A COMPARISON OF ERADICATION TECHNIQUES FOR A NONINDIGENOUS EMERGENT PLANT SPECIES (*COLOCASIA ESCULENTA*)

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

ABSTRACT

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Colocasia esculenta (L.) Schott is a nonindiginous emergent plant species that was introduced to Spring Lake and the upper San Marcos River (Hays County, Texas) ecosystem in the 1900s. This species forms dense stands along the river and has demonstrated the ability to dominate many areas previously inhabited by native vegetation. Texas Parks and Wildlife Department has listed *C. esculenta* as an exotic species needing management consideration. In this study, four eradication techniques were applied to *C. esculenta* growing along the banks of Spring Lake and the San Marcos River at five week intervals from November 2004 to November 2005. The four techniques were manual removal, application of the herbicide glyphosate, mechanical

cutting with hand shears, and a combination of mechanical cutting followed by application of glyphosate to the cut petiole. Data collected and analyzed included leaf cover of *C. esculenta*, number of treatment applications required to achieve eradication, amount of time required to apply each eradication technique, and percent cover of other plant species growing in each quadrat. The effectiveness of each eradication technique was based on four criteria: the extent of decrease in *C. esculenta* leaf cover, the number of treatment applications required to achieve eradication, the amount of time for the application of the technique, and the extent of growth by other plant species.

After one year *C. esculenta* leaf cover following both manual removal and herbicide application was significantly less than the leaf cover of the mechanical cutting technique and the control ($F_{4, 25} = 34.704$, $p = <0.001$). Manual removal required significantly fewer treatment applications to eradicate *C. esculenta* than the mechanical cutting and the combination mechanical cut/herbicide techniques ($F_{4, 25} = 16.671$, $p = <0.001$) while the herbicide application required significantly fewer applications than the mechanical cutting technique ($F_{4, 25} = 16.671$, $p = <0.001$). Neither the mechanical cutting nor the combination mechanical cut/herbicide technique resulted in eradication of *C. esculenta*. The manual removal technique required significantly less application time than both the mechanical cutting technique and the combination mechanical cut/herbicide technique ($F_{4, 25} = 17.364$, $p = <0.001$). The herbicide application resulted in a significantly greater total percent plant cover, excluding *C. esculenta*, than the control ($F_{4, 25} = 3.192$, $p = 0.03$). Based on the four criteria manual removal and herbicide application techniques are the only techniques effective in eradicating *C. esculenta*.

CHAPTER I

INTRODUCTION

The impacts of introducing invasive species to an ecosystem are well documented. Biological invasion now ranks among the world's greatest threats to native ecosystems (Zavaleta, 2000). Invasive species pose a serious threat to biodiversity (Sakai et al., 2001) and there is clear evidence that biological invasions contribute substantially to an increasing rate of extinction (Vitousek et al., 1996). The World Conservation Congress (Gutin, 1999) and the Environmental Protection Agency (Cangelosi, 2003) declared invasives second only to habitat loss as a threat to global diversity and endangered species. Nonindigenous species have contributed to the decline of 42 percent of federally listed endangered and threatened species illustrating the severe impact they have on surrounding ecosystems (Schmitz & Simberloff, 1997; Burkhart, 1999). In conjunction with environmental impacts, biological invasions cost the United States $123 billion annually (Burkhart, 1999).

Nonindigenous plant invasions have been widely recognized as the greatest threat to biodiversity in an invaded ecosystem (Van Wilgen et al., 1996) and a serious threat to North America's ecology, environment, and economy (Sheley & Clark, 2003). After decades of control in North America, invasive plants cover an estimated 405 million hectares and continue to increase in area by nearly 14 percent per year (Sheley & Clark, 2003). Common effects of plant invasions include changes to local biodiversity;

competition with native species for nutrients, light, and space; reduction in oxygen levels; increase in water loss due to evapo-transpiration; and restriction of navigation and recreational activities (Parker & Reichard, 1998; Xiaoyan et al., 2003). These impacts can lead to a reduction in species richness, plant diversity, and community productivity (DiTomaso, 2000). Economically, nonindigenous plant invasions have caused an overall reduction of 12 percent in crop yields, which represents approximately $32 billion in lost crop production annually (Pimentel et al., 2000) and costs for control efforts can amount to hundreds of millions of dollars per year (Simberloff, 2003).

Numerous case studies have been conducted showing the impacts of nonnative plant species on biodiversity. In Florida's national wildlife refuges, nonindigenous plant species aggressively invade undisturbed areas or outcompete native species, including threatened and endangered species (Maffei, 1997). They crowd out native plants on which wildlife depend, poison and irritate wildlife, and alter ecosystems by increasing evaporation (Maffei, 1997). Three exotic species that have been the focus of intensive impact studies in Florida are the Brazilian pepper (*Schinus terebinthifolius*), melaleuca (*Melaleuca quinquenervia*), and Australian pine (*Casuarina equisetifolia*). Brazilian pepper outcompetes native species, eliminating herbaceous vegetation and alters successional patterns within Everglades National Park (Doran & Jones, 1997). Melaleuca's impenetrable stands displace virtually all other vegetation (Bright, 1995) and are eliminating useful wildlife habitat within Everglades National Park by providing poor habitat and undesirable forage for native fauna (Doran & Jones, 1997). The Australian pine has altered the dune ecosystem along Blowing Rocks Preserve on Jupiter Island causing a severe impact on the nesting sites of three federally listed endangered and threatened species, the leatherback sea turtle (*Dermochlys coriacea*), the loggerhead sea turtle (*Caretta caretta*), and the green sea turtle (*Chelonia mydas*). Randall et al. (1997) have shown that Australian pine provides an extensive amount of shade to the beach, which lowers the temperature of the sand where incubating eggs are buried. The altered temperature promotes the production of a higher ratio of males to females, which is detrimental to the populations of these species. The exposed roots of this tree also interfere with the female's ability to excavate nests and entangle the turtles to the point of trapping and killing both adults and hatchlings (Randall et al., 1997).

Plant invasions are not limited to terrestrial habitats. A well documented wetland invasive plant species is purple loosestrife (*Lythrum salicaria*). Considered one of the worst invasive nonnative species of North America wetlands (Morrison, 2002), this plant is spreading at a rate of 115,000 hectares per year (Pimentel et al., 2000) threatening the ecological integrity of North America wetlands by forming monotypic stands and altering the diversity of native wetland ecosystems (Gardner et al., 2001). When growing in a nonnative habitat with no known natural predator, purple loosestrife has demonstrated extremely high productivity and increased biomass (Gutin, 1999; Sakai et al., 2001; Albright et al., 2004). Studies have documented the competitive displacement of numerous plant and animal species (Gardner et al., 2001; Nagel & Griffin, 2001; Albright et al., 2004) contributing to the decline of diversity and the extinction of some rare species (Carroll, 1994; Nagel & Griffin, 2001). Competitive stands have suppressed the biomass of 44 native plants and endangered animal species, including cattail (*Typha* spp.), bulrush (*Scirpus* spp.) (Nagel & Griffin, 2001), the bog turtle (*Clemmys muhlenbengii*) and several duck species (Pimental et al., 2000; Sakai et al., 2001).

Lythrum salicaria also changes the nitrogen cycling and sediment chemistry of the wetland ecosystems in which it invades (Gardner et al., 2001). *Lythrum salicaria* now occurs in 48 states and costs $45 million per year for control and in forage losses (Pimentel et al., 2000).

An example of a wetland ecosystem that has been highly invaded by exotic plant species is Spring Lake and the San Marcos River (Hays County, Texas). With an average spring flow of 4.81 m^3/s and a mean water temperature range of 21.5-22.5 °C (Groeger et al., 1997) the springs at San Marcos have exhibited the greatest flow dependability and environmental stability of any spring system in the southwestern United States (U.S. Fish and Wildlife Service, 1996). The constancy of the environment has allowed for the invasion of a number of exotic species that have a significant influence on this ecosystem (Groeger et al., 1997). Both Texas Parks and Wildlife Department (1994) and U.S. Fish and Wildlife Service (1996) list the introduction of nonnative flora and fauna into the San Marcos River system as being a problematic situation for the endemic species. Four dams, erected in the 1930s, have provided deeper areas (Owens et al., 2001) and a reduction in peak flood energy which has led to an increase of nonnative vegetation within Spring Lake and the San Marcos River (Earl & Wood, 2002). These encroaching nonindigenous species are adversely affecting and displacing native aquatic species (Lemke, 1989). Nearly 80 percent of all native aquatic plants along the shoreline of the San Marcos River have been replaced by introduced nonnative plant species since the 1930s (Owens et al., 2001). Lemke (1989) found that 8 of 31 macrophyte species, or 25 percent, of the taxa collected in the upper San Marcos River were nonnative.

Texas Parks and Wildlife Department (1994) and the U.S. Fish and Wildlife Service (1996) list several nonnative species that have invaded the San Marcos River ecosystem. On both lists is the nonnative wild taro or elephant ear (*Colocasia esculenta* (L.) Schott). *Colocasia esculenta*, belonging to the Arum family (Araceae), is an emergent aquatic and semi-aquatic herbaceous species with wide ecological variation in respect to habitat. Being a perennial, it is capable of producing large (60 cm length and 35 cm width) leaves on long 1-2.5 meter petioles (Weber, 2003) that emanate from an upright corm. Under ideal growing conditions, a single *C. esculenta* plant can grow 2.4 meters high with a similar spread in width. Planted under unflooded conditions, *C. esculenta* is a nine to eleven month crop (Miyasaka et al., 2003) demonstrating five distinct growth phases in which root and shoot growth reach a maximum at four to six months and corm size reaches a maximum at nine months. *Colocasia esculenta* crop yield can be reduced by stresses of low water, low nitrogen, and low or high temperature (Miyasaka et al., 2003) with temperature stress being the most significant factor affecting growth (Lu et al., 2001). The optimum temperature for *C. esculenta* growth is 28°C (Miyasaka et al., 2003). *Colocasia esculenta* has also been shown to be well adapted to shade conditions and when planted at 30 percent full sunlight is capable of increasing stomatal and chlorophyll densities, presumably increasing photosynthetic efficiency at low light levels (Miyasaka et al., 2003). Reproduction of *C. esculenta* is mostly vegetative, rarely by seed (Kikuta et al., 1938), and occurs when whole corms divide in winter or early spring. Only a portion of the corm crown and petiole is needed to establish a new plant. When the main corm is harvested and the top, with or without its leaf stalks still attached, is tossed aside, it can survive and grow new roots.

Colocasia esculenta has been cultivated for more than 6000 years for its edible corm that can weigh from 0.9 to 1.8 kilograms (Youngken, 1919) and is the fifth most consumed root vegetable worldwide (Mace & Godwin, 2002). It was originally brought from Africa to the Americas as a food crop for slaves (Akridge & Fonteyn, 1981) and introduced into Florida and other southern states in 1910 by the U.S. Department of Agriculture as a substitute crop for potatoes. Evidence suggests the introduction of *C. esculenta* to the San Marcos Springs headwaters occurred in the early 1900s with floods encouraging the spread of the corms downstream where dense stands of *C. esculenta* developed along the banks of the river (Akridge & Fonteyn, 1981). *Colocasia esculenta* occupies a variety of habitats along the San Marcos River. It has been found growing in high and low light regimes, all types of substrate from rock, gravel and silt, to deep mud (Staton, 1992), but seems to grow best in the silty anaerobic soils lining the riverbanks (Akridge & Fonteyn, 1981). The rate of water current varies from slower pools, steady current, to swift current where *C. esculenta* exist (Staton, 1992). It is found at the river's edge to 1-2 meters toward mid-channel with stands measuring up to 35 meters in length and up to 5 meters in width. Dense stands are known at least 42 kilometers downstream from the headwaters (Texas Parks and Wildlife Department, 1994). Due to its dominant presence on the riverbanks of the San Marcos, Colorado, Guadalupe, and Blanco rivers, *C. esculenta* is considered a naturalized taxon of the rivers of south-central Texas (Akridge & Fonteyn, 1981).

One of the major impacts of the invasion of *C. esculenta* is the displacement of native shoreline vegetation (Staton, 1992). Extensive stands of this herb alter the vegetational structure and dynamics of riparian plant communities (Weber, 2003). Listed by the Florida Exotic Pest Plant Council as a category 1 species, *C. esculenta* is known to disrupt native plant communities in Florida to the point of eliminating native plant species (Christman, 2003). The same impacts that have occurred in Florida are occurring in the San Marcos River ecosystem. Staton (1992) conducted a species diversity comparison study in the San Marcos River from 1975 to 1991 that indicated an overall decrease in the population size of native plant species with an increase in exotic species. *Colocasia esculenta* demonstrated its superior ability at competition during the 16 years of Staton's study and increased in frequency at the monitoring stations by 33 percent, occupying 16.1 percent of total area. It showed potential for dominating many sites previously inhabited by native vegetation. *Colocasia esculenta* invasion of the river edge has also narrowed the river and crowded other aquatic species in many places (U.S. Fish and Wildlife Service, 1996). It is possible that Texas wild rice (*Zizania texana*) grows in mid-channel due to competition with *C. esculenta* in the shallower, slower waters (Staton, 1992). *Colocasia esculenta* is also present in the area occupied by the San Marcos gambusia (*Gambusia georgei*) and may have decreased its habitat suitability and contributed to its decline (U.S. Fish and Wildlife Service, 1996). Along with its encroachment, decomposition of *C. esculenta* increases the incidence of heavy sedimentation, especially in areas of increased runoff (Texas Parks and Wildlife Department, 1994) altering the substrate within the ecosystem. A further negative impact of nonindigenous plant invasions is increased water loss due to evapo-transpiration (Xiaoyan et al., 2003). Studies of the evapo-transpiration rates of *C. esculenta* show water use efficiency to be low, ranging from 2960 kg to 4260 kg of water required to produce 1 kg of dry biomass (Shih & Snyder, 1985).

Colocasia esculenta exhibits an effective defense mechanism. Crystals of calcium oxalate are found within the corms and leaves in the form of defensive raphide idioblasts (Youngken, 1919; Sunnel & Healey, 1979; Sunnel & Healey, 1985). The density of these crystals can be as high as 120,000/cm^3 (Sunnel & Healey, 1979) rendering them ecologically significant (Sunnel & Healey, 1985). When the plant is eaten or handled raw, a painful burning sensation is caused due to the crystals penetrating the mucous membrane and skin (Black, 1918; Sunnel & Healey, 1979; Sunnel & Healey, 1985). The production of crystal calcium oxalate, combined with its introduction as a nonnative species, has left *C. esculenta* with no known predator in the San Marcos River ecosystem. Lacking natural predation increases the invasive species competitive properties and ability to invade (Carroll, 1994; Nagel & Griffin, 2001).

Due to its impact on the surrounding ecosystem, Texas Parks and Wildlife Department (1994) has listed *C. esculenta* as an exotic species that needs management consideration. The San Marcos and Comal Springs and Associated Aquatic Ecosystems Recovery Plan (U.S. Fish and Wildlife Service, 1996) lists two objectives that focus on impacts and control or removal of nonnative species from the San Marcos aquatic ecosystem, with *C. esculenta* mentioned throughout the plan. Control of invasive species has become a very significant environmental issue (Gutin, 1999). A rationale for removing an invasive non-native species is to increase diversity and abundance of native species (Morrison, 2002).

Studies of invasive species may provide opportunities to better understand aspects of community dynamics and are critical for application in restoration biology (Sakai et al., 2001). Little information has been collected on the eradication of *C. esculenta* and the subsequent plant growth of the riparian community where this exotic plant exists. The objective of this study is to test the effectiveness of eradication techniques in their ability to eradicate *C. esculenta* while allowing subsequent growth of other plant species. The eradication techniques to be tested are manual removal, herbicide application, mechanical cutting, and a combination of mechanical cutting followed by herbicide application.

Four criteria will be used to measure the effectiveness of each technique in eradicating *C. esculenta*. These criteria are the extent of decrease in *C. esculenta* leaf cover, the number of treatment applications required to achieve eradication, the amount of time required for the application of the technique, and the extent of revegetation by other plant species.

CHAPTER II

MATERIALS AND METHODS

Study Site

The San Marcos River is a unique spring fed river system receiving its source from the Edwards Aquifer southern region called the San Antonio segment. The headwaters issue from several large fissures and numerous smaller solution openings along the San Marcos Springs fault forming a spring outfall with the second highest discharge in Texas (Brune, 1981). The river flows primarily southeastward for approximately 112 km before joining the Guadalupe River near Gonzales, Texas (Owens et al., 2001). The Blanco River joins the San Marcos, providing a major tributary, at 3.4 km downstream from the headwaters. There are smaller tributaries above this point that include four creeks (Sink, Sessoms, Purgatory, and Willow), numerous storm sewers, and one wastewater treatment plant discharge.

The springs that give rise to the San Marcos River are impounded within the area of a 7.9 ha lake (Fields et al., 2003) called Spring Lake, which was created from damming the river in 1849 (Earl & Wood, 2002). The area between the headwaters, including Spring Lake, and the first few kilometers of the San Marcos River boast one of the greatest known biodiversities of organisms of any aquatic ecosystem in the southwestern United States (U.S. Fish and Wildlife Service, 1996). The springs and upper reaches of the San Marcos River harbor many endemic or range restricted organisms (Groeger et al., 1997). Five species have been federally listed as endangered and one species as threatened. The endangered species are the fountain darter (*Etheostoma fonticola*), San Marcos gambusia (*Gambusia georgei*), Texas wild rice (*Zizania texana*), Texas blind salamander (*Eurycea rathbuni*), and the Comal Springs riffle beetle (*Heterelmis comalensis*). The San Marcos salamander (*Eurycea nana*) is listed as threatened (U.S. Fish and Wildlife Service, 1996). The San Marcos gambusia, San Marcos salamander, and Texas wild rice are endemic to the San Marcos River, and the fountain darter, Texas blind salamander, and Comal Springs riffle beetle can only be found in this river and surrounding aquatic ecosystems (Texas Parks and Wildlife Department, 1994).

Experimental Design

The experimental design consisted of a randomized block design (Krebs, 1999) to test the effects of four eradication techniques and the extent of growth by other plant species occurring in the treatment area. Six blocks were established in November 2004; three along the banks of Spring Lake and three along the banks of the San Marcos River in San Marcos, Hays County, Texas (Fig. 1).

Each of the six blocks contained five meter square quadrats. To ensure minimal encroachment from surrounding plants, a buffer zone of 61 cm was established and maintained by manually removing all *C. esculenta* plants, including corms, from the adjacent area outside the individual quadrats within each block. A control and the four eradication techniques (manual removal, herbicide application, mechanical cutting, and a combination mechanical cutting followed by herbicide application) were randomly

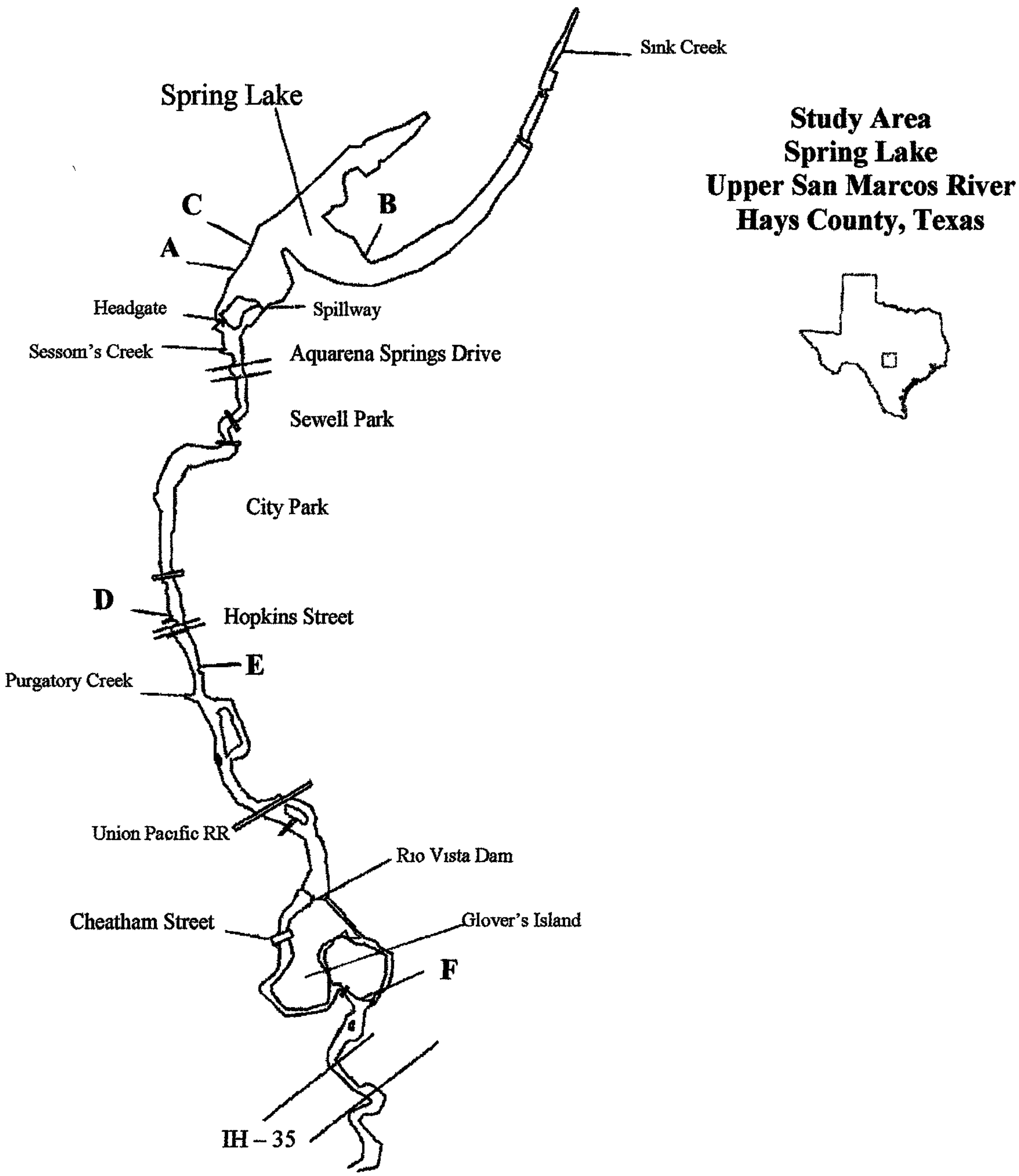

Figure 1. Map of Spring Lake and the upper San Marcos River illustrating the six blocks (A-F) in which the eradication techniques were applied from November 2004 – November 2005 (Texas Parks and Wildlife Department, 2001).

assigned to the quadrats within each block. The manual removal technique consisted of pulling the entire plant, including the corm, from the soil. In the herbicide application technique, a sponge was used to wick the entire top surface area of each individual leaf blade with glyphosate. The cutting technique used hand shears to cut the petiole at ground or water level. In the combination mechanical cut/herbicide application technique, hand shears were used to cut the petiole at ground or water level followed by slowly dripping glyphosate (using a plastic drop bottle) onto the cut surface of the petiole until the petiole absorbed no more glyphosate.

Nelson and Getsinger (2000) evaluated the efficacy of four aquatic herbicides (diquat, 2,4-D, triclopyr, and glyphosate) for control of *C. esculenta* and found a one percent solution of glyphosate was sufficient to eliminate shoot and root biomass. Due to this finding, glyphosate was the herbicide selected to use in this study and the concentration was set at one percent in an aqueous solution. Since glyphosate is a broad-spectrum herbicide and could threaten adjacent vegetation, the herbicide was applied directly to the blade and cut petiole to ensure that stands of *Z. texana* and other natives were not impacted.

Colocasia esculenta plant cover was measured prior to the application of eradication techniques. Three methods of measurement were used to collect *C. esculenta* plant cover data: leaf area index, line intercept, and the Daubenmire method. A leaf area index measurement was recorded for individual blades of *C. esculenta* within each quadrat. The following equation, recommended by Lu et al. (2004) for estimating the area of a *C. esculenta* leaf blade, was used for this measurement:

$$A = K \times L_{SA} \times W_P$$

In this equation K is the leaf area coefficient (set at 0.87), L_{SA} is the leaf length measured from the sinus base to the leaf apex along midrib, and W_P is the leaf width passing the petiole-attaching point and perpendicular to L_{SA}.

Percent cover of *C. esculenta* was also measured using the line intercept method. This method consists of horizontal, linear measurements of plant intercepts along the course of a line. Within each quadrat, three lines running parallel to the water line were used and the length of each blade intercepting the corresponding line, regardless if it overlapped with neighboring foliage, was measured and recorded. This technique allowed for leaf cover to be greater than 100 percent due to the morphology of *C. esculenta* with its multiple canopy layers.

The Daubenmire method (1959) was also used to approximate the percent cover of *C. esculenta* within each quadrat. This method consists of estimating percent cover and then applying it to six different coverage classes (1-6) based on a midpoint range; one being low percent coverage and 6 being high percent coverage (Daubenmire, 1959).

Initial data were collected on all other plant species growing within each quadrat prior to the application of treatment techniques. The line intercept method was used to measure percent cover of the other plant species within each quadrat. The same intercept lines used to determine percent cover of *C. esculenta* were also used to collect these data. The entire plant cover (stems and leaves) that fell along the transect of each line, regardless whether it overlapped with neighboring foliage, was measured and recorded. This technique allowed for plant cover to be greater than 100 percent in order to account for multiple canopy layers and maintain consistency with data collected for *C. esculenta.* The Daubenmire method was also used to approximate the percent cover of each plant species. Plant species were identified following the *Manual of Vascular Plants of Texas* (Correll & Johnston, 1979).

The individual eradication techniques were then applied and the amount of time required for each technique was recorded. These methods were repeated at five week intervals for a full growing season from November 2004 to November 2005 (Table 1).

Table 1. Specific dates for each of the eleven eradication technique applications from November 2004 – November 2005.

Treatment	Dates
1	November 25, 2004
2	January 1, 2005
3	February 5, 2005
4	March 12, 2005
5	April 16, 2005
6	May 21, 2005
7	June 25, 2005
8	July 30, 2005
9	September 3, 2005
10	October 8, 2005
11	November 12, 2005

Analyses

To determine the effectiveness of each technique used to eradicate *C. esculenta* a single factor ANOVA was conducted to analyze the plant cover data gathered by the leaf area index, line intercept, and Daubenmire methods. A test of homogeneity of variances was established and a Dunnett C post hoc test was used when significance was shown (confidence interval 95 percent) or a Tukey's HSD post hoc test used if no significance was expressed.

A single factor ANOVA, followed by the appropriate post hoc test, was also used to determine significance between the number of applications needed to achieve eradication, as well as the amount of time required to perform each technique.

The extent of growth by other plant species was analyzed using a single factor ANOVA for the data collected by the line intercept and Daubenmire methods. A test of homogeneity of variances was established and a Dunnett C post hoc test was used when significance was shown (confidence interval 95 percent) or a Tukey's HSD post hoc test if no significance was expressed.

A Pearson correlation test was conducted to determine the relationship between the different types of measurements used to collect plant cover of *C. esculenta* (leaf area index, line intercept, and Daubenmire method). A separate Pearson correlation test was conducted to determine the relationship between the different types of measurements used to collect percent cover of revegetated plants (line intercept and the Daubenmire method).

CHAPTER III

RESULTS

Prior to the initial application of eradication techniques, there was no significant difference ($F_{4, 25} = 0.191$, $p = 0.941$) in *C. esculenta* leaf cover between quadrats assigned to the control and individual eradication techniques (Appendix 1). *Colocasia esculenta* leaf cover increased over time in the control, reaching a peak in June 2005 then began to decline, but was still greater at the end of the experiment than at the onset of the experiment (Fig. 2). However, leaf cover of *C. esculenta* plants treated with each of the four eradication techniques showed an overall decrease (Fig. 2).

After one year of applying the eradication techniques, following the last treatment application, there were significant differences in leaf cover ($F_{4, 25} = 34.704$, $p = <0.001$) (Table 2). The *C. esculenta* leaf cover in both manual removal and herbicide application techniques was significantly lower than the leaf cover of the mechanical cutting technique (Fig. 2; Table 2). *Colocasia esculenta* leaf cover was significantly higher in the control than in any of the eradication techniques (Fig. 2; Table 2).

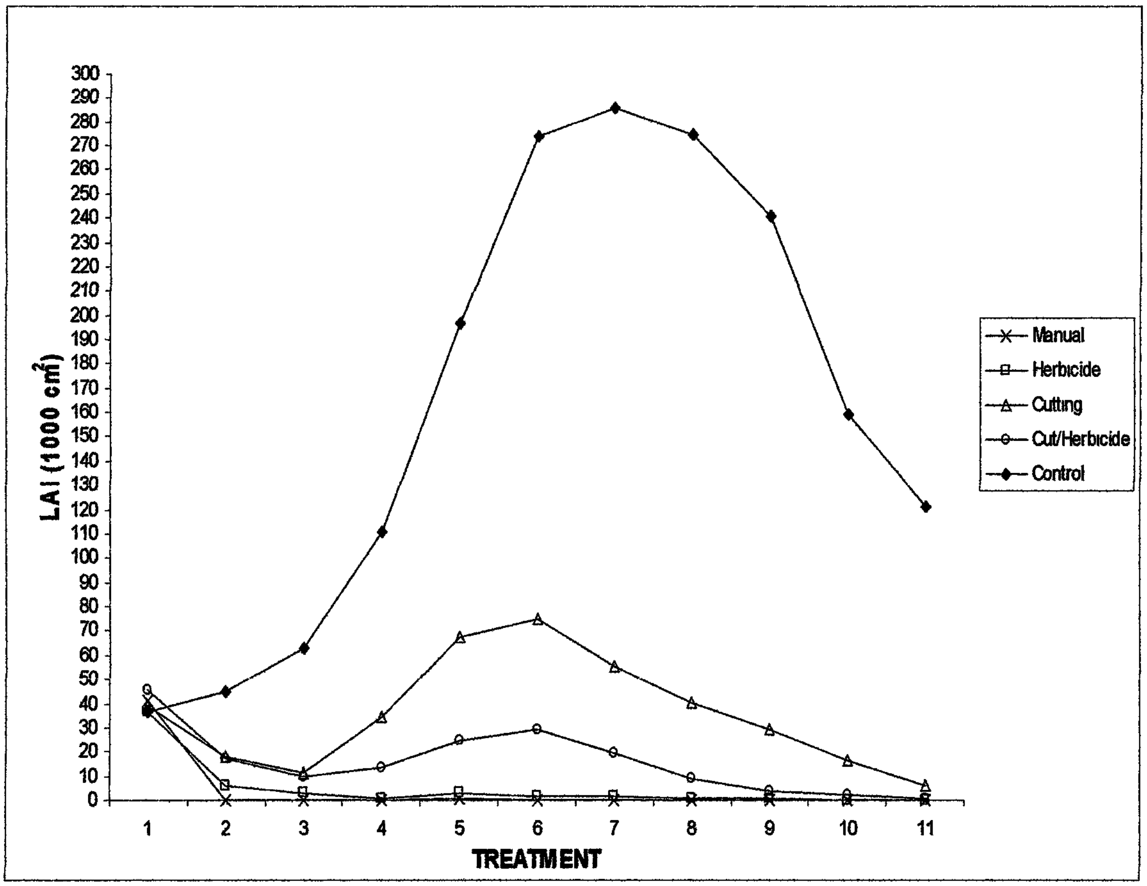

Figure 2. *Colocasia esculenta* leaf cover (leaf area index cm^2) measured in control and individual eradication technique plots over treatment intervals (November 2004 – November 2005).

Table 2. Leaf area index (cm^2) of *Colocasia esculenta* following the last treatment application in November 2005. ("X" represents significant difference, "NS" represents no significant difference, and "-" represents a comparison to itself) (Single Factor ANOVA; $F_{4,25} = 34.704$, p = <0.001).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	0.00	0.00	-	NS	X	NS	X
Herbicide	1.89	4.62	NS	-	X	NS	X
Cutting	981.29	556.23	X	X	-	NS	X
Cut/Herbicide	70.87	70.64	NS	NS	NS	-	X
Control	20216.15	8286.38	X	X	X	X	-

A Pearson correlation test was conducted to analyze the relationship between the leaf cover data collecting methods (leaf area index, line intercept, and Daubenmire). The test revealed a 99.9 percent confidence interval supporting a strong correlation among these methods (Appendix 2). Due to this correlation, only results of the leaf area index method are shown.

The manual removal technique was significantly different ($F_{4, 25} = 16.671$, $p = <0.001$) in the number of treatment applications needed to achieve eradication of *C. esculenta* compared to the mechanical cutting and the combination mechanical cut/herbicide techniques (Table 3). The manual removal technique required the fewest applications and achieved eradication in an average of 5.2 treatments (Fig. 3; Table 3). The herbicide application technique achieved eradication in an average of eight treatments, which was a significantly lower number of applications ($F_{4, 25} = 16.671$, $p = <0.001$) than the mechanical cutting technique (Table 3). Neither the mechanical cutting technique nor the combination mechanical cut/herbicide application technique resulted in complete eradication (Fig. 3; Table 3).

Table 3. Number of technique treatment applications required to achieve eradication of *Colocasia esculenta*. The cutting and cut/herbicide techniques did not achieve eradication in the eleven treatment applications from November 2004 – November 2005. ("X" represents significant difference, "NS" represents no significant difference, and "-" represents a comparison to itself) (Single Factor ANOVA; $F_{4, 25} = 16.671$, $p = <0.001$).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	5.17	2.79	-	NS	X	X	-
Herbicide	8.00	2.28	NS	-	X	NS	-
Cutting	12.00	0.00	X	X	-	NS	-
Cut/Herbicide	11.33	1.21	X	NS	NS	-	-
Control	9.13	3.31	-	-	-	-	-

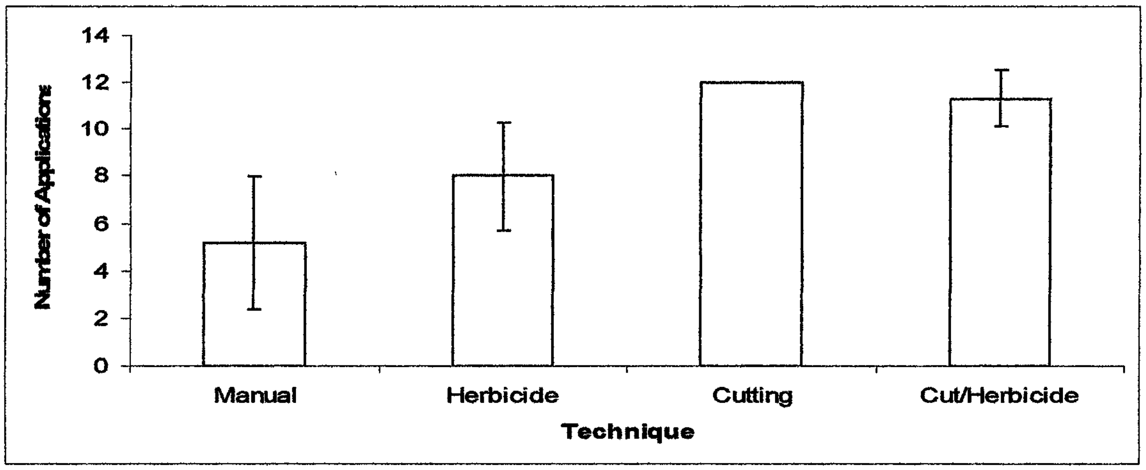

Figure 3. Number of technique treatment applications (mean and SD) required to achieve eradication of *Colocasia esculenta.* The cutting and cut/herbicide techniques did not achieve eradication in the eleven treatment applications from November 2004 – November 2005 (Single Factor ANOVA; $F_{4, 25} = 16.671$, p = <0.001).

The total amount of time required for the application of eradication techniques was significantly different ($F_{4, 25} = 17.364$, p = <0.001) in the manual removal technique compared to both the mechanical cutting technique and the combination mechanical cut/herbicide technique (Table 4; Fig. 4). The manual removal technique required the least amount of application time followed by the herbicide application technique. The combination mechanical cut/herbicide technique required the greatest amount of application time (Table 4; Fig. 4).

Table 4. Total amount of time (seconds) required for the application of individual eradication techniques from November 2004 – November 2005. ("X" represents significant difference, "NS" represents no significant difference, and "-" represents a comparison to itself) (Single Factor ANOVA; $F_{4, 25} = 17.364$, p = <0.001).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	553.00	660.42	-	NS	X	X	NS
Herbicide	1485.17	956.50	NS	-	NS	NS	NS
Cutting	2809.67	1064.56	X	NS	-	NS	X
Cut/Herbicide	4867.67	2022.50	X	NS	NS	-	X
Control	0.00	0.00	NS	NS	X	X	-

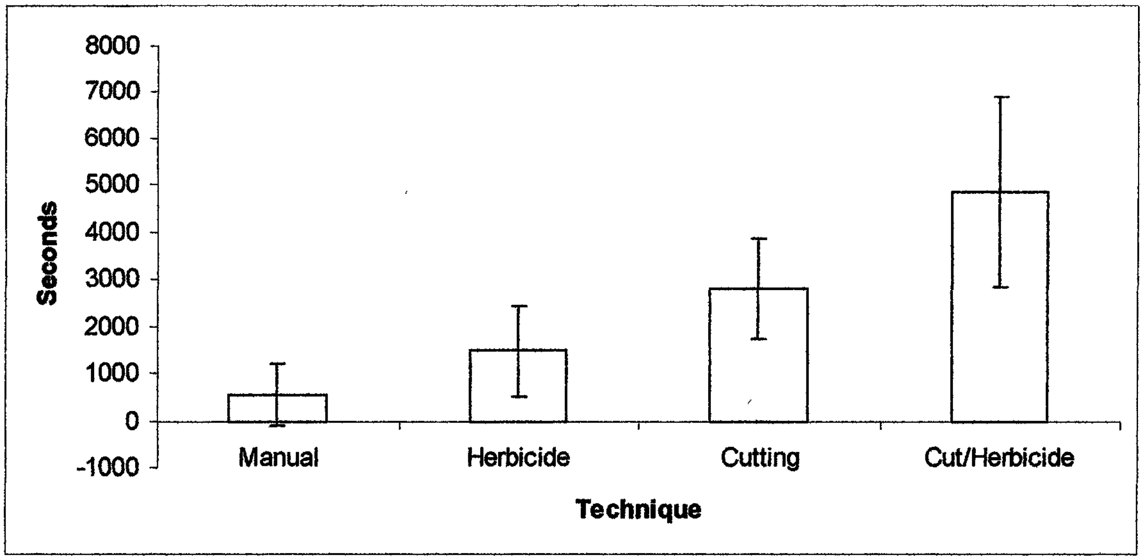

Figure 4. Total time (mean and SD) required to apply each eradication technique (Single Factor ANOVA; $F_{4,25} = 17.364$, $p = <0.001$).

In the first treatment, the herbicide application technique required the most time followed by the manual removal technique (Fig. 5). However, by the second application the manual removal technique ranked lowest in application time and remained the lowest throughout the experiment (Fig. 5).

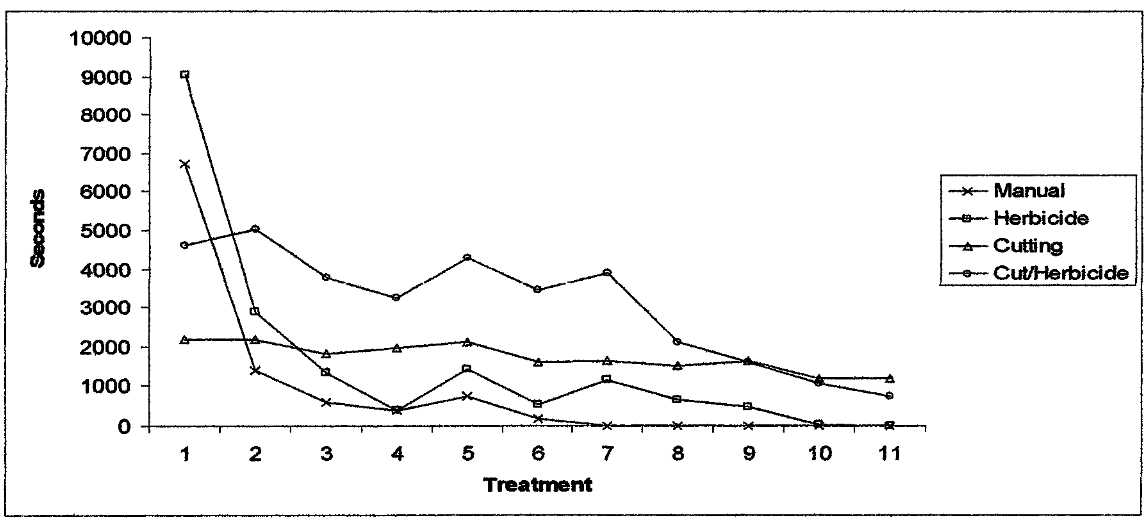

Figure 5. Time (seconds) required to perform the different eradication techniques during each treatment application from November 2004 – November 2005.

Prior to the initial application of eradication techniques, there was no significant difference ($F_{4, 25} = 0.559$, $p = 0.694$) in percent cover of other plant species, excluding *C. esculenta*, among quadrats assigned to the control and individual eradication techniques (Fig. 6; Appendix 3).

The average plant cover by species other than *C. esculenta* in all quadrats prior to the first treatment in November 2004 was one percent and steadily increased until reaching a peak in September 2005 with an average of seventy three percent of all quadrats occupied by other plant species. Following the last treatment in November 2005, the average plant cover by species other than *C. esculenta* was thirty eight percent (Fig. 6). These data demonstrate the ability of other plant species to grow in the quadrats following the removal of *C. esculenta*.

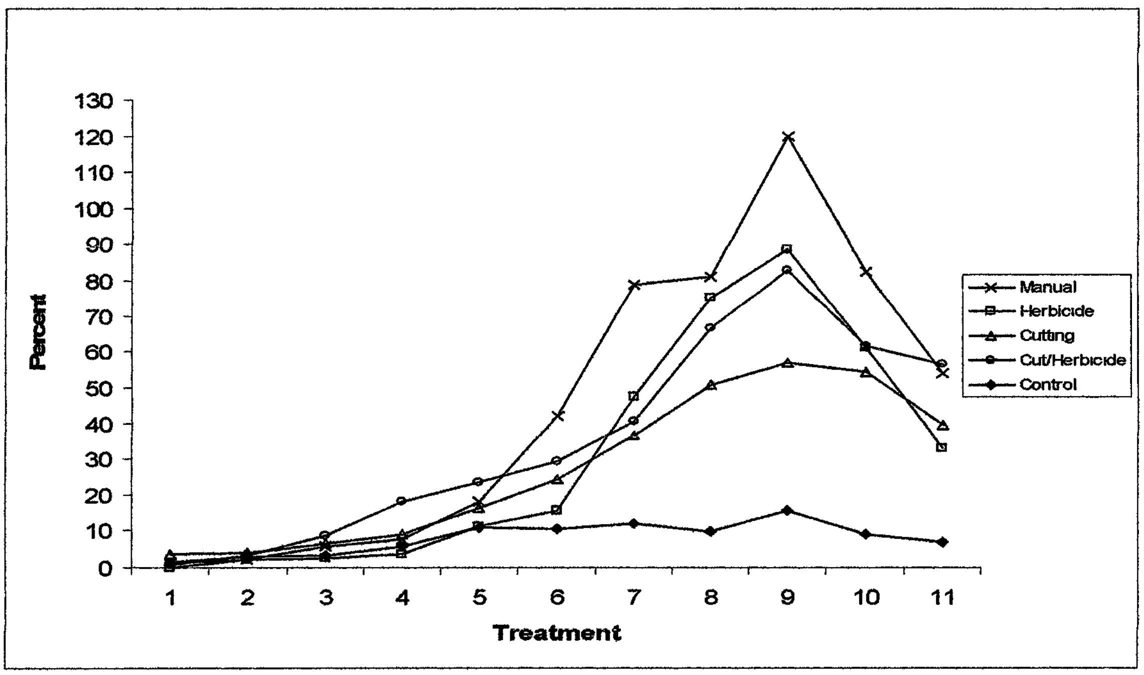

Figure 6. Percent cover of plant species other than *Colocasia esculenta*, using the line intercept method, summing all treatment applications from November 2004 – November 2005 for each eradication technique (Single Factor ANOVA; $F_{4, 25} = 3.192$, $p = 0.03$).

Following the last treatment application the mechanical cutting technique was significantly different than the control ($F_{4, 25} = 3.038$, $p = 0.036$) in the extent of plant cover by species other than *C. esculenta* (Fig. 6; Appendix 4). The mechanical cutting technique had a higher plant cover than the control. Even though the combination mechanical cut/herbicide and the manual removal techniques were not significantly different from the control, these techniques had higher plant cover mean values, excluding *C. esculenta*, than the mechanical cutting technique (Fig. 6; Appendix 4).

The percent plant cover by species other than *C. esculenta*, summed from all treatment applications from November 2004 – November 2005, revealed a significant difference ($F_{4, 25} = 3.192$, $p = 0.03$) in the herbicide application technique and the control (Fig. 7; Appendix 5). The quadrats that received the herbicide application technique showed a higher plant cover, excluding *C. esculenta*, than the control. The manual removal and the combination mechanical cut/herbicide techniques showed higher mean values than the herbicide application technique, even though these techniques were not significantly different than the control (Fig. 7; Appendix 5).

Each total mean value is a sum of the percent cover for each quadrat assigned to the technique with eleven data collections spanning one year (Fig. 7; Appendix 5). The ANOVA statistical test requires a total number that represented percent plant cover in order to analyze variance. The summing of percent cover yields a percent greater than one-hundred (Stephenson & Buell, 1965).

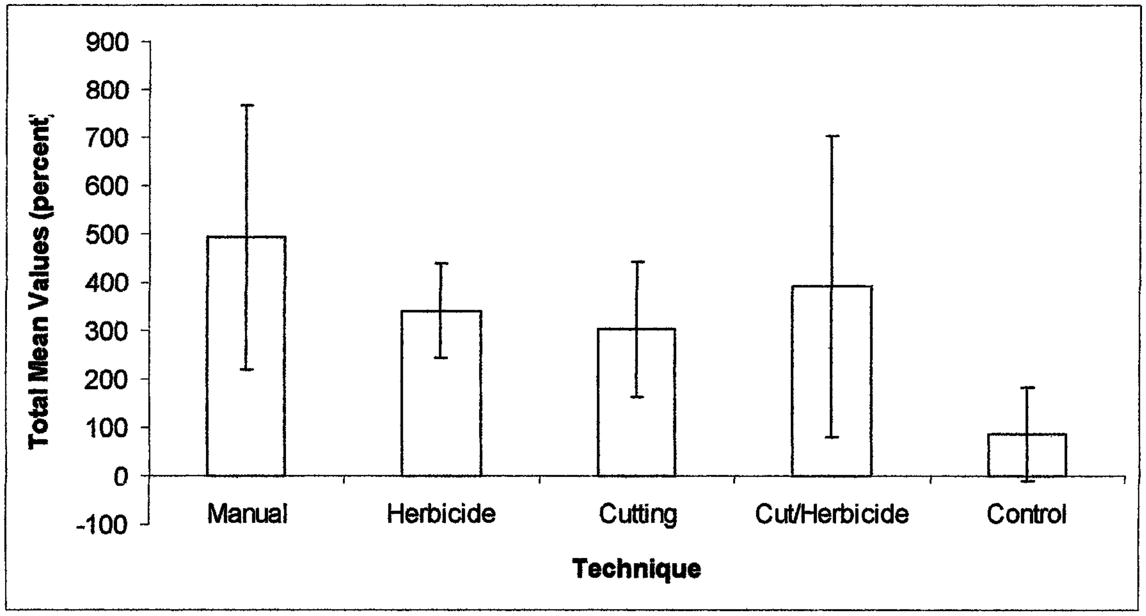

Figure 7. Total percent cover (mean and SD) of plant species other than *Colocasia esculenta*, using the line intercept method, within each eradication technique. Each total mean value is a sum of percent cover for each quadrat assigned to the technique with eleven data collections spanning one year (Single Factor ANOVA; $F_{4, 25} = 3.192$, $p = 0.03$).

A Pearson correlation test was conducted to analyze the relationship between the data collecting methods (line intercept and Daubenmire) for plant species, other than *C. esculenta*, occupying the quadrats. The test revealed a minimum 95 percent confidence interval, with a 99 percent confidence interval being more prevalent, supporting a strong correlation between these methods (Appendix 6). Due to this correlation, only results of the line intercept method are shown.

The four most common species (Table 5) found occupying the quadrats, upon the removal of *C. esculenta* were: false nettle (*Boehmeria cylindrica*) with 86 percent cover, hygro (*Hygrophila polysperma*) with 72 percent, elderberry (*Sambucus canadensis*) with 48 percent, and water primrose (*Ludwigia octovalvis*) with 47 percent cover (Fig. 8).

Table 5. Plant species colonizing quadrats following the removal of *Colocasia esculenta*.

Species Number	Common Name	Scientific Name	Family
1	Watersprite	*Ceratopteris thalictroides*	Parkeriaceae
2	Climbing hempweed	*Mikania scandens*	Asteraceae
3	Boxelder	*Acer negundo*	Aceraceae
4	Marsh fleabane	*Pluchea odorata*	Asteraceae
5	Rice cutgrass	*Leersia oryzoides*	Poaceae
6	Bald cypress	*Taxodium distichum*	Cupressaceae
7	Elderberry	*Sambucus canadensis*	Caprifoliaceae
8	Frostweed	*Verbesina virginica*	Asteraceae
9	Heart-leaved ampelopsis	*Ampelopsis arborea*	Vitaceae
10	American sycamore	*Platanus occidentalis*	Platanaceae
11	Japanese honeysuckle	*Lonicera japonica*	Caprifoliaceae
12	Hygro	*Hygrophila polysperma*	Acanthaceae
13	Paleyellow iris	*Iris pseudacorus*	Iridaceae
14	Water primrose	*Ludwigia octovalvis*	Onagraceae
15	False nettle	*Boehmeria cylindrica*	Urticaceae
16	Wild onion	*Allium canadense*	Liliaceae
17	Water pennywort	*Hydrocotyle umbellata*	Apiaceae
18	Poison ivy	*Toxicodendron radicans*	Anacardiaceae
19	Japanese privet	*Ligustrum lucidum*	Oleaceae
20	Watercress	*Rorippa nasturtium-aquaticum*	Brassicaceae
21	Celery-leaved buttercup	*Ranunculus sceleratus*	Ranunculaceae

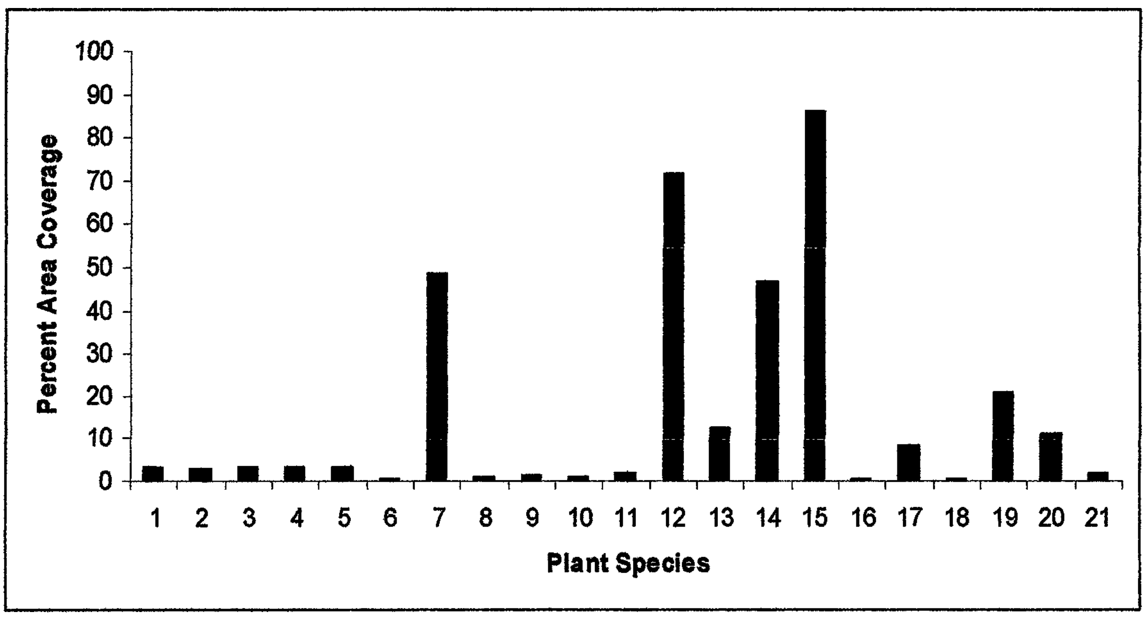

Figure 8. Total percent plant cover, data collected using the line intercept method, of individual plant species colonizing quadrats following the removal of *Colocasia esculenta* (species listed by number as in Table 5).

CHAPTER IV

DISCUSSION

This study tested four techniques to eradicate *Colocasia esculenta*: manual removal, herbicide application, mechanical cutting, and a combination of mechanical cut followed by herbicide application. These techniques have also been used in attempts to eradicate other aquatic invasive plants.

Manual removal has been shown to be very effective at removing emergent weeds (Seagrave, 1988). This method has demonstrated success in controlling wetland plants such as *Phragmites australis* (Moreira, Monteiro, & Sousa, 1999) and *Lythrum salicaria* (Morrison, 2002). However, previous studies refer to this method as being potentially slow and laborious, as well as causing changes to river bank dynamics (Seagrave, 1988). In this study, the manual removal technique effectively achieved eradication in the fewest applications and resulted in the lowest overall *C. esculenta* leaf cover. It also required the least application time. This method was slow and laborious in the beginning, however it rapidly became the least time consuming and least laborious technique. The manual pull technique did impact the habitat as a change in river bank dynamics was observed, through erosion and disruption of the soil bed, following the application of this technique.

Herbicide application, as a control method of nonnative plant species, is well documented. Success has been shown in many emergent invasive species such as

Monochoria vaginalis, *Sagittaria sagittifolia*, *Polygonum* sp., *Cyperus difformis*, *Scirpus* sp., *Typha* sp., *Crassula helmsii* (Child & Spencer-Jones, 1995) and *Phragmites australis* (Moreira, Monteiro, & Sousa, 1999). In this study, even though it did not succeed as quickly as the manual removal technique, the herbicide application technique effectively eradicated *C. esculenta* in eight treatment applications. This technique required more application time than the manual removal technique; however it required approximately half the amount of time as the mechanical cut technique and less than a third the amount of time as the combination mechanical cut/herbicide technique.

A major concern with herbicide application in Spring Lake and the upper San Marcos River ecosystem is the potential impact to neighboring stands of Texas wild rice and other flora and fauna. Previous research has shown that aquatic herbicides have been safely used to remove a target species with minimal harm to non-target communities (Nelson & Getsinger, 2000). In the current study, the herbicide application technique was the only eradication technique resulting in a significant increase in growth of other plant species than *C. esculenta* in comparison to the control. These data suggest that glyphosate had no peripheral impact on the surrounding plant ecosystem. This eradication technique caused little disruption to the soil bed and less severe erosion occurred than in the manual removal technique.

Cutting, as a control technique, can be effective and is very selective (Seagrave, 1988) however it tends to offer only a short term method of control (de Waal, 1995). Success by cutting has been shown in common reeds from river banks (Moreira, Ferreira et al., 1999). The mechanical cut technique did not achieve eradication in this study.

With exception of the control, it had the highest overall mean value for *C. esculenta* leaf cover. It required the second longest application time of any technique.

Combinations of techniques have also been applied to control nonnative plant species. Cutting followed by an herbicide application has been successful on *Melaleuca quinquenervia* (Tenenbaum, 1996), *Fallopia japonica* (de Waal, 1995), *Typha* sp. (Moreira, Monteiro, & Sousa, 1999), *Phragmites australis* (Monteiro et al., 1999), and *Lythrum salicaria* (Carroll, 1994). The positive effect of plant cutting on herbicide efficacy may be due to the depletion of rhizome reserves (Monteiro et al., 1999; Moreira, Ferreira et al., 1999). This method tends to result in a shorter treatment period to achieve success (Child et al., 1998). However, the combination mechanical cutting followed by herbicide application technique did not eradicate *C. esculenta* in this study. This technique required the greatest amount of application time, necessitating more than eight times the amount of application time than the manual removal technique.

Even though it was not applied in this study, another technique used in eradication programs is biological control. This technique can be successful, but it can also have peripheral implications on the surrounding ecosystem. Taro leaf blight (*Phytophthera colocasiae*), a melon aphid (*Aphis gossypii*) vectored disease, is the best documented pest of *C. esculenta*. It restricts the *C. esculenta* population in the Pacific and impedes its expansion in the United States by causing corm rot (Coleson & Miller, 2005). The leafhopper (*Tarophagus proserpina*) is also documented to lower the yield of *C. esculenta* by feeding on plant fluids and attracts sooty molds and ants by secreting honeydew on leaves and stems. Resource managers today are divided over the technique of biological control and report that sophisticated testing needs to be conducted to determine if the new organisms will stray from the targeted species (Tenenbaum, 1996). Due to the fact that the Spring Lake and upper San Marcos River ecosystems are fragile with respect to endangered and threatened species, a biological eradication program would need a substantial amount of research and prior testing before being implemented.

Studies suggest that a revegetation program with desirable and competitive plant species is important to maintain suppression of an invasive species following control or eradication programs (DiTomaso, 2000; Simberloff, 2003; Eiswerth et al., 2005). Restoration programs serve to impede the growth of an invasive species, curb their fertility, deny them competitive advantages, and minimize the chance of reinvasion (Edwards et al., 1995). A major limitation in restoration programs is choosing a plant species more vigorous than the invasive species (DiTomaso, 2000). This study revealed four species that grew effectively in the quadrats following the removal of *C. esculenta*: false nettle (*Boehmeria cylindrica*), hygro (*Hygrophila polysperma*), elderberry (*Sambucus canadensis*), and water primrose (*Ludwigia octovalvis*). False nettle and water primrose could be included in a restoration program at the water margins, where as elderberry could be included in drier conditions. A restorative program using these species would lessen the impact of erosion following the removal of *C. esculenta*. *Hygrophila* is an introduced species and known to be highly invasive, and therefore would not be recommended for a restoration program.

Eradication is ultimately the most desirable response to a new plant invasion, especially when it appears likely to interfere with an important native species (Doyle, 2001). Scientists may be skeptical of eradication efforts due to the beliefs that eradication is not feasible, it may be costly, and it may entail collateral damage

(Simberloff, 2003). Plant eradication remains at low visibility due to the difficulty in obtaining conclusive literature, thus leading to a sense of pessimism in regards to eradication. This "sense of doom" is unwarranted because eradication can succeed (Simberloff, 2003). Many eradication programs of terrestrial and wetland plant species are in the process of succeeding. Witchweed (*Striga asiatica*), in North Carolina, is one example of an eradication plan on its way to success. Over fifty years this species has been reduced from 160,000 hectares to about 1500 hectares and has been restricted to one area of North Carolina (Dybas, 2004). Other notable projects heading toward success are Karoo thorn (*Acacia karoo*) from Western and Victoria Australia, Taurian thistle (*Onopordum tauticum*) from Victoria Australia, kochia (*Kochia scoparia*) in Western Australia, and Asian common rice (*Oryza rufipogon*) in Everglades National Park (Simberloff, 2003). Densities of branched broomrape (*Orobanche ramosa*) and goatsrue (*Galega officinalis*) have been substantially reduced and in Kruger National Park, South Africa, ten invasive plant species have been successfully eliminated (Simberloff, 2003).

Both manual removal and herbicide application were found to be effective in eradicating *C. esculenta* in this study. However, this study was conducted on a relatively small scale and efforts on a much larger scale would be required to remove this invasive species from the Spring Lake and San Marcos River ecosystem. Nevertheless, eradication is possible. If these techniques are applied in a program and successful eradication of *C. esculenta* is achieved in the Spring Lake and San Marcos River ecosystem, the diversity and abundance of native plant species would be increased.

APPENDICES

Appendix 1: Leaf area index (cm^2) of *Colocasia esculenta* prior to application of eradication techniques ("NS" represents no significant difference and "-" represents a comparison to itself).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	6831.40	2438.12	-	NS	NS	NS	NS
Herbicide	6054.00	2877.90	NS	-	NS	NS	NS
Cutting	6462.86	3971.70	NS	NS	-	NS	NS
Cut/Herbicide	7585.68	5034.85	NS	NS	NS	-	NS
Control	6095.55	2719.85	NS	NS	NS	NS	-

Appendix 2: Pearson's correlation table comparing the *Colocasia esculenta* leaf cover data collection methods: leaf area index (LAI), line intercept (LI), and Daubenmire (D).

Treatment	1	2	3	4	5	6	7	8	9	10	11	total
LI / LAI	0.67	0.80	0.98	0.96	0.97	0.84	0.84	0.93	0.89	0.93	0.96	0.94
Significance	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
alpha	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Treatment	1	2	3	4	5	6	7	8	9	10	11	total
LAI / D	0.63	0.88	0.89	0.91	0.94	0.93	0.90	0.94	0.94	0.96	0.95	0.98
Significance	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
alpha	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Treatment	1	2	3	4	5	6	7	8	9	10	11	total
D / LI	0.63	0.88	0.89	0.91	0.94	0.93	0.90	0.94	0.94	0.96	0.95	0.98
Significance	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
alpha	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Appendix 3: Line intercept percentages of plant species other than *Colocasia esculenta* prior to the application of eradiation techniques ("NS" represents no significant difference and "-" represents a comparison to itself).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	1.00	2.45	-	NS	NS	NS	NS
Herbicide	0.00	0.00	NS	-	NS	NS	NS
Cutting	3.56	8.71	NS	NS	-	NS	NS
Cut/Herbicide	0.81	1.67	NS	NS	NS	-	NS
Control	1.33	3.27	NS	NS	NS	NS	-

Appendix 4: Line intercept percentages of plant species other than *Colocasia esculenta* following the last application of eradiation techniques in November of 2005 ("X" represents significant difference, "NS" represents no significant difference, and "-" represents a comparison to itself).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	53.86	32.68	-	NS	NS	NS	NS
Herbicide	32.83	16.20	NS	-	NS	NS	NS
Cutting	39.58	12.30	NS	NS	-	NS	X
Cut/Herbicide	56.44	48.64	NS	NS	NS	-	NS
Control	6.78	9.57	NS	NS	X	NS	-

Appendix 5: Total line intercept percentages of plant species other than *Colocasia esculenta* for all the treatment applications from November 2004 – November 2005 ("X" represents significant difference, "NS" represents no significant difference, and "-" represents a comparison to itself).

Techniques	Mean	SD	Manual	Herbicide	Cutting	Cut/Herbicide	Control
Manual	492.42	272.73	-	NS	NS	NS	NS
Herbicide	340.81	98.06	NS	-	NS	NS	X
Cutting	301.97	139.85	NS	NS	-	NS	NS
Cut/Herbicide	392.00	312.74	NS	NS	NS	-	NS
Control	87.56	96.51	NS	NS	NS	NS	-

Appendix 6: Pearson's correlation table comparing the plant cover data collection methods for species other than *Colocasia esculenta*: Line intercept (LI) and Daubenmire (D).

Treatment	1	2	3	4	5	6	7	8	9	10	11	total
D / LI	0.40	0.66	0.51	0.56	0.58	0.65	0.66	0.57	0 60	0.42	0.56	0.67
Significance	0.029	<.001	0.004	0.001	0.001	<.001	<.001	0.001	<.001	0.020	0.001	<.001
alpha	0.050	0.001	0.010	0.010	0.010	0.001	0.001	0.010	0.001	0.050	0.010	0.001

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