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Controlling Kudzu (Pueraria montana) in Riparian Zones and High Risk Areas

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CONTROLLING KUDZU (*PUERARIA MONTANA)* IN RIPIARIAN ZONES AND HIGH RISK AREAS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Forest Resources

by
Casey Harve Newton
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Accepted by:
Dr. Elena A. Mikhailova, Committee Chair
Dr. Saara J. DeWalt
Dr. Christopher J. Post

ABSTRACT

The effects of polyethylene sheeting as a thermal covering to eradicate kudzu were investigated on an area within the Clemson University Experimental Forest in Clemson, South Carolina on a Cecil clay loam. In 2005, the highest reduction of live root crowns was observed in the complete season treatment (covered for the entire growing season) with a reduction of 42% of live root crowns compared to control (no covering) plots. The next most effective was the one-week treatment (covered for one week, uncovered for one week, then repeated throughout the growing season) that reduced root crowns by 35%. The least effective treatment was the four-week treatment (covered for one week, uncovered for four weeks, and repeated) which killed 24% of root crowns. In 2006, the three treatments had similar efficacy of about 97%. The use of polyethylene sheeting appears not to be cost effective for general control of large kudzu infestations, but is highly desirable and effective for small kudzu patches on urban sites or in riparian zone buffers.

DEDICATION

Dr. Larry Nelson had outstanding foresight in recognizing the many problems associated with nonnative invasive plant species across the southeastern United States. His research and outreach activities were and continue to be extremely helpful in securing funding for invasive plant research and management and developing programs to address invasive plant management and identification across the southeastern United States. Dr. Larry Nelson gave tremendous amounts of his time and effort to the design and implementation of this study and we would like to thank him and his family.

ACKNOWLEDGMENTS

The following people and organizations have contributed to this study: the Kudzu Coalition of Spartanburg, SC, the Clemson University Experimental Forest, and Knight Cox. We thank William C. Bridges, Jr. for statistical help. Special thanks is given to the Clemson University Department of Forestry and Natural Resources for their diligence in making sure this project was continued after the untimely death of Dr. Larry Nelson. Dr. Larry Nelson gave tremendous amounts of his time and knowledge to the installment and design of this study and passed away before being able to realize the practical application of this method. Financial support was provided by a Clemson University Integrated Pest Management (CUIPM) grant. This article is Technical Contribution No. 5327 of the Clemson University Experiment Station.

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PREFACE

The southeastern United States faced a large problem with soil degradation in the early part of the 20th century. Overfarming of cotton led to soil erosion on a monumental scale. Large gullies and depressions formed as a result of this erosion. Productivity suffered dramatically as a result of erosion and the depletion of soil nutrients. The growth characteristics and soil stabilizing ability of kudzu led to its' widespread planting on these areas throughout the southeastern United States. The Soil Conservation Service promoted the planting of kudzu from 1920 to 1950. Stream banks, rights of way, and other heavily eroded land was targeted by this program. During this time, approximately eight- million seedlings were distributed to landowners in the southeastern United States. Farmers were paid eight-dollars an acre to plant kudzu on their eroded lands. Kudzu was planted on approximately one-million hectares between 1920 and 1950 (Miller and Miller, 1999). As land began to decrease in productivity for cotton due to a reduction of soil nutrients and insect infestations such as the boll weevil, people abandoned these lands and moved to urban areas (Miller and Edwards, 1983). Many of the lands that were abandoned reverted to secondary forest growth (Miller and Edwards, 1983). Kudzu that had been planted in these areas began to spread and eventually outcompeted many of the native species. It was during this period that kudzu was recognized as a problem weed. It was taken off of the list of acceptable plantings under the Agricultural Conservation Program in the 1950's. Though it was recognized as a problem, it didn't become federally listed as a noxious weed until 1997 (Blaustein, 2001). Therefore, federal funding was not available for the control and eradication of the plant until the noxious weed listing in 1997.

The following study addresses the issue of controlling and eradicating kudzu in riparian zones and other sensitive areas. Stream banks and areas containing high-value vegetation in which kudzu is present are commonly not treated due to the potential detrimental effects of herbicides in these areas as well as the high costs associated with their application. This study uses non-chemical methods to control kudzu in sensitive areas, such as riparian zones. To date, there is little information regarding this approach.

The application of polyethylene sheeting as a thermal covering is a non-herbicidal method of controlling and eradicating kudzu. This type of thermal treatment is an effective method in an Integrated Pest Management (IPM) program used to restore these areas to their native vegetation.

Thermal treatments have been used extensively in agricultural applications to control weeds in row crops. The term most commonly used for this type application is solarization. Solarization is a safe and effective method of removing unwanted vegetation and pathogens. It has been proven to increase the amount of nitrogen available for the uptake of plants, as well as other essential macro and micronutrients (Horowitz et al., 1983). Polyethylene sheeting used as a thermal covering produces a greenhouse effect (Marenco and Lustosa, 2000). This causes the soil temperature and the temperature in the space between the soil and the sheeting to rise to a level that is lethal to plant growth. This technique was used and evaluated on a kudzu infestation in the Clemson Experimental Forest in Clemson, SC in 2005 and 2006.

CONTROLLING KUDZU (*PUERARIA MONTANA*) IN RIPARIAN ZONES AND HIGH-RISK AREAS

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Introduction

The National Invasive Species Management Plan (NISMP) defines invasive species as “a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health” (Federal Register, 1999). Nonnative invasive plant species have become an increasingly damaging and threatening problem to native forest and plant communities in the United States. Ease of travel for people throughout the world and the great number of goods brought into the United States daily are together causing an exponential increase in the occurrence of nonnative invasive plant species in the United States and the problems that arise from them (Rejmanek, 1996; Starfinger et al., 1998; Mooney and Hobbs, 2000). The annual cost to control invasive plant species in the United States is estimated to exceed $24 billion (McNeely, 2001). Invasive plant species are spreading across approximately 700,000 ha of wildlife habitat each year (Babbitt, 1998).

The majority of these plants were introduced to the United States without the accompaniment of their native controls, such as insects, diseases, and foraging animals (Mack et al., 2000). They also have been shown to have a greater allocation to reproduction and a lower rate of seed predation (Erfmeier and Bruelheide, 2004; Grigulis et al., 2001). Therefore, they have the ability to out-compete native species for nutrients and water and to grow unchecked (Mack et al., 2000). The loss of native plants decreases the biodiversity of flora and fauna from these landscapes (Fritts and Rodda, 1998; Holway et al., 2002). In addition, nonnative invasive plants increase the fuel load of forest communities, leading to an increase in the frequency, intensity, and severity of wildfires (Brooks et al., 2004). Nutrient and hydrological cycling are altered by nonnative invasive plant species (MacDonald et al., 1989). These effects have led to a decrease in forest and crop productivity. A loss of forested recreation areas is also a direct result of the spread of nonnative invasive plant species in the US.

Because of its long growing season and mild winters, the southeastern United States is a prime location for non-native invasive plant species. Some of these species have been planted purposely as crops for ground cover, livestock forage, soil stabilization, and numerous other purposes initially thought to be beneficial (Miller, 2003). Many planted as ornamentals have escaped cultivation and exacerbated an already large problem (Miller, 2003). Others were brought here in shipments (deliberately and accidentally), translocated locally by birds or other migratory animals, and by a host of other accidental means (U.S. Congress, Office of Technology Assessment, 1993).

Overfarming of cotton and various other crops across the southeastern United States in the 19th century caused large-scale soil degradation, which led to a massive erosion problem in the early 20th century (Sorrells, 1983). Large gullies and depressions formed as a result. Soil organic matter was reduced to a very small proportion, which caused a decline in agricultural productivity (Adams, 1949; Langdale et al., 1979; Stallings, 1950). Attempts to reverse this situation led to widespread planting of kudzu (*Pueraria montana*). Kudzu has dense rooting capabilities, annually produces a thick litter layer, and has high leaf nitrogen because of its nitrogen-fixing properties (Forseth and Innis, 2004). These properties made it an attractive choice for controlling erosion, restoring soil organic matter, and possibly restoring essential nutrients to native communities (Bailey, 1939). It was therefore planted on approximately one-million hectares between 1920 to 1950 for erosion control and as a forage crop (Miller and Miller, 1999).

Kudzu has accomplished many of the goals for the areas in which it was planted. However, the much larger problems inherent in the invasive nature of kudzu have caused a return to poor productivity on these lands. Kudzu has become an extremely large problem in regards to forest management (Effective Kudzu Control, 2001). Forested areas in which kudzu is present along the perimeter have the potential to become overcome once a harvesting operation is conducted (Effective Kudzu Control, 2001). An increase of sunlight reaching the forest floor allows adjacent kudzu infestations to spread into the harvested area and overtop recently planted seedlings (Effective Kudzu Control, 2001). One question posed by Forseth and Innis (Forseth and Innis, 2004) regarding long term effects from kudzu infestations is “what are the effects of large stands of kudzu on watershed nitrogen cycles and soil nitrogen saturation”? Approximately 810,000 ha of forestland in the United States are infested with kudzu (Corley et al., 1997).

Difficulty of control and eradication of a kudzu infestation is primarily determined by the age of the infestation (Miller, 1996). The infestations most difficult to control are those that are greater than ten years in age (Miller, 1996). This has been determined to be the age in which roots become excessively large and are able to store a large amount of carbohydrates (Miller, 1996). In order to determine the age of the infestation in question, examine a subset of the kudzu root crowns on the soil surface. If the mean diameter of the root crowns measured is equal to or exceeds two inches, it is deemed to be greater than ten years in age (Miller, 1996). Infestations that are ten years old or greater will require more intensive treatments, whether herbicides or alternative methods of control are used (Miller, 1996). Soils that have a high percentage of clay require more intensive treatments to achieve eradication (Miller, 1996). This is especially applicable for the application of herbicide treatments to infestations present on old terraces (Miller, 1996).

Chemical methods of control are the primary means of treating kudzu-infested areas. The herbicides Tordon® 101 Mixture, which contains 2,4-D [(2,4-dichlorophenoxy)acetic acid] and picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) and Tordon® K, which contains picloram (Ransom 2007), are both Dow Elanco products that have proved to be most cost- effective herbicides in eradicating kudzu (Miller and True, 1986). However, the Tordon® products, which are extremely effective on legume species such as kudzu (Miller 1996), are restricted-use products because they contain picloram, which is water soluble and can leach through sandy soils into the groundwater (Miller, 1996). These products cannot be used in or near stream banks where entry into other bodies of water is likely, or where crops or sensitive plants, trees, and other vegetation could come into contact with the chemical (Miller, 1996). Trees or other vegetation with roots near the herbicide application can be severely injured or killed (Miller, 1996). Plants that are introduced soon after application of the herbicide can also be severely injured or killed (Miller, 1996). The application of these restricted-use herbicides requires a permit from state regulatory agencies or county agents after each situation is reviewed to determine the proper procedures for use (Miller, 1996). Glyphosate [N-(phosphonomethyl)glycine] formulated as Rodeo® and Accord® (Monsanto products) and Triclopyr (triethanolamine salt = [(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid) formulated as Garlon® 3A (Dow

Elanco product) can be used near water in streamside management zones (Ransom, 2007). Veteran® 720 (Riverdale Chemical Company product) contains 2,4-D and can also be used in these areas (Miller, 1996). However, these products are less effective than the Tordon® compounds and must be applied over several successive years to achieve complete eradication (Miller, 1996). Although these products are labeled for use in and near water, their actual use in these areas is commonly discouraged; the labels typically instruct that the products should “not be used directly over water or near water that will be used for irrigation or domestic use” (Miller and Edwards, 1983). Herbicide leaching and their persistence in the soil is a potential environmental and human health risk (Berisford et al., 2006). Currently, there is limited information on alternative methods of kudzu control in areas in which chemical methods cannot be employed.

Kudzu is a stoloniferous plant with a semiwoody tuberous root (Miller and Miller, 1999). When a kudzu vine makes contact with the ground and remains in that position for a period of time, a node (root crown) is formed that quickly develops primary roots. Vines eventually begin to grow and spread from this node. “For eradication, every kudzu plant in and around a patch must be killed, or the spread from any surviving plants can make all prior efforts and investments useless" (Miller, 1996). Kudzu is somewhat rhizomatous when buried with leaf litter (Miller and Miller, 1999), but has limited ability to spread beneath the surface of the soil. As much as fifty-percent of the plant’s biomass is the root system that supports the plant (Wechsler, 1977). Both overgrazing and polyethylene sheeting covering kudzu patches have been proposed to control kudzu because they kill or stunt the aboveground growth, limiting the plant’s ability to photosynthesize and contribute to its carbohydrate reserves in its tuberous root. Numerous landowners are proponents of the use of livestock for overgrazing kudzu biomass (Miller, 1996). Three to four years of close grazing when eighty-percent of the plant's biomass is consumed as been shown to be effective (Miller, 1996). The most effective timing and method of overgrazing occurs during the months of August and September followed by restoration using tree species and other native vegetation with fast growth rates, then again grazed for two consecutive years (Miller, 1996). The most effective species for livestock grazing has been shown to be sheep and cattle (Miller, 1996). Areas adjacent to streams and other areas of high-risk cannot be treated in the same manner as other areas. The use of polyethylene sheeting as an alternative kudzu control and eradication method has been proposed for use in these areas.

A cost-effective method of eradicating kudzu is needed in order for control to occur on a large scale. The estimated cost due to lost productivity of forestland that has been infested with kudzu is forty-eight dollars per acre per year (Dangerfield, 2002). "The present net value of an average stand of pines grown on cutover land for twenty-five years in the southeast is approximately six-hundred-fifty dollars per acre. Kudzu control costs exceed two-hundred dollars per acre per year for five years. Thus, kudzu control for forest production is not economically feasible." (Dangerfield, 2002).

The objectives of this study were the following: (1) to develop an environmentally safe method of buffering streams, and other bodies of water adjacent to kudzu infestations, from the effects of herbicide toxicity; (2) to determine the most effective way to use polyethylene sheeting to reduce kudzu root crowns over a two-year period;

and (3) to evaluate the cost effectiveness of thermal kudzu treatments.

Materials and Methods

Study Site and Treatments. The location for this study was the Clemson University Experimental Forest in Clemson, SC (34° 41’ 55.7” N, 82° 52’ 45.7” W). The site used for the study is a 1.2 ha kudzu infestation, at least 30 years old, which is bordered on the north by a 15-year-old loblolly pine plantation. Local businesses and county highways border the remaining three sides.

This site is within the Southern Outer Piedmont ecoregion (Griffith et al., 2002). Mean temperatures for this site range from -2°C to 10°C in January, and summer temperatures range from 20°C to 32°C in July (Griffith et al., 2002). There are between 190 and 230 frost-free mean days annually, and mean annual precipitation ranges from 112 to 142 cm (Griffith et al., 2002).

The slope for the site ranges from 6% to10% with a south-west aspect. There are several terraces across the tract. Aerial photographs dated 1938 show that this was once a homesite with the terraces planted in row crops. The soil is a highly erodable Cecil clay loam (fine, kaolinitic, thermic Typic Kanhapludult) (Web Soil Survey, 2007).

A randomized complete block design was used for the study. Four manipulative treatments using translucent polyethylene sheeting were installed for this study in preparation for the 2005 growing season: (1) complete season: covered completely during the growing season; (2) one-week interval: covered for one week, uncovered for the next week; (3) two-week interval: covered for one week, uncovered for two-weeks; and (4) four-week interval: covered for one-week, uncovered for four-weeks. Untreated control areas (control) were sampled immediately outside the plots. Each treatment was replicated three times. The plots used for the manipulative treatments measured 20 feet by 100 feet (6.1 m by 30.5 m). Translucent polyethylene sheeting used during the 2005 growing season was not UV-resistant. The number of treatments, plot size, and study materials were amended for the 2006 growing season after analysis of the 2005 data.

The same study site was used for the 2006 growing season with the application of only the complete season, one-week interval, and four-week interval treatments, replicated three times. Untreated control areas were again sampled immediately outside the plots (n=9). Each plot measured 20 feet by 30 feet (6.1 m by 9.1 m). [1]UV-resistant, translucent polyethylene sheeting was used in each treatment in 2006.

Methods and Measurements. A temperature gradient test using two thermal chambers was conducted over seven days in July 2005 to determine the temperature regime under translucent and black polyethylene sheeting. Temperature readings were taken from thermocouples placed at depths of 1.5, 5, 10, 20, 40, and 60 cm below the sheeting surface of both thermal chambers. This temperature gradient test is important because of the large amount of biomass that must be dealt with in the early part of the growing season. Dead biomass from the previous year's growth as well as new live growth biomass is present at the beginning of each year's growing season. For a thermal treatment to be effective, intense heat must penetrate through the biomass to reach the root crowns on the soil surface.

Before the installation of the polyethylene sheeting treatments, two circular mil-acre (1.12 m radius) plots were installed inside each of the replications to sample the live root crowns. These mil-acre plots were installed 3 m from the edge of each replication. The center of each mil-acre plot was marked to ensure that the same location was sampled at the completion of each growing season. These mil-acre plots were maintained throughout the duration of the two-year study. The polyethylene treatments were installed the first week of June 2005 and 2006. The treatments were maintained throughout the growing season. Weeds were pulled manually between plots to ensure that the edge effect between plots did not introduce bias. The polyethylene sheeting was removed in late October at the conclusion of each growing season (signaled by the first major frost). Root crown counts were conducted in December of 2005 and 2006 to determine the mortality rate for each treatment in each year.

Statistical Analysis. All statistical analyses were performed with SAS v. 9.0 (SAS, 2002). The probability of mortality for an individual kudzu root crown for each treatment in each year was calculated using PROC GLIMMIX. A binomial distribution and a logit link were used to model the probability of root crown mortality for each treatment (complete season, one-week, and four-week) in each year (2005 and 2006). The least squares means and 95% confidence intervals were calculated for each treatment and year combination.

Results and Discussion

Temperature Regime. The temperature gradient test provided valuable information on the shade of plastic best-suited for application as a thermal treatment. The translucent sheeting demonstrated uniform heat intensity throughout the space between the surface of the sheeting and the soil surface (Figure 1). Heat uniformity ensures that kudzu biomass does not act as a thermal insulator for root crowns. The black polyethylene sheeting demonstrated a higher temperature at the surface of the sheeting than did the translucent sheeting. However, the black polyethylene sheeting did not demonstrate uniform heat intensity throughout the space created by the chamber (Figure 1). Therefore, translucent polyethylene sheeting demonstrated superior, more uniform thermal capabilities for use in this type of application.

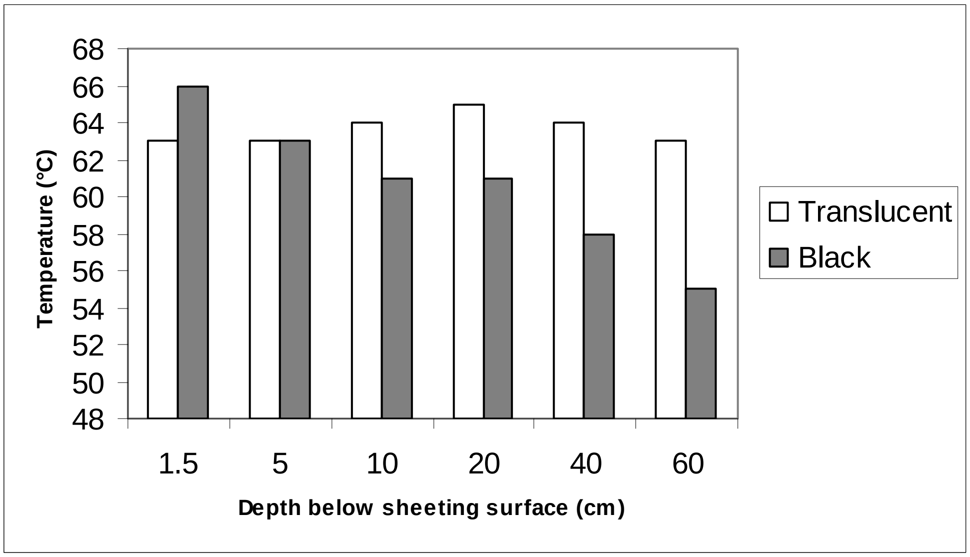


Figure 1. Temperature gradient inside translucent and black polyethylene sheeting thermal chambers (ambient temperature = 32° Celsius).

Vegetation Responses. A significant treatment-by-year interaction demonstrated that the treatments had different effects on kudzu mortality over the two years of the experiment (Table 1).

Table 1. Type III tests of fixed effects for differences among treatments and years in probability of kudzu root crown mortality.

Type III Tests of Fixed Effects				
Effect	DF	DF	F Value	Pr > F
Treatment	3	31	129.61	<0.0001
Year	1	31	194.24	<0.0001
Treatment by Year	3	31	16.65	<0.0001

The probability of root crown mortality was substantially higher in the second year of the study than in the first year for all of the treatments except for the control (Figure 2).

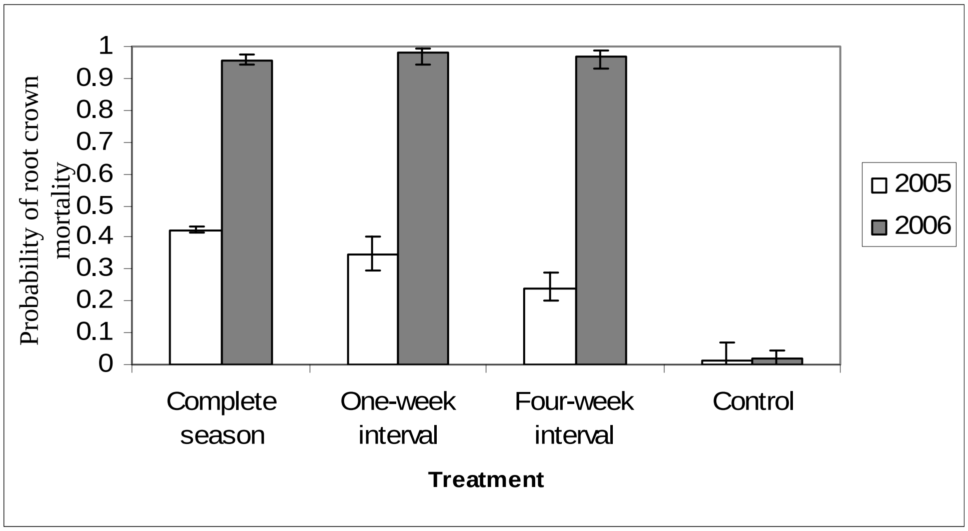


Figure 2. Probability of root crown mortality for each year and each treatment (upper and lower 95% confidence intervals are shown).

There was no statistical difference between the three manipulative treatments in their effectiveness in killing kudzu root crowns (Table 2). Although not statistically

Table 2. Root crown mortality data (2005, 2006).

Treatment	Replication	Live Root Crowns	Dead Root Crowns	Root Crown Mortality Rate
		2005		
Complete	1	41	45	52%
	2	45	35	44%
	3	96	52	35%
Total	-----	182	132	42%
One-week	1	69	54	44%
	2	50	46	48%
	3	113	23	17%
Total	-----	232	123	35%
Four-week	1	98	41	29%
	2	80	33	29%
	3	125	22	15%
Total	-----	303	96	24%
Control (total)	1-9	432	7	2%
		2006		
Complete	1	0	77	100%
	2	2	40	95%
	3	5	34	87%
Total	-----	7	151	96%
One-week	1	0	68	100%
	2	0	71	100%
	3	4	48	92%
Total	-----	4	187	98%
Four-week	1	0	76	100%
	2	0	70	100%
	3	7	54	89%
Total	-----	7	200	97%
Control (total)	1-9	446	9	2%

significant, the complete season treatment tended to be the most effective in reducing the volume of live root crowns in 2005 (Figure 2, Table 2). This treatment produced a mortality rate of 44%. The one-week interval was the next most effective treatment, producing a mortality rate of 36%. The lowest mortality rate was seen in the four-week interval treatment, with a rate of 22%. In contrast, only 1.6% of root crowns died in the control plots in 2005.

In the second consecutive year of the study, each manipulative treatment showed a substantial increase in the mortality rate of kudzu root crowns over that achieved in 2005 (Figure 2, Table 2). Data from the 2006 growing season demonstrated a cumulative effect for the two consecutive years of the study. The treatments had statistically equivalent effectiveness in increasing kudzu root crown mortality, with a mean rate of 97% killed. The control plots for the 2006 growing season demonstrated a negligible root crown mortality rate of approximately 2%.

These data suggest that two consecutive years of application are required for the effective eradication of kudzu root crowns using translucent polyethylene sheeting treatments. In addition, the near equal effectiveness of each treatment suggests that the least expensive and intensive treatment can be implemented with approximately the same results as the most intensive treatment.

The polyethylene thermal treatments effectively killed the live biomass, which inhibited plant photosynthesis and contribution to its carbohydrate reserves. However, this study did not completely analyze the effectiveness of the treatments in eliminating the carbohydrate reserves of the tuberous roots. Evaluations should be conducted on the study site for the next two growing seasons to determine the effectiveness of the treatments in eliminating carbohydrate reserves.

Cost of Control. After two consecutive years of application, the most cost-effective treatment was determined to be as operationally effective as the most intensive treatment. Therefore, the four-week interval would be the most practical treatment to implement (Table 3). This treatment would allow the application of four times the area of the covered complete season treatment. In practice, the polyethylene sheeting would be moved once weekly on a four-week rotation throughout the growing season. This treatment would cost approximately $1485 per ha to implement. However, this cost includes the product cost alone; other costs, such as labor and transportation are not provided in the analysis. There would be a significant labor cost associated with moving the sheeting once weekly for the deployment of the four-week treatment, and this labor cost could be a major deterrent in the use of this treatment. Deployment of the complete season and one-week interval treatments would have a higher product cost, but much lower labor costs. These considerations would need to be weighed by land managers to determine the cost-effectiveness of the various treatments.

The use of non-ultraviolet-light-resistant translucent polyethylene sheeting during the 2005 growing season was not cost-effective because ultraviolet light quickly degraded the sheeting to the point that it decomposed into small pieces. This required the periodic purchase and installation of additional sheeting throughout the 2005 growing season, and the decomposed sheeting left a large amount of environmental waste that was difficult and expensive to remove. The ultraviolet-light-resistant polyethylene sheeting used during the 2006 growing season should be usable over many additional growing seasons.

Table 3. Dollars Per Hectare for UV-Resistant Polyethylene Sheeting.

Treatment	Dollars Per Hectare*
Covered Entire Season	$5940
One-week interval	$2970
Four-week Interval	$1485

*(Transportation and labor costs are not included in this estimate.) Example of calculations: 107,639.1ft² (1 ha) / 2000 ft² (1 sheet) = 54 sheets/ha 54 sheets/ha X $110 (approximate cost per sheet) = $5940.00

Conclusion

This study was effective in the development of an alternative method for controlling kudzu without the use of herbicides. The method of covering kudzu infestations with translucent polyethylene sheeting would be both effective and efficient in eradicating and controlling kudzu in riparian zones and other sensitive areas. In order to be successful, treatments must be applied for two consecutive years. The most cost-effective treatment evaluated in this study is the four-week interval treatment.

Sources of Materials

UV-resistant, translucent polyethylene sheeting used for this study was purchased from Jade Systems LLC (189 McCraw’s Hill Drive, Hendersonville, NC 28792). The sheeting was purchased in 20 feet by 100 feet (6.1m by 30.5m) rolls. Eight-inch spikes were used to fasten the polyethylene sheeting to the ground and were purchased from The Home Depot®.

CONCLUSION

This study produced the following conclusions: (1) translucent polyethylene sheeting is superior to black polyethylene sheeting for use as a thermal covering for eliminating kudzu root crowns; (2) two consecutive years of application are required to achieve a significant root crown mortality rate; (3) polyethylene sheeting used as thermal coverings demonstrated their effectiveness in eliminating kudzu root crowns and live biomass; (4) the most cost effective treatment (four-week interval) is as operationally effective as the most intensive treatment (complete season) after the second consecutive year of application; and (5) ultraviolet-light-resistant polyethylene sheeting is required for this type of application, due to its cost effectiveness of being reusable for multiple growing seasons.

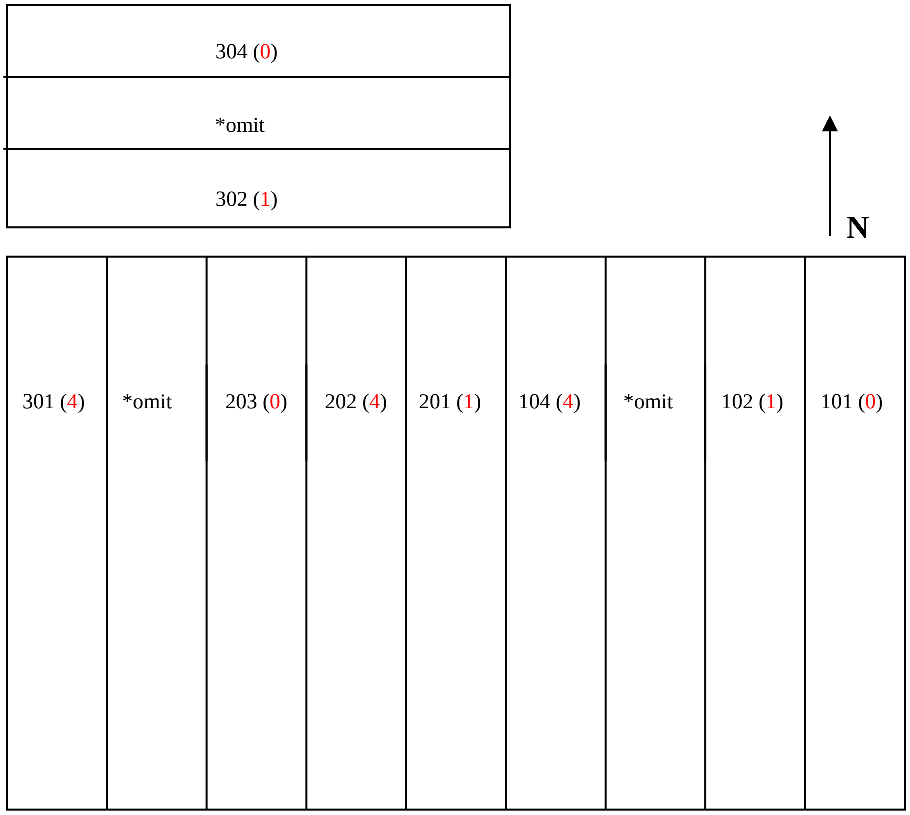
Thermal treatments are a viable non-chemical alternative for controlling and eradicating kudzu. There is considerable evidence that this method increases the amount of available nitrogen as well as other essential macro and micronutrients. This method would be practical for use in riparian and streamside management zones, as well as other sensitive areas, such as high-value vegetation areas. This method would provide a buffer that would allow safe herbicide use but with reduced risks to water quality and high-value vegetation. Solarization is an environmentally sound method that is effective in the process of restoring riparian zones to their native vegetation.

APPENDICES

Appendix A.

Experimental layout with treatment legend and mil-acre plot.

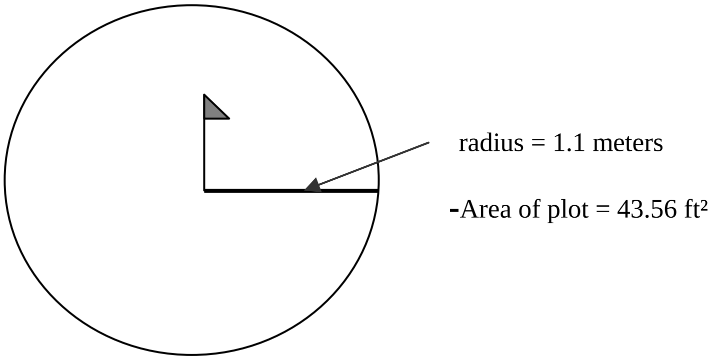
Experimental layout



- Complete Season Treatment Plot #'s: 101, 203, 304 (denoted by 0)
- One-week treatment plot #'s: 102, 201, 302 (denoted by 1)
- Four-week treatment plot #'s: 104, 202, 301 (denoted by 4)

*Omitted plots are 2005 two-week treatment plots.

Circular mil-acre plot (1.1 meter radius) in which root crowns are periodically counted to determine the root crown mortality rate for each treatment.



Appendix B.

Representative photos.

The Cheoah River in western NC, an
example of a riparian zone where kudzu is present.

The experiment site showing three treatments.

The experiment site showing the center of a circular mil-acre plot.

Thermal chambers used to determine temperature gradient.

Appendix C.

Raw data (2005).

Treatment	Replication	Mil-acre plot	Live	Dead	Total	Mortality rate
Complete	101	a,b,c,d	41	45	86	0.523256
	203	a	23	3	26	0.115385
	203	b	2	14	16	0.875
	203	c	12	12	24	0.5
	203	d	8	6	14	0.428571
	304	a	7	26	33	0.787879
	304	b	45	13	58	0.224138
	304	c	30	9	39	0.230769
	304	d	14	4	18	0.222222
	TOTAL	--	182	132	314	0.420382
One-week	102	a	28	11	39	0.282051
	102	b	14	14	28	0.5
	102	c	7	14	21	0.666667
	102	d	20	15	35	0.428571
	201	a	17	6	23	0.26087
	201	b	16	16	32	0.5
	201	c	10	11	21	0.52381
	201	d	7	13	20	0.65
	302	a	39	2	41	0.04878
	302	b	33	7	40	0.175
	302	c	30	7	37	0.189189
	302	d	11	7	18	0.388889
	TOTAL	--	232	123	355	0.346479
Four-week	104	a	33	4	37	0.108108
	104	b	24	6	30	0.2
	104	c	15	22	37	0.594595
	104	d	26	9	35	0.257143
	202	a	24	6	30	0.2
	202	b	12	13	25	0.52
	202	c	23	10	33	0.30303
	202	d	21	4	25	0.16
	301	a	46	5	51	0.098039
	301	b	29	8	37	0.216216
	301	c	36	6	42	0.142857
	301	d	14	3	17	0.176471
	TOTAL	--	303	96	399	0.24062
Control	1	--	22	2	24	0.083333
	2	--	40	1	41	0.02439
	3	--	40	1	41	0.02439
	4	--	38	0	38	0
	5	--	44	0	44	0
	6	--	52	1	53	0.018868
	7	--	70	0	70	0
	8	--	72	0	72	0
	9	--	54	2	56	0.035714
	TOTAL	--	432	7	439	0.015945

Raw data (2006).

Treatment	Replication	Mil-acre plot	Live	Dead	Total	Mortality rate
Complete	101	a	0	49	49	1
	101	b	0	28	28	1
	203	a	2	20	22	0.909091
	203	b	0	20	20	1
	304	a	5	19	24	0.791667
	304	b	0	15	15	1
	TOTAL	--	7	151	158	0.955696
One-week	102	a	0	36	36	1
	102	b	0	32	32	1
	201	a	0	32	32	1
	201	b	0	39	39	1
	302	a	1	27	28	0.964286
	302	b	3	17	20	0.85
	TOTAL	--	4	183	187	0.97861
Four-week	104	a	0	38	38	1
	104	b	0	38	38	1
	202	a	0	36	36	1
	202	b	0	34	34	1
	301	a	5	28	33	0.848485
	301	b	2	26	28	0.928571
	TOTAL	--	7	200	207	0.966184
Control	1	--	44	2	46	0.043478
	2	--	42	0	42	0
	3	--	51	1	52	0.019231
	4	--	59	0	59	0
	5	--	48	0	48	0
	6	--	62	1	63	0.015873
	7	--	44	2	46	0.043478
	8	--	58	2	60	0.033333
	9	--	38	1	39	0.025641
	TOTAL	--	446	9	455	0.01978

Appendix D.

SAS program.

```
/*Program to calculate probability of a kudzu individual being dead under the four
treatments in the two years. Repeated measures analysis was not conducted because the
location of the plots differed between the two years.*/
data kudzu;
input year treat$ plot$ alive dead total;
cards;
2006    Complete        101     0       77      77
2006    Complete        203     2       40      42
2006    Complete        304     5       34      39
2006    Oneweek         102     0       68      68
2006    Oneweek         201     0       71      71
2006    Oneweek         302     4       44      48
2006    Fourweek        104     0       76      76
2006    Fourweek        202     0       70      70
2006    Fourweek        301     7       54      61
2006    Control 1       44      2       46
2006    Control 2       42      0       42
2006    Control 3       51      1       52
2006    Control 4       59      0       59
2006    Control 5       48      0       48
2006    Control 6       62      1       63
2006    Control 7       44      2       46
2006    Control 8       58      2       60
2006    Control 9       38      1       39
2005    Complete        101     41      45      86
2005    Complete        203     45      35      80
2005    Complete        304     96      52      148
2005    Control 1       21      2       23
2005    Control 2       40      1       41
2005    Control 3       40      1       41
2005    Control 4       45      0       45
2005    Oneweek         102     69      54      123
2005    Oneweek         201     50      46      96
2005    Oneweek         302     113     23      136
2005    Control 5       38      0       38
2005    Control 6       44      0       44
2005    Control 7       52      1       53
2005    Control 8       43      1       44
2005    Fourweek        104     98      41      139
2005    Fourweek        202     80      33      113
2005    Fourweek        301     125     22      147
2005    Control 9       70      0       70
2005    Control 10      72      0       72
2005    Control 11      54      2       56
```

```
2005     Control 12         50         0           50;

proc glimmix data=kudzu ;
  class treat year plot;
  model dead/total= treat|year/ dist=bin link=logit;
lsmeans treat/ pdiff ilink cl;
  lsmestimate treat 'com vs con' 1 -1  0  0/ilink cl ;
  lsmestimate treat 'com vs four'1  0 -1  0/ilink cl ;
  lsmestimate treat 'com vs one' 1  0  0 -1/ilink cl ;
  lsmestimate treat 'con vs four'0  1 -1  0/ilink cl ;
  lsmestimate treat 'con vs one' 0  1  0 -1/ilink cl ;
  lsmestimate treat 'four vs one'0  0  1 -1/ilink cl ;
lsmeans treat*year /pdiff ilink cl;
   title 'Effect of different management techniques on kudzu crown survival across 2
years';
run;
quit;
```

```
Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

Model Information

Data Set                          WORK.KUDZU
Response Variable (Events)    dead
Response Variable (Trials)     total
Response Distribution           Binomial
Link Function                      Logit
Variance Function                Default
Variance Matrix                  Diagonal
Estimation Technique          Maximum Likelihood
Degrees of Freedom Method  Residual


Class Level Information

Class    Levels    Values

treat      4      Complete Control Fourweek Oneweek
year       2      2005 2006
plot      21      1 10 101 102 104 11 12 2 201 202 203 3 301 302 304 4 5 6 7 8 9
```

```
Number of Observations Read         39
Number of Observations Used         39
Number of Events                   902
Number of Trials                  2652
Dimensions

Columns in X                15
Columns in Z                 0
Subjects (Blocks in V)       1
Max Obs per Subject         39

Optimization Information

Optimization Technique        Newton-Raphson
Parameters in Optimization    8
Lower Boundaries              0
Upper Boundaries              0
Fixed Effects                 Not Profiled

Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

Iteration History

                                            Objective                        Max
Iteration     Restarts     Evaluations      Function         Change        Gradient

0                0             4          106.39712226          .          4.71875
1                0             3           99.970149269    6.42697299      2.384157
2                0             3           99.637384178    0.33276509      0.231064
3                0             3           99.635059313    0.00232486      0.002096
4                0             3           99.635059117    0.00000020      1.845E-7

Convergence criterion (GCONV=1E-8) satisfied.

Fit Statistics

-2 Log Likelihood              199.27
AIC  (smaller is better)       215.27
AICC (smaller is better)       220.07
BIC  (smaller is better)       228.58
CAIC (smaller is better)       236.58
HQIC (smaller is better)       220.05
Pearson Chi-Square             110.32
Pearson Chi-Square / DF          3.56
```

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
treat	3	31	129.61	<0.0001
year	1	31	194.24	<0.0001
treat*year	3	31	16.65	<0.0001

treat Least Squares Means

treat	Estimate	Standard Error	DF	t Value	Pr > |t|	Alpha	Lower	Upper	Mean
Complete	1.3751	0.2016	31	6.82	<0.0001	0.05	0.9639	1.7862	0.7982
Control	4.0838	0.2450	31	16.67	<0.0001	0.05	4.5835	-3.5841	0.01656
Fourweek	1.1015	0.2010	31	5.48	<0.0001	0.05	0.6916	1.5114	0.7505
Oneweek	1.5943	0.2588	31	6.16	<0.0001	0.05	1.0665	2.1221	0.8312

Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

treat Least Squares Means

treat	Standard Error Mean	Lower Mean	Upper Mean

treat	Standard Error Mean	Lower Mean	Upper Mean
Complete	0.03247	0.7239	0.8565
Control	0.003991	0.01012	0.02701
Fourweek	0.03763	0.6663	0.8193
Oneweek	0.03631	0.7439	0.8930

Differences of treat Least Squares Means

treat	_treat	Estimate	Standard Error	DF	t value	Pr > |t|	Alpha	Lower	Upper
Complete	Control	5.4588	0.3173	31	17.21	<0.0001	0.05	4.8118	6.1059
Complete	Fourweek	0.2736	0.2847	31	0.96	<0.3440	0.05	-0.3070	0.8541
Complete	Oneweek	-0.2192	0.3280	31	-0.67	<0.5089	0.05	-0.8883	0.4498
Control	Fourweek	-5.1853	0.3169	31	-16.36	<0.0001	0.05	-5.8316	-4.5390
Control	Oneweek	-5.6781	0.3564	31	-15.93	<0.0001	0.05	-6.4049	-4.9513
Fourweek	Oneweek	-0.4928	0.3277	31	-1.50	<0.1427	0.05	-1.1611	0.1755

treat*year Least Squares Means

Treat	Year	Estimate	Standard Error	DF	t-value	PR > |t|	Alpha	Lower	Upper	Mean
Complete	2005	-0.3212	0.1143	31	-2.81	0.0085	0.05	-0.5544	-0.08804	0.4204
Complete	2006	3.0714	0.3866	31	7.94	<0.0001	0.05	2.2828	3.8599	0.9557
Contro	2005	-4.2644	0.3560	31	-11.98	<0.0001	0.05	-4.9906	-3.5383	0.01386
Control	2006	-3.9031	0.3367	31	-11.59	<0.0001	0.05	-4.5898	-3.2164	0.01978
Fourweek	2005	-1.1494	0.1171	31	-9.81	<0.0001	0.05	-1.3883	-0.9105	0.2406

treat*year Least Squares Means

treat	year	Standard Error Mean	Lower Mean	Upper Mean
Complete	2005	0.02786	0.3649	0.4780
Complete	2006	0.01637	0.9074	0.9794
Control	2005	0.004868	0.006756	0.02824
Control	2006	0.006528	0.01005	0.03855
Fourweek	2005	0.02140	0.1997	0.2869

Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

treat*year Least Squares Means

Treat	Year	Estimate	Standard Error	DF	t-value	Pr > |t|	Alpha	Lower	Upper	Mean
Fourweek	2006	3.3524	0.3845	31	8.72	<0.0001	0.05	2.5682	4.1366	0.9662
Oneweek	2005	-0.6346	0.1115	31	-5.69	<0.0001	0.05	-0.8620	-0.4071	0.3465
Oneweek	2006	3.8232	0.5054	31	7.56	<0.0001	0.05	2.7924	4.8540	0.9786

treat*year Least Squares Means

treat	year	Standard Error Mean	Lower Mean	Upper Mean
Fourweek	2006	0.01256	0.9288	0.9843
Oneweek	2005	0.02526	0.2969	0.3996
Oneweek	2006	0.01058	0.9423	0.9923

Differences of treat*year Least Squares Means

Standard
treat year _treat _year Estimate Error DF t Value Pr > |t| Alpha

Treat	Year	_treat	_year	Estimate	Standard Error	DF	t-value	Pr > |t|	Alpha
Complete	2005	Complete	2006	-3.3926	0.4032	31	-8.41	<0.0001	0.05
Complete	2005	Control	2005	3.9432	0.3739	31	10.55	<0.0001	0.05
Complete	2005	Control	2006	3.5819	0.3556	31	10.07	<0.0001	0.05
Complete	2005	Fourweek	2005	0.8282	0.1637	31	5.06	<0.0001	0.05
Complete	2005	Fourweek	2006	-3.6736	0.4012	31	-9.16	<0.0001	0.05
Complete	2005	Oneweek	2005	0.3133	0.1597	31	1.96	0.0588	0.05
Complete	2005	Oneweek	2006	-4.1444	0.5182	31	-8.00	<0.0001	0.05
Complete	2006	Control	2005	7.3358	0.5256	31	13.96	<0.0001	0.05

Differences of treat*year Least Squares Means

Treat	Year	_treat	_year	Lower	Upper
Complete	2005	Complete	2006	-4.2149	-2.5703
Complete	2005	Control	2005	3.1806	4.7059
Complete	2005	Control	2006	2.8567	4.3071
Complete	2005	Fourweek	2005	0.4944	1.1620
Complete	2005	Fourweek	2006	-4.4918	-2.8554
Complete	2005	Oneweek	2005	-0.01240	0.6391
Complete	2005	Oneweek	2006	-5.2013	-3.0875
Complete	2006	Control	2005	6.2639	8.4077

Effect of different management techniques on kudzu crown survival across 2 years
The GLIMMIX Procedure
Differences of treat*year Least Squares Means

Treat	Year	_treat	_year	Estimate	Standard Error	DF	t-Value	Pr > |t|	Alpha
Complete	2006	Control	2006	6.9745	0.5127	31	13.60	<0.0001	0.05
Complete	2006	Fourweek	2005	4.2208	0.4040	31	10.45	<0.0001	0.05
Complete	2006	Fourweek	2006	-0.2810	0.5453	31	-0.52	0.6099	0.05
Complete	2006	Oneweek	2005	3.7059	0.4024	31	9.21	<0.0001	0.05
Complete	2006	Oneweek	2006	-0.7518	0.6364	31	-1.18	0.2464	0.05
Control	2005	Control	2006	-0.3613	0.4900	31	-0.74	0.4664	0.05
Control	2005	Fourweek	2005	-3.1151	0.3748	31	-8.31	<0.0001	0.05
Control	2005	Fourweek	2006	-7.6168	0.5240	31	-14.53	<0.0001	0.05
Control	2005	Oneweek	2005	-3.6299	0.3731	31	-9.73	<0.0001	0.05
Control	2005	Oneweek	2006	-8.0876	0.6182	31	-13.08	<0.0001	0.05
Control	2006	Fourweek	2005	-2.7537	0.3565	31	-7.72	<0.0001	0.05
Control	2006	Fourweek	2006	-7.2555	0.5111	31	-14.20	<0.0001	0.05
Control	2006	Oneweek	2005	-3.2685	0.3547	31	-9.22	<0.0001	0.05
Control	2006	Oneweek	2006	-7.7263	0.6073	31	-12.72	<0.0001	0.05
Fourweek	2005	Fourweek	2006	-4.5018	0.4020	31	-11.20	<0.0001	0.05
Fourweek	2005	Oneweek	2005	-0.5148	0.1617	31	-3.18	0.0033	0.05
Fourweek	2005	Oneweek	2006	-4.9726	0.5188	31	-9.58	<0.0001	0.05
Fourweek	2006	Oneweek	2005	3.9870	0.4004	31	9.96	<0.0001	0.05
Fourweek	2006	Oneweek	2006	-0.4708	0.6351	31	-0.74	0.4641	0.05
Oneweek	2005	Oneweek	2006	-4.4577	0.5176	31	-8.61	<0.0001	0.05

Differences of treat*year Least Squares Means

Treat	Year	_treat	_year	Lower	Upper
Complete	2006	Control	2006	5.9289	8.0201
Complete	2006	Fourweek	2005	3.3968	5.0447
Complete	2006	Fourweek	2006	-1.3932	0.8311
Complete	2006	Oneweek	2005	2.8852	4.5266
Complete	2006	Oneweek	2006	-2.0497	0.5460
Control	2005	Control	2006	-1.3607	0.6380
Control	2005	Fourweek	2005	-3.8795	-2.3506
Control	2005	Fourweek	2006	-8.6856	-6.5481
Control	2005	Oneweek	2005	-4.3908	-2.8690
Control	2005	Oneweek	2006	-9.3485	-6.8267
Control	2006	Fourweek	2005	-3.4807	-2.0267
Control	2006	Fourweek	2006	-8.2979	-6.2131
Control	2006	Oneweek	2005	-3.9919	-2.5452
Control	2006	Oneweek	2006	-8.9649	-6.4877
Fourweek	2005	Fourweek	2006	-5.3216	-3.6820
Fourweek	2005	Oneweek	2005	-0.8447	-0.1850
Fourweek	2005	Oneweek	2006	-6.0307	-3.9144
Fourweek	2006	Oneweek	2005	3.1704	4.8035
Fourweek	2006	Oneweek	2006	-1.7660	0.8245

```
        Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure


Differences of treat*year Least Squares Means

                  treat     year    _treat      _year     Lower      Upper

             Oneweek     2005   Oneweek    2006    -5.5134    -3.4021


Least Squares Means Estimates

                                  Standard
  Effect       Label    Estimate     Error  DF   t Value   Pr > |t|   Alpha     Lower     Upper

  treat   com vs con      5.46    0.317    31    17.21    <0.0001    0.05    4.8118    6.1059

Least Squares Means Estimates

                                          Standard
                                            Error      Lower       Upper
           Effect     Label        Mean      Mean       Mean        Mean

           treat   com vs con      0.996     0.00134      0.9919      0.9978


Least Squares Means Estimates

                                     Standard
 Effect        Label        Estimate     Error      DF  t Value  Pr > |t|   Alpha     Lower     Upper

 treat   com vs four    0.274          0.285     31     0.96    0.3440    0.05   -0.3070    0.8541



Least Squares Means Estimates

                                                Standard
                                                  Error      Lower       Upper
            Effect        Label         Mean      Mean       Mean        Mean

            treat      com vs four    0.568        0.0698      0.4238      0.7014
```

Least Squares Means Estimates

```
                                 Standard
  Effect    Label      Estimate    Error    DF  t Value  Pr > |t|  Alpha    Lower    Upper

  treat   com vs one    -0.219      0.328    31   -0.67   0.5089   0.05  -0.8883   0.4498
```

Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

Least Squares Means Estimates

```
                                Standard
                                  Error     Lower     Upper
Effect    Label           Mean     Mean      Mean      Mean

treat    com vs one      0.445     0.081    0.2915    0.6106
```

Least Squares Means Estimates

```
                                Standard
Effect      Label      Estimate   Error    DF  t Value    Pr > |t|  Alpha    Lower     Upper
treat   con vs four    -5.19       0.317    31  -16.36    <0.0001    0.05  -5.8316   -4.5390
```

Least Squares Means Estimates

```
                                              Standard
                                                Error      Lower       Upper
          Effect     Label          Mean         Mean       Mean        Mean

           treat   con vs four    0.00557     0.00175    0.002925    0.01057
```

Least Squares Means Estimates

```
                               Standard
Effect     Label      Estimate   Error    DF  t Value    Pr > |t|  Alpha    Lower     Upper

treat   con vs one     -5.68      0.356    31  -15.93    <0.0001    0.05  -6.4049   -4.9513
```

Least Squares Means Estimates

```
                                           Standard
                                             Error     Lower      Upper
         Effect     Label           Mean      Mean      Mean       Mean
```

```
          treat   con vs one       0.00341     0.00121    0.001651    0.007025
Least Squares Means Estimates

                                     Standard
Effect      Label        Estimate     Error    DF  t Value  Pr > |t|   Alpha     Lower     Upper

treat   four vs one        -0.493     0.328     31    -1.50   0.1427    0.05   -1.1611    0.1755
```

Effect of different management techniques on kudzu crown survival across 2 years

The GLIMMIX Procedure

```
Least Squares Means Estimates

                                       Standard
                                        Error     Lower     Upper
          Effect     Label       Mean    Mean      Mean      Mean

           treat   four vs one   0.379   0.0771    0.2385    0.5438
```

Appendix E.

SAS PROC GLIMMIX procedure output.

Treatment	Year	Estimate	Error	DF	t value	Lower SE	Upper SE
Complete	2005	-0.3212	0.1143	31	-2.81	0.0555	0.0576
Complete	2006	3.0714	0.3866	31	7.94	0.0483	0.0237
Control	2005	-4.2644	0.356	31	-11.98	0.007104	0.01438
Control	2006	-3.9031	0.3367	31	-11.59	0.00973	0.01877
Fourweek	2005	-1.1494	0.1171	31	-9.81	0.0409	0.0463
Fourweek	2006	3.3524	0.3845	31	8.72	0.0374	0.0181
Oneweek	2005	-0.6346	0.1115	31	-5.69	0.0496	0.0531
Oneweek	2006	3.8232	0.5054	31	7.56	0.0363	0.0137

Treatment	Year	Prob	Alpha	Lower	Upper
Complete	2005	0.0085	0.05	-0.5544	-0.08804
Complete	2006	<0.0001	0.05	2.2828	3.8599
Control	2005	<0.0001	0.05	-4.9906	-3.5383
Control	2006	<0.0001	0.05	-4.5898	-3.2164
Fourweek	2005	<0.0001	0.05	-1.3883	-0.9105
Fourweek	2006	<0.0001	0.05	2.5682	4.1366
Oneweek	2005	<0.0001	0.05	-0.862	-0.4071
Oneweek	2006	<0.0001	0.05	2.7924	4.854

Treatment	Year	Mean	Std Error Mean	Lower Mean	Upper Mean
Complete	2005	0.4204	0.02786	0.3649	0.478
Complete	2006	0.9557	0.01637	0.9074	0.9794
Control	2005	0.01386	0.004868	0.006756	0.02824
Control	2006	0.01978	0.006528	0.01005	0.03855
Fourweek	2005	0.2406	0.0214	0.1997	0.2869
Fourweek	2006	0.9662	0.01256	0.9288	0.9843
Oneweek	2005	0.3465	0.02526	0.2969	0.3996
Oneweek	2006	0.9786	0.01058	0.9423	0.9923

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