RESTORATION OF NATIVE PLANTS THROUGH CHEMICAL CONTROL

OF ALLIGATORWEED (*Alternanthera philoxeroides*) AT

EUFAULA NATIONAL WILDLIFE REFUGE.

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Shannon Louise Allen

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Shannon Louise (Smith) Allen, daughter of Samuel Franklin and Betty Tee (Funk) Smith, was born May 26, 1976, in Bowling Green, Kentucky. She graduated from Bowling Green High School in 1994. She attended Auburn University and received a Bachelor of Science degree in Wildlife Science in August 1999. She wed Frank Allen, son of Mary (Freel) Thomas, on June 16, 2001 and moved to Barbour County, AL. She entered Graduate School, Auburn University in August 2003.

THESIS ABSTRACT

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Moist-soil management is a technique used to improve quality of wetland habitats for a variety of waterbird species, but alien invasive plant species may impact success of moist-soil management. Alligatorweed (*Alternanthera philoxeroides* (Mart.) Griseb.) is an alien invasive wetland plant that competes with and displaces important native plant species used as food sources by migratory waterfowl. Control of alligatorweed is a priority for managers whose goal is to provide waterfowl habitat. In this study, I varied timing and rate of application of triclopyr and imazapyr herbicides to evaluate effects on alligatorweed and native plants during the year of application and one year later.

Four experimental blocks were established at Eufaula National Wildlife Refuge of Alabama and Georgia on the Chattahoochee River in April 2004. Treatments consisted of herbicides ($n = 2$), application rates ($n = 3$), and application dates ($n = 3$), which were randomly assigned to experimental plots ($5m^2$) within each block. Control plots ($n = 6$) were randomly assigned to each block at each application date. I estimated plant biomass and species composition by clipping all aboveground plant parts in randomly placed quadrats ($0.25m^2$; $n = 2$) in experimental plots in October 2004 and October 2005. Percent cover tracked alligatorweed response during the first and second growing season after treatment.

Imazapyr controlled alligatorweed more effectively at April application in 2004, but triclopyr resulted in greater native plant biomass and native plant seed biomass than imazapyr. There was no difference between herbicides at July application. High application rates resulted in less alligatorweed biomass and greater native plant biomass at April application, but there was no difference between rates at July application. Alligatorweed and native plant biomass did not differ between triclopyr and imazapyr in October 2005, but September application resulted in less alligatorweed biomass than April or July. One year after treatment, plots treated with high rates contained less alligatorweed biomass than plots treated with low rates.

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I. INTRODUCTION

Wetlands have only recently been recognized as integral components of healthy ecosystems because the functions they provide have not always been valued by humans (Dahl and Allord 1999, Brinson and Malvarez 2002). They support a high diversity of wetland plants and invertebrates that provide food and habitat for numerous animal species, including amphibians, fishes, and migratory waterfowl, resulting in one of the most productive habitat types in the world (Stewart 1999, Gibbs 2000, Brinson and Malvarez 2002). In addition, wetlands provide services that are ecologically, economically, and socially useful to society. Water storage by floodplain wetlands reduces or eliminates extensive flooding damage that can occur when wetland functions are degraded (Novitzki *et al.* 1999). Preservation of functioning, healthy wetlands may be less costly than repairing damage caused by flooding (Carter *et al.* 1979). Healthy wetlands naturally filter and purify poor-quality or polluted water, making it suitable for human use (Elder 1987, Mitsch and Gosselink 1993). Groundwater recharge by wetlands is beneficial to communities that rely on aquifers for drinking water. Wetlands provide numerous social values including aesthetics and recreational activities such as fishing, boating, birding, and waterfowl hunting that translate directly into income. For example, three million waterfowl hunters spent 1.4 billion dollars on 29 million hunt days in the United States in 2001 (Interior *et al.* 2003).

As important as wetlands are to healthy ecosystems and to society, widespread drainage, degradation, and loss have occurred worldwide (Mitsch and Gosselink 2000). In the United States alone, more than one-half of the almost 90 million wetland hectares present in the 1600s have been lost (Dahl and Johnson 1991, Council 1995). Presently, development is the greatest cause of wetland loss, while conversion to agriculture led other land uses (silviculture, pasture, dam construction and subsequent flooding, etc.) in the past (Dahl 2000, Brinson and Malvarez 2002).

Land-use changes alter hydrology of wetlands, the most important factor determining wetland characteristics, reducing productivity, impairing wetland function, and reducing available wildlife habitat (Frayer *et al.* 1983, Fredrickson and Reid 1990, Carter 1999). Consequently, a large number of wetland obligates, such as the wood stork (*Mycteria americana*) and swamp pink (*Helonias bullata*), are listed as "threatened" or "endangered" under the United States Endangered Species Act of 1973 (Wilcove *et al.* 1993, Boylan and MacLean 1997). Also, population decline of many waterfowl species in the past 70 years is attributed to wetland loss and degradation (Bellrose and Trudeau 1988, Devries *et al.* 2003). Wetland loss in the United States continues, albeit at a lesser rate, even following passage of several protective federal laws (Clean Water Act of 1977, Food Security Act of 1985, Emergency Wetlands Resources Act of 1986, North American Wetland Conservation Act of 1989) (Dahl 2000).

Because of the great value of wetlands and their high degree of loss, protection and management of remnant natural, restored and managed wetlands should be a high priority for biologists, managers and society (Reid 1993). Additional hydrologic alterations, disturbance, contaminants (temperature, chemical, nutrient, etc.), habitat fragmentation, and alien invasive species are threats that should be monitored and prevented. These threats often are compounding, making wetlands more susceptible to other problems that decrease wetland health and therefore value (Bedford *et al.* 1999, Galatowitsch *et al.* 1999, Brinson and Malvarez 2002). For example, changes in wetland hydrology (duration and frequency of flooding) may alter vegetation and allow alien invasive species to become established (Seabloom *et al.* 1998, Carter 1999, Davis *et al.* 2000, Griffith and Forseth 2003). Wetland management should be directed towards preventing these harmful alterations, but also should focus on enhancing functionality, health, and value to wildlife.

Moist-soil management is one method that increases the value of managed wetlands for wildlife. It was first used by waterfowl biologists in the 1940s and is currently used extensively to improve the quality of wetland habitats for a variety of waterbirds (Rundle and Fredrickson 1981, Nyman *et al.* 1990, Laubhan and Fredrickson 1993, Reid 1993, Colwell and Taft 2000, Parsons 2002). Control of wetland hydrologic cycles is used to promote establishment of desirable plant species and decrease habitat suitability for undesirable vegetation (Fredrickson and Taylor 1982, Haukos and Smith 1993). Moist-soil management also is beneficial because invertebrate diversity and density can increase (Fredrickson and Reid 1988, Anderson and Smith 2000), providing a source of protein that is required for avian reproduction (Myers *et al.* 1979, Haukos and Smith 1993, Anderson and Smith 1998, Davis and Smith 1998).

In moist-soil management, managed wetlands are drained in spring or early summer to moist-soil conditions, allowing germination and growth of moist-soil plants (Fredrickson 1991). Flooding wetlands to 10 to 25 cm deep in autumn provides habitat for migrating and wintering waterfowl and other waterbirds that forage for seeds and invertebrates (Fredrickson and Taylor 1982, Taft *et al.* 2002).

Alien wetland plants increasingly are becoming a problem in wetland habitats and may impact success of moist-soil management. The addition of alien plants to wetlands also may alter parameters that affect distribution and abundance of native plant species, such as quality and quantity of light (Chambers and Kalff 1985), interspecific competition (Madsen 1991*b*), nutrient availability (Blindlow 1992), disturbance (Crowder and Painter 1991), water temperatures (Madsen and Brix 1997), turbidity (Belcher and Wilson 1989, Bedunah 1992, Schmitz *et al.* 1993), pH (Brandrud 2002), and sediment composition (Carpenter 1980, Knapton and Petrie 1999, Gleason *et al.* 2003). Purple loosestrife (*Lythrum salicaria* L.), Eurasian watermilfoil (*Myriophyllum spicatum* L.) and alligatorweed (*Alternanthera philoxeroides* (*Mart*.) Griseb.) are a few important alien plants that create dense monospecific stands that displace native wetland plants, are not extensively utilized by waterfowl, and whose presence may deplete valuable native seed banks (Powers *et al.* 1978, Carpenter 1980, Howard-Williams *et al.* 1987, Thompson *et al.* 1987, Madsen *et al.* 1991, Holmes 2002). Monospecific stands negatively affect invertebrate community composition and species richness by reducing vegetation structure complexity (Cyr and Downing 1988, Chilton 1990, Jeffries 1993, Trammell and Butler 1995, Humphries 1996, Jackson 1997, Douglas and O'Connor 2003). These changes can negatively impact waterfowl, waterbirds, and other organisms that rely on wetlands for food and habitat resources (Keast 1984, Herkert 1995, Igl and Johnson 1997, Madsen 1997, Benedict and Hepp 2000).

There are about 400 alien plant species in wetland ecosystems in the United States (Cohen and Carlton 1995, Ruiz *et al.* 1999) and approximately $145 million is spent annually to control those considered invasive (Pimental *et al.* 2000). Their control is necessary for maintenance and restoration of healthy, functioning wetland ecosystems, including native plant communities (Nichols 1991, Smart and Doyle 1995). Introduction and spread of alien plant species into these ecosystems is usually very rapid because of increased ecosystem susceptibility due to degradation (land use changes, hydrologic disruption, etc.) and because waterways act as corridors for dispersal (Thompson *et al.* 1987, Catling and Porebski 1995, Johansson *et al.* 1996, Lachance and Lavoie 2002). However, even healthy wetland plant communities can become invaded (Madsen 1991). Some believe that extensive and rapid spread of alien plant species is leading to homogenization of wetland and aquatic habitats worldwide (Carlton and Geller 1993, Carlton 1996).

Alligatorweed is wetland plant native to South America where it is found from Venezuela to Buenos Aires Province in Argentina (Vogt *et al.* 1979). It was introduced into Mobile Bay, AL in the United States in the late 1800s from ship ballast (Zeiger 1967), resulting in 266,085 ha infested by 1963 (Coulson 1977). Alligatorweed is a problem in wetland habitats from Florida north to 38°N latitude and west to Texas, with some isolated infestations occurring in California below 37°N latitude (USDA and NRCS 2004). Thirty other countries consider alligatorweed invasive and include Australia, Burma, China, India, Indonesia, New Zealand, and Thailand.

There are 170 species of *Alternanthera* in the western hemisphere and 120 species occur in South America (Vogt *et al.* 1979). Only 5% of the species in South America are aquatic. Fifteen native and nonnative species of *Alternanthera*, most of which are terrestrial, occur in the United States. *Alternanthera sessilis,* another nonnative species, is the only other aquatic member that occurs in the Southeast (Godfrey and Wooten 1981).

Alligatorweed is an evergreen, perennial herb that exhibits vigorous growth and tolerance of a wide range of environmental conditions. Leaves are shiny, spear-shaped, opposite, sessile, entire, and 2-7 cm long and 1-2 cm wide. Small white papery flowers, 8-15 mm in diameter, arise from leaf axils. Alligatorweed establishes in water, wet soil of banks, or roots in mats of other vegetation (Eggler 1953). Alligatorweed also has been documented growing on dry land, but aquatic growth always exceeds terrestrial growth (Julien *et al.* 1995, Sainty *et al.* 1998). Temperature is the most important factor limiting further range expansion of alligatorweed, because exposed stems and leaves are killed by frost and ice (Julien *et al.* 1992). However, protected nodes survive to generate the next season's growth (Julien *et al.* 1995).

Alligatorweed has a dual reproductive strategy, considered important for successful plant invasions (Huenneke and Vitousek 1990). It successfully reproduces by seed in its native habitat, but normally does not produce viable seed elsewhere (Holm *et al.* 1997). Instead, it relies on asexual reproduction from any root fragment or piece of stem that contains a node. This contributes to the genetic uniformity in populations of alligatorweed and makes some populations more susceptable to biological control agents (Van Driesche and Bellows Jr. 1996, Ye *et al.* 2003).

By obstructing light penetration and lowering oxygen levels in water (Quimby and Kay 1977, Buckingham 1996), alligatorweed competes with and displaces native plants (Vogt *et al.* 1992, Holm *et al.* 1997). Increases in native plant populations have been observed after alligatorweed control, contributing to the idea that it disrupts native wetland plant communities (Vogt *et al.* 1992). Mats of alligatorweed restrict stream flow, increasing sedimentation and negatively affecting aquatic vegetation, fishes, and invertebrates (Coulson 1977).

Alligatorweed causes economic damage by interfering with many uses of water (Holm *et al.* 1997). Dense mats prevent irrigation canals from draining, create blockages in bends of rivers and streams, result in flooding and structural damage, create mosquito habitat, and prevent fishing, swimming, and navigation (Penfound *et al.* 1945, Tarver *et al.* 1986, Chester 1988). Further, consumption of the terrestrial form has caused photosensitization of skin and cancerous lesions in light pigmented cattle (Bourke and Rayward 2003).

Control of alligatorweed has been difficult because physical control methods such as mowing, disking, and burning are not effective and possibly spread the plant (Holm *et al.* 1997). The alligatorweed flea beetle (*Agasicles hygrophila* Selman and Vogt) is host-specific (Maddox *et al.* 1971) and have proven extremely successful for control of alligatorweed in many countries (Coulson 1977, Vogt *et al.* 1992). However, beetles do not overwinter well where mean winter temperatures are < 11.1°C, so other control measures are needed at more northern latitudes (Coulson 1977, Vogt *et al.* 1992).

Herbicides also have not been entirely successful at controlling alligatorweed. Nodes may hinder translocation of herbicides to the underwater portion of the mats (Maddox *et al.* 1971, Madsen *et al.* 1988). In addition, abnormal growth of root primordia at nodes has been found to block vascular tissues and indirect connections between the axillary buds and the stems also may prevent translocation of herbicides (Zu Burg *et al.* 1961).

Numerous herbicides have been used in an attempt to control alligatorweed. Glyphosate controls floating mats but does not affect the terrestrial form or submerged roots due to poor translocation (Bowmer *et al.* 1993, Tucker 1994). Dichlobenil is useful for spot treatments on banks or shallow water, but is non-selective, making it inappropriate for wetland restoration (Eggler 1953). Metsulfuron methyl is successful on the terrestrial form and is selective for grasses, but use near water is prohibited (Bowmer *et al.* 1989). Multiple applications of 2,4-D are required to control alligatorweed, but complete control is not obtained (Eggler 1953).

There are currently eight herbicides registered by the Environmental Protection Agency for use in aquatic or wetland habitats (complexed copper, 2,4-D, diquat, endothall, fluridone, glyphosate, triclopyr amine, and imazapyr). They can be economical, environmentally compatible, and safe when used according to label directions. This study concentrated on the two most recent approvals, triclopyr amine and imazapyr, in an attempt to evaluate their use in controlling alligatorweed and allowing native plants to reestablish in moist-soil managed wetlands.

Triclopyr amine [[3,5,6-trichloro-2-pryidinyl)oxy], acetic acid] (Renovate*) was approved in December 2002 by the EPA for use in aquatic habitats. It is classified as a systemic herbicide and is selective for dicots (Smart *et al.* 1995, Getsinger *et al.* 1997). Triclopyr is a growth regulator because it mimics the plant growth hormone auxin. In low concentrations, this leads to uncontrolled cell division and growth, and vascular tissue destruction, while in high concentrations triclopyr hinders cell division and growth (Tu *et al.* 2001).

Preliminary studies show selectivity of triclopyr allows native monocots to survive most application rates. This is an important quality for use in wetland restoration projects because monocots are an important wetland group. Native plants such as elodea (*Elodea canadensis* Rich.), sago pondweed (*Potamogeton pectinatus* L.), and wild celery (*Vallisneria americana* Michx.) show no visual effects after treatment, while the alien Eurasian watermilfoil showed significantly reduced biomass (Netherland and Getsinger 1992, Sprecher and Stewart 1995).

Bioaccumulation is not a concern because triclopyr amine is readily degraded in the environment. Photolysis, microbes, and hydrolysis degrade triclopyr amine into triclopyr acid. The half-life is two hours due to photodegredation on soil (McCall and Gavit 1986), and one to twelve hours in water (Johnson *et al.* 1995*a*). Microbial degradation into carbon dioxide, water, and organic acids occurs at a faster rate in higher sunlight, more moist soils, and higher temperatures (Johnson 1995b). Hydrolysis occurs promptly in the environment and within plants (Smith 1976). Triclopyr is very mobile and therefore effective in aquatic environments because it binds weakly to soil and is soluble in water (McCall and Gavit 1986). Accumulation in sediment, shellfish, and fish is very low (Green *et al.* 1989).

Triclopyr amine and triclopyr acid have been found to be toxic to various organisms. The oral LD50 for rats is 630-729 mg/kg. The LD50 for mallard ducks (*Anas platyrhynchos* L.) and Northern bobwhite quail (*Colinus virginianus* L.) are 1,698 mg/kg and 2,935 mg/kg, respectively. The LC50 of the acid and amine for rainbow trout

(*Oncorhynchus mykiss* Walbaum) are 117 mg/L and 552 mg/L, respectively, and are 148 mg/L and 891 mg/L for the bluegill sunfish (*Lepomis macrochirus* Rafinesque). Severe eye damage to humans can occur because of the high pH of triclopyr amine (Tu *et al.* 2001).

Imazapyr (±-2-[4,5-dihydro-4-methyl-4(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid) (Habitat®) was approved in November 2003 by the EPA for use in aquatic habitats. It is a broad-spectrum herbicide that controls annual and perennial grasses, broadleaf weeds, and woody species. Imazapyr is classified as an ALS regulator because it inhibits acetolactate synthase, which catalyzes synthesis of branched amino acids required for protein synthesis and cell growth. Care must be taken around desirable natives because imazapyr leaks from the roots of target species and may be absorbed by other species (Tu *et al.* 2001).

Imazapyr has the potential to be very persistent and mobile in the environment. Imazapyr is more mobile at high temperatures, high pH, and high soil moisture (Dickens and Wehtje 1986, Vizantinopoulos and Lolos 1994). Average half-life in soil, due to microbial metabolism, is several months (Vizantinopoulos and Lolos 1994). In water, the half-life is two days by photodegredation (Mallipudi *et al.* 1991). Hydrolysis does not readily occur.

Imazapyr is only slightly toxic to various organisms. The LD50 for rats is >5,000 mg/kg. The LD50 for mallard ducks and Northern bobwhite quail is >2,150 mg/kg. The LC50 for rainbow trout, bluegill sunfish, channel catfish (*Ictalurus punctatus* Rafinesque), and water fleas (*Daphnia magna*) are >100 mg/L. It can be an eye and skin irritant to humans, but is of relatively low toxicity (American Cyanamid 1997).

Improving the quality of wetland habitats for migrating and wintering waterfowl is the primary objective of moist-soil managers and is an important consideration when managing exotic plant species with herbicides (Reinecke *et al.* 1989, Kaminski *et al.* 2003). Herbicides can be species-selective if application rate and timing of application are appropriate, which is important when managing for native plant species desirable to waterfowl (Getsinger 1998). Application of herbicides in the spring rather than the fall should control alligatorweed, but allow native plants sufficient time to germinate and grow. However, plants accumulate carbohydrates and other nutrients in their storage structures in the fall; therefore herbicides are more likely to be transported with them into the roots, resulting in death of the treated plants (Chapin *et al.* 1990, Wyka 1999). Consequently, application of herbicides in the fall should better control alligatorweed, but may not allow with-in year native plant growth desired by moist-soil managers. Triclopyr amine and imazapyr were tested at different application rates and application times to determine the best treatment to control alligatorweed and restore native wetlands plants in moist-soil managed wetlands.

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II. USE OF HERBICIDES TO CONTROL ALLIGATORWEED AND RESTORE NATIVE VEGETATION TO MANAGED WETLANDS

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ABSTRACT: Moist-soil management is used by wetland managers to improve the quality of wetland habitats for a variety of waterfowl and other waterbirds. However, alien plants such as alligatorweed (*Alternanthera philoxeroides* (*Mart.*) *Griseb.*) may impact success of moist-soil management by competing with and displacing important native plant species used as food by migratory waterfowl; therefore control of alligatorweed is a priority for managers whose goal is to provide waterfowl habitat. A randomized block design was used to test variations in timing (n = 2) and rate (n = 3) of triclopyr amine and imazapyr and their effects on alligatorweed and native plants in treatment year and one year later. High rate resulted in less alligatorweed biomass than low or medium rate in treatment year and one year later. Triclopyr amine application resulted in greater native plant biomass than imazapyr, but there was no difference between herbicides one year later. Increasing application rate at April application decreased alligatorweed biomass and increased native plant biomass in treatment year. However, plots with the least alligatorweed biomass in treatment year had the least alligatorweed biomass and greatest native plant biomass one year later. This study demonstrates restoration of native plant species in moist-soil managed wetlands through chemical control of alligatorweed.

Key Words: alien plant species, *Alternanthera philoxeroides*, imazapyr, moist-soil management, restoration, triclopyr amine

INTRODUCTION

Moist-soil management has been used by waterfowl biologists since the 1940s (Nyman *et al.* 1990), and currently is used extensively to improve quality of wetland habitats for a variety of waterbird species (Rundle and Fredrickson 1981, Laubhan and Fredrickson 1993, Reid 1993, Parsons 2002). Managed wetlands are drained in spring or early summer to moist-soil conditions to promote establishment of desirable plant species and increase diversity and density of invertebrates that are an important dietary protein source (Haukos and Smith 1993, Ellison and Bedford 1995, Anderson and Smith 2000, Bowyer *et al.* 2005). Wetlands are flooded in autumn to provide habitat for migrating and wintering waterfowl and other waterbirds that forage for seeds and invertebrates (Fredrickson and Taylor 1982, Taft *et al.* 2002).

Alien plants are an increasing problem in wetland habitats and may impact success of moist-soil management. Invasive plants can directly displace native plants by competition (Madsen *et al.* 1991, Barrat-Segretain 2005, Thomson 2005) and indirectly by altering the physical environment such as light level and water quality (Blindlow 1992, D'Antonio and Vitousek 1992, Barrat-Segretain and Elger 2004). Establishment of alien plants decreases quality of habitats for waterfowl, waterbirds, and other organisms (Keast 1984, Madsen 1997, Benedict and Hepp 2000). For example, monospecific stands of alien invasive plants can negatively affect invertebrate communities by reducing vegetation complexity and oxygen levels (Cheruvelil *et al.* 2002, Douglas and O'Connor 2003, Strayer *et al.* 2003). Control of invasive vegetation and re-establishment of native vegetation often are necessary management goals, and herbicides can be used by wetlands managers to meet these objectives (Netherland and Getsinger 1992, Getsinger *et al.* 1997).

Alligatorweed (*Alternanthera philoxeroides* (*Mart.*) *Griseb.*) is an alien plant that has invaded many wetlands in the southern United States. It is an evergreen, perennial herb native to South America that grows in a variety of conditions (Eggler 1953, Zhang *et al.* 1993, Julien *et al.* 1995). Alligatorweed forms dense mats on moist-soil and over open water. It reproduces asexually in the United States, and new plants develop from any piece of root fragment or stem that contains a node (Spencer and Coulson 1976). Alligatorweed alters wetland plant communities by reducing light penetration, lowering oxygen levels in water and competing with native plants (Quimby and Kay 1977, Vogt *et al.* 1992, Buckingham 1996, Holm *et al.* 1997). Unlike many native wetland plants, alligatorweed is not a valuable waterfowl food because it usually does not produce seeds (Holm *et al.* 1997).

Control of alligatorweed has proven to be difficult because physical control methods such as mowing and disking only redistribute and possibly spread the plant (Holm *et al.* 1997). Alligatorweed flea beetles (*Agasicles hygrophila*) have been used successfully to control alligatorweed where mean winter temperatures are > 11.1°C, but additional control measures are needed in more northern areas (Coulson 1977, Vogt *et al.* 1992). Herbicides may be useful for controlling alligatorweed and restoring wetland plant communities, but extensive testing in managed wetlands has not been completed (Bowmer *et al.* 1989, Bowmer *et al.* 1993, Tucker 1994, Kay 1999). In particular, herbicides recently licensed for use in wetlands have not been evaluated.

The objective of this study was to vary timing and rate of application of triclopyr amine and imazapyr and evaluate effects on alligatorweed and native plants during the year of application and one year later. Timing of herbicide application is important because it can affect degree of control of invasive species and damage to associated native species, which may impact the suitability of habitat for wintering waterfowl (Harrington and Miller 2005, Judge *et al.* 2005). For example, I predicted that early season use of herbicides would result in greater biomass and seed production of native plants than late season herbicide use because of the extended growing season.

STUDY AREA

The study was conducted in the Kennedy (182 ha) and Bradley (305 ha) units of Eufaula National Wildlife Refuge (ENWR; 32°N, 85°W) in southeastern Alabama and southwestern Georgia. ENWR (4,452 ha) is located on the northern portion of the Walter F. George Reservoir, an impoundment of the Chattahoochee River (Figure 1).

Moist-soil management is used at ENWR to provide food and habitat for migratory waterfowl (Fredrickson and Taylor 1982). Drawdown of managed wetlands begins in mid-March and continues until moist-soil conditions are reached. Moist-soil water levels are monitored by refuge staff and maintained throughout the growing season to allow growth of desirable plant species (Table 1). Re-flooding of moist-soil impoundments begins in late October. Alligatorweed dominates many of the managed wetlands at ENWR and numerous control methods have been used unsuccessfully, including mowing, disking, burning, herbicide application, and release of alligatorweed flea beetles.

METHODS

Experimental Design

I used a randomized block design with four replications. Four experimental blocks were established in April 2004 within managed wetlands of the Kennedy ($n = 2$) and Bradley ($n = 2$) units of ENWR. Treatments consisting of herbicides ($n = 2$), application rates ($n = 3$), and application dates ($n = 2$) were randomly assigned to experimental plots (5 m x 5 m) within each block. Control plots ($n = 4$) were included in each block.

I tested triclopyr amine (Renovate®, SePRO, Carmel, IN 46032) and imazapyr (Habitat®, BASF, Florham Park, NJ 07932) in this study because of their recent approval by the Environmental Protection Agency for use in wetlands. Each herbicide was mixed with a nonionic surfactant (Top Surf ®, Agriliance, LLC, St. Paul, MN 55164) and applied on two dates, 28 April and 13 July 2004. Two swaths per plot were applied with a 2L CO_2-pressurized backpack spray unit with a five-nozzle boom (2.5m width). Application rates for triclopyr included: low (4.8L ha^{-1} or 12mL $plot^{-1}$), medium (9.6L ha^{-1} or 24mL $plot^{-1}$), and high (14.4L ha^{-1} or 36mL $plot^{-1}$). These rates were applied using 935L ha^{-1} or 2.4L $plot^{-1}$ of water and 0.25% nonionic surfactant. Application rates for imazapyr included: low (1.2L ha^{-1} or 3mL $plot^{-1}$), medium (2.4L ha^{-1} or 6mL $plot^{-1}$), and high (3.6L ha^{-1} or 9mL $plot^{-1}$). These rates were applied using 467L ha^{-1} or 1.2L $plot^{-1}$ of water and 0.25% nonionic surfactant. Application rates were within the range of rates recommended by manufacturers. Control plots received no water, herbicide, or surfactant.

Percent Cover, Stem Density, and Height of Alligatorweed

Percent cover, stem density, and height of alligatorweed were estimated for experimental and control plots immediately before herbicides were applied to experimental plots and then monthly from March to October 2005. I randomly placed two subplots (1 m x 1 m) in each experimental plot and estimated percent cover of all plant species. Height of alligatorweed was measured at the corners of each subplot (n = 4), and alligatorweed stem density was measured by counting individual alligatorweed stems in quadrats (0.25 m x 0.25 m; n = 2) within each subplot.

Plant Biomass

In October 2004 and 2005, I estimated plant biomass and species composition in experimental and control plots by clipping all above ground plant parts in randomly placed quadrats (0.25 m x 0.25 m; n = 2). Clipped plants were placed in plastic bags, transported to Auburn University where plants were separated and identified to species (Godfrey and Wooten 1978, 1981) and oven dried (60°C) to constant mass. Alligatorweed was weighed to the nearest 0.01g. Native plants and their seeds were weighed to the nearest 0.01g, and then seeds were separated and weighed alone to the nearest 0.01g.

Statistical Analysis

Each year a four-way ANOVA (PROC MIXED)(SASInstitute 2003) was used to test effects of block (n = 4), herbicide (n = 2), application rate (n = 3), application timing (n = 2), and all interactions on biomass of either alligatorweed or native plants. Block was specified as the random variable, while herbicide, application date and application timing were fixed variables. Biomass of native plants used in the ANOVA included all native plants and their seeds. Nonsignificant interactions ($P > 0.10$) were excluded from final models. I tried using pretreatment values of percent cover, stem density, or height of alligatorweed as covariates, but they were not significant ($P > 0.10$) and were not used in the analysis. Tukey-Kramer tests were used to conduct pair-wise comparisons of least squares means to separate significant main effects and interaction effects. Four control plots were included in each block and so were not replicated across all treatments; therefore, Dunnett's test was used to test for differences in alligatorweed biomass between control and treatments. All tests were significantly different at $P \leq 0.10$ to reduce the chance of type II error due to small sample size. Linear regression (PROC REG; SAS Institute 2003) was used to test relationships among biomass of alligatorweed, native plants, and native plant seed.

RESULTS

Year of treatment

Alligatorweed. Alligatorweed biomass was influenced by the interaction of herbicide and application date ($F_{1,37} = 4.67$, $P = 0.04$). Biomass of alligatorweed was lower with imazapyr (34.97 ± 7.85 g/0.25m^2) than with triclopyr amine (68.79 ± 7.85 g/0.25m^2) when applied in April, but alligatorweed biomass did not differ between herbicides when they were applied in July (imazapyr: 8.69 ± 7.85 g/0.25m^2 and triclopyr amine: 8.61 ± 7.85 g/0.25m^2).

Biomass of alligatorweed also was affected by the interaction of rate and date of application ($F_{2,37} = 2.72$, $P = 0.08$). In April, high application rate of herbicides resulted in less alligatorweed biomass than low application rate; however, all application rates in July were equally effective at reducing alligatorweed biomass (Fig. 2A). Low and high application rates in July provided better control of alligatorweed than low and medium rates in April, and medium application rate in July controlled alligatorweed better than low rate in April (Fig. 2A).

Percent cover of alligatorweed was reduced immediately after applying triclopyr amine at all application rates in April, but began increasing 3-4 weeks later (Fig. 3A). Percent cover of alligatorweed actually increased immediately following application of imazapyr in April, but began decreasing about 2 weeks after application. Percent cover of alligatorweed remained low for medium and high rates of imazapyr, but increased at week 8 for the low application rate (Fig. 3B). In July, percent cover of alligatorweed declined immediately after applying either triclopyr amine (Fig. 4A) or imazapyr (Fig. 4B) and remained below control levels until October.

In April, only imazapyr applied at high rate reduced alligatorweed biomass to below that of the control (Table 2). All treatments applied in July reduced biomass of alligatorweed to below that of control plots (Table 2).

Native plants. I collected 13 species of native plants in October 2004 (Appendix A). Biomass of native plants was affected by herbicide ($F_{1,38} = 7.58$, $P = 0.01$). Application with triclopyr amine (59.94 ± 14.55 g/0.25m^2) resulted in greater native plant biomass than application with imazapyr (27.94 ± 14.55 g/0.25m^2). Biomass of native plants also was affected by the interaction of rate and date of application ($F_{2,38} = 2.91$, $P = 0.07$).

High application rate of herbicides in April resulted in greater biomass of native plants than did low application rate in April and medium and high rates in July (Fig. 2B). Different application rates in July did not affect native plant biomass (Fig. 2B). No treatments applied in April or July increased native plant biomass to greater than that of control plots (Table 2).

There was a slight increase in biomass of native plants as alligatorweed biomass decreased after applying herbicides in April (y = 96.02 – 0.62x; adj $r^2 = 0.1$; $P = 0.07$), but no relationship ($P > 0.10$) following the July application. Biomass of native plant seeds increased as native plant biomass increased, and the relationship did not differ between April (b = 0.16 ± 0.04) and July (b = 0.15 ± 0.03) herbicide applications, so data were combined (Fig. 5).

Year after treatment

Alligatorweed. I also evaluated effects of treatments applied in 2004 on biomass of alligatorweed in October 2005. Biomass of alligatorweed was affected by application rate ($F_{2,39} = 3.45$, $P = 0.04$). High application rate (20.72 ± 9.89 g/0.25m^2) resulted in less alligatorweed biomass than low application rate (40.70 ± 9.89 g/0.25m^2), but alligatorweed biomass at the medium application rate (31.78 ± 9.89 g/0.25m^2) did not differ from either low or high rates. Biomass of alligatorweed also was affected by the interaction of herbicide and application date ($F_{1,39} = 6.37$, $P = 0.02$). Alligatorweed biomass did not differ between herbicides after April application, but July application of imazapyr resulted in less alligatorweed biomass than either herbicide applied in April

(Fig. 6A). Further, July application of triclopyr amine resulted in less alligatorweed biomass than April application of imazapyr (Fig. 6A).

Treatments in April did not reduce alligatorweed biomass to below that of control plots (Table 2). In July, only triclopyr amine applied at high rate and imazapyr applied at medium and high rates reduced alligatorweed biomass to below that of control plots (Table 2).

Native Plants. I collected 15 species of native plants in October 2005 (Appendix B). Biomass of native plants was affected by the interaction of herbicide and application date ($F_{1,39} = 7.88$, $P = 0.008$). There was no difference between triclopyr amine and imazapyr at April or July application, but July application of imazapyr resulted in greater native plant biomass than April application of either herbicide (Fig. 6B).

Biomass of native plants declined as alligatorweed biomass increased and the relationship did not differ between April ($\underline{b} = -1.37 \pm 0.27$) and July ($\underline{b} = -2.09 \pm 0.84$) herbicide applications, so data were combined (Fig. 7). There was a positive relationship between biomasses of native plants and native seeds that did not differ between April ($\underline{b} = 0.16 \pm 0.04$) and July ($\underline{b} = 0.15 \pm 0.02$) so those data also were combined (Fig. 8). No treatments applied in April or July increased native plant biomass to greater than that of control plots (Table 2).

DISCUSSION

Year of treatment

Three factors may have contributed to the greater biomass of native plants following application of triclopyr amine (63g/ 0.25m^2) compared to imazapyr (28g/

$0.25m^2$). First, fewer native plant species, especially monocots, may have been killed by application of triclopyr amine than imazapyr because triclopyr amine is a synthetic auxin selective for broad leaf plants whereas imazapyr is a broad-spectrum herbicide (Tu *et al.* 2001). Second, imazapyr is moderately mobile and more persistent in the soil compared to triclopyr, so that plants germinating after imazapyr application may have been affected by residual herbicide activity in the soil (Coffman *et al.* 1993, Cox 2000). Third, triclopyr amine reduced alligatorweed percent cover much more quickly than imazapyr after treatment in April (Fig. 3). Imazapyr inhibits production of amino acids that are stored by plants, so death does not occur until those resources diminish (Tu *et al.* 2001). This difference in timing of herbicide effectiveness in spring could provide a critical window of opportunity for native plants to germinate and grow (Harper 1977). High plant biomass in a community has been shown to negatively affect seedling establishment (Gaudet and Keddy 1988, Weigelt *et al.* 2002), so decreasing alligatorweed biomass in the spring, even just for a short time, may have provided suitable growing conditions for native plants. Alligatorweed became re-established from underground nodes (Julien *et al.* 1992) following April application of triclopyr amine, but the delay apparently allowed sufficient time for native plants to become established, resulting in increased native plant biomass prior to autumn flooding.

Alligatorweed exhibits several traits that may give it a competitive advantage over other plant species. It is evergreen, grows quickly, produces high biomass, and forms dense canopies (Gaudet and Keddy 1988, Tilman 1988, Wisheu and Keddy 1992, Greulich and Bornette 2003). Alligatorweed forms dense canopies in early spring that effectively block light and space needed by native plants to germinate and grow (Fig. 3)

(Durden *et al.* 1975, Liu *et al.* 2004). Other studies have shown increased recruitment and growth of native plant seedlings when more space and light are made available after invasive plants are controlled (Walker and Vitousek 1991, Barrat-Segretain 1996, Barrat-Segretain and Elger 2004). For example, control of Eurasian watermilfoil (*Myriophyllum spicatum* L.) with triclopyr resulted in increases in native plant biomass that remained dominant for two years after treatment (Getsinger *et al.* 1997). Similarly, removal of the alien invasive ripgut brome (*Bromus diandrus* (Roth.)) increased seedling recruitment of the endangered dune evening primrose (*Oenothera deltoides* (Torr. and Fremont)) (Thomson 2005). Early alligatorweed control may allow re-established native plants to compete with alligatorweed, helping to maintain it at reduced levels until autumn.

Both triclopyr amine and imazapyr applied at any rate in July were effective at reducing alligatorweed biomass. Plants, especially perennials, accumulate carbohydrates and other nutrients in roots and other storage structures in autumn (Chapin III *et al.* 1990, Wyka 1999); therefore herbicides are more likely to be transported with them into the roots, resulting in death of the plant. This explains why low application rates of herbicides late in the season worked well to control alligatorweed, whereas use of herbicides in July did not allow production native plant biomass to be as high as did April applications.

Most of the dominant native plant species (e.g. *Polygonum* sp., *Echinochloa crus-galli*, etc.) in my study are valuable waterfowl foods (Low and Bellrose 1944, Haukos and Smith 1993, Cronk and Fennessy 2001). Diversity of the dominant native plants was greater for plots treated with triclopyr amine in April and imazapyr in July. Plots treated with imazapyr in April and triclopyr amine in July were more likely to contain a singe dominant species. Additionally, native monocots and annual plants that are the target species of many moist-soil managers were more common after April application than after July application (Appendix A) (Low and Bellrose 1944, Fredrickson and Taylor 1982).

Biomass of native seeds was related positively to native plant biomass and plots treated with high rates in April tended to have greater native seed production than plots treated with low rates. For example, plots treated with low rate contained from 87 -124 kg/ha of native seeds while plots treated with high rate contained 536- 672 kg/ha. Seed production in plots treated with medium and high rates fell within ranges reported in other studies of managed wetlands. Seed production ranged from 331-1,084 kg/ha in Mississippi and from 565-2,047 kg/ha in Illinois (Bowyer *et al.* 2005, Reinecke and Hartke 2005). Plots treated in July had lower seed production (0-393 kg/ha) than plots treated in April because there was less native plant biomass and the plants had less time to produce seed after herbicide application.

Year after treatment

Better control of alligatorweed in treatment year resulted in less alligatorweed biomass and greater native plant biomass the year after treatment. Plots treated with high herbicide rate still contained less alligatorweed biomass and more native plant biomass than plots treated with low herbicide rate one year later. These same plots, especially following July application of imazapyr, resulted in the greatest native seed biomass (716 - 1312 kg/ha). Plots treated with triclopyr amine or imazapyr did not differ in alligatorweed biomass or native plant biomass at April or July application. However, diversity of dominant native plants was greater for plots treated with triclopyr amine than imazapyr at April and July applications. Results indicate that control of alligatorweed in one year allows native plant species to reestablish naturally the next year, probably because of decreased competition with alligatorweed.

MANAGEMENT IMPLICATIONS

One of the primary objectives of moist-soil managers is to improve the quality of wetland habitats for migrating and wintering waterfowl (Reinecke *et al.* 1989, Kaminski *et al.* 2003). However, in many cases, alien invasive plant species such as alligatorweed can decrease native plant biomass and native plant seed production. My results indicate that using the herbicides triclopyr amine or imazapyr to control alligatorweed and re-establish native vegetation is a realistic tool for improving managed wetlands degraded by alligatorweed, but two conflicting strategies were revealed. Wetland managers who want to control alligatorweed and see the greatest improvement in habitat quality for waterfowl in the treatment year should apply triclopyr amine at high rate in April. Wetland managers who can wait one year after treatment to accomplish the greatest improvement on habitat quality should apply a high rate of either herbicide in July. Managers can alter specific dates to meet their management plans and goals, but this study provides management techniques to improve moist-soil wetlands degraded by alligatorweed and provide migratory waterfowl with more plentiful native food sources. Both methods may be useful, because managers of moist-soil wetlands often vary habitat management to enhance diversity of habitats available at any given time for waterfowl and other waterbirds (Laubhan and Fredrickson 1993, Parsons 2002, Taft *et al.* 2002).

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Figure 1. Location of study sites within Eufaula National Wildlife Refuge, AL.

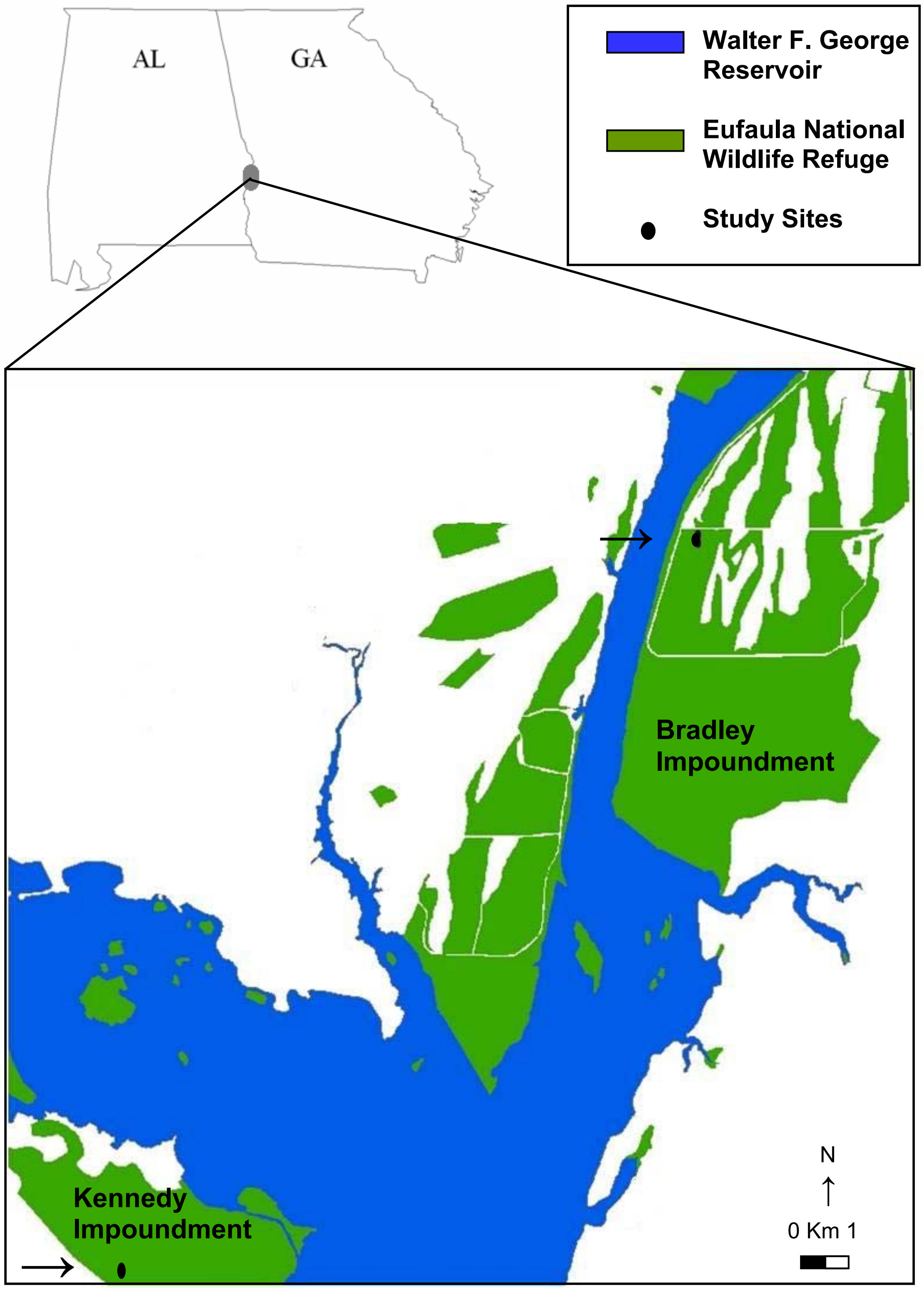
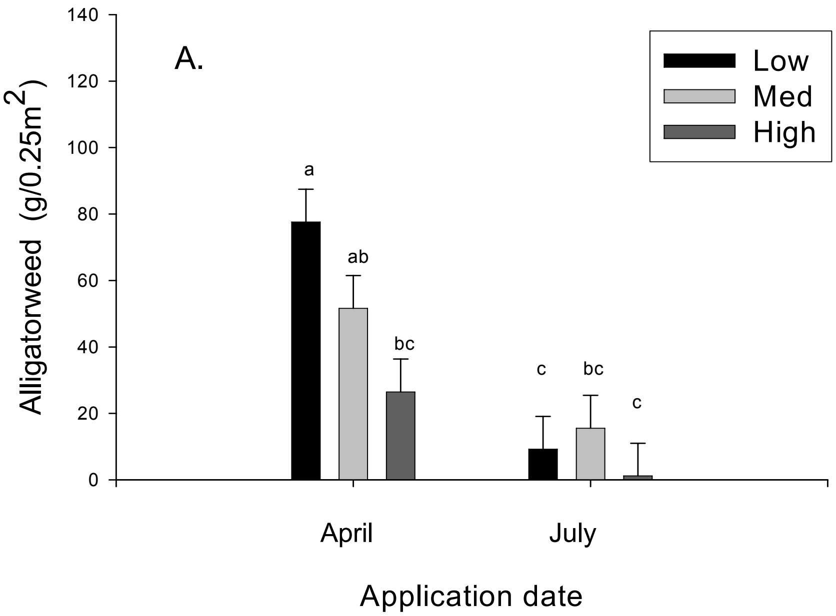

AL
GA
Walter F. George Reservoir
Eufaula National Wildlife Refuge
Study Sites
Bradley Impoundment
Kennedy Impoundment
N
0 Km 1

Figure 2. Comparisons of least squares means (± SE) of alligatorweed dry mass (A) and native plant dry mass (B) collected in October 2004 after applying either triclopyr amine or imazapyr at low, medium, and high rates in April and July 2004. Bars with different letters within plant types indicate significance at $P \leq 0.10$ level.


A.
Low
Med
High
Alligatorweed (g/0.25m2)
140
120
100
80
60
40
20
0
a
ab
bc
c
bc
c
April
July
Application date

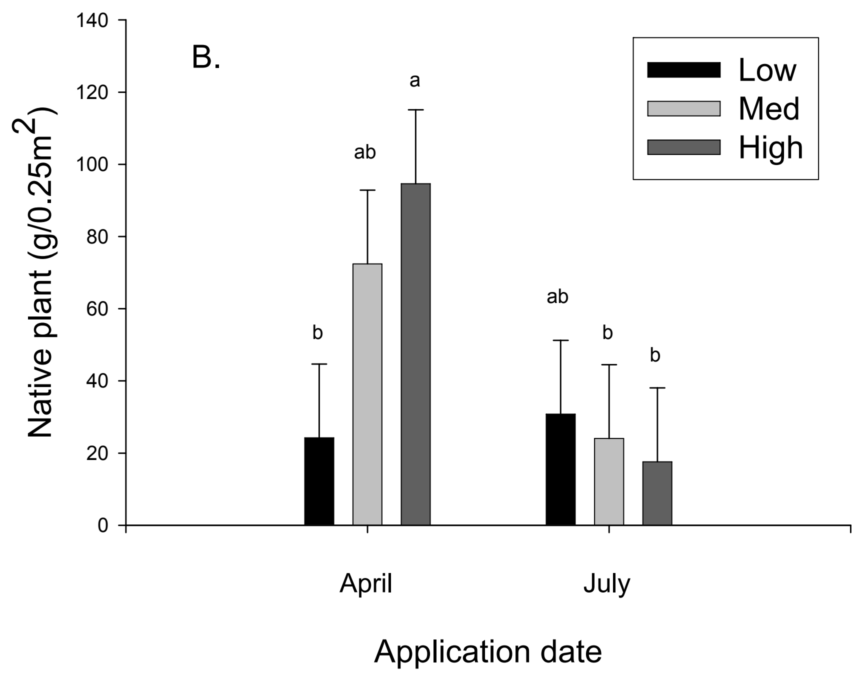

B.
Low
Med
High
Native plant (g/0.25m2)
140
120
100
80
60
40
20
0
b
ab
a
ab
b
b
April
July
Application date

Figure 3. Percent cover of alligatorweed on control plots and on experimental plots after April 2004 application of triclopyr (A) or imazapyr (B) at low, medium, and high rates.

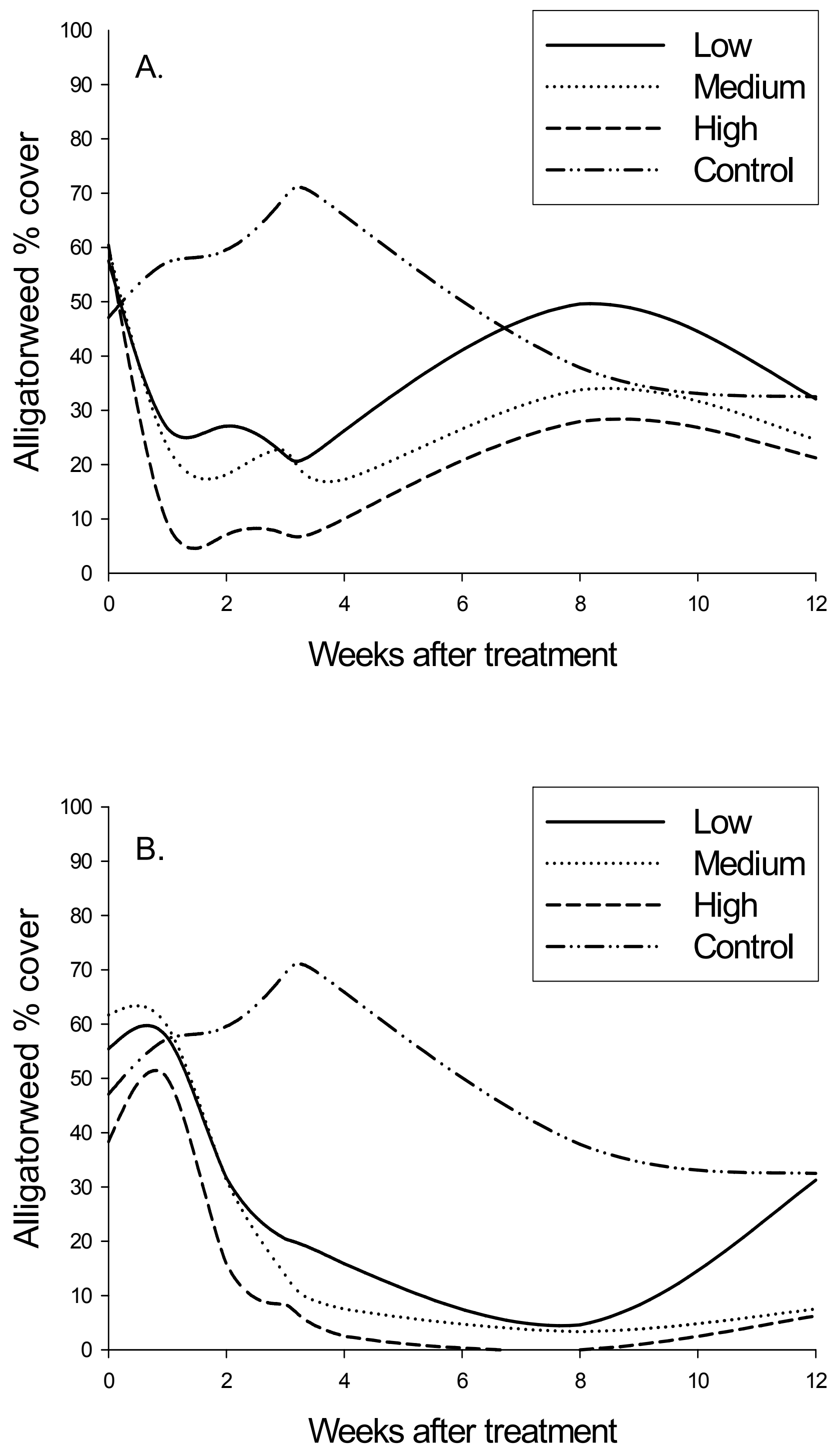


Figure 4. Percent cover of alligatorweed on control plots and on experimental plots after July 2004 application of triclopyr (A) or imazapyr (B) at low, medium, and high rates.

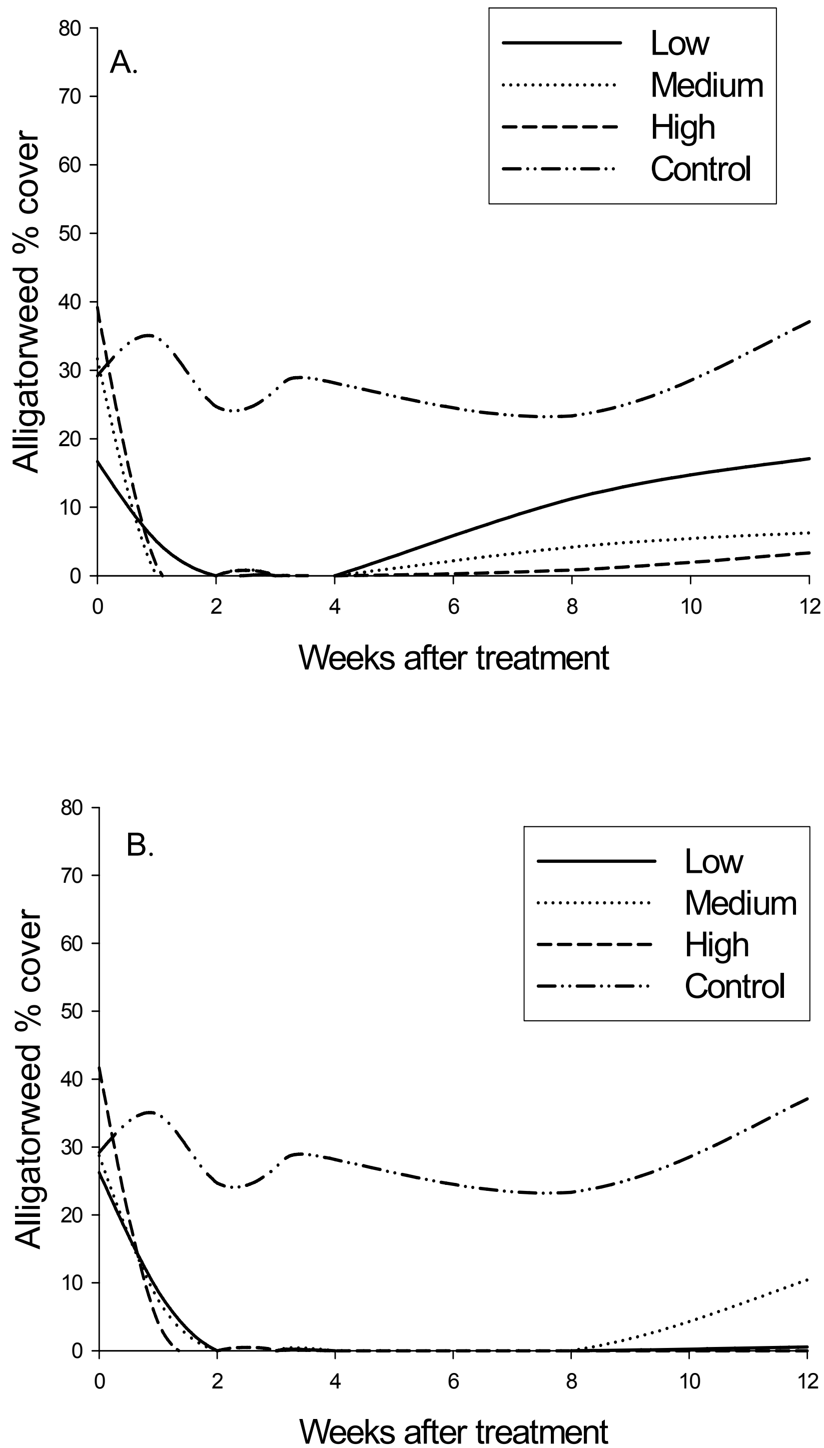


Figure 5. Relationship between native plant dry mass and native plant seed dry mass in October 2004 following April (●) and July (○) herbicide application in 2004.

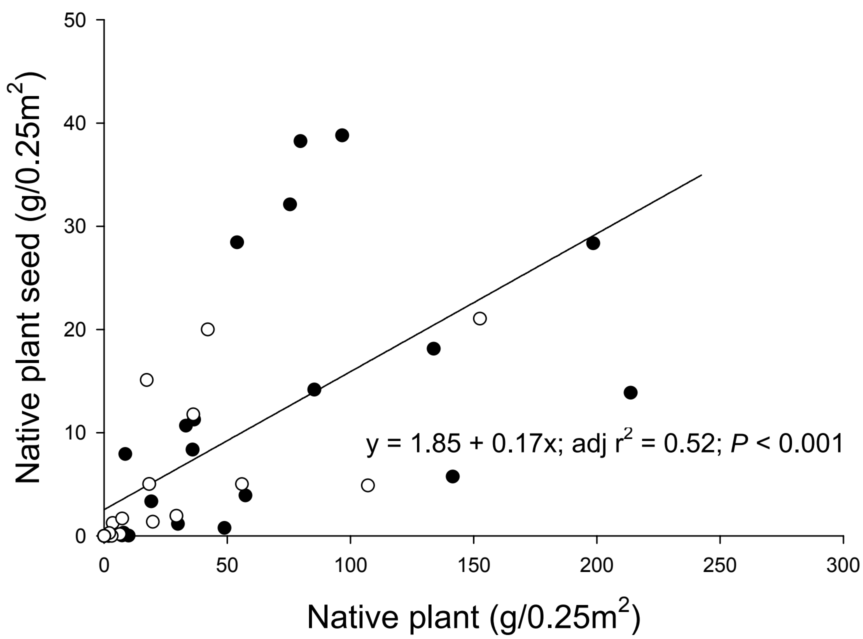


Figure 6. Comparisons of least squares means (± SE) of alligatorweed dry mass (A) and native plant dry mass (B) collected in October 2005 after applying either triclopyr amine ( ) or imazapyr ( ) in April and July 2004. Bars with different letters within plant types indicate significance at $P \leq 0.10$ level.

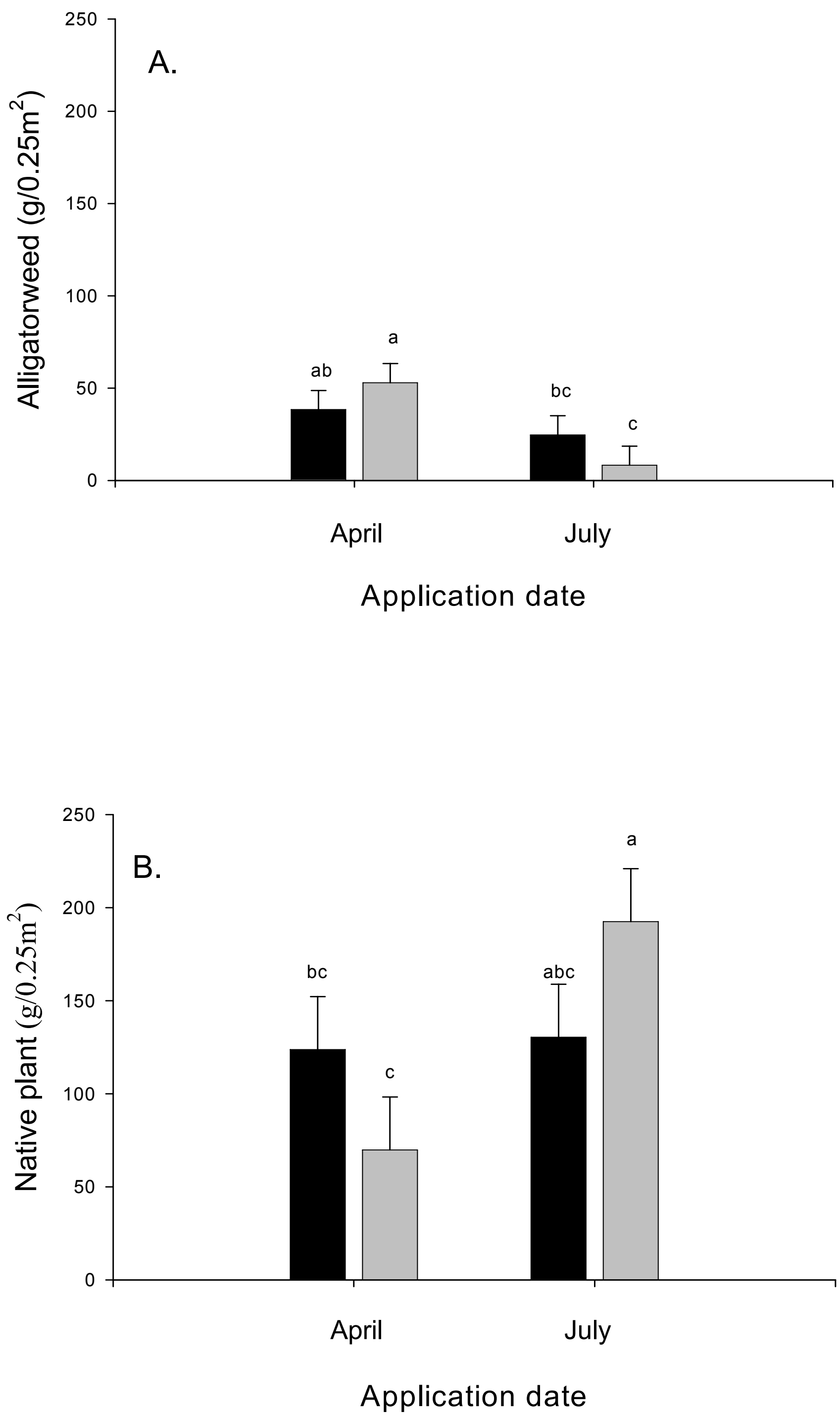

A.
Alligatorweed (g/0.25m2)
250
200
150
100
50
0
ab
a
bc
c
April
July
Application date
B.
Native plant (g/0.25m2)
250
200
150
100
50
0
bc
c
abc
a
April
July
Application date

Figure 7. Relationship between alligatorweed dry mass and native plant dry mass in October 2005 following April (●) and July (○) herbicide application in 2004.

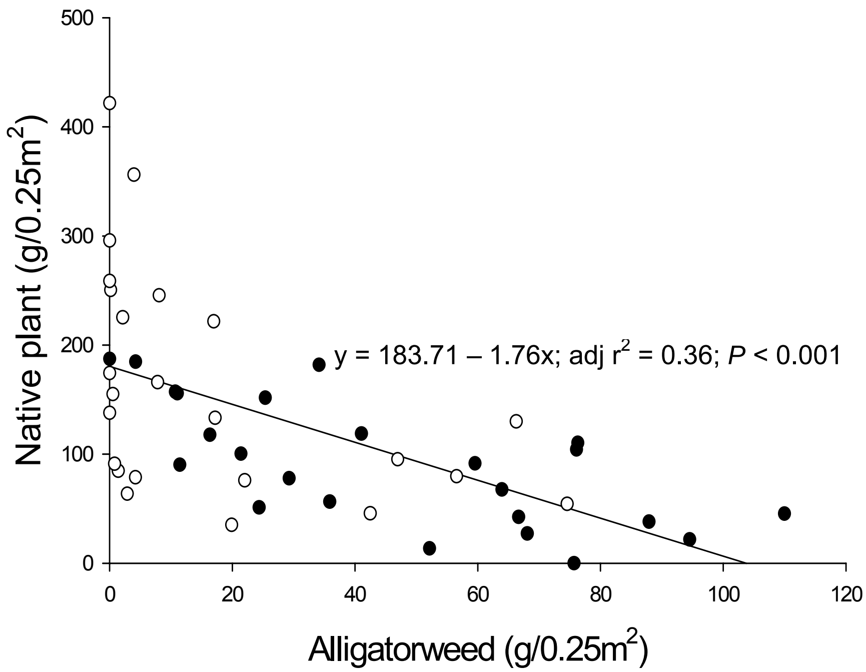


Figure 8. Relationship between native plant dry mass and native plant seed dry mass in October 2005 following April (●) and July (○) herbicide application in 2004.

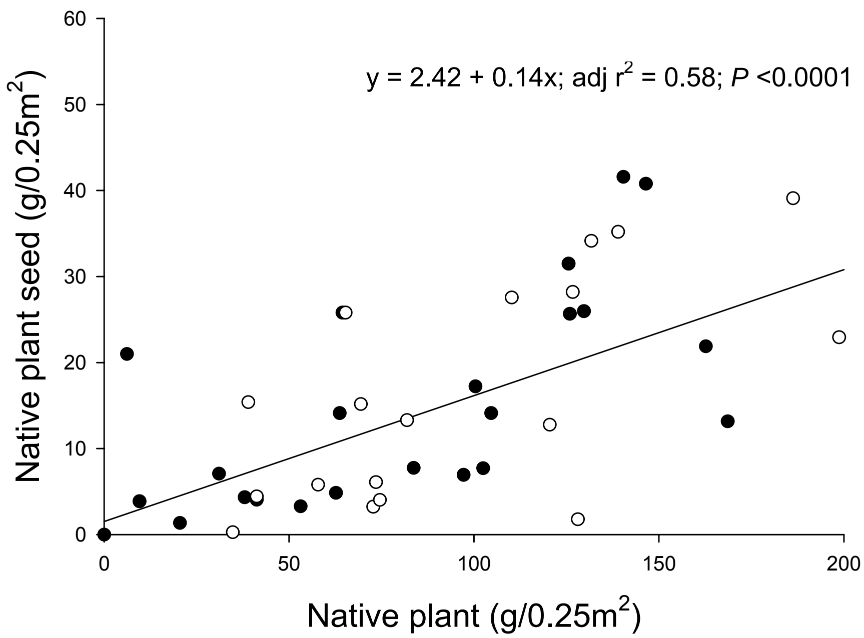


Table 1. Native and nonnative plants found in experimental plots at Eufaula National Wildlife Refuge, AL and GA, 2004-2005.

Scientific Name	Common Name	Group[a]	Duration[b]	Wildlife Use
Nonnative Species				
Alternanthera philoxeroides	alligatorweed	d	p	unknown
Native Species				
Aeschynomene indica (L.)	sensitive joint vetch	d	a/p	unknown
Azolla caroliniana (Willd.)	mosquito fern	f	a	unknown
Bidens mitis (Michx.) Sherff	marsh beggartick	d	a	seed
Brasenia schreberi (J.F. Gmel.)	water shield	d	p	seed
Bromus latiglumis (J.F. Gmel.)	earlyleaf brome	m	p	seed
Cephalanthus occidentalis (L.)	common buttonbush	d	p	seed, cover
Cyperus erythrorhizos (muhl.)	red rooted sedge	m	a/p	seed
Cyperus pseudovegetus (Steud.)	flatsedge	m	p	seed
Diodia virginiana (L.)	Virginia buttonweed	d	p	seed
Echinochloa crusgalli (L.) Beauv.	barnyard grass	m	a	seed, cover
Hydrolea quadrivalvis (Walt.)	waterpod	d	p	unknown
Leersia oryzoides (L.) Sw.	cutgrass	m	p	seed
Leptochloa panicea (Retz.) Ohwi.	sprangletop	m	a/p	seed
Ludwigia decurrens (Walt.)	wingleaf primrose-willow	d	a/p	browse
Ludwigia repens (Forst.)	creeping primrose-willow	d	p	browse
Panicum sp.	panicum	m	p	seed, cover
Polygonum densiflorum (Meisn.)	denseflower knotweed	d	a/p	seed, cover
Polygonum hydropiperoides (Michx.)	swamp smartweed	d	p	seed, cover
Polygonum pensylvanicum (L.)	Pennsylvania smartweed	d	a	seed, cover
Polygonum punctatum (Ell.)	dotted smartweed	d	a/p	seed, cover

Table 1. continued

Scientific Name	Common Name	Group [a]	Duration [b]	Wildlife Use
Rhynchospora corniculata (Lam.)	gray horned beakrush	m	p	seed
Rhynchospora divergens (Chapm.)	spreading beaksedge	m	p	seed
Rhynchospora inundata (Oakes) Fern	narrowfruit beakrush	m	p	seed
Sagittaria lancifolia (L.)	bulltongue arrowhead	m	p	unknown
Sesbania herbacea (P. Mill.) McVaugh	hemp sesbania	d	a	cover
Scirpus cyperinus (L.) Kunth	woolgrass	m	p	seed, cover
Tridens flavus (L.) Hitchc.	purpletop tridens	m	p	seed

[a] Indicates group classification (m = monocotyledon, d = dicotyledon, f = fern).

[b] Indicates duration (a = annual, p = perennial).

Table 2. Comparisons between treatments and control [a, b] values (least-squares means ± SE) of alligatorweed (Aw) and native plant dry mass ($g/0.25m^2$). Dry mass of treatments and control were measured in October 2004 and 2005, treatments were applied in April and July in 2004.

		Application date											
		April						July					
		Triclopyr			Imazapyr			Triclopyr			Imazapyr		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
2004													
	Aw	92.45	73.50	40.41	62.74	29.72	12.46	14.25	9.22	2.35	4.21	21.86	$1.3e^{-13}$
	SE	16.39	16.39	16.39	16.39	16.39	15.11	16.39	16.39	16.39	16.39	16.39	16.39
							***	**	***	***	***	**	****
	Native	33.24	88.36	97.59	15.08	56.44	91.67	60.39	31.74	21.09	0.65	1.60	0.04
	SE	30.96	30.96	30.96	30.96	30.96	30.96	30.96	30.96	30.96	30.96	30.96	30.96
2005													
	Aw	34.77	42.45	37.99	75.45	50.44	32.95	34.1	28.19	11.78	18.49	6.03	0.18
	SE	16.77	16.77	16.77	16.77	16.77	16.77	16.77	16.77	16.77	16.77	16.77	16.77
									**		**	***	
	Native	135.44	97.04	138.8	31.58	86.89	90.97	114.68	106.32	170.2	160.18	207.78	209.54
	SE	46.55	46.55	46.55	46.55	46.55	46.55	46.55	46.55	46.55	46.55	46.55	46.55

[a] Dry mass of alligatorweed controls in 2004 (78.11 ± 8.2 $g/0.25m^2$) and 2005 (53.99 ± 12.96 $g/0.25m^2$)

[b] Dry mass of native plant controls in 2004 (75.38 ± 16.03 $g/0.25m^2$) and 2005 (128.86± 30.9 $g/0.25m^2$)

* $P \leq 0.10$, ** $P \leq 0.05$, *** $P \leq 0.01$, **** $P \leq 0.001$

Table 3. Dominant [a] native plant species collected in October 2004 and October 2005 after applying either triclopyr amine or imazapyr at low, medium, or high rates in April or July 2004.

			Dominant species	
Application Date	Herbicide	Rate	2004	2005
April	Triclopyr	Low	*Polygonum densiflorum* *Leptochloa panacea*	*Polygonum densiflorum*
		Medium	*Echinochloa cru-sgalli* *Polygonum densiflorum*	*Polygonum densiflorum* *Polygonum punctatum*
		High	*Echinochloa crus-galli* *Leersia oryzoides*	*Polygonum densiflorum* *Polygonum hydropiperoides*
	Imazapyr	Low	*Echinochloa crus-galli*	*Polygonum hydropiperoides*
		Medium	*Echinochloa crus-galli*	*Polygonum densiflorum*
		High	*Echinochloa crus-galli*	*Echinochloa crus-galli*
July	Triclopyr	Low	*Polygonum punctatum*	*Polygonum hydropiperoides* *Leptochloa panicea*
		Medium	*Polygonum densiflorum*	*Polygonum densiflorum*
		High	*Polygonum densiflorum*	*Polygonum densiflorum* *Leptochloa panicea*
	Imazapyr	Low	*Panicum* sp. *Diodia virginiana*	*Echinochloa crus-galli*
		Medium	*Polygonum densiflorum* *Panicum* sp.	*Echinochloa crus-galli*
		High	*Panicum* sp.	*Echinochloa crus-galli* *Sesbania herbacea*

[a] Plant species that singly or combined comprised ≥ 50% of total native plant dry mass ($g/0.25m^2$).

III. **EVALUATION OF TRICLOPYR AND IMAZAPYR TO CONTROL ALLIGATORWEED (*Alternanthera philoxeroides*) IN MOIST-SOIL MANAGED WETLANDS**

SHANNON L. ALLEN, GARY R. HEPP, and JAMES H. MILLER

Abstract: Alligatorweed is an alien plant that has invaded wetland habitats and altered native wetland plant communities worldwide. It is difficult to control with traditional herbicides because nodes hinder translocation to underground plant parts that provide resources for regrowth. A randomized block design was used to test variations in timing ($n = 3$) and rate ($n = 3$) of triclopyr amine and imazapyr and their effects on alligatorweed one year later. High application rate resulted in less alligatorweed biomass than low or medium rates. July and September applications resulted in less alligatorweed biomass than April application. Alligatorweed biomass and percent cover treatment means from medium and high rates applied in July and September were lower than control means while April applications were not. Herbicides controlled alligatorweed equally well at all application times. This study reveals that rate and timing of herbicide application are important considerations when managing alligatorweed.

Nomenclature: imazapyr, triclopyr amine, alligatorweed, *Alternanthera philoxeroides* (Mart.) Griseb.

Additional index words: moist-soil wetlands, dry mass, percent cover, invasive plants.

INTRODUCTION

Alligatorweed (*Alternanthera philoxeroides* (Mart.) Griseb.) is an internationally recognized alien invasive plant native to South America that has invaded many wetlands in the southern United States and other countries including Australia, China, India, Indonesia, New Zealand and Thailand. Alligatorweed is an evergreen, perennial herb that tolerates a wide range of environmental conditions, exhibits vigorous growth, and forms dense mats on moist-soil and over open water (Eggler 1953, Zhang *et al.* 1993, Sainty *et al.* 1998). It reproduces asexually in the United States and new plants develop from any piece of root fragment or stem that contains a node (Spencer and Coulson 1976, Holm *et al.* 1997, Shen *et al.* 2005). Because exposed stems and leaves are killed by frost and ice, temperature is the most important factor limiting further range expansion of alligatorweed (Julien *et al.* 1992). Nodes protected by water or vegetation survive to generate the next season's growth (Julien *et al.* 1995).

Alien invasive wetland plants can displace native plants directly by competition (Madsen *et al.* 1991, Barrat-Segretain 2005, Thomson 2005) and indirectly by altering the physical environment such as light and water quality (Blindlow 1992, D'Antonio and Vitousek 1992, Barrat-Segretain and Elger 2004). Monospecific stands of alien invasive plants, for example, can negatively affect invertebrate communities by reducing vegetation complexity or reducing oxygen levels (Cheruvelil *et al.* 2002, Douglas and O'Connor 2003, Strayer *et al.* 2003). Specifically, studies have shown that alligatorweed reduces light penetration, lowers oxygen levels in water, competes with native plants, and alters wetland plant communities (Quimby and Kay 1977, Vogt *et al.* 1992, Buckingham 1996, Holm *et al.* 1997).

Alligatorweed can cause extensive economic damage (Holm *et al.* 1997). Dense mats prevent irrigation canals from draining, create blockages in rivers and streams result in flooding and structural damage, create mosquito habitat, and prevent fishing, swimming, and navigation (Penfound *et al.* 1945, Tarver *et al.* 1986, Chester 1988). Further, consumption of the terrestrial form has caused photosensitization of skin and cancerous lesions in cattle (Bourke and Rayward 2003).

Control of alligatorweed has been difficult because physical control methods such as mowing and disking only redistribute and possibly spread the plant (Holm *et al.* 1997). The alligatorweed flea beetle (*Agasicles hygrophila* Selman and Vogt), which feeds on the leaves and stems of alligatorweed, has been extremely successful where mean winter temperatures are >11.1°C, but other control measures are needed at more northern latitudes (Maddox *et al.* 1971, Selman and Vogt 1971, Coulson 1977, Vogt *et al.* 1992). Herbicides have not been entirely successful at controlling alligatorweed, possibly because nodes hinder translocation of herbicides to the underwater portion of plants (Eggler 1953, Maddox *et al.* 1971, Madsen *et al.* 1988). In addition, abnormal growth of root primordia at nodes has been found to block vascular tissues (Zu Burg *et al.* 1961) and indirect connections between the axillary buds and the stems also may prevent translocation of herbicides (Zu Burg *et al.* 1967, Tucker 1994).

Control of alligatorweed was attempted in the past with many different herbicides. Glyphosate controls floating mats of alligatorweed, but does not affect the terrestrial form or submerged roots due to poor translocation (Bowmer *et al.* 1993, Tucker 1994). Dichlobenil is useful for spot treatments on banks or shallow water, but is non-selective, making it inappropriate for wetland restoration (Eggler 1953). Metsulfuron is successful on the terrestrial form and is selective for grasses, but cannot be used near water (Bowmer *et al.* 1989). Multiple applications of 2,4-D are required to control alligatorweed, but complete control is not obtained (Eggler 1953). An additional complication with alligatorweed control is herbicide treatments over water can break apart mats, which float downstream and invade previously unaffected areas (Holm *et al.* 1997).

Triclopyr amine (triethylamine salt of triclopyr) and imazapyr (isopropylamine salt of imazapyr) herbicides were recently approved for use in aquatic or wetland habitats and should be tested for efficacy of controlling alligatorweed. The objective of this study was to evaluate effects of varying rate (low, medium, and high) and timing of application (early-, mid-, and late-season) of triclopyr and imazapyr on alligatorweed biomass.

MATERIALS AND METHODS

Study Site. The study was conducted at Eufaula National Wildlife Refuge (ENWR, 32°N, 85°W) in southeastern Alabama and southwestern Georgia on the Kennedy (182 ha) and Bradley (304 ha) Units. ENWR (4,452 ha) is located on the northern portion of the Walter F. George Reservoir, an impoundment of the Chattahoochee River (Fig. 1).

Managers use moist-soil management at ENWR to provide food and habitat for migratory waterfowl, a primary goal for the refuge (Fredrickson and Taylor 1982). Drawdown of managed wetlands begins in mid-March and continues until moist-soil conditions are reached, usually about mid-April. Moist-soil levels are monitored by refuge staff and maintained throughout the growing season to allow growth of desirable vegetation desirable. Re-flooding of moist-soil impoundments begins the last week of October.

Alligatorweed dominates many of the managed wetlands at ENWR, reducing the efficacy of moist-soil management and interfering with the goals of ENWR. Control methods not successful in controlling alligatorweed at ENWR include mowing, disking, burning, herbicide application, and release of alligatorweed flea beetles.

Experimental Design. I used a randomized block design with four replications. Four experimental blocks were established in April 2004 within managed wetlands of the Kennedy (n = 2) and Bradley (n = 2) units of ENWR. Treatments consisting of herbicides (n = 2), application rates (n = 3), and application dates (n = 3) were randomly assigned to experimental plots (5m x 5m) within each block. Control plots (n = 6) were included in each block.

I tested triclopyr (Renovate®, SePRO, Carmel, IN 46032) and imazapyr (Habitat®, BASF, Florham Park, NJ 07932), which are approved by the Environmental Protection Agency for use in aquatic habitats. Each herbicide was applied on three dates, 28 April, 13 July and 28 September 2004. Two swaths per plot were made with a 2L CO_2-pressurized backpack spray unit equipped with a five-nozzle boom (2.5m wide spray band) held about 60 cm above the vegetation. The boom was fitted and calibrated with flat-fan spray nozzles (nozzle 11006VH, Visiflo, Spraying Systems Co., Wheaton, IL 60189) at a pressure of 200kPa. Air temperature during treatments ranged from 12.8°C to 26.7°C and wind speed ranged from 0 kph to 8 kph.

Application rates for triclopyr included: low (4.8L ha^{-1} or 12mL $plot^{-1}$), medium (9.6L ha^{-1} or 24mL $plot^{-1}$), and high (14.4L ha^{-1} or 36mL $plot^{-1}$). These rates were applied according to label specifications using 935L ha^{-1} or 2.4L $plot^{-1}$ of water and 0.25% (v/v) nonionic surfactant (Top Surf ®, Agriliance, LLC, St. Paul, MN 55164). Application rates for imazapyr included: low (1.2L ha^{-1} or 3mL $plot^{-1}$), medium (2.4L ha^{-1} or 6mL $plot^{-1}$), and high (3.6L ha^{-1} or 9mL $plot^{-1}$). These rates were applied according to label specifications using 467L ha^{-1} or 1.2L $plot^{-1}$ of water and 0.25% (v/v) nonionic surfactant (Top Surf ®, Agriliance, LLC, St. Paul, MN 55164). All application rates were within the range recommended by manufacturers. Control plots received no water, herbicide, or surfactant.

Percent Cover, Stem Density, and Height of Alligatorweed. Percent cover, stem density, and height of alligatorweed were estimated immediately before herbicides were applied to experimental plots and monthly from March to October 2005. I randomly placed two subplots (1.0m x 1.0m) in each experimental plot and estimated percent cover of alligatorweed. Height of alligatorweed above the soil was measured at the corners of each subplot (n = 4), and alligatorweed stem density was estimated by counting individual alligatorweed stems in quadrats (0.25m x 0.25m; n = 2) within each subplot.

Plant Biomass: In October 2005, I estimated biomass of alligatorweed in experimental plots by clipping all above ground plant parts in randomly placed quadrats (0.25 m x 0.25 m; n = 2). Clipped plants were placed in plastic bags, transported to Auburn University, and oven dried (60°C) to constant mass. Dried samples were weighed to the nearest 0.01g.

Statistical Analysis: Four-way ANOVA (PROC MIXED; SAS Institute 2003) was used to test effects of block (n = 4), herbicide (n = 2), application rate (n = 3), application timing (n = 3), and all interactions on biomass of alligatorweed. Block was specified as the random variable and herbicide, application rate, and application timing were fixed variables. Pretreatment values of percent cover, stem density, or height of alligatorweed were tested as covariates, but they were not significant ($P > 0.10$). Nonsignificant ($P > 0.10$) interactions were excluded from final models. Tukey-Kramer tests were used to conduct pair-wise comparisons of least squares means to separate significant main effects and interaction effects. Six control plots were included in each block and so were not replicated across all treatments; therefore, Dunnett's test was used to test for differences in alligatorweed biomass between means of control and means of treatments. Changes in pre- and post-treatment values of percent cover were tested with paired t-tests. All tests were significant at $P \leq 0.10$ to reduce the chance of type II error due to small sample size.

RESULTS AND DISCUSSION

Biomass of alligatorweed was affected by application rate ($F_{2,61} = 7.28$, $P = 0.0015$). High application rate resulted in less alligatorweed biomass than low or medium rates, but alligatorweed biomass did not differ between low and medium application rates (Table 1).

Biomass of alligatorweed also was affected by the interaction of herbicide and application date ($F_{2,61} = 4.17$, $P = 0.02$). July and September applications of imazapyr resulted in less alligatorweed biomass than April application of imazapyr (Table 2). September application of triclopyr resulted in less alligatorweed biomass than April application, while July application was not different from either April or September application (Table 2).

Treatments applied in April did not reduce alligatorweed biomass to below that of control plots (Table 3). With July treatment, only triclopyr applied at the high rate and imazapyr applied at all rates reduced alligatorweed biomass to below that of the control (Table 3). September application of triclopyr at the high rate and imazapyr at medium and high rates reduced alligatorweed biomass to below that of control plots (Table 3).

Treatments applied in April did not reduce percent cover of alligatorweed to below that of control plots (Table 3). With July treatment, only imazapyr applied at medium and high rates reduced percent cover of alligatorweed to below that of control plots (Table 3). September application of triclopyr and imazapyr at high rates reduced percent cover of alligatorweed to below that of control plots (Table 3).

When pre- and posttreatment values of percent cover of alligatorweed were evaluated, April applications of triclopyr applied at high rate and imazapyr applied at medium rate reduced alligatorweed cover by more than 30% (Table 4). July applications of triclopyr and imazapyr at medium and high rates reduced alligatorweed cover from pretreatment values (Table 4). September applications of triclopyr and imazapyr applied at high rates reduced alligatorweed cover from pretreatment values (Table 4).

Managers of protected areas such as ENWR prefer to use the lowest herbicide rates possible for alien invasive plant control to reduce cost and reduce harm to non-target organisms (Tu *et al.* 2001). However, alligatorweed has proven to be difficult to control with herbicides in the past and higher application rates often are necessary for successful control (Eggler 1953, Bowmer *et al.* 1989, Bowmer *et al.* 1993, Tucker 1994). In the current study, the fact that herbicides applied at high rates resulted in less alligatorweed biomass than either low or medium application rates substantiate those earlier findings that tested other herbicides. In addition, four of six treatments with high application rate resulted in less alligatorweed biomass than the control (Table 4). All high rate treatments, with the exception of April application of imazapyr, reduced percent cover of alligatorweed from pretreatment values.

Because complete control of alligatorweed was not achieved in this study, multiple applications of low rates within the same year or in consecutive years possibly could provide equal or even better control of alligatorweed than a single application of a high rate. An initial application weakens the plant, making it more susceptible to subsequent applications within the same year, and has been used to control other alien invasive plants such as Siam weed (*Chromolaena odorata* (L.) King and H.E. Robins) (Ikuenobe and Ayeni 1998). Herbicide application in consecutive years is a valuable control method when plants resprout from underground parts not killed with the first application, and has been used to control alien invasive plants such as Japanese stiltgrass (Microstegium vimineum (Trin.) A. Camus), fennel (*Foeniculum vulgare* P. Mill.), and reed canarygrass (*Phalaris arundinacea* L.) (Paveglio and Kilbride 2000, Judge *et al.* 2005, Ogden and Rejmanek 2005).

Life history characteristics (ex. timing of seed production, accumulation of nutrients, etc.) of alien invasive plants can be useful when determining the best means of control (Nichols and Shaw 1986, Mack *et al.* 2000, Kolar and Lodge 2001). Previous studies have indicated that alligatorweed is difficult to control because translocation of herbicides is inhibited by nodes and other structural characteristics (Zu Burg *et al.* 1967, Tucker 1994). Plants, especially perennials, accumulate carbohydrates and other nutrients in their roots and other storage structures in late summer and autumn (Chapin III *et al.* 1990, Wyka 1999); therefore, herbicides are more likely to be transported with them into roots, resulting in death of the plant. In support of this idea, July and September applications of triclopyr or imazapyr resulted in less biomass and percent cover of alligatorweed than when applied in April. In addition, most treatments in July and September resulted in lower percent cover of alligatorweed than pretreatment values.

Differences between application dates in the control of alligatorweed also are apparent in the speed at which the herbicides took effect. Following application of herbicides in July and September 2004, percent cover of alligatorweed was reduced immediately after applying either triclopyr or imazapyr, and remained below control levels until October. In contrast, percent cover of alligatorweed remained high for a week or two after application of herbicides in April until finally decreasing (see Fig. 4, Chapter1). Again, this probably is due to the natural accumulation of materials by plants into their roots.

Alligatorweed also exhibits seasonal fluctuations in plant size, which may explain why April applications were not as effective as July or September applications. In this study, for example, April pretreatment percent cover values were much greater than July or September values. This may explain the significant differences between pre- and posttreatment percent cover values at that application date even though biomass and percent cover values were not different from the control values. Other studies also have shown that alligatorweed grows quickly in the spring, increasing plant height, biomass and mat thickness, then reduces its growth rate later in the year (Julien *et al.* 1992, Liu *et al.* 2004). Greater plant size reduces concentration of herbicides within a plant, which in turn decreases the amount of herbicide translocated to underground plant parts (Bowmer and Eberbach 1993).

Management Implications

This study showed that the best control of alligatorweed in managed wetlands occurred with high application rate of triclopyr or imazapyr in July or September. This gives managers some flexibility in their timing of application, but exhibits the need for higher application rates to control alligatorweed. Because there was no difference in alligatorweed control between triclopyr and imazapyr at April, July, and September application dates, managers must decide which herbicides to apply based on other factors such as availability, herbicide cost, or environmental effects.

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Figure 1. Location of study sites within Eufaula National Wildlife Refuge.

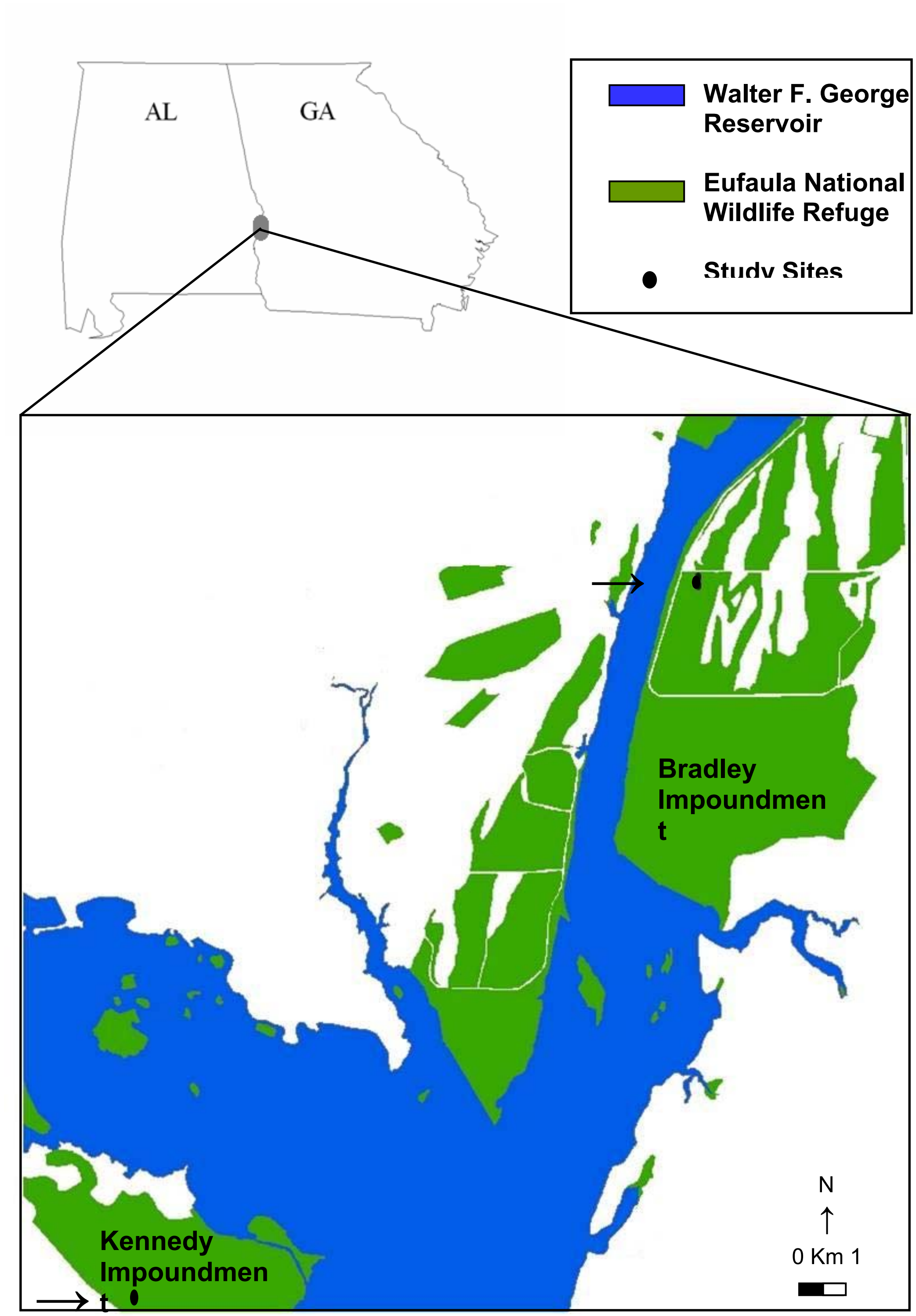

Table 1. Comparisons of alligatorweed dry mass (least-squares means ± SE) collected in October 2005 after applying triclopyr or imazapyr at low, medium, and high rates in 2004. Least-squares mean with different letters indicate significance ($P \leq 0.10$).

Application rate	Dry mass (g/0.25m^2)
Low	35.5 ± 8.54 a
Medium	26.9 ± 8.54 a
High	15.0 ± 8.54 b

Table 2. Comparisons alligatorweed dry mass (least squares means ± SE) collected in October 2005 after applying triclopyr or imazapyr in April, July or September 2004. Least squares with different letters indicate significance ($P \leq 0.10$).

Herbicide	Application date		
	April	July	September
Imazapyr	53.0 ± 9.35 a	8.23 ± 9.35 c	14.0 ± 9.35 c
Triclopyr	38.4 ± 9.35 ab	24.7 ± 9.35 bc	16.5 ± 9.35 c

Table 3. Comparisons of dry mass (g/0.25m^2) and percent cover least-squares means (± SE) of alligatorweed between treatments and control [a, b] values. Values of treatments and controls were measured in October 2005 after application of low, medium, or high rates of triclopyr or imazapyr in April, July or September 2004.

	Application date																	
	April						July						September					
	Triclopyr			Imazapyr			Triclopyr			Imazapyr			Triclopyr			Imazapyr		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Dry mass																		
$\bar{X}$	34.8	42.5	38.0	75.5	50.4	33.0	35.0	28.2	11.8	18.5	6.03	0.18	22.1	21.4	5.90	28.0	12.7	1.36
SE	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
									***	*	***	****			**		**	****
Percent cover																		
$\bar{X}$	23.3	35.8	28.3	39.2	28.3	19.6	30.8	17.5	18.3	17.6	7.6	3.4	21.7	25.0	4.2	24.2	28.3	9.8
SE	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08	9.08
											****	****			****			**

[a] Dry mass of controls (52.66 ± 11.31 g/0.25m^2)

[b] Percent cover of controls (34.24 ± 6.38 g/0.25m^2)

* $P \leq 0.10$, ** $P \leq 0.05$, *** $P \leq 0.01$, **** $P \leq 0.001$

Table 4. Change between pretreatment and mean alligatorweed percent cover (± SE) taken in October 2005 (posttreatment) after application of low, medium, or high rates of triclopyr or imazapyr in April, July or September 2004.

	Application date																	
	April						July						September					
	Triclopyr			Imazapyr			Triclopyr			Imazapyr			Triclopyr			Imazapyr		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Pretreatment																		
$\bar{X}$	57.5	60.0	60.3	55.5	61.5	38.3	16.8	32.0	40.0	26.3	28.8	41.8	22.9	27.5	20.4	24.6	23.3	23.3
SE	13.4	9.0	9.8	7.3	9.5	11.1	2.7	3.5	7.5	8.5	4.9	5.3	4.7	3.1	3.2	4.9	3.8	4.5
Posttreatment																		
$\bar{X}$	23.3	35.8	28.3	39.2	28.3	19.6	30.8	17.5	18.3	14.6	5.0	3.8	21.7	25.0	4.2	24.2	28.3	9.8
SE	9.6	14.2	5.6	10.2	10.0	8.5	12.6	3.8	5.7	4.7	2.6	2.8	10.8	9.8	1.7	9.6	10.8	4.4
Change																		
$\bar{X}$	-34.2	-24.2	-31.9	-16.3	-33.2	-18.7	+14.1	-14.5	-21.7	- 11.7	-24.2	-38.0	-1.3	-2.5	-16.3	- 0.4	+5.0	-13.6
SE	19.5	23.0	5.5	17.1	12.5	17.8	11.9	1.7	7.7	9.4	2.3	7.3	14.2	12.4	4.2	13.4	7.2	3.1
			***		*			***	***		***	**			**			**

*$P \leq 0.10$, ** $P \leq 0.05$, *** $P \leq 0.01$,

APPENDIX A. Dry mass ($\bar{X}$ ± SE) of wetland plant species collected in subplots ($0.25m^2$) at sampling sites in managed wetlands at Eufaula National Wildlife Refuge, AL and GA, October 2004.

					Dry mass ($g/0.25m^2$)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Triclopyr	Low	4	*A. philoxeroides*	92.45	26.79
				C. pseudovegetus	0.45	0.45
				D. virginiana	0.54	0.54
				L. panicea	9.9	19.75
				Panicum sp.	0.096	0.096
				P. densiflorum	14.02	14.02
				P. hydropiperoides	8.22	16.97
		Medium	4	*A. philoxeroides*	73.5	15.89
				C. pseudovegetus	0.14	0.14
				D. virginiana	1.91	1.91
				E. crusgalli	34.61	23.48
				L. oryzoides	1.69	1.39
				Panicum sp.	0.28	0.20
				P. densiflorum	30.57	3.07
				P. hydropiperoides	5.2	3.07
				P. punctatum	13.97	11.61
		High	4	*A. philoxeroides*	40.41	24.12
				C. pseudovegetus	0.41	0.41
				D. virginiana	4.05	3.80
				E. crusgalli	66.52	58.68
				L. oryzoides	41.14	41.14
				L. panicea	18.21	17.23

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Triclopyr	High	4	*Panicum* sp.	0.11	0.06
				P. densiflorum	30.32	30.32
				P. hydropiperoides	8.15	6.93
	Imazapyr	Low	4	*A. philoxeroides*	62.74	16.11
				D. virginiana	1.09	0.47
				E. crusgalli	10.69	10.69
				L. oryzoides	2.06	2.06
				Panicum sp.	0.48	0.24
				P. hydropiperoides	1.14	1.14
		Medium	4	*A. philoxeroides*	29.73	1.83
				D. virginiana	0.05	0.03
				E. crusgalli	55.41	32.12
				L. oryzoides	0.80	0.80
				Panicum sp.	0.05	0.05
				P. punctatum	0.15	0.15
		High	4	*A. philoxeroides*	12.46	1.46
				D. virginiana	3.50	2.17
				E. crusgalli	68.82	54.09
				S. herbacea	19.34	19.34
April	Control		8	*A. philoxeroides*	70.54	12.25
				C. occidentalis	0.40	0.40
				D. virginiana	0.87	0.50
				E. crusgalli	2.46	1.61

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Control		8	*L. oryzoides*	1.49	1.45
				L. panicea	1.42	0.84
				Panicum sp.	0.69	0.25
				P. densiflorum	79.68	55.14
				P. hydropiperoides	16.56	11.92
				P. punctatum	1.96	1.50
				S. herbacea	0.09	0.09
July	Triclopyr	Low	4	*A. philoxeroides*	14.25	8.76
				D. virginiana	1.03	1.03
				E. crusgalli	2.11	1.24
				L. panicea	10.88	7.50
				Panicum sp.	0.26	0.24
				P. densiflorum	6.77	6.77
				P. hydropiperoides	3.76	3.56
				P. punctatum	35.71	35.71
		Medium	4	*A. philoxeroides*	9.22	5.26
				D. virginiana	0.24	0.24
				L. panicea	16.63	11.12
				Panicum sp.	0.53	0.53
				P. densiflorum	27.78	26.57
				P. hydropiperoides	0.42	0.42

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
July	Triclopyr	High	4	*A. philoxeroides*	2.34	1.07
				L. panicea	12.63	12.62
				P. densiflorum	16.72	13.33
				P. hydropiperoides	0.70	0.60
				P. punctatum	2.83	2.83
				S. herbacea	2.29	2.29
	Imazapyr	Low	4	*A. philoxeroides*	4.21	2.76
				D. virginiana	0.48	0.48
				L. oryzoides	0.02	0.02
				L. panicea	0.14	0.14
				Panicum sp.	0.49	0.43
		Medium	4	*A. philoxeroides*	21.86	21.53
				E. crusgalli	0.38	0.38
				L. oryzoides	0.50	0.50
				Panicum sp.	0.72	0.72
				P. densiflorum	1.05	1.05
				S. herbacea	0.07	0.05
		High	4	*Panicum* sp.	0.04	0.04
July	Control		8	*A. philoxeroides*	85.68	17.30
				Cyperus spp.	2.19	4.94
				C. erythrorhizos	0.08	0.08
				C. occidentalis	0.81	1.61
				C. pseudovegetus	2.03	1.86
				D. virginiana	0.37	0.37

APPENDIX A. Continued

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
July	Control		8	*E. crusgalli*	0.30	0.30
				L. oryzoides	0.05	0.04
				L. panicea	0.51	0.35
				Panicum sp.	0.05	0.03
				P. densiflorum	30.92	25.06
				P. hydropiperoides	13.27	11.43
				P. punctatum	15.21	7.65
				S. herbacea	5.47	19.31

APPENDIX B. Dry mass ($\bar{X}$ ± SE) of wetland plant species collected in subplots ($0.25m^2$) at sampling sites in managed wetlands at Eufaula National Wildlife Refuge, AL and GA, October 2005.

					Dry mass ($g/0.25m^2$)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Triclopyr	Low	4	*A. philoxeroides*	34.77	15.56
				D. virginiana	8.91	6.03
				L. panicea	20.68	20.68
				R. inundata	0.79	0.79
				R. corniculata	1.13	1.13
				Panicum sp.	0.01	0.01
				P. densiflorum	79.0	45.15
				P. hydropiperoides	21.95	17.71
		Medium	4	*A. philoxeroides*	42.45	21.26
				D. virginiana	4.58	2.72
				L. panicea	8.89	8.89
				P. densiflorum	46.15	46.15
				P. hydropiperoides	4.82	3.85
				P. punctatum	22.56	22.56
				R. corniculata	6.74	5.05
		High	4	*A. philoxeroides*	38.0	13.21
				D. virginiana	5.2	3.68
				E. crusgalli	1.44	1.44
				L. panicea	31.99	31.99
				P. densiflorum	65.88	38.47

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Triclopyr	High	4	*P. hydropiperoides*	30.44	18.81
				R. inundata	3.09	2.19
April	Imazapyr	Low	4	*A. philoxeroides*	75.45	12.47
				D. virginiana	8.35	5.11
				L. panicea	0.33	0.33
				Panicum sp.	0.02	0.02
				P. densiflorum	3.36	3.36
				P. hydropiperoides	16.56	9.58
				R. inundata	1.54	1.54
		Medium	4	*A. philoxeroides*	75.45	12.47
				D. virginiana	8.10	8.10
				P. densiflorum	57.81	33.96
				P. hydropiperoides	16.16	12.06
				R. corniculata	0.99	0.99
		High	4	*A. philoxeroides*	32.95	13.68
				D. virginiana	14.21	10.32
				E. crusgalli	60.5	43.68
				H. quadrivalvis	0.08	0.08
				L. divergens	0.005	0.005
				L. panicea	0.56	0.56
				P. densiflorum	5.03	5.03
				P. hydropiperoides	0.47	0.32
				P. pennsylvanicum	0.51	0.51
				R. corniculata	4.31	4.31

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
April	Control		8	*A. philoxeroides*	48.05	13.53
				D. virginiana	1.37	0.87
				H. quadrivalvis	0.08	0.08
				L. panicea	14.32	8.10
				R. corniculata	0.58	0.58
				R. inundata	0.18	0.18
				Panicum sp.	0.009	0.009
				P. densiflorum	54.69	45.98
				P. hydropiperoides	21.38	13.35
				P. punctatum	35.45	35.45
July	Triclopyr	Low	4	*A. philoxeroides*	34.10	15.85
				D. virginiana	3.85	3.85
				H. quadrivalvis	0.08	0.07
				L. panicea	29.33	28.79
				P. densiflorum	21.46	15.82
				P. hydropiperoides	33.60	11.17
				P. punctatum	23.13	23.13
				R. inundata	0.15	0.15
				S. herbacea	0.37	0.37
		Medium	4	*A. philoxeroides*	28.19	13.81
				D. virginiana	0.38	0.38
				E. crusgalli	5.02	2.24
				L. panicea	13.81	13.25
				L. repens	0.45	0.45

Date	Herbicide	Rate	*n*	Species	Dry mass ($g/0.25m^2$) $\bar{X}$	SE
July	Triclopyr	Medium	4	*P. densiflorum*	55.76	37.72
				P. hydropiperoides	18.73	12.17
				P. punctatum	1.86	1.86
				R. corniculata	5.88	5.37
				R. inundata	0.89	0.89
				S. herbacea	0.46	0.46
		High	4	*A. philoxeroides*	11.76	4.87
				C. pseudovegetus	0.62	0.62
				D. virginiana	1.39	0.87
				E. crusgalli	1.06	1.06
				L. panicea	54.21	47.12
				L. repens	2.83	2.83
				R. corniculata	0.08	0.08
				R. inundata	1.93	1.93
				P. densiflorum	83.29	56.58
				P. hydropiperoides	20.58	7.30
				S. herbacea	1.12	1.12
	Imazapyr	Low	4	*A. philoxeroides*	18.49	15.94
				D. virginiana	5.45	4.04
				E. crusgalli	113.22	83.54
				H. quadrivalvis	1.26	1.26
				L. panicea	8.99	8.99
				L. repens	0.10	0.10
				Panicum sp.	0.008	0.008

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
July	Imazapyr	Low	4	*P. hydropiperoides*	0.53	0.39
				P. punctatum	45.77	45.77
				R. inundata	1.45	1.45
				R. corniculata	0.72	0.72
				S. herbacea	15.71	10.50
		Medium	4	*A. philoxeroides*	6.03	4.73
				C. pseudovegetus	0.13	0.13
				D. virginiana	7.53	5.74
				E. crusgalli	168.13	101.58
				H. quadrivalvis	0.17	0.17
				L. panicea	2.37	2.37
				L. repens	3.97	3.97
				Panicum sp.	0.17	0.17
				P. densiflorum	2.46	2.46
				P. hydropiperoides	0.28	0.28
				R. inundata	2.68	2.68
				S. herbacea	49.12	33.86
		High	4	*A. philoxeroides*	0.18	0.13
				D. virginiana	7.18	5.12
				E. crusgalli	87.44	49.34
				L. panicea	5.50	5.50
				Panicum sp.	0.018	0.018
				P. densiflorum	21.78	21.78
				P. hydropiperoides	0.23	0.23

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
July	Imazapyr	High	4	*S. herbacea*	81.43	48.98
				R. corniculata	0.50	0.50
July	Control		8	*A. philoxeroides*	59.94	18.09
				D. virginiana	6.60	3.30
				E. crusgalli	0.05	0.05
				L. panicea	2.82	2.82
				Panicum sp.	0.03	0.03
				P. densiflorum	62.74	34.35
				P. hydropiperoides	43.03	16.60
				R. corniculata	0.58	0.58
				R. inundata	0.05	0.05
September	Triclopyr	Low	4	*A. philoxeroides*	22.06	12.93
				D. virginiana	7.62	4.95
				E. crusgalli	7.63	7.19
				H. quadrivalvis	16.49	16.49
				L. panicea	17.50	14.27
				L. repens	0.04	0.02
				P. densiflorum	66.13	40.00
				P. hydropiperoides	23.85	20.98
				R. corniculata	1.06	1.06
				S. herbacea	1.63	1.63
		Medium	4	*A. philoxeroides*	21.43	11.68
				D. virginiana	3.79	2.19
				C. pseudovegetus	0.22	0.22

					Dry mass ($g/0.25m^2$)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
September	Triclopyr	Medium	4	*E. crusgalli*	3.3	2.3
				R. inundata	0.63	0.63
				H. quadrivalvis	0.06	0.06
				L. repens	0.06	0.06
				P. hydropiperoides	66.26	38.43
				P. densiflorum	68.27	39.50
		High	4	*A. philoxeroides*	5.92	3.42
				D. virginiana	4.31	3.24
				E. crusgalli	46.66	32.60
				H. quadrivalvis	8.32	4.92
				L. panicea	1.85	1.34
				L. repens	1.11	1.11
				Panicum sp.	0.02	0.02
				P. hydropiperoides	12.78	6.93
				P. densiflorum	54.61	48.38
				R. corniculata	2.27	2.27
				S. herbacea	2.52	1.88
	Imazapyr	Low	4	*A. philoxeroides*	27.94	10.76
				D. virginiana	6.50	4.59
				E. crusgalli	3.12	3.12
				H. quadrivalvis	1.19	0.74
				L. repens	0.04	0.03
				Panicum sp.	0.33	0.27
				P. hydropiperoides	2.25	2.24

APPENDIX B. Continued

					Dry mass ($g/0.25m^2$)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
September	Imazapyr	Low	4	*P. densiflorum*	63.93	39.37
				R. corniculata	0.45	0.45
				S. herbacea	11.16	11.16
		Medium	4	*A. philoxeroides*	12.73	5.71
				D. virginiana	19.98	17.24
				E. crusgalli	72.22	38.83
				H. quadrivalvis	0.85	0.85
				L. panicea	2.74	2.74
				L. repens	0.02	0.02
				Panicum sp.	0.23	0.23
				P. densiflorum	8.55	8.55
				P. hydropiperoides	3.67	3.13
				P. punctatum	17.82	17.82
				S. herbacea	52.46	50.15
		High	4	*A. philoxeroides*	1.36	1.25
				D. virginiana	24.36	15.69
				E. crusgalli	136.62	56.64
				L. panicea	1.61	1.61
				Panicum sp.	0.02	0.02
				P. densiflorum	4.05	4.05
				P. hydropiperoides	0.07	0.07
				S. herbacea	36.06	21.52
Control	September		8	*A. philoxeroides*	50.01	10.88

APPENDIX B. Continued

					Dry mass (g/0.25m^2)	
Date	Herbicide	Rate	*n*	Species	$\bar{X}$	SE
Control	September		8	*D. virginiana*	8.93	5.25
				L. panicea	0.55	0.37
				Panicum sp.	0.25	0.16
				P. densiflorum	71.36	32.58
				P. hydropiperoides	35.11	15.70
				R. divergens	0.25	0.25
				R. corniculata	0.28	0.28