab	1.05 ab
Bispyribac Sodium	2.35 a	6.64 a	3.28 ab
Penoxsulam	0.10 a	0.00 b	0.00 b

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table 4.8 Mean above ground biomass (g DW pot^{-1}) of American pondweed following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4, 8, and 12 WAT

American Pondweed[a,b]

Herbicide	**4 WAT**	**8 WAT**	**12 WAT**
Reference	4.43 ab	3.55 b	3.52 ab
Copper	4.28 ab	2.56 bc	3.07 ab
Flumioxazin	1.82 b	1.20 bc	2.87 ab
Endothall	1.12 b	1.75 bc	1.93 ab
Diquat	2.06 b	7.19 a	2.49 ab
Imazamox	4.12 ab	0.96 bc	3.15 ab
Fluridone	1.98 b	0.91 bc	1.31 b
Bispyribac Sodium	9.05 a	0.52 c	4.99 a
Penoxsulam	0.85 b	0.51 c	0.54 b

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table 4.9 Mean aboveground biomass (g DW pot^{-1}) of bladderwort following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2013 at 4 WAT

Bladderwort[a,b]	
Herbicide	**4 WAT**
Reference	0.22 abc
Copper	0.41 ab
Flumioxazin	0.10 bc
Endothall	0.22 abc
Diquat	0.00 c
Imazamox	0.15 abc
Fluridone	0.48 a
Bispyribac Sodium	0.09 bc
Penoxsulam	0.31 abc

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

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CHAPTER V

OPERATIONAL HYDRILLA MANAGEMENT WITHIN THE ROSS BARNETT RESERVOIR

Invasive aquatic plants, such as hydrilla, are continuing to cause nuisance problems to water resources across the United States (Madsen 2004). Due to the increasing infestations, sound aquatic plant management techniques are critical in order to gain an advantage when dealing with these aggressive invaders. Every water body has certain characteristics that make it unique and thus may require different management strategies. Furthermore, different areas within the same water body may require different management strategies. Since the discovery of hydrilla in the Ross Barnett Reservoir in 2005, varying management strategies have been utilized in order to gain control of hydrilla. While treatments in some areas have been a success, other areas have shown repeated hydrilla occurrences annually. Based on hydrilla tuber surveys between Ross Barnett Reservoir and unmanaged hydrilla infestations on the Tennessee-Tombigbee Waterway, herbicide treatments within the Ross Barnett are limiting tuber production and above ground biomass within areas infested with hydrilla. The Tenn-Tom Waterway showed significantly higher above ground biomass, tuber biomass, tuber weight, and tuber density when compared to Ross Barnett. Point-intercept data within hydrilla sites on the Ross Barnett also showed that herbicide treatments are providing selective control of hydrilla with little long-term adverse effects to native plants.

Due to insufficient control in some hydrilla sites on the Ross Barnett treated with the systemic herbicide fluridone, rhodamine WT dye was used to track water movement in some of these areas. Rapid dissipation of herbicide residues results in poor plant control due to short contact time with the target plant species (Netherland and Getsinger 1992). Fluridone is degraded primarily by photolysis (Mossler et al. 1989), but water exchange rates have been shown to have an impact on fluridone half-lives within larger treatment areas (Fox et al. 1993, Getsinger et al. 1990, Getsinger et al. 1992). The water exchange data collected at Ross Barnett showed that areas infested with hydrilla experience rapid water exchange patterns. Hydrilla sites located close to intermittent tributaries and/or residual areas, where increased water flow and boat traffic are present, resulted in rapid water exchange thus herbicide treatments in these areas need to utilize multiple contact herbicides annually. Protected inlets, sheltered from wind, that receive little boat traffic and wave action would be better suited for systemic herbicide treatments.

With the discovery of fluridone resistant hydrilla in Florida (Michel et al. 2004), it is important to use multiple chemistries for long term hydrilla management projects. The first new chemistries with hydrilla activity since the registration of fluridone in 1986 have recently been approved for aquatic use (Netherland 2011). The new ALS-inhibiting herbicides fluridone, penoxsulam, and bispyribac sodium showed selective hydrilla control after 12WAT. Penoxsulam and bispyribac sodium may be terrific options for long term hydrilla management in areas that have received multiple fluridone applications or areas with fluridone resistant strains of hydrilla. Penoxsulam and bispyribac sodium also showed more selectivity among co-occurring native species.

When dealing with aquatic plant problems, there is no individual "cure-all" solution, no management technique is flawless (Madsen 2000). Over time management techniques will need to be altered based on success or failure of the management program (Madsen 2005). Long term management should be an ongoing process, where information regarding past successes and failures can be utilized (Madsen 2005). Unmanaged, aggressive species such as hydrilla have the ability to cause detrimental impacts to aquatic systems, but management techniques provide a collective solution (Madsen 2000).

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APPENDIX A

CORE SAMPLING AND POINT-INTERCEPT DATA

2012 TO 2013

Table A.1 Core sampling data from 2007 on the Tennessee-Tombigbee Waterway (Robles 2009) and 2012-2013 at the Ross Barnett Reservoir. Means within columns with the same letter are not statistically significant at p=0.05.

Waterbody	Season	Tuber wt. (g DW m^{-2}.)	Tuber Biomass (g DW m^{-2})	Tuber Density (N m^{-2})	Above Ground Biomass (g DW m^{-2})
Tenn-Tom Waterway	Winter (2007)	0.06B	3.20B	31.48B	420A
	Spring (2007)	0.38A	21.34A	140.74A	146.11B
Ross Barnett Reservoir	Winter (2012-2013)	0.00C	0.03C	1.04C	0.00C
	Spring (2012-2013)	0.01BC	0.51BC	6.94C	0.09C

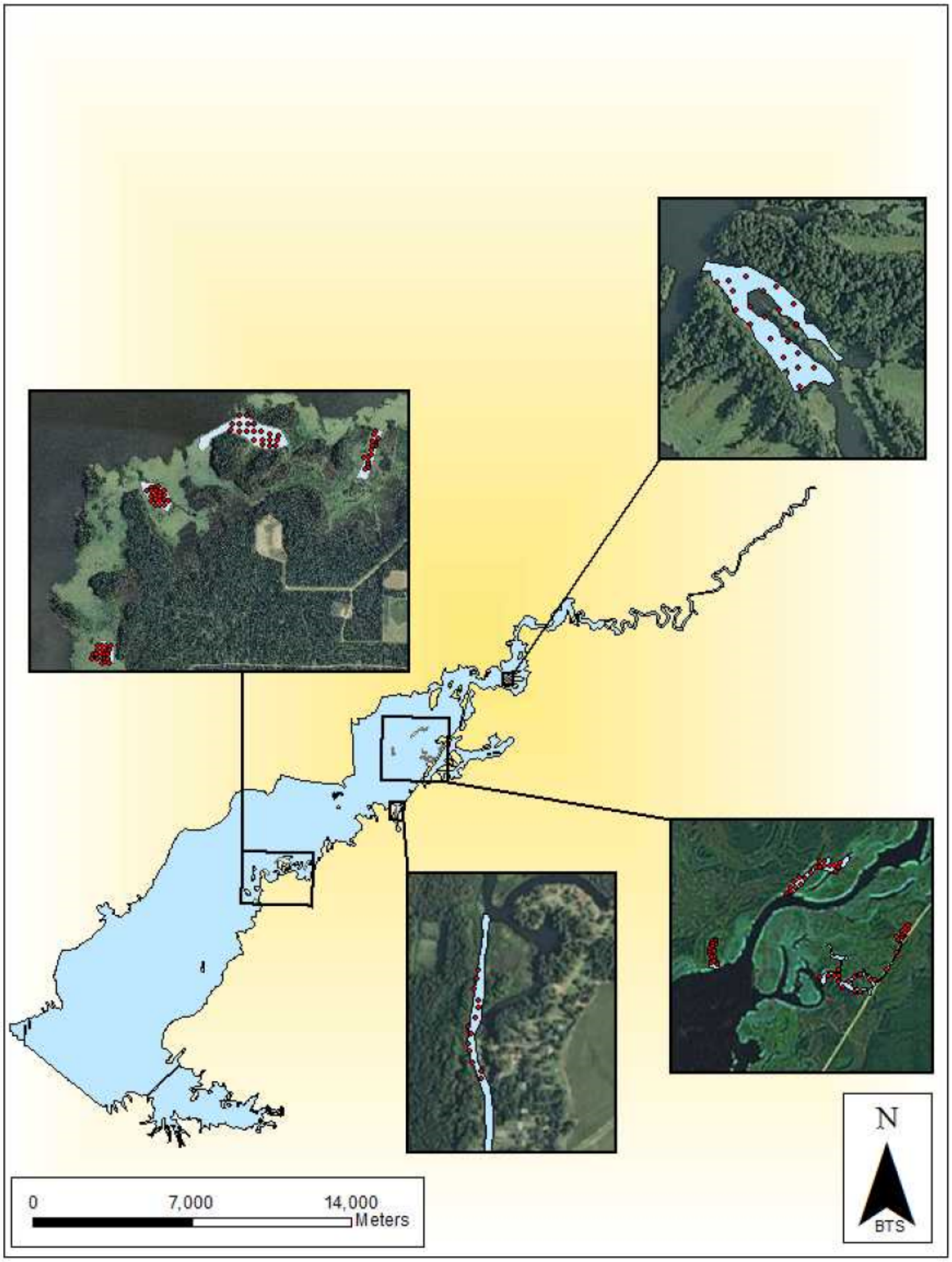

Figure A.1 Points sampled within hydrilla sites during September 2012 at the Ross Barnett Reservoir

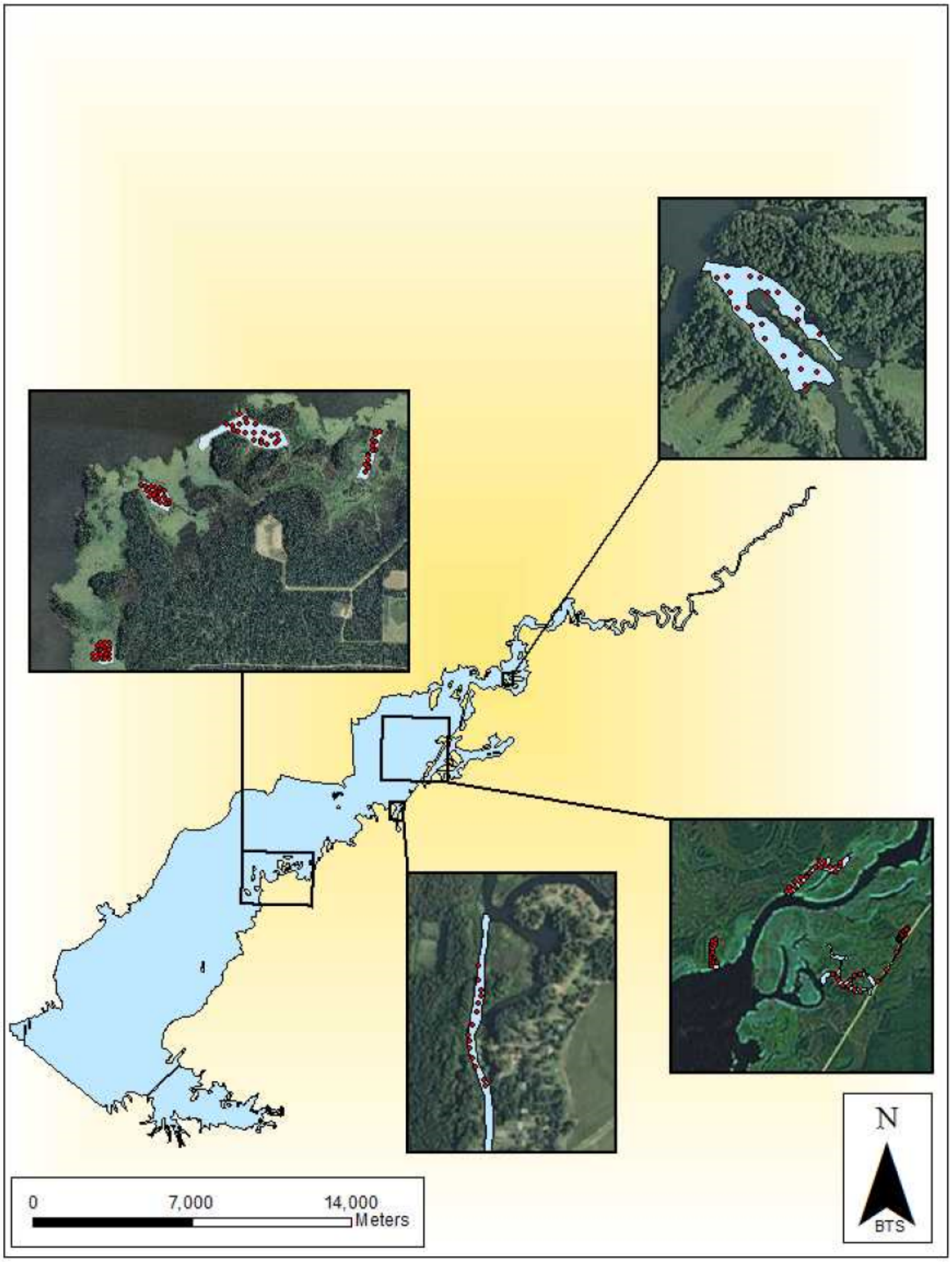

Figure A.2 Points sampled within hydrilla sites during September 2012 at the Ross Barnett Reservoir

APPENDIX B

DATA AFFECTING RHODAMINE WT DYE DISSIPATION WITHIN HYDRILLA SITES

Figure B.1 Rhodamine WT Dye being applied to the water column in sampling plot 4 at the Ross Barnett Reservoir

Table B.1 Weather data for Jackson, MS 2011 during Rhodamine WT dye study (http://www.wunderground.com/history/airport/KJAN/2011/7/2/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA)

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**
	June 27	June 28	June 29	June 30	July 1	July 2
Wind Direction	South	North	North	Northeast	Northeast	Northeast
Wind Speed	5 mph	5 mph	3 mph	3 mph	3 mph	3 mph
Max Wind Speed	12 mph	28 mph	12 mph	13 mph	13 mph	13 mph
Precipitation	0.00"	0.00"	0.00"	0.00"	0.00"	0.00"

Table B.2 Weather data for Jackson, MS 2012 during Rhodamine WT dye study (http://www.wunderground.com/history/airport/KJAN/2011/7/2/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA)

	Monday June 18	**Tuesday** June 19	**Wednesday** June 20	**Thursday** June 21	**Friday** June 22	**Saturday** June 23
Wind Direction	South Southeast	Southeast	North	Northeast	North Northeast	Northeast
Wind Speed	9 mph	7 mph	4 mph	2 mph	5 mph	4 mph
Max Wind Speed	20 mph	16 mph	12 mph	13 mph	17 mph	12 mph
Precipitation	0.00"	0.00"	0.00"	0.00"	0.00"	0.00"

APPENDIX C

2012 HERBICIDE TRIAL DATA

Table C.1 Mean aboveground biomass (g DW pot^{-1}) of hydrilla following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12WAT

	Hydrilla[a,b]		
Herbicide	4 WAT	8 WAT	12 WAT
Reference	20.96 ab	28.77 abc	57.30 a
Copper	7.13 b	21.86 bc	47.42 ab
Flumioxazin	18.07 ab	31.58 abc	40.87 abc
Endothall	35.61 a	45.95 a	32.17 abc
Diquat	23.56 ab	22.19 bc	31.73 abc
Imazamox	28.01 ab	22.14 bc	47.42 ab
Fluridone	29.23 ab	43.96 a	42.23 abc
Bispyribac Sodium	21.87ab	40.16 ab	18.20 c
Penoxsulam	35.41 a	16.28 c	26.10 bc

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.2 Mean aboveground biomass (g DW pot^{-1}) of elodea following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 Ltanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12 WAT

Elodea[a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	22.70 ab	49.41 a	27.49 ab
Copper	0.07 b	0.00 c	0.00 c
Flumioxazin	10.83 b	12.56 bc	16.52 abc
Endothall	55.00 a	62.78 a	36.69 a
Diquat	0.10 b	0.00 c	0.00 c
Imazamox	6.43 b	13.46 bc	8.30 bc
Fluridone	15.17 b	25.47 b	28.01 ab
Bispyribac Sodium	12.40 b	48.28 a	32.53 a
Penoxsulam	13.73 b	20.29 bc	24.98 ab

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.3 Mean aboveground biomass of (g DW pot^{-1}) of sago pondweed following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12 WAT

Sago Pondweed[a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	12.16 cb	9.37 ab	8.46 abc
Copper	7.53 cb	1.25 c	2.50 bc
Flumioxazin	35.09 a	7.70 ab	5.23 abc
Endothall	15.9 b	3.45 bc	3.57 abc
Diquat	0.78 c	0.00 c	0.10 c
Imazamox	9.72 cb	3.46 bc	4.47 abc
Fluridone	15.01 b	6.09 abc	12.40 a
Bispyribac Sodium	8.74 cb	10.23 a	10.03 ab
Penoxsulam	14.03 cb	9.37 abc	3.93 abc

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.4 Mean aboveground biomass (g DW pot^{-1}) of coontail following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12 WAT

Coontail [a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	0.26 a	0.21 ab	0.40 a
Copper	0.00 b	0.00 b	0.00 c
Flumioxazin	0.08 ab	0.20 ab	0.03 bc
Endothall	0.21 ab	0.43 a	0.13 bc
Diquat	0.00 b	0.00 b	0.00 c
Imazamox	0.18 ab	0.08 ab	0.06 bc
Fluridone	0.28 a	0.28 ab	0.12 bc
Bispyribac Sodium	0.25 a	0.07 ab	0.20 b
Penoxsulam	0.22 ab	0.37 ab	0.10 bc

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.5 Mean aboveground biomass (g DW pot^{-1}) of American lotus following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12 WAT

American Lotus [a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	3.38 a	6.65 a	33.45 ab
Copper	0.19 c	0.90 a	12.70 bcd
Flumioxazin	1.02 bc	0.12 a	6.60 bcd
Endothall	0.62 c	0.74 a	42.47 a
Diquat	0.79 bc	0.00 a	0.70 d
Imazamox	0.02 c	15.65 a	4.70 dc
Fluridone	2.17 ab	1.84 a	0.00 d
Bispyribac Sodium	0.05 c	0.13 a	31.67 abc
Penoxsulam	0.68 c	4.76 a	32.77 ab

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.6 Mean aboveground biomass (g DW pot^{-1}) of white water lily following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12 WAT

White Water Lily [a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	23.51 ab	12.24 bc	8.70 a
Copper	27.07 a	28.66 a	14.26 a
Flumioxazin	0.48 c	3.17 c	5.33 a
Endothall	23.61 ab	15.66 abc	4.23 a
Diquat	21.61 ab	17.67 ab	12.60 a
Imazamox	28.27 a	21.06 ab	8.36 a
Fluridone	9.35 bc	2.25 c	1.83 a
Bispyribac Sodium	22.75 ab	11.05 bc	1.26 a
Penoxsulam	23.33 ab	10.96 bc	4.93 a

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.7 Mean aboveground biomass (g DW pot^{-1}) of American pondweed following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 4, 8, and 12WAT

American Pondweed [a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	13.65 ab	21.07 ab	19.03 ab
Copper	8.25 ab	21.66 ab	27.03 a
Flumioxazin	3.85 ab	11.02 ab	22.77 ab
Endothall	2.13 b	0.85 b	0.13 b
Diquat	17.56 ab	25.24 a	21.40 ab
Imazamox	14.27 ab	19.31 ab	23.10 ab
Fluridone	17.39 ab	26.27 a	15.70 ab
Bispyribac Sodium	20.84 a	17.94 ab	13.80 ab
Penoxsulam	4.56 ab	3.10 b	7.20 ab

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.

Table C.8 Mean above ground biomass (g DW pot^{-1}) of water primrose following submersed aquatic herbicide treatment with the indicated herbicide in 1,143 L tanks at the R.R. Foil Plant Research Center, Mississippi State University, during summer 2012 at 8 and 12 WAT

Water Primrose [a,b]

Herbicide	4 WAT	8 WAT	12 WAT
Reference	N/A	170.63 ab	104.17 ab
Copper	N/A	165.63 abc	119.57 ab
Flumioxazin	N/A	155.90 abc	114.87 ab
Endothall	N/A	162.83 abc	81.80 ab
Diquat	N/A	97.60 bc	49.13 b
Imazamox	N/A	106.10 bc	156.73 ab
Fluridone	N/A	27.06 c	120.20 ab
Bispyribac Sodium	N/A	266.83 a	123.43 ab
Penoxsulam	N/A	121.27 bc	181.73 a

[a] Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P \leq 0.05$ level of significance.
[b] Analyses were conducted within weeks not across weeks, therefore comparisons can only be made within a given column.