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Biomass, Leaf Area, and Resource Availability of Kudzu Dominated Plant Communities Following Herbicide Treatments and Induced Competition from High Density Loblolly Pine Stands
(Under the direction of TIMOTHY B. HARRINGTON)

Kudzu (*Pueraria lobata* (Willd.) Ohwi) is an exotic vine that threatens forest vegetation of the Southeast. This study evaluated the combined effects of herbicide treatments and induced competition for controlling kudzu.

Five herbicides (clopyralid, metsulfuron, picloram, tebuthiuron, and triclopyr) were applied as broadcast treatments to individual plots in July 1997, followed by a December 1997 burn. Spot treatments were applied to re-sprouts in June 1998 and 1999. High-density loblolly pine stands of 100 seedlings each were planted at three densities (0, 1, and 4 seedlings m⁻²). Plots were measured for cover, biomass, leaf area, soil water content, PAR, and pine performance for two to three years.

Herbicide treatments resulted in the development of four distinct communities. The untreated check remained a kudzu-dominated community while herbaceous-dominated communities resulted from metsulfuron, picloram, and triclopyr. Blackberry dominated the clopyralid treatment while a relative absence of all vegetation developed in the tebuthiuron treatment.

INDEX WORDS: *Pueraria lobata*, *Pinus taeda*, vines, competition, exotic species, photosynthetically active radiation, soil water content

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CHAPTER 1

LITERATURE REVIEW

HISTORY

Although kudzu was introduced to the United States in 1876 at the Centennial Exposition, it did not become a problem until the middle part of the 20th century. Initially it was used as a home ornamental, later a livestock forage, and finally an erosion deterrent (Sturkie and Grimes 1939, O'Brien and Skelton 1946, McKee and Stephens 1943). During the Depression, the Soil Conservation Service raised 86 million seedlings for cooperating landowners to plant on depleted farmland for \$8.00 an acre (Shurtleff and Aoyagi 1977, Hoots 1996). Before 1950, three million acres of kudzu were planted, including abandoned cropland, roadsides, and other eroding areas in the South (Hoots 1996). The large number of kudzu seedlings successfully helped fight erosion on the degraded landscape of the South.

But as the United States began to regain its economic balance in mid-20th century, the vine became a problem. The warm, wet climate of the southeastern United States was ideal for kudzu and not greatly dissimilar from native Asia where it is not a pest problem (Tsugawa et al. 1985, Tsugawa 1986, Tsugawa et al. 1993b, Teramura et al. 1991).

Longer growing seasons with periodic droughts accentuated the competitiveness of the vine. Invasion problems were exacerbated by the distribution of planting. Kudzu was originally planted at high densities to ensure success, but the resulting abundance improved the opportunity for kudzu invasion of adjacent sites.

Kudzu was considered to be delicate as a seedling and too fragile to survive. Some inferior strains may have died, but the strongest strains remained. In the 1950's, Watkinsville, GA had the distinction of being the source area of Kudzu 23, an extraordinarily drought resistant strain having nearly round, fine-textured leaflets (Tsugawa 1986).

By the 1950's, the "Miracle Vine" that was proclaimed to have saved the South (Hoots 1996) seemed unstoppable. It was established on roadsides and from these corridors it invaded adjacent private lands. Where it was planted on private land, kudzu could escape to adjoining properties. It was possible to overgraze kudzu, but where it escaped from the reach of grazing animals it flourished.

The disastrous results of kudzu infestation are often used as a case against introduction of exotic species. With few natural enemies and many environmental advantages, the distribution of kudzu has become extensive. Kudzu did not evolve in the plant communities of North America, so the evolutionary system of checks and balances are not present to restrict its abundance sufficiently to allow other native plants to survive (Tennessee Exotic Plant Pest Council 1997).

MORPHOLOGICAL AND REPRODUCTIVE CHARACTERISTICS

Kudzu is a partially woody, nitrogen-fixing, perennial vine in the family Leguminosae. Its genus, *Pueraria*, contains 10 species (Tsugawa 1986). *Pueraria lobata* (Willd.) Ohwi is the species that was introduced to the United States. Until 1947 it was also known as *P. thunbergiana* (Siebold & Zucc) Benth (Edwards 1982) and *P. hirsuta* Matsum (Tsugawa 1986). *P. lobata* is native to Asia, including China, India, Japan, and Taiwan. It was introduced to the United States and has become naturalized as far west as east Texas to central Oklahoma and as far north as Pennsylvania, Illinois, and Connecticut. The largest concentration of kudzu is in the Southeast, which was the area of greatest introduction. States with the greatest area of kudzu include Mississippi, Alabama, and Georgia (Radford et al. 1968).

Kudzu is deciduous. Leaves are delicate and pubescent and have a compound trifoliate formation with a thick petiole. Wechsler (1977) reported leaf area index (leaf area per unit of ground area) values as high as $7 \text{ m}^2 \text{ cm}^{-2}$, indicating a dense foliar canopy.

Kudzu can have both crawling and climbing growth habits depending on its environment. It climbs vertical structures by twining (Carter and Teramura 1988). Of the four vine types Darwin (1905) classified, twining vines were considered less advanced. These vines must wrap entirely around the object it is ascending. When climbing,

the length of stem produced is one and a half to two times more than the actual height attained.

Stems are strong and are used for baskets (Shurtleff and Aoyagi 1977, Hoots 1996). Kudzu has been reported to elongate between 19 to 33 cm in 24 hours and up to 2.5 cm at night (Wechsler 1977, Shurtleff and Aoyagi 1977). As a semi-woody perennial, some stems die back to a root crown after a frost. However, some vines thicken and over-winter to preserve the previous year's position (Tsugawa et al. 1993b). Most kudzu that occupies forest edge sites exhibits this growth form with vines having diameters exceeding 2 cm. In this way, kudzu conserves growth energy and can continue to produce leaves the next season in a high light environment. Thickening of some vines is characteristic of the species and occurs in Japan as well (Tsugawa 1986). These vines may live for a yet undetermined amount of time (Everest et al 1991).

Extensive root systems, which are deep, and tuberous (Everest et al. 1991, Mooney and Gartner 1991, Sasek and Strain 1988), support the uncommonly large growth potential of these plants. They grow irregularly, often looping underground. The longest root excavated was 3.7 m in length with a weight of 181.4 kg (Tennessee Exotic Plant Pest Council 1997, Miller and Edwards 1983). Large roots can grow up to 17.8 cm in diameter and penetrate the soil to depths of 1 to 3 m through a hard pan (Wechsler 1977).

Kudzu has a grape scented, purple flower, commonly found on climbing vines. Tsugawa (1986) reports that Japanese kudzu has high seed production, and depending on the strain, has up to 29% higher seed viability than is typically observed in the United States. In the U. S., it produces seed in the late summer and fall but seeds are rarely viable (Shurtleff and Aoyagi 1977) and seedlings are generally too delicate to survive (Wechsler 1977). In most situations, kudzu propagates vegetatively. Where nodes of the plant contact the soil, roots form (Everest et al. 1991, Tennessee-Exotic Plant Pest Council 1997). If the new node is successful at generating supportive roots, a plantlet will develop. Mature stands are vigorous and in some cases support a plant every 0.33 to 0.66 m² (Everest et al. 1991). This allows over 10,000 plants per hectare (Tsugawa 1986).

Due to its reliance on vegetative propagation, kudzu infestations are generally localized. The spread of kudzu appears to depend on partial to full sun conditions. It does kill edge trees and slowly advances into forest but this movement is slow compared to the progression of infestation in open fields.

PHYSIOLOGICAL ECOLOGY

Kudzu research has generally been limited to laboratory conditions. Part of the difficulty in developing a kudzu control strategy is the lack of definitive ecological and physiological research. Kudzu seems

to follow general patterns characteristic of most vines. Background information on basic vine ecology can be found in Appendix A.

Energy Allocation and Reserves

The amount of energy that kudzu requires to climb by twining is great considering its stem length to height ratio (Carter and Teramura 1988). Because kudzu vines have little structural support to enable a vertical growth habit, the height ultimately attained will be considerably less than the amount of stem produced. To be able to compensate for this energy expenditure, kudzu follows a growth and carbon allocation pattern similar to that of other vines.

A cycle of energy allocation begins in the spring with stored carbohydrates in the roots used for stem elongation to claim a superior position in the upper canopy of a plant community (Teramura et al. 1991). At this early stage, photosynthate allocation would be limited because little photosynthesis is occurring. Kudzu has large tuberous roots, which may represent substantial storage of starches and sugars (Mooney and Gardner 1991, Carter and Teramura 1988, Carter et al. 1989). If the area is populated with deciduous plants, kudzu takes advantage of their vertical structure before they leaf out. At this time, light is abundantly available.

Once a superior position in its environment is attained, the plant has a better ability to grow and produce more photosynthetic tissue

(Wilson 1988). Subsequent production of leaves increase total plant photosynthesis (Wechsler 1977). After the first few months of prolific stem and leaf production, allocation begins to shift from aboveground formation to allocation of resources to root reserves (Mooney and Gartner 1991, Teramura et al. 1991). Thus, reserves are replenished and extended, ensuring the continuation of the cycle. These growth processes may allow kudzu to survive repeated pest control treatments (herbicide applications, defoliation, etc.) for many years.

Kudzu root reserves are not infallible. It is presumed that too much reserve lost through control treatments results in dormancy (Everest et al. 1991, Miller 1996, 1997). However, dormancy in kudzu can only last as long as maintenance respiration allows. Below-ground respiration costs can be substantial (Teramura et al. 1991). Nitrogen fixation is an intensive energy consuming process. This may be another non-growth expenditure of root reserves (Wechsler 1977, Lynd and Ansman 1990).

Mooney and Gartner (1991) propose that even though costs are high to maintain this type of root system, these reserves represent insurance against disaster. They state that it is possible that storage is so immense that the plant may not be able to use all of the reserves in one season due to environmental limitations of water, nutrients, and light.

Lack of mechanical structure aboveground may have a parallel to the below-ground characteristics of kudzu. Large diameter, structural roots are not needed. This could result in the development of more efficient absorption structures for water and nutrients (Putz 1991).

Growth Habit

Tsugawa et al. (1992a) studied growth characteristics of climbing and crawling kudzu growth habits. Foliage dry weight was the same in both types of plants as was leaf area production; only location of this tissue differed. Climbing kudzu concentrated energy efforts almost entirely on the main stem while crawling kudzu allocated more energy to primary and secondary branching. Climbing kudzu allocated more leaf area higher on the main stem, whereas crawling kudzu distributed the leaf area throughout the stem. Root weights and total plant mass were higher in climbing kudzu plants.

Kudzu climbs to compete successfully for light. From a carbon allocation perspective, climbing is costly to carbohydrate reserves but crawling does not ensure full access to light. The rapid growth rate of kudzu allows it to quickly colonize an area. In almost all cases, this colonization leads to dominance over most low ground-covering plant communities. Mats of pure kudzu can cover a field with more than a meter in height of kudzu foliage. Intraspecific competition in this monospecific community is more intense than the interspecific

competition in the environment of kudzu climbing at forest edge (Tsugawa et al. 1993a, 1993b). When climbing kudzu competes with edge trees for light resources, it may be competing for resources at differing proportions in differing locations of the environment. The advantage partially lies in opportunity. Edge kudzu does reach the upper-canopy and does have superior light advantage over kudzu growing in monospecific stands. Kudzu, like other vines, concentrates its carbon allocation to leaves to take advantage of its superior position in a forest canopy (Castellanos 1991). More reserves may be gained, used, and stored. This makes climbing kudzu more difficult to kill. Additional effort and higher herbicide rates are generally recommended for climbing kudzu (Everest et al. 1991).

Shade Tolerance and Photosynthesis

Kudzu characteristics (rapid growth, shade intolerance, N-fixing capabilities, and high productivity) indicate that it is an early to mid-successional species (Hegarty and Caballe 1991). Optimum habitats are forest edge and disturbed areas (Miller 1982, 1996, McIntyre and Lavoirel 1994, Tennessee Exotic Plant Pest Council 1997). It is not adapted to grow in shaded forest understories. Unlike Japanese honeysuckle, which reaches an optimum photosynthesis level at low light, kudzu requires a high light environment. Carter and Teramura (1988) and Carter et al. (1989) found that, to achieve 90% of the maximum rate of

photosynthesis, kudzu required a photosynthetic photon flux density (PPFD) of $860 \mu\text{mol m}^{-2} \text{s}^{-1}$. The same collection of studies showed that the water use efficiency of kudzu was low at low light intensities but increased rapidly as light conditions improved.

Research by Tsugawa et al. (1985) found that emergence and axillary shoot growth are inhibited by shade. Root weights were significantly lower and diameters half the values in 83% shade than those in 0% shade. Another study by Tsugawa et al. (1992b) alludes to an associated large shrub, *Pleioblastus chino* var. *virides*, which inhibited kudzu growth in the field partially by light competition.

In contrast with these results, one study concluded that kudzu was the most shade tolerant of all plants tested (Fujita et al. 1993). However, the plants tested were tropical pasture legumes. Of the handful of studies on kudzu shade tolerance, most involve comparisons with temperate plants. By these comparisons, kudzu is confirmed as the least shade tolerant.

Although, individual leaf photosynthesis of kudzu (max CO_2 flux density $7.2 \mu\text{mol m}^{-2} \text{s}^{-1}$) is not higher than many native early succession species (Carter and Teramura 1988, Wechsler 1977), kudzu has many growth and physiological advantages that allow for greater whole plant photosynthesis.

Wechsler (1977) found that kudzu has maximum photosynthetic rates at higher temperatures than many plants ($18\text{-}30^\circ \text{C}$). In summer,

photosynthesis was inhibited only at temperatures between 30 to 33° C, which although higher than ragweed (20° C), is of limited advantage in the South where these temperatures are often exceeded. However, he noted that the position of kudzu leaves change during the course of the day. During times of higher temperatures, trifoliolate kudzu leaflets bend at the petiole to decrease the angle of direct sunlight. This lowers leaf temperature that would otherwise exceed air temperature due to radiation. Keeping leaves cooler avoids photo-inhibition and allows photosynthesis to continue at nearly optimum rates in less than desirable conditions (Castellanos 1991). Therefore, with these adjustments, high temperatures and intense solar radiation do not restrict productivity and subsequent colonization of new sites by kudzu.

Wechsler (1977) speculated that the extensive rooting depth of kudzu allowed it to avoid drought stress, and thus maintain higher photosynthesis than surrounding plants. Midday xylem pressure potentials of kudzu changed little over the course of the day under drought conditions at -1 to -2 bars. It is possible that kudzu avoids xylem tensions and maintains high rates of productivity by using the high water capacitance of the tuberous root system (Teramura et al. 1991).

Total canopy photosynthesis benefits from these adaptations, since much of the canopy is at or near its productive potential. In addition, a kudzu canopy is comprised of a higher ratio of leaves to stem than most

plants. This collection-support ratio is another advantage that allows higher total plant photosynthesis (Wechsler 1977). Increased productivity increases leaf area production, which leads to a compounding increase in plant weight accumulation (Sasek and Strain 1989).

CONTROL METHODS

As kudzu has occupied and excluded large areas of native vegetation, control measures have been initiated to check its spread. These control measures include grazing, mowing, burning, and herbicides.

Grazing is an effective method that was first suggested when kudzu was used as livestock fodder (O'Brien and Skelton 1946). Farmers found that young kudzu was easily overgrazed and that to keep kudzu productive in the pastures it was necessary to rotate pastures, allowing the plants to recover. Recently, it has been found that kudzu infestations younger than 25 years can be controlled by repeated grazing. However, all kudzu must be accessible. Fencing must incorporate all crowns of the kudzu infestation (Everest et al. 1991). Drawbacks to this type of control include accessibility to water and the expense of proper containment for the animals. However, this approach has been applied successfully with goats (Minor 1998).

An advantage to this type of control is the constant pressure of animal herbivory on the infestation. The rapid growth rate of kudzu allows it to move to better conditions and its reserves permit it to wait out conditions beyond its capacity to move. The constant pressure of removing aboveground vegetation draws reserves from the roots. It consistently loses this energy which is being expended on vegetation that should be photosynthesizing but that is steadily consumed.

Another control measure frequently used is mowing. Mowing equipment is usually readily available, although at times expensive. To keep continual pressure on the infestation, the stand must be mowed at least every two weeks. A problem with mowing is gaining entry to all areas of the kudzu infestation. Kudzu crowns can be examined in the winter to estimate the extent of the infestation to target control areas (Everest et al. 1991). If crowns are located beyond safe areas to mow, another control method must be employed.

Bio-control methods use a living parasite to control an infestation. Recently, bacteria, fungus, and insects have been used (Ross and Lembi 1999). Bio-control of kudzu with insects is currently being researched at NCSU (Orr, unpublished).

Herbicides have been shown to be the most operable control method; however, accomplishing total control may require repeated treatments for 3 to 10 years for young stands and 7-10 years for mature. It is recommended that re-treatments should use half of the original

herbicide rate that was applied in the first treatment. All kudzu crowns must be treated successfully or the spread of persisting plants will re-infest the site (Everest et al 1991, Miller 1982, 1996).

A number of herbicides are labeled for kudzu control. Choosing a chemical depends on the specific situation and environmental factors of the infestation. These include, but are not limited to, location, soil type, proximity of desirable plants, and vigor of kudzu plants.

Clopyralid (Transline®), metsulfuron (Escort®), picloram (Tordon® 101-M), tebuthiuron (Spike® 20P), and triclopyr (Garlon® 4) are the herbicides that were tested in this study. Mechanisms of action and other details of these herbicides are included in Appendix B.

Clopyralid received a forestry use registration from the Environmental Protection Agency in 1998. In 1986, Michael tested it in a forestry capacity and found that clopyralid provided a reasonable degree of kudzu control and was tolerated by pines. Clopyralid performed best on clay loam sites over clayey sites. Williamson (1990) recommended clopyralid for kudzu control but noted that it targeted legumes and had a narrow control spectrum. It has the potential to keep a desirable vegetation community intact but if a higher degree of control is needed, another herbicide should be used.

Edwards and Gonzales (1986) evaluated three herbicides, metsulfuron, hexazinone, and sulfometuron, for kudzu control and

simultaneous regeneration of pine. Metsulfuron was the most effective of the treatments tested.

Picloram is a restricted use pesticide (RUP) and may not be used in sandy, well-drained soils without a special research permit. It easily moves in the soil profile and may contaminate ground and surface water (Michael et al. 1989). However, it is highly effective and has been recommended since the early 1970's (Miller 1994). Miller has studied kudzu eradication with picloram extensively and found it to be consistently the most effective herbicide (1982, 1985, 1986, 1988, and 1994). Because it is costlier, Miller (1996) recommends metsulfuron in kudzu infestations less than ten years old only if it is not possible to use picloram.

Tebuthiuron is another herbicide with potential for kudzu control but it does not have a forestry use registration. It has high persistence in the soil and will kill annual and perennial plants up to 15 months after treatment (DowAgrosciences 1998b). Miller (1996, 1998) indicated that tebuthiuron is the most promising single application treatment if there are no desirable trees or other vegetation present in the surrounding area. Like picloram, tebuthiuron moves easily in the soil and can be a danger to ground water. It must be used with caution.

Michael (1982) found that triclopyr controls kudzu but at rates that would also kill pines. Miller (1996) recommends triclopyr as he did metsulfuron only when picloram cannot be used. He does note that

under older pine (dbh >14 cm), triclopyr may be used as a spot treatment to retreat kudzu sprouts.

Subject to the varying conditions of infestations, kudzu can be controlled with the various methods available. All kudzu infestations should be evaluated for their individual characteristics before treatment. No single method has produced 100% efficacy. Age, vigor, and the previous land-use and disturbance history of the area are factors that should always be considered for all pest management situations (Ross and Lembi 1999) but are doubly important with kudzu control. If the stand is an original area of the early planting, vigor and root reserves may affect the duration of treatment needed, prolonging it for many years.

All control programs for kudzu must consider a landscape scale. Infestations range over broad areas. All landowners in the area must participate to completely control the kudzu infestation. Size of the infestation, proximity to desirable vegetation, accessibility, future plans for the area, and landowner participation are important to consider before a control regime is begun (Everest et al. 1991).

No method has consistently and entirely controlled kudzu. Because of the variety of conditions in which kudzu flourishes and its vigorous growth characteristics as an exotic weed, there may never be a single method of control to eradicate kudzu and allow the residual community to survive. As more information is collected about the

physiology of the plant and applied to designing control measures, better consistency of control is likely to result.

INTEGRATED PEST MANAGEMENT (IPM) RESEARCH

A combination of control methods may yield quicker, less expensive, and more efficient results by keeping constant pressure on an infestation. Insecticide development mandated the first concepts of integrating control mechanisms to reduce environmental exposure. A target species' ecology and biology can be used to identify weaknesses in its lifestyle (Ross and Lembi 1999). An example is using a control method not related to herbicides, like induced competition, to further control the target plant when herbicide effects have lessened. This is likely to add another element of control.

This research will use IPM strategies. A combination of treatments including herbicides and induced competition from loblolly pines will be used to control kudzu infestations.

CHAPTER 2

BIOMASS, LEAF AREA, AND RESOURCE AVAILABILITY OF KUDZU DOMINATED PLANT COMMUNITIES FOLLOWING HERBICIDE TREATMENTS AND INDUCED COMPETITION FROM HIGH DENSITY LOBLOLLY PINE STANDS

ABSTRACT

Kudzu (*Pueraria lobata* (Willd.) Ohwi) is an exotic vine that threatens natural forest vegetation of the Southeast. It invades forest edge and has the potential to overtake sites prepared for planting. The objectives of this study are to test five herbicides for their efficacy in controlling kudzu, monitor the recovering community, and test the feasibility of combining herbicides and induced competition to control kudzu.

At the Savannah River Site, a National Environmental Research Park, near Aiken, SC, four kudzu-dominated sites were selected for study. Six herbicide treatment plots (five herbicides and an untreated check) were established. Manufacturer recommended rates for the individual herbicide applications were applied in July 1997. Each block was burned in December 1997 in preparation for loblolly pine planting (*Pinus taeda* L.). High-density pine stands of 100 seedlings each were

planted at 0, 1 and, 4 pines per m² in January 1998. The herbicide treatment plots were spot treated for kudzu in June 1998 and 1999.

Percent cover by species, kudzu biomass, and kudzu growth analysis variables (leaf area index [LAI], specific leaf area [SLA], and leaf weight ratio) were taken before herbicide treatment. Six weeks after treatment, in June 1998, and in August 1998 and 1999, percent cover by species was recorded again. Biomass of kudzu, blackberry, herbs, and pine and other growth analysis measures were sampled in August 1998 and 1999. Regression equations were developed for predicting biomass and leaf area index from cover. Percentage of maximum photosynthetically active radiation (PAR) at the soil surface was measured in August 1998 and 1999, and percentage soil water content was measured monthly from April to October in 1998 and 1999. Pine height and ground line diameters were measured at planting and in January 1999.

Four distinct plant communities resulted from the main treatments. The untreated check continued to be kudzu-dominated despite a large flush of herbaceous cover in 1998 (187 g m⁻²), which subsided in 1999 (44 g m⁻²) as kudzu regained dominance. The untreated check had the lowest PAR reaching the soil surface and had the second lowest pine survival rate (42%). Blackberry dominated the clopyralid treatment due to the herbicide's selection for kudzu and herbaceous vegetation. Metsulfuron, picloram, and triclopyr each

resulted in herbaceous-dominated communities as the herbicides effectively controlled kudzu and blackberry. The tebuthiuron treatment was persistent enough to keep biomass of all vegetation at low levels, including the planted pines (21% survival). In this treatment, kudzu biomass declined significantly but at slower rates than in the other herbicide treatments. PAR and soil water content in the tebuthiuron treatment exceeded those of the other treatments.

Growth analysis measurements indicated that the stands were as vigorous as kudzu growing in native plant communities of Asia. Over the course of this study, kudzu leaf area decreased due to effects of fire but 1999 recovery was indicated by an average LAI value of $3 \text{ m}^2 \text{ m}^{-2}$ and SLA of $275 \text{ cm}^2 \text{ g}^{-1}$.

In the herbicide treated plots, kudzu abundance did not differ significantly among pine densities most likely because the herbicide treatments had reduced kudzu cover to 1% or less. However, there were microclimate differences. Percent PAR reaching soil surface declined with increasing pine density.

All herbicides in this study reduced kudzu to levels approaching eradication; however, no method was completely successful.

INTRODUCTION

Kudzu (*Pueraria lobata* (Willd.) Ohwi) has become a serious problem in the South as well as other parts of the United States. First

introduced as a home ornamental and livestock forage, kudzu is best known for its rapid growth and anti-erosion properties (Edwards 1982, Shurtleff and Aoyagi 1977). Widespread planting in the 1930's and 1940's has resulted in extended infestations on both private and public lands (Everest et al. 1991, Hoots 1996).

There are many broad concerns relevant to kudzu as a plant pest species. Forestry problems include invasion of site prepared areas, killing edge trees, and increasing fire risk during the winter (Putz 1991).

Kudzu is an early to mid-successional species as determined by its rapid growth rate, dispersal, and shade intolerance (Wechsler 1977, Miller 1985 and 1997, Tennessee Exotic Plant Pest Council 1997). Fujita et al. (1993), Tsugawa et al. (1992a), Carter and Teramura (1988), and Carter et al (1989) studied the shade sensitivity of kudzu and found the plant to be moderately intolerant. Results suggested that in addition to having lower stem and root weights, axillary branch development was inhibited in shaded plants. Carter and Teramura (1988) found that at low light levels typical of Maryland hardwood forests, most kudzu plants did not survive. To reach 90% of maximum photosynthesis kudzu plants required $860 \mu\text{mol m}^{-2} \text{s}^{-1}$ of photosynthetic photo flux density, a value that was seldom reached under such conditions.

Kudzu eradication has been attempted on a large scale since the 1950's (Shurtleff and Aoyagi 1977, Everest et al. 1991, Hoots 1996). Of the control methods used, herbicides seem to be the most successful

(Tennessee Exotic Plant Pest Council 1997, Miller 1996). Grazing is effective on stands less than 25 years old, however, problems of fresh water and containment of livestock limit widescale use of this method. Mechanical methods, such as mowing, have demonstrated some success but also have limiting conditions. In both of these methods, frequent defoliation depletes the root reserves that support rapid growth rates of kudzu. These root reserves are thought to be substantial and may be the source of energy that enables kudzu to recover vigorously from treatment (Mooney and Gartner 1991, Teramura et al. 1991).

Herbicides are quick and effective but, in most cases, lack constant control pressure on the stand. Translocated herbicides get distributed throughout the plant, including the root in some cases, and may stimulate a state of dormancy for an entire season. Early June is believed to be the ideal timing for herbicide treatments because during this period kudzu is in the transition between drawing from root reserves and allocating production for growth (Teramura et al. 1991, Mooney and Gartner 1991). Herbicides will stop the photosynthetic processes by killing the leaves. However, unless the herbicide is translocated to the roots and is specifically formulated for perennial species, only one season of growth will be affected.

Another positive aspect of herbicide control is selectivity. For example, clopyralid is a highly selective herbicide that targets legumes (Williamson 1990). However, tebuthiuron is a non-selective herbicide

which will damage or kill any vegetation it contacts (DowAgrosciences 1998b). Picloram and triclopyr will kill young pines but clopyralid and metsulfuron will not (DowAgrosciences 1998a, 1998c, 1998d, E. I. du Pont de Nemours and Company 1998).

To assist in extending control pressure on infestations, plant pest management methods can be combined to improve efficacy and efficiency, possibly at lower costs (Tennessee Exotic Plant Pest Council 1997, Ross and Lembi 1999, Ware 1994). Integrated pest management (IPM) uses the physiology and ecology of a pest to identify and exploit weaknesses in its life cycle. Therefore, along with chemical control, a biological or mechanical control method can be added.

Attempting kudzu control while establishing pine stands has been studied previously but the objective was not to use induced competition of pine as additional treatment. One example, Michael (1986), reports that simultaneous control of kudzu and regeneration of pine with clopyralid or imazapyr is possible on clay loam sites but more difficult on clay sites. Imazapyr may persist in clay longer causing pines to grow slower. Pines must be healthy and uninhibited in growth to eventually out distance recovering kudzu. Another study, Edwards and Gonzales (1986), used several rates of metsulfuron and found it to be more effective than hexazinone or sulfometuron in deterring kudzu while fostering establishment of pine seedlings. Both studies reported only a single season of growth.

The objectives of this study were to test five herbicides for efficacy of kudzu control for three years. The herbicides selected for this study have diverse chemical characteristics that influence their selectivity. This may affect the recovering community, which was also monitored. The final objective of this study was to determine if combining herbicide treatments with induced competition from high density pine plantings would augment control of kudzu over that from a single method of control.

METHODS AND MATERIALS

Study Area

Four study sites (Burma, Cloverleaf, Home, and Reactor) were located at the Savannah River Site, a National Environmental Research Park, near Aiken, SC. Each site had relatively uniform coverage of kudzu and was 0.4 to 0.8 ha in area. Historical information suggests that each of the study sites was formerly in agriculture prior to 1950. Soil series on the study sites were typical of Upper Coastal Plain soils, including Troup (Cloverleaf site); Alley, Dothan, and Varina (Home site); Fuquay (Burma site); and an Udorthent fill soil (Reactor site). See Appendix C for soil characteristics.

Treatments and Experimental Design

Each site was divided into six plots of equal area and one main plot treatment was randomly assigned to each:

1. untreated check
2. clopyralid (Transline ®): 0.22 kg a. i. ha⁻¹
3. triclopyr (Garlon ® 4): 2.13 kg a. i. ha⁻¹
4. metsulfuron (Escort ®): 0.17 l a. i. ha⁻¹
5. picloram + 2,4-D (Tordon ® 101-M): 0.34 kg picloram a. i. ha⁻¹
0.67 kg of 2,4-D a. i. ha⁻¹
6. tebuthiuron (Spike ® 20P): 2.13 kg a. i. ha⁻¹

The initial herbicide treatments were applied in July 1997. Data collected in 1997 had a randomized complete block design.

In December 1997, each study site was broadcast burned in preparation for planting of pine seedlings. Genetically improved loblolly pine seedlings (1+0) were hand planted with dibbles in January 1998 at three densities within each main plot: 0, 1, or 4 seedlings m⁻². The purpose of the pine plantings was to induce variable levels of interspecific competition within each main plot to potentially exclude recovering kudzu. Pine seedlings were specifically selected to have groundline diameters of 5 mm or more. The loblolly pine stands were considered split plots. Each stand contained 100 seedlings each. The inner 36 seedlings per stand were designated for monitoring of survival and growth; the outer two rows were designated as buffers. Data

collected in 1998 and 1999 had a randomized complete block design with a factorial arrangement of split plots.

To further control the recovering kudzu, spot applications of the same herbicides were conducted in June 1998 and 1999. For these supplemental treatments, clopyralid was the only herbicide to be broadcast applied because of its pine tolerance and the high amount of kudzu recovery that had occurred in this treatment. The individual manufacturers recommended the specifications for each herbicide treatment.

Of these chemicals, tebuthiuron was the only granular herbicide, and therefore it was soil applied with a fertilizer spreader. All other herbicides were applied with backpack sprayers at a spray volume of 935 l ha⁻¹ with 0.25% surfactant to ensure full coverage of the kudzu canopy.

Between each herbicide treatment and along the perimeter of the main plots, a buffer strip was maintained to prevent invasion of kudzu from adjacent areas. The buffer strip was 1-m wide and was kept vegetation-free with monthly applications of paraquat (Gramoxone Extra®, 2.5 % solution in water plus 0.125 % non-ionic surfactant) during the growing season.

Vegetation Measurements

Cover--Measurements of percentage cover by species were estimated visually within each of three 1-m² quadrats per split plot (total of 9 for

each herbicide treatment per site). The measurements were taken in July 1997 (pretreatment), August 1997 (8 weeks after the first herbicide treatment), June 1998 (before the second herbicide application), August 1998 (8 weeks after the first spot herbicide application), and August 1999 (eight weeks after the second spot treatment). Four species groups were evaluated: kudzu, blackberry, herbs, and pines. An angular transformation ($\arcsin(\sqrt{\text{percentage cover}})$) was applied to normalize the cover data prior to statistical analysis. There were 192 cover measurements in 1997 and 216 in 1998-1999 (1997: 4 sites X 6 herbicide plots X 8 quadrats per herbicide plot = 192; 1998-1999: 4 sites X 6 herbicide plots X 3 pine split plots X 3 quadrats per pine split plot = 216). Although not specifically reported in this chapter, cover was a necessary measurement to predict biomass and LAI. Treatment responses for cover are reported in Appendix D.

Biomass—Aboveground biomass was clipped within 1-m² quadrats during July 1997 and August 1998 and 1999. No herbicide or pine planting treatments had yet been applied in 1997; therefore only biomass samples of kudzu were taken from each main plot (4 sites X 6 herbicide plots = 24 total). Four species groups were sampled in 1998 and 1999: kudzu, blackberry, herbs, and pine. In each main plot, biomass samples were collected from two pine plots: 0 and seedlings m⁻² (4 sites X 6 herbicide plots X 2 pine split plots = 48 total). One pine seedling was

collected from a buffer row within each 4-seedlings-m⁻² split plot (24 total). All biomass samples were placed in plastic bags and returned to the laboratory for processing. In the laboratory, the samples were transferred to paper bags, dried to a constant weight at 65°C, and weighed (nearest 0.1 g). Kudzu biomass was separated into foliage and stem components. To complete the biomass data set for the entire study, biomass was estimated from cover measurements using regression equations developed for each species group (see Appendix E).

Leaf area--Leaf area samples of kudzu were taken in July 1997. Twenty intact and fully developed leaves were selected randomly from each 1-m² quadrat. In August 1998 and 1999, leaf area samples were taken only from the untreated check because very little kudzu remained for sampling in the herbicide treatments. Leaf area samples were collected in 1998 and 1999 from each of the 0, 1, 4 seedlings m⁻² split plots (4 sites X 3 pine split plots X 2 samples = 24 total). Leaf area of each sample was determined with an AgVision video image analysis system (Decagon Devices, Inc, Pullman, WA). The samples were then dried to a constant weight at 65°C and weighed (nearest 0.01 g). In the 1999 samples, leaves were collected from the upper and lower layers of the kudzu canopy to ascertain differences in specific leaf area (SLA; cm² g⁻¹ foliage dry weight) due to canopy position. SLA is a measure of the surface area per unit weight of the individual leaves. It provides an index

of leaf thickness. Total leaf area of kudzu for each quadrat was calculated by multiplying its foliage dry weight by the mean value of specific leaf area for a given sample year. Leaf area index (LAI; $\text{m}^2 \text{m}^{-2}$ of kudzu in each quadrat), a measure of the amount of leaf area per unit of ground area, was predicted from cover through a regression analysis (see Appendix E). In addition, the leaf weight ratio was calculated for each kudzu sample. LWR is the ratio of leaf dry weight to total above ground dry weight. It reflects leafiness by weight of sample contributing to production.

Soil water-- Soil water content (volumetric percentage at 0-45 cm depth) was measured monthly April to October 1998 and May to October 1999 by time domain reflectometry (TDR) (TRASE Systems, SoilMoisture Equipment Corporation, Goleta, CA). A pair of stainless steel rods was located near the center of each pine split plot. A total of 72 pairs were installed (4 sites X 6 herbicide plots * 3 pine split plots = 72).

Light--Photosynthetically active radiation (PAR) was measured with a sunfleck ceptometer (Decagon Devices, Pullman, WA). Measurements were taken in August 1998 on two consecutive, clear days between 1100 and 1400 hours. In August 1999, measurements were taken on a single day between 1000 and 1600. Readings were taken above the canopy and at ground level to quantify the proportion of light reaching the forest

floor. Values for proportion of maximum PAR were normalized with an angular transformation. Because 1998 readings were taken during similar conditions over two days, PAR readings had little diurnal variation. However, diurnal variation was present in the 1999 readings, and these data were analyzed by including a time variable as a covariate to account for the systematic changes in solar intensity.

Pine measurements--Ground line diameter (mm) and height (cm) of each loblolly pine seedling were measured in January 1998, immediately after planting and again one year later.

Statistical Analysis

The July and August 1997 measurements were analyzed using a randomized complete block design with factors of sites (blocks) and herbicide treatments. In 1998 and 1999, the experimental design was a randomized complete block with factors of sites (blocks), herbicide treatments (main plots), and pine densities (split plots). This design was used for all vegetation and resource measurements. In addition, a maximum value of soil water content was identified for each TDR pair and used as a covariate to adjust means for local differences in soil series. Data was analyzed with analysis of variance (ANOVA) (SAS 1989) using a 95% significance level to detect differences among herbicide treatments, pine densities, or their interaction.

The five herbicides compared in this study have different levels of selectivity, translocation, and mode of action. In addition, the interaction of effects of herbicide treatments and pine densities was rarely significant. Therefore, a set of five orthogonal contrasts was selected to differentiate among herbicide effects:

- I. Untreated check versus herbicide treatments
- II. Granular versus liquid herbicides: Tebuthiuron was a granular herbicide and was translocated differently than the spray-applied treatments. This contrast separated effects of tebuthiuron from the spray-applied treatments.
- III. Herbicides tolerated by pines versus herbicides not tolerated by pines: Two of the liquid herbicides (clopyralid and metsulfuron methyl) are tolerated by pines, and thus, ideal for combining kudzu control with induced competition for pine. Pines are intolerant of the remaining two herbicides (picloram and triclopyr). This contrast determined if choosing a certain herbicide for pine safety resulted in a loss of efficacy of kudzu control.
- IV. Picloram versus triclopyr: Picloram has higher persistence, toxicity, and soil activity than triclopyr. This contrast compared performance of these two herbicides because of potential differences in their efficacy and persistence.

- V. Metsulfuron versus clopyralid: There are differences in selectivity and cost between metsulfuron and clopyralid. This contrast compared the performance of these two strikingly different herbicides.

The rationale for selecting this set of orthogonal contrasts is explained further in Appendix D. The contrasts were used to analyze responses of all variables to the herbicide treatments, with the exception of the kudzu growth analysis variables (LAI, SLA, and LWR) which were measured only in the untreated check. For the kudzu growth analysis variables, all possible comparisons of least squares means were conducted with Bonferroni probabilities (Neter et al. 1989).

RESULTS

Pre-treatment Characteristics of the Kudzu Stands

Biomass

Measurements taken June 1997 indicated the presence of differences among blocks for the pre-treatment characteristics of the kudzu stands. Tables 1-2 report the responses for the kudzu growth analysis variable, and Table 3 reports the biomass responses by species group.

The Reactor site had lower total kudzu weight than the other sites (84 g m⁻²). The orthogonal contrasts indicated that there was less kudzu

on the untreated check plots than the other treatment plots (191 g m^{-2} , $P=0.002$).

The untreated check contained more herbaceous weight than the other treatment plots (49 g m^{-2} , $P=0.001$). However, the tebuthiuron plots also contained higher amounts of herbaceous weight than the other spray treatments (36 g m^{-2} , $P=0.028$).

The untreated check had 41 g m^{-2} of blackberry biomass, which was the greatest value observed for all main treatment plots ($P=0.004$). The tebuthiuron plot had significantly less blackberry biomass values, averaging 19 g m^{-2} ($P=0.038$). Pine intolerant herbicide plots had more blackberry biomass than pine tolerant plots ($P=0.004$).

Kudzu Growth Analyses

Specific leaf area (SLA) measurements were not different among sites in 1997 (Table 1). All SLA values were between $281 \text{ cm}^2 \text{ g}^{-1}$ and $326 \text{ cm}^2 \text{ g}^{-1}$. However, leaf area index (LAI) did differ. The Reactor site had the lowest LAI of all the sites ($P<0.050$) at $1.1 \text{ m}^2 \text{ m}^{-2}$. The second lowest LAI value was found at the Home site ($2.3 \text{ m}^2 \text{ m}^{-2}$). The Cloverleaf ($4.8 \text{ m}^2 \text{ m}^{-2}$) and Burma Road ($3.8 \text{ m}^2 \text{ m}^{-2}$) sites had the highest LAI values. The leaf weight ratio (LWR) of the Reactor site was significantly higher than that of the Home site (46% versus 33%) ($P=0.050$). Values for the other sites were 34-39.1% and did not differ significantly ($P>0.050$).

Table 1. Pre-treatment mean values of growth analysis variables for kudzu by study site at the Savannah River Site, South Carolina.

Site	Total dry weight g m^{-2}	Specific leaf area $\text{cm}^2 \text{g}^{-1}$	Leaf area index $\text{m}^2 \text{m}^{-2}$	Leaf weight ratio (%)
Cloverleaf	378.7	326.0	4.8	39.1
Home	228.6	302.7	2.3	33.5
Burma	349.0	281.3	3.8	38.2
Reactor	84.4	288.5	1.1	45.8
Average	348.0	305.5	4.0	37.7

Table 2. Mean values of growth analysis variables for kudzu by year of the study at the Savannah River Site, South Carolina.

	1997	1998	1999
Total dry weight g m^{-2}	348.0	180.9	285.9
Foliage dry weight g m^{-2}	131.2	61.9	112.4
Specific leaf area $\text{cm}^2 \text{g}^{-1}$	305.5	170.8	275.3 (233.7 upper) (341.7 lower)
Leaf area index $\text{m}^2 \text{m}^{-2}$	4.0	1.0	3.1
Leaf weight ratio (%)	37.7	34.2	39.3

Table 3. Orthogonal contrasts and significance levels (*P*) for estimated biomass (g m⁻²) of kudzu, blackberry, herbs, and pine in response to five herbicide treatments and broadcast burning at the Savannah River Site, South Carolina.

Contrast I: Untreated check (U) versus herbicide treatments (H)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	U	H	P	U	H	P	U	H	P	U	H	P
7-97	190.8	236.7	0.002	41.1	26.6	0.003	49.0	25.9	0.001	---	---	---
8-97	267.7	20.4	<0.001	30.4	20.5	<0.001	39.3	13.3	<0.001	---	---	---
6-98	211.2	21.4	<0.001	42.0	23.1	<0.001	124.8	178.8	0.820	6.3	6.5	0.276
8-98	228.0	22.3	<0.001	24.1	20.3	<0.001	186.9	197.1	0.151	5.3	6.5	<0.001
8-99	266.3	6.9	<0.001	20.3	21.5	0.006	44.3	390.0	<0.001	3.2	12.0	<0.001

Contrast II: Tebuthiuron (granular-G) versus spray-applied herbicides (S)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	G	S	P	G	S	P	G	S	P	G	S	P
7-97	218.9	241.1	0.182	19.2	28.5	0.038	36.1	23.3	0.028	---	---	---
8-97	62.7	9.9	<0.001	17.0	21.5	0.006	13.2	13.5	0.971	---	---	---
6-98	17.1	21.7	0.181	11.9	26.0	0.227	35.7	214.6	<0.001	5.7	6.7	<0.001
8-98	13.5	10.8	0.003	9.7	23.0	0.011	41.1	236.2	<0.001	5.7	6.7	<0.001
8-99	7.4	6.8	0.354	8.3	24.8	0.002	113.3	460.3	<0.001	4.0	14.0	<0.001

Table 3 continued

Contrast III: Pine tolerant (T) versus pine intolerant (I) herbicides												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	T	I	P	T	I	P	T	I	P	T	I	P
7-97	248.7	233.6	0.313	22.2	34.9	0.004	23.4	23.2	0.862	---	---	---
8-97	11.8	8.0	<0.001	36.8	5.9	<0.001	14.5	12.2	0.260	---	---	---
6-98	25.3	19.6	0.003	43.6	8.3	<0.001	154.8	216.5	0.008	6.7	6.8	0.394
8-98	12.4	9.3	<0.001	38.3	7.7	0.003	211.9	260.4	<0.001	6.6	6.9	0.026
8-99	7.7	11.8	0.003	3803	11.3	<0.001	320.4	600.2	<0.001	13.8	14.3	0.774

Contrast IV: Picloram (P) versus triclopyr (T)

Contrast IV: Picloram (P) versus triclopyr (T)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	P	T	P	P	T	P	P	T	P	P	T	P
7-97	250.9	216.3	0.196	43.2	26.6	0.022	18.3	28.1	0.098	---	---	---
8-97	7.6	8.3	0.455	5.5	6.2	0.593	11.7	12.7	0.694	---	---	---
6-98	10.0	29.2	<0.001	7.6	9.1	0.304	164.1	268.9	0.005	6.7	6.9	0.619
8-98	8.9	9.7	0.361	8.2	7.2	0.279	298.4	222.3	0.095	6.8	6.9	0.771
8-99	6.3	5.6	0.365	15.2	7.4	0.001	684.3	516.0	0.154	11.8	16.8	0.012

Table 3 continued

Contrast V: Metsulfuron (M) versus clopyralid (C)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	M	C	P	M	C	P	M	C	P	M	C	P
7-97	235.1	262.2	0.220	18.3	26.0	0.098	24.3	22.5	0.767	---	---	---
8-97	8.8	14.8	<0.001	6.5	67.1	<0.001	14.4	14.6	0.959	---	---	---
6-98	19.4	31.1	0.006	6.9	80.2	<0.001	193.8	115.7	0.004	6.9	6.4	0.038
8-98	9.2	15.5	<0.001	5.9	70.7	<0.001	328.1	95.7	<0.001	6.6	6.5	0.870
8-99	7.4	7.9	0.612	5.0	71.6	<0.001	490.7	150.0	<0.001	14.7	12.7	0.282

Pre-treatment Responses

Kudzu Growth Analysis

After the initial treatment, the untreated check maintained higher LAI values ($2.6 \text{ m}^2 \text{ m}^{-2}$) than all herbicide treatments for the remainder of the study ($P < 0.001$) (Figure 1). In August 1997, LAI values in each of the herbicide treated areas decreased to negligible levels. The tebuthiuron treatment had higher LAI than the other herbicide treatments ($P < 0.001$).

Kudzu LAI of the tebuthiuron plot no longer differed from the other treatments beginning in June 1998 ($P = 0.181$). Varying degrees of kudzu recovery in the spray-applied herbicide treatments in June 1998 caused kudzu LAI following pine tolerant herbicides to differ from that following pine intolerant herbicides. Within these groups, picloram had lower LAI ($P < 0.001$) than triclopyr and clopyralid was higher than metsulfuron ($P = 0.006$). In August 1998, the tebuthiuron treatment had the highest LAI of the herbicide treatments ($P = 0.003$). In 1999, areas treated with pine tolerant herbicides had a higher kudzu LAI than areas treated with pine intolerant herbicides ($P = 0.003$).

Total kudzu dry weight varied among sample dates ($P = 0.012$). It was highest in 1997 (348 g m^{-2}), lowest in 1998 (181 g m^{-2}), but

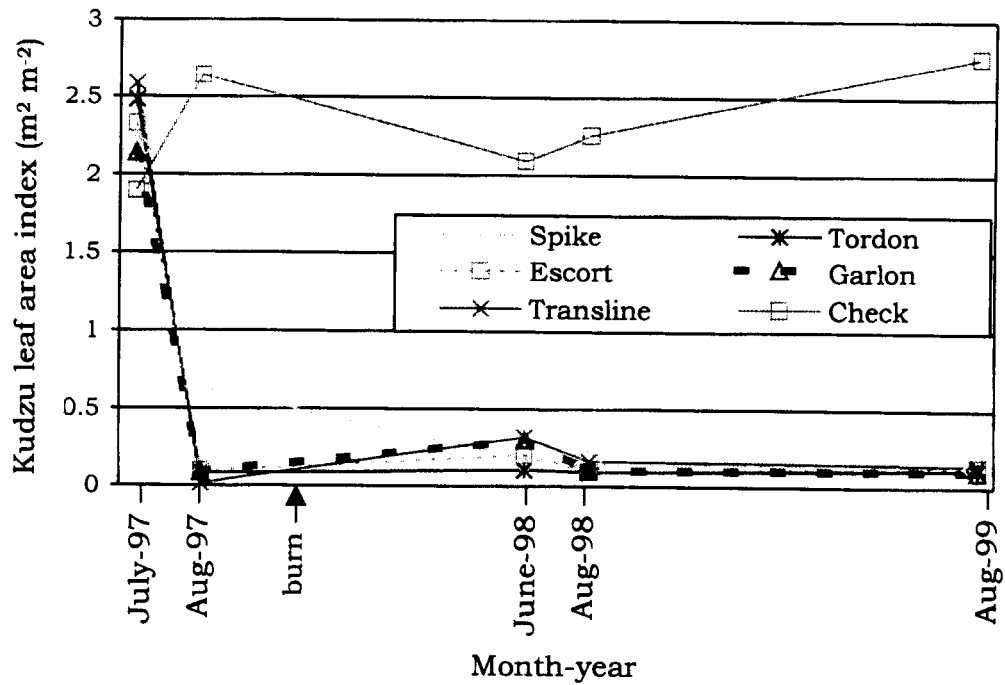


Figure 1. Estimated leaf area index of kudzu in response to five herbicide treatments and broadcast burning at Savannah River Site, South Carolina.

recovered in 1999 (286 g m^{-2}). Foliage dry weight follows this pattern as well. Second-year dry weight (1998, 62 g m^{-2}) is significantly lower than 1997 (131 g m^{-2} , $P=0.035$) but recovers in 1999 (112 g m^{-2}).

Presumably, there was less stem present in 1998 due to the broadcast burn.

Values of SLA and LAI also varied among sample dates ($P < 0.001$)(Table 2). Both showed the same pattern as total dry weight. The 1998 season had the lowest SLA ($171 \text{ cm}^2 \text{ g}^{-1}$) and LAI ($1.0 \text{ m}^2 \text{ m}^{-2}$). The kudzu plants were required to grow as sprouts from rootstocks in 1998 because all aboveground biomass had been consumed in the fire. The low LAI suggests a single layer of kudzu leaves was present in 1998. This is supported by the SLA, which is low and indicates thick leaves. Beadle (1993) reports that leaves in full sun will be thicker than leaves in partial sun. With only a single layer of kudzu leaves present, the SLA average was brought down to the lowest value observed in the study.

Multiple comparisons of least squares means indicate that SLA in 1997 was not significantly different from SLA in 1999 ($P=0.518$). The same is the case for LAI ($P=0.137$). Differences in allocation effected LWR only slightly. Although the lowest overall value of LWR was observed in 1998, the highest value was in 1999.

An additional study in 1999 revealed differences in SLA between upper and lower layers of the canopy. Leaves in the upper canopy layer

had lower SLA ($234 \text{ cm}^2 \text{ g}^{-1}$) than those in the lower canopy layer ($342 \text{ cm}^2 \text{ g}^{-1}$, $P < 0.001$).

Estimated Biomass

Figure 2 illustrates the estimated biomass responses by species group for the duration of the study. Table 3 has the corresponding orthogonal contrasts and significance levels of estimated biomass.

After the initial herbicide treatment in 1997, the untreated check had higher kudzu biomass throughout the study ($P < 0.001$). Clopyralid was not effective on blackberry. Blackberry biomass increased substantially and caused the high level of significance reported in the four contrasts involving clopyralid.

In August 1997, herbaceous biomass in the untreated check was higher than the other main treatments; however, there was less blackberry. Tebuthiuron had higher kudzu biomass than the other chemical treatments. Kudzu biomass of pine intolerant herbicide treatments was greater than that in pine intolerant herbicide mostly due to the limited efficacy of clopyralid.

In the 1998 growing season, herbaceous biomass in the untreated check did not differ from that of the herbicide treatments. However in August, herbaceous biomass following tebuthiuron was lower than that of the herbicide treatments ($P = 0.011$) and kudzu biomass was higher ($P = 0.003$).

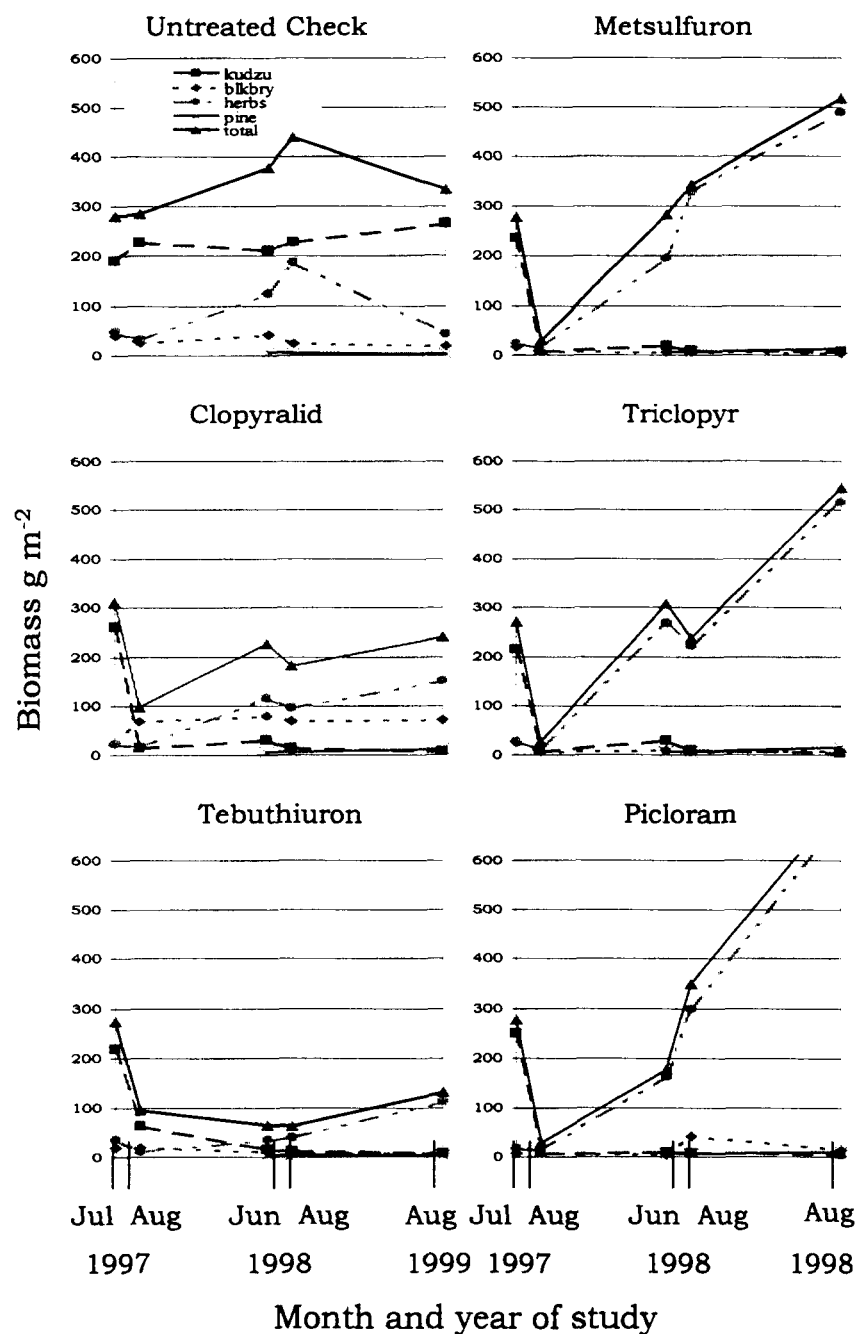


Figure 2. Estimated biomass responses of kudzu, blackberry, herbs, and pine in response to five herbicide treatments and broadcast burning at the Savannah River Site, South Carolina

Kudzu recovery in June 1998 resulted in pine tolerant herbicides having more kudzu biomass than pine intolerant herbicides. Pine intolerant herbicides tended to have more kudzu biomass as well.

In 1999, herbaceous biomass in the untreated check declined to pre-treatment levels. This resulted in values that were less than herbaceous treatments. The herbaceous biomass in the tebuthiuron treatment continued to be significantly lower than the spray treatments. Again, plots treated with pine intolerant herbicides had significantly higher herbaceous biomass but lower kudzu than those treated with pine tolerant herbicides. In 1998 and 1999 herbs may have been excluded by blackberry. Contrast V of Table 3 indicates higher levels of herbs in the metsulfuron plots.

In June 1998 and August 1999, a significant pine density treatment effect observed for blackberry biomass indicated more blackberry in the 1 pine per m² plots than in either the 0 or 4 pine per m² plots.

In the pine density treatments, there was little to no difference in kudzu, herb, or blackberry. As the pines get taller and more competitive, these differences will become apparent.

Pine Measurements

Pre-treatment Characteristics

Pre-treatment stem diameter and height of planted loblolly pines were similar among treatments. Only one contrast between metsulfuron and clopyralid indicated a difference in size (data not presented).

Post-treatment Responses

The first two orthogonal contrast could not be performed for pine diameter and height due to the high levels of mortality observed in the tebuthiuron and untreated check plots. Based on the results of ANOVA, there were few differences in individual contrasts for either pine diameter or height among herbicide or pine density treatments (Table 4). However, the untreated check had the smallest diameters (6.2 and 5.9 mm in 1 and 4 pine m⁻² densities, Table 4), followed by clopyralid.

Total stem volume of the pine stands in the untreated check were significantly lower than those in herbicide-treated plots ($P < 0.001$). Tebuthiuron plots had lower stand volume than spray-applied treatments ($P < 0.001$). There were no other differences detected by the orthogonal contrasts.

Tebuthiuron plots had the lowest pine survival percentage at 34%, followed by the untreated check at 42%. All other herbicide treated plots had 80% survival or greater.

Table 4. Orthogonal contrasts and significance levels (*P*) for January 1999 of pine height (cm), ground line diameter (mm), biomass (g m⁻²), survival (%), and height-to-diameter ratio (%) of loblolly pine in response to five herbicide treatments and broadcast burning at the Savannah River Site, South Carolina.

variable	Contrast I		Contrast II		Contrast III		Contrast IV		Contrast V		
	untreated check vs. herbicides	<i>P</i>	tebuthiuron vs. spray applied herbicides	<i>P</i>	pine tolerant herbicides vs. not tolerant	<i>P</i>	picloram vs. triclopyr	<i>P</i>	metsulfuron vs. clopyralid	<i>P</i>	
height (cm)	43.9	44.0	---	---	49.5	49.0	48.2	49.8	50.7	48.3	0.001
diameter (mm)	6.1	7.0	---	---	7.7	7.7	7.5	7.8	8.5	7.0	<0.001
survival (%)	41.6	68.4	<0.001	<0.001	83.1	88.9	89.2	88.7	85.6	80.7	0.339
biomass ¹ (g m ⁻²)	9.6	17.3	<0.001	0.592	19.2	16.5	16.0	17.0	23.6	14.8	0.004
stand volume (cm ³ m ⁻²)	0.004	0.023	<0.001	<0.001	0.024	0.028	0.027	0.029	0.028	0.019	0.090
H:D ratio (%)	74.5	62.9	<0.001	0.006	62.6	63.8	63.9	63.8	59.8	69.4	0.001

¹ Estimated values

Even with the low survival of the tebuthiuron treated plots, as a whole the untreated check had a lower survival than the herbicide treatments. Pine survival in the tebuthiuron treatment was significantly lower than those of the other chemical treatments. The pine tolerant herbicides had only a slightly lower survival rate.

None of the pine variables differed significantly among planting densities, indicating that pine responses were a function only of the herbicide treatments and not intraspecific competition.

Comparisons of the height to diameter ratio (H:D) were performed to determine if the treatments had affected stem form of loblolly pine. Values of H:D were greater in the untreated check than in the herbicide treatments ($P < 0.001$). H:D was less in tebuthiuron plots than in the other herbicide treatments ($P = 0.006$).

Soil Water

In 1998, there were no clear differences among treatments (Figure 3). Plots treated with metsulfuron were generally driest, while tebuthiuron plots were wettest. Otherwise, during most of the year the patterns were erratic. In 1999 (Figure 4), distinct trends developed among the different herbicide treatments. Again, metsulfuron plots were driest and tebuthiuron areas wettest. However, most of the orthogonal contrasts indicated that differences did not exist among treatments.

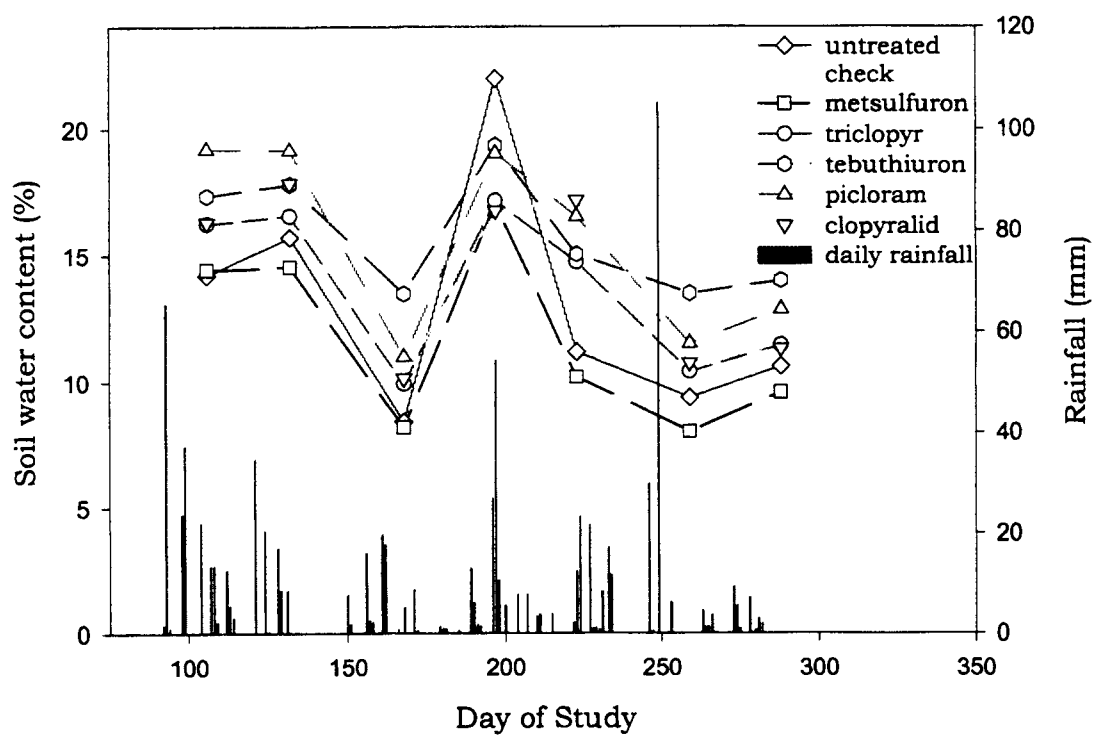


Figure 3. 1998 percentage soil water content in response to five herbicide treatments, broadcast burning, and daily precipitation at the Savannah River Site, South Carolina.

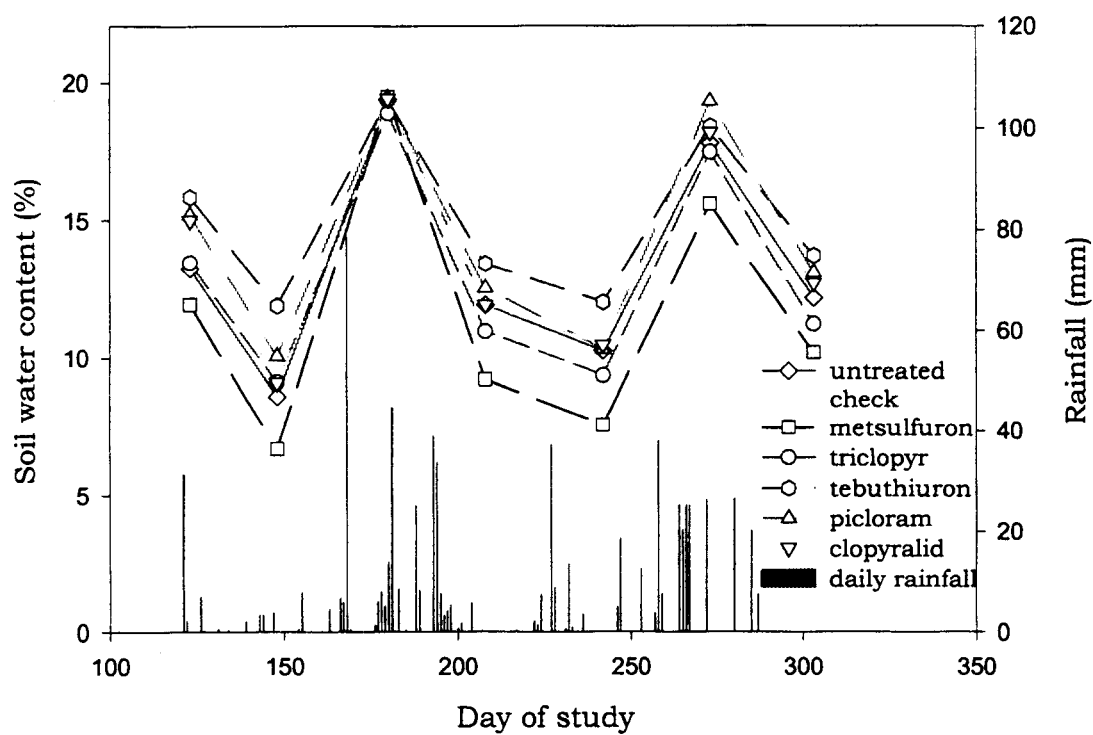


Figure 4. 1999 percentage soil water content in response to five herbicide treatments, broadcast burning, and daily precipitation at the Savannah River Site, South Carolina.

An exception was the contrast of tebuthiuron versus the spray-applied herbicides. As mentioned in the biomass section of the results, tebuthiuron plots supported little vegetation. The high soil water content values of this treatment indicate very little plant uptake of available water. Metsulfuron plots generally had lower values of soil water but The differences were not statistically significant. Soil water content did not vary significantly among pine densities.

Several herbicide-by-pine density treatment interactions were detected for soil water content. A significant interaction was observed in August ($P=0.061$), September ($P=0.014$), and October ($P=0.024$) of 1998. In 1999, the interaction was significant in April ($P=0.003$), July ($P=0.064$), August ($P=0.064$), and September ($P=0.055$). These interactions may be explained by variation in herbicide selectivity, and site occupancy of loblolly pine among treatments. Herbicide selectivity may have facilitated some differences in the species comprising individual herb communities. More likely causing these interactions was the rate of growth of the pine seedlings. A regression analysis indicated that soil water content had a significant negative relationship with pine stand basal area for several of the monthly measurements of soil water content.

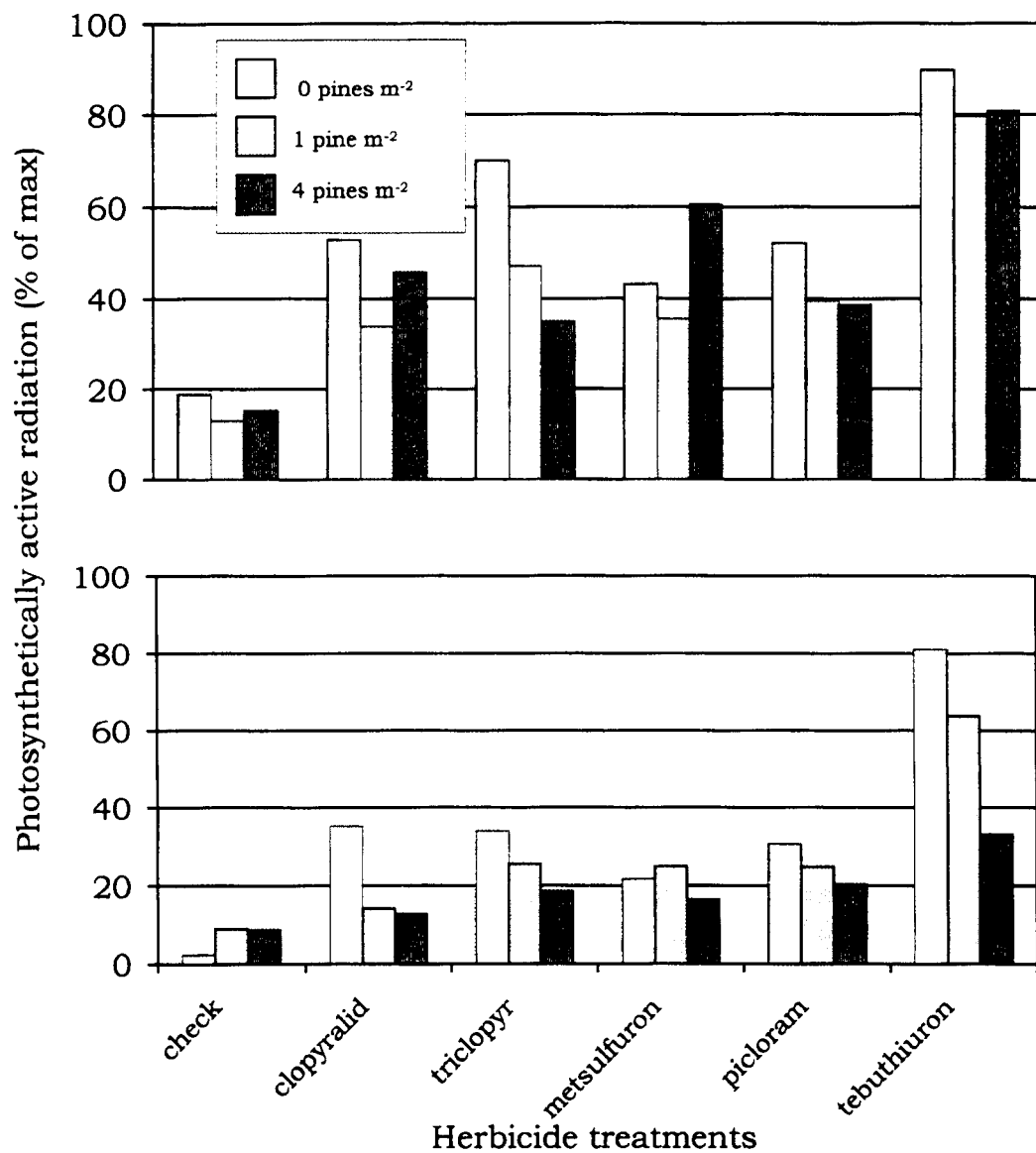


Figure 5. 1998 (A) and 1999 (B) percentage of maximum photosynthetically active radiation at soil surface in response to five herbicide treatments, broadcast burning, and two pine densities at the Savannah River Site, South Carolina.

Photosynthetically Active Radiation

In 1998, the untreated check plots had the lowest average PAR percentage reaching the ground surface at 16% ($P<0.001$) (Figure 5). With a value of 71%, tebuthiuron had the highest average PAR percentage ($P<0.001$). All other treatments were between 35% and 45% of maximum PAR and did not differ from each another.

Differences among pine density treatments occurred in 1998. The 0 pine m^{-2} density generally had higher PAR percentages than either the 1 or 4 pines m^{-2} densities. Multiple comparisons indicated that PAR percentage in the 4 pine m^{-2} density did not differ from that of the 1 pine m^{-2} density.

Average PAR percentage was lower overall in 1999 than in 1998 (Figure 5B). The untreated check again had the lowest value of 9% and was different from the herbicide treatments ($P<0.001$) which averaged 23%. The average PAR percentage was greater in (59%, $P<0.001$). Clopyralid, metsulfuron, picloram, and triclopyr plots had average PAR percentages of 21%, 21%, 25%, and 26%, respectively with no significant differences among these treatments. The 0 pine m^{-2} density had the highest PAR percentage, followed by the 1 pine m^{-2} densities.

DISCUSSION AND CONCLUSION

Site disturbance history and selectivity of the herbicide treatments resulted in the development of four distinctly different plant communities. The untreated check remained a kudzu-dominated community. Herb dominance was evident in the metsulfuron, picloram, and triclopyr treatments. Clopyralid plots were dominated by blackberry. The tebuthiuron treatment eliminated most plant cover.

Kudzu-Dominant Community

The untreated check remained dominated by kudzu for the entire study. Only in 1998 were any discernible amounts of herbs present. This flush of herb growth was attributed to the December 1997 broadcast burn. Unlike in Japan, where Tsugawa et al (1993b) reasoned that kudzu can grow in association with other plants (twining upwards and co-existing), in the present study herbs could not coexist with kudzu and diminished in biomass in the 1999 season.

Overall kudzu LAI and SLA values in the untreated check were consistent with those reported by Tsugawa et al (1993b), but LWR in this study was much higher. High LWR indicates increased carbon allocation to foliage. This implies more leaves per plant, which contributes to higher overall rates of canopy photosynthesis (Wechsler 1977). Higher photosynthetic rates presumably allow more allocation to kudzu root storage, and as a result, kudzu plants in the untreated check could

quickly recover from the consumption of all aboveground biomass in the fire.

Tsugawa et al (1993b) reported that kudzu LAI increased from June to July and was highest in July at $3.7 \text{ m}^2 \text{ m}^{-2}$. In August, the LAI dropped to $3.0 \text{ m}^2 \text{ m}^{-2}$, which coincided with branch production in new stems. In our study, LAI in the untreated check of this experiment dropped in 1998 ($1.0 \text{ m}^2 \text{ m}^{-2}$) presumably due to increased allocation of stem growth as well as competition with herbs.

The maximum SLA of the Tsugawa et al. study was $310 \text{ cm}^2 \text{ g}^{-1}$, which was an indicator of high vigor. In 1997, untreated kudzu in this study averaged $306 \text{ cm}^2 \text{ g}^{-1}$. SLA of the untreated check dropped during stem production in 1998 but again recovered close to previous vigor in 1999. High recovery and vigor were apparent in LWR, which was higher in 1999 (39%) than in previous measurements.

A study in Watkinsville, GA (Wechsler 1977) reported higher values of LAI ($7 \text{ m}^2 \text{ m}^{-2}$) and above-ground biomass (867 g m^{-2}). These values may be higher because of the genetic strain of kudzu. Watkinsville is recognized as the source for Kudzu 23, a very drought resistant kudzu strain. Wechsler was probably working with this type of kudzu.

The untreated check plots were characterized by a low light environment, which hampered pine performance. The pine trees that survived were etiolated (abnormally elongated) and had poor stem form.

The weight of living and dead kudzu foliage that was present on top of pines also deformed surviving stems.

There was no distinct pattern in soil water content. The untreated check plots had intermediate soil water in comparison to the other treatment conditions. Kudzu roots are established at depths where hydraulic lift is possible. It is feasible that kudzu has the capacity to lift water to the nutrient zone for uptake (Caldwell et al. 1998). This may explain the moderately wet conditions in relation to the other herbicide treatment conditions.

Herb-Dominant Community

The metsulfuron, picloram, and triclopyr treatments shifted the plant community from one dominated by kudzu to one dominated by an array of early successional herb species, including: horseweed (*Conyza* spp), ragweed (*Ambrosia artemisiifolia*), dogfennel (*Eupatorium capillifolium*), broomsedge (*Andropogon* spp), and asters (family Asteraceae) (Ricklefs 1990, Murphy 1998). These species were also found in studies of old-field succession from the same region (Keever 1950, Monk and Gabrielson 1985, Ricklefs 1990).

Geographical location and the type of disturbances determine the character of succession on a site (Ricklef 1990). In this study, the disturbances were the herbicide treatments and broadcast burning. As discussed, the fire effect on the plant community was evident especially

in 1998. The flush of herb growth in 1998 was mainly ragweed. A study by Keever (1950) suggests that in the location of these study sites, and with the possibility of an agricultural site history, the dominant species in the first year after disturbance should have been horseweed.

However, horseweed is a winter annual and young plants were destroyed in the fire. This led to the high volume of ragweed and may be a reason it is known to follow fire on old field sites.

The presence of kudzu on the sites can also be considered a disturbance. It was estimated that each study site had a continual infestation of kudzu for at least 20 years. Some agricultural weed seeds in the soil seed bank may have expired during the time of kudzu infestation (Ross and Lembi 1999). The sharp increase in herbs, and thus, total biomass in 1999 is possibly due to an influx of wind dispersed seed and continued favorable germination conditions.

Differences in herbaceous communities among herbicide treatments were not apparent. With the severe disturbance associated with removal of kudzu and fire, perhaps the more subtle influences of the herbicide disturbance were overpowered. Overall, pine seedlings grew well and for the most part were fostered by conditions created in these herb-dominated communities.

Blackberry-Dominant Community

Blackberry began to dominate the clopyralid plots as early as August 1997. Herb presence was much lower in these plots. Kudzu recovery was high but spot treatments were consistently effective. Although pines present tended to be etiolated in January 1999, weights were comparable to those of the other species groups (Table 4). This cannot be explained by significantly lower levels of PAR percentage or soil water content. Resource availability in clopyralid plots was not different than that of the other spray-applied herbicides.

Low Vegetation Abundance Community

Of the herbicides studied, tebuthiuron was the herbicide of greatest toxicity and persistence (See Appendix B). Almost all pines were killed and little herbaceous vegetation was present in the second year following application.

In the first year, tebuthiuron had slightly higher kudzu abundance than the other herbicide treatments. The label states that tebuthiuron may take an extended time to kill older perennial species (Dow AgroSciences 1998b). Even without further applications, tebuthiuron will remain active in the soil environment for at least 12 to 15 months after last application. Most of the kudzu remaining in the tebuthiuron plots is expected to die within a few seasons (Miller 1982, 1985, Hamel and Shade 1985).

Tebuthiuron plots tended to have higher availabilities of light and soil water. Since little vegetation was present, it can be assumed that this was due to lack of canopy for interception and reductions in soil water uptake.

Pine Density Treatments

At this point in the study, the pine densities have had very little effect on kudzu. This is mainly because in the herbicide treatments there was little kudzu remaining to compete with the pines. Pines in the untreated check were little more than trellises for the kudzu to grow upon.

Resource availability was affected by the presence of high density pine stands. PAR percentage decreased with increases in pine density. This indicates that as pines continue to grow, the light environment will deteriorate further, particularly in the herb-dominant communities. Due to the high densities, the crowns of the pines are likely to reach crown closure by the year 2000.

Other research has used shade to control the type and abundance of vegetation. Monk and Gabrielson (1985) used artificial shade in a plant community succession experiment. They found that shade affected early successional species more than species generally found later in the sere. Kudzu was not a part of their experiment but some control of shade intolerant plants was achieved by artificial shade. They also found

that some early successional species in the absence of artificial shade were suppressed by root competition from young pine trees. Therefore, it seems likely that as the pines get older in the present study, competitive exclusion of most plant species will occur.

The untreated check and clopyralid treatments had an elongating effect on the pine stem form. This etiolation signals allocation to aboveground and not belowground morphology. It may hinder the seedlings' nutrient uptake and thus growth, as well as stability (Smith and Hayward 1985). This is usually caused by low levels of light availability. The PAR percentage in the clopyralid treatment was not different from the other spray treatments. However, the high volume of blackberry and type of interception may have had an effect on the quality of light. Light quality was not measured. Low red:far red ratios could have caused elongation of pine stems (Federer and Tanner 1966, Smith and Hayward 1985).

Conclusion

Some type of plant community analysis, including responses to disturbance, should always be included when formulating herbicide prescriptions. In this study, fire had a distinct effect as did the various herbicides. Kudzu recovery in response to the herbicide and broadcast burn treatments differed because of variations in the species' ability to resprout from crowns and trellis on recovering herbaceous vegetation.

The abundance of blackberry in the clopyralid plots is an example of a treatment that can be considered beneficial or not depending on the expected use of the land. All effects on the area's environment contribute to the recovering plant community. The community's recovery after fire and herbicide treatment can be predicted to a certain degree and would be helpful in assisting landowners. How the landowner expects to use the land after treatment is equally important as the treatment itself.

As forest land management intensifies, herbicide technology is becoming ever more important. However, limiting environmental exposure to herbicides by combining other forms of control limits the potential for accidents and misuse. More research is needed in integrated pest management (IPM) to find efficient combinations of treatments. This study shows deteriorating light conditions with higher pine densities but additional kudzu control from this treatment has not yet been observed. The future of our study, as well as new studies on IPM, will help determine better treatments for kudzu and other exotic weeds.

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APPENDIX A

GENERAL VINE INFORMATION

VINE CLASSIFICATION

Vines have been studied as an example of evolutionary development for over a century. Darwin (1905) was among the first scientists to classify vines into groups. These groups include the adventitious root/hook, twining, tendril, and adhesive climbers. The adventitious root/hook climbers are considered the least advanced although they are better adapted to clambering over low rock facings, et cetera. They must have a substrate that allows for the clamping roots or hooks to find a niche. The next group is the twiners. Kudzu belongs to this group. Twiners are more advanced than the previous group because they need only an object higher than they to twine around and gain height. However, twiners are limited somewhat by diameter. As they produce more stem to use in twining than they gain in height, they must reach some balance to be efficient (Carter and Teramura 1988). They must regain what energy they expel in producing more vine through the advantage of better light capture. The third group, the tendril climbers, is among the most advanced. As long as there is a hold or small

protrusion such as bark for the sensitive tendrils to find, a vine has the potential to climb straight up a support. Hegarty and Caballe (1991) mention that tendrils are very tender when young. They tend to be better at climbing around tree crowns instead of ascending the bole. Considered the most advanced, adhesive climbers usually have discs or tendrils with adherent to further anchor them onto a support.

There are more modern classifications, although Darwin's classification is still widely used. Gentry (1991) has classified vines by ecological circumstances. Lianas are thick woody stemmed vines growing in mature forests. Vines are plants with thinner stems found in disturbed habitats or edge. Kudzu displays characteristics of both depending on the immediate environment.

CHARACTERISTICS

Vines are common traits of unstable landscapes (McIntyre and Lavorel 1994). Most vines are clumped in disturbance areas, especially where there has been a shift in nutrient availability and soil quality. They are abundant in forest gaps and in areas of a break in the landscape (slopes, water courses) where tree canopies are irregular and light penetrates distinctly at varying levels (Hegarty and Caballe 1991).

All vine growth strategy evolved for rapid growth rate (Darwin 1905, Mooney and Gartner 1991) and achieve this by allocating production resources differently than other plants (Castellanos 1991).

Vines have very little mechanical support structure. They rely entirely on trees, shrubs, or other structures for upright support. Instead of using energy for mechanical support, vines can use this for other structural demands like stem elongation as well as photosynthetic apparatus production to increase efficiency. Through elongation, a superior position for light capture can be attained with few limitations on photosynthetic potential (Darwin 1905). Because of these efforts, the products of photosynthesis increase exponentially (Castellanos). The vine can become a center of super-production. While light capture is improved and the plant is flourishing, competitors are being shaded out (Darwin, Sasek and Strain 1988). Neighboring trees and other plants do not allocate as much photosynthate to photosynthetic apparatus production and thus do not have the high whole plant photosynthesis rates that distinguish vines.

The end result of vine ecology and physiology is to maximize light harvesting (Darwin 1905, Sasek and Strain 1988 1989, Tsugawa et al 1992a, Teramura et al 1991). Most plants are confined to a sessile life form and can only move their genetics, achieving this by seed dispersal (Ross and Lembi 1999). Vines have evolved to climb. They are able to move plant parts, including photosynthetic apparatus, physically from poor conditions to better conditions. Usually this movement consists of elongating into areas of better light capture. However, some plants

propagate vegetatively and can move to better soil conditions as well. No vine illustrates this action better than kudzu.

Many vine competition studies stress that of aboveground competition for light is primary form of competition (Sasek and Strain 1988 1989, Tsugawa et al 1992a, Teramura et al 1991). Dillenburg et al (1993) emphasized the importance of belowground competition in a study with Japanese honeysuckle (*Lonicera japonica*) and sweetgum (*Liquidambar styraciflua*). They concluded that belowground competition was more involved with plant success than aboveground. Trees subjected to *L. japonica* interference belowground but not aboveground had lower growth than uninfested trees.

VINE PROBLEMS

Carter and Teramura (1989), Hammel and Shade (1985), as well as Wechsler (1977) consider kudzu as the most important weed associated with forestry in the United States. However, vines in general pose problems in forestry. Not only do they take over expensive site prepared areas and kill edge trees, but also cause problems in production and harvesting. They are, by nature, "light-hungry" and extend into tree canopies (Castellanos 1991, Hegarty 1991). Heavy competition for light and other resources can cause forest stands to grow slower, thus increasing the time in between harvests, killing trees, and reducing yields. Putz (1991) has reported cases where several types of vines have reduced the quality of stands from chip-and-saw or saw log grades to

pulpwood grades by scarring and bending bole-wood as well as causing nutrient deficiencies which may debilitate resource capture.

Vines can extend above the tree canopy and become entangled in several treetops. Thinning problems have been reported in the tropics where vines have torn down or ripped out the tops of crop trees when the tree to be thinned was cut (Putz 1991). Harvesting in a heavily infested area can be difficult because of the tangled nature of vines in the logging slash. This may carry over to the regeneration of the site. Vines can lay dormant and unreachable to aerial sprays under logging slash (Putz 1991). Herbicide prescriptions may not account for vines hidden under logging debris. Any herbaceous control not effective on vines could compound the problem by causing conditions fostering vine release.

FUTURE RESEARCH

The twining action of kudzu is readily apparent anywhere the vine exists. But in some cases at forest edges, kudzu and other vines appear to extend up a tree without climbing. That is, there are vine bases that extend to a branch instead of around the bole. These vines are most likely the result of a climbing vine that became a support structure for other vines. A vine that initially had a climbing habit could have been loosened by weather or some other environmental condition, lost its hold, and extended down toward the ground. It may have continued to grow but towards the ground. Kudzu, and other opportunist vines, will take

advantage and grow on these fallen, slender vines conserving energy that would have been lost growing up a large diameter tree (personal observation).

This indicates a large assumption in the literature of the phenomenon of vines reaching the upper tree canopy. Some research details vines consuming vast amounts of energy to ascend large diameter structures attempting to gain light advantage in the future. Others study vines 30 m in the upper tree canopy with limited account of the path taken to this height. Most of the former studies are laboratory or field experiments on young trees and vines. The latter tend to be silviculture or extension related studies. The rationale of root reserves and better light capture in attaining these heights are valid but there are no studies on the likelihood of a "team effort" (for the lack of a better term) of vines climbing on vines. As vines lose their hold and fall, they provide a better, more energy conserving, pathway to superior light capture. Further effort into supporting this idea is out of the scope of this thesis but it is an interest for future vine studies.

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APPENDIX B

HERBICIDES

Herbicides were the main treatment in this experiment. As industry and the public becomes more educated about herbicides, more herbicides are being used safely, properly, and with more efficiency than traditional methods. Mechanical preparation is more expensive and damaging to a valuable soil base. Fire is being used more often and to better public response than ever before. However, air quality and safety considerations limit the use of fire as a plant control method. As another consideration, the effects of fire can be short-lived (Barbour et al 1980).

Thorough application of herbicides cannot be stressed enough. The herbicides in this study encompass a range of characteristics and different application techniques. Application method is important to get the active ingredient to the site of action in the target plant. Generally less than 1% of the active ingredient applied to an area actually reaches the site of action in a plant (Ross and Lembi 1999). To keep waste down

to a minimum it is imperative to apply at the right conditions with the correct equipment.

One caution in using herbicides on kudzu is to adhere strictly to the recommended rates. The delicacy of kudzu leaves results in quick kill. If rates are too high, the possibility exists that the chemical will kill the components of the leaf before it is translocated through the plant (Ware 1994, Ross and Lembi 1999). Only leaves in contact with herbicide spray will be killed. Translocation is absolutely necessary for the demise of the target plant.

HERBICIDE TREATMENTS

The herbicides in this experiment include clopyralid, triclopyr, metsulfuron, a picloram mixture with 2,4-D, and tebuthiuron. Rates were recommended by the manufacturers and distributors for control of kudzu (Table AppB1).

All herbicides in this experiment were spray applied with the exception of tebuthiuron, which was applied with a fertilizer spreader. The application of the herbicides was always in mid to late June (1997, 1998, and 1999) at time of active growth. Spray application was by foot with backpack sprayers.

Although several of the herbicides used are classified in the same chemical families, each herbicide had unique characteristics (Table

AppB2). Families represented in this study are the piconilic acids, sulfonylureas, and phenylureas.

Ross and Lembi (1999) as well as Ware (1994), discuss the attributes of the different chemical families. Clopyralid, picloram, and triclopyr are considered piconilic acids. Metsulfuron is a sulfonylurea and tebuthiuron is a phenylurea.

Piconilic acids are growth regulators. They act as auxin mimics. This unregulated action causes parts of the target plant to grow uncontrollably. A twisted form results as the plant essentially grows itself to death. Piconilic acids are more effective on broadleaf species than on grasses and are widely used in the turf-grass industry.

Sulfonylureas are ALS/AHAS inhibitors. These chemicals inhibit a plant's ability to manufacture the enzymes that create the branched chain amino acids valine, leucine, and isoleucine. The only source of amino acids in a plant is what it manufactures. The loss of these essential components causes loss of growth and eventually death. Both the piconilic acids and sulfonylureas are symplastically translocated. They move in the phloem of the target plant as the sugar sinks dictate. The newest foliage is affected first because elements for growth are moving to these areas of the plant and therefore carry the herbicide to these areas.

Phenylureas are chemicals that inhibit photosynthesis. They are generally soil applied and therefore eventually leech into the soil layer where it is absorbed by the roots. Apoplastically translocated, they readily travel through the xylem and act on older foliage first. They travel upward through the target plant.

INDIVIDUAL CHARACTERISTICS

Clopyralid: Transline (Dow AgroSciences 1998)

This herbicide is used in early postemergence applications in forestry, rangeland and right-of-way uses to control broadleaf and woody weed species. Clopyralid is applied by spray at time of the target plant's active growth. Therefore it is generally absorbed by foliage, however it does remain residually in the soil and is taken up by roots. As a growth inhibitor, clopyralid also affects respiration.

Clopyralid does not bind strongly to the soil. Once in the soil it is broken down by microbes and degradation is faster in conditions that favor the microbes. Therefore, anaerobic conditions may lengthen the persistence of clopyralid. Depending on the conditions present at application, half life can range from 15 to 287 days. Groundwater contamination will be a concern in areas of low organic matter content and low clay presence. Loamy to sandy soil pose larger problems as permeability is higher. It is recommended that clopyralid is used with caution in these areas.

Metsulfuron methyl: Escort (E. I. du Pont de Nemours and Company 1998)

Metsulfuron is used in agricultural, forestry, and industrial capacities. It targets broadleaf plants and annual grasses with some degree of control in woody plants. It is generally sprayed postemergence in most situations with the exception of rangeland, brush, and pasture situations where it can also be applied preemergence.

For forestry, metsulfuron is used in site preparation and release. The chemical is labeled to be safe over pines.

Although metsulfuron quickly stops the growth of target plants, visual symptomology may take several weeks. However, since the active growth of the target plant is stopped, its competitive ability in the community has also ceased. The plant is no longer a problem. Visual symptoms include a purple discoloration as well as chlorosis followed by necrosis. Vein discoloration and terminal death are also early symptoms.

The chemical is absorbed by foliage but also has some residual soil activity and can be taken up through roots. It is systemic and readily moves through the plant. Metsulfuron inhibits the production of essential amino acids used especially in cell division.

Adsorption of the chemical to the soil is low in clay. Organic matter present in the soil does bind. However, especially sandy soils

may leach. Metsulfuron is degraded by soil microbes and chemical hydrolysis. Rate of degradation is dependent on soil conditions such as moisture content, pH, and temperature. The half-life is subject to conditions and soils but is generally 7- 42 days.

A unique feature about metsulfuron is that it is biologically active at low use rates. Combining effectiveness and this environmental safety feature makes metsulfuron a chemical of choice in many applications.

Picloram: Tordon 101-M (Dow AgroSciences 1998)

Picloram is a granular or spray formulation restricted use herbicide (RUP). It can only be applied by a licensed applicator. It is a pre- or post-emergence herbicide with a forestry registration. Annual and perennial broadleaf and woody plants are targets of this chemical.

The RUP designation is due to the ease of movement of picloram in the soil, which may endanger groundwater. Poor binding to soils facilitate this movement. It is moderately persistent with a half-life of 20 to 30 days. It degrades slowly in the soil depending on conditions favoring microbes. However, picloram photo-degrades readily.

Organic matter and clays adsorbs the active ingredient. Sandy soils pose a leeching danger. Picloram is not labeled for highly permeable loamy to sandy soils.

Picloram is an auxin mimic. Epinasty is characteristic symptomology.

Tebuthiuron: Spike (Dow AgroSciences 1998)

By far the most powerful herbicide used, tebuthiuron rates an EPA toxicity class III (slightly toxic). It is broad-spectrum herbicide used in rangelands, industrial settings, non-croplands, and rights of way. It does not target specific plants.

Tebuthiuron has a granular formulation. It becomes active after adequate rainfall incorporates the chemical to the root zone of susceptible plants. Symptomology includes leaf chlorosis succeeded by defoliation. Large perennials make take a few years to die.

Tebuthiuron is highly persistent in soils and depends on microbial degradation. Half-life extends 12 to 15 months in areas with moderate rainfall. It is also poorly bound to soils and moves freely in course textures. However, there is little or no lateral movement in soils with clay or organic matter. To incorporate tebuthiuron in the soil, a soaking rain is needed soon after application. In granular form, tebuthiuron can move off site in flowing water or winds. Extra caution must be used to protect off target areas. Any damage can last for years.

Triclopyr: Garlon (Dow AgroSciences 1998)

Triclopyr is a selective, auxin mimic effective on broadleaf and woody plants, especially root sprouting perennials. It is registered for forestry, industrial, and rights of way.

Although it is not strongly adsorbed and has a potential to be mobile in soil, it is rarely a problem. Half-life in the soil ranges from 30 to 90 days. The main off target concern is volatility. Triclopyr readily volatilizes in warm conditions when using a water carrier.

OTHER HERBICIDES USED

Paraquat: Grammoxone Extra (Zeneca 1998)

This herbicide was used to maintain borders around the individual main treatment plots. It is a contact herbicide and one of the few dangerous chemicals. It is considered a restricted use pesticide and also carries the "DANGER-POISON" warning with the skull and cross bones signal. The chemical may be fatal if swallowed or inhaled in concentrated form (Zeneca 1998). The preparation and application was handled with great care.

Paraquat is used as a defoliant for cotton. It is used preplant and preemergence as well as postemergence directed spray and dormant season applications. It is a photosystem I inhibitor and acts with a free radical oxygen to rapidly destroy membrane (Ross and Lembi 1999). A unique characteristic of paraquat is that due to it being a photosystem I inhibitor, it only works in the daytime when light processes are active.

SAFETY

Safety is a major consideration in kudzu control. In most cases, little history is known about the site of infestation. Dangers under the tangled mat of kudzu are unknown. Much of the kudzu planted in the United States protected abandoned, eroding farmland. Many farms were left as they were with open wells, old disking equipment, and other hazardous implements now unseen under tangled vines. Hidden dangers as simple as old stumps or ditches can damage mowing equipment and injure the human mower. One reason for the high cost of herbicide control is liability to employee applicators. Falling into old wells or tripping with a backpack sprayer full of herbicide is a legitimate consideration for ground applicators.

Table B1. Names and rates of herbicides used to control kudzu at the Savannah River Site, South Carolina. All liquid herbicides were mixed with 0.25 percent surfactant in 935 l ha⁻¹ (100 gal acre⁻¹)

Common Name	Trade Name	Rate (Metric)	Rate (US)
clopyralid	Transline ®	1.5 l ha ⁻¹	21 oz acre ⁻¹
triclopyr	Garlon ® 4	7.2 l ha ⁻¹	3.1 qt acre ⁻¹
metsulfuron methyl	Escort ®	0.29 l ha ⁻¹	4 oz acre ⁻¹
picloram + 2,4 D	Tordon ® 101-M	14.0 l ha ⁻¹	6 qt acre ⁻¹
tebuthiuron	Spike ®	22.4 kg ha ⁻¹	20 lb acre ⁻¹

Table B2. General characteristics of herbicides used in this study to control kudzu at the Savannah River Site, South Carolina.

Common Name	Chemical Class	Trans-location	Soil mobility	Residual activity (max)	Res-trictions
clopyralid	Piconilic Acid	Symplastic	Some	Little	
triclopyr	Piconilic Acid	Symplastic	Some	Little	
met-sulfuron	Sul-fonylurea	Symplastic	Some	Little	
picloram + 2,4 D	Piconilic Acid	Symplastic	Much, good soil movement	6 months	RUP ¹
teb-uthiuron	Phenylurea	Apoplatic	Good soil movement (lateral)	2 years	Ground-water

¹ Restricted use pesticide: especially mobile in sandy soils

Table B3. Active ingredient rates and 1997-1999 costs of herbicide treatments used to control kudzu at the Savannah River Site, South Carolina. All costs are based on 1999 retail value, reported by Timberland Enterprises, Greensboro, GA.

Herbicide	Active ingredient	1997 cost	Yearly re-treatment costs*	Total study cost
clopyralid	.22 kg ai ha ⁻¹	\$113.51 ha ⁻¹	\$56.76 ha ⁻¹	\$103.37
metsulfuron	.17 l ai ha ⁻¹	\$176.43 ha ⁻¹	\$22.05 ha ⁻¹	\$96.38
picloram	.34 kg ai ha ⁻¹	\$119.25 ha ⁻¹	\$14.90 ha ⁻¹	\$65.08
2,4-D	.67 kg ai ha ⁻¹			
tebuthiuron	4.48 kg ai ha ⁻¹	\$298.99 ha ⁻¹	\$74.75 ha ⁻¹	\$201.16
triclopyr	2.13 kg ai ha ⁻¹	\$155.13 ha ⁻¹	\$19.39 ha ⁻¹	\$84.76

*Typically, one half the rate is used in the re-treatment of a kudzu patch (Everest et al 1991). It was estimated that areas in this study were spot treated in 1998 and 1999 using one quarter of the rate used in 1997, except tebuthiuron (estimated to use one half of the original application) and clopyralid (broadcast sprayed at the original rate).

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APPENDIX C SOIL SERIES¹

Table C1. Characteristics of soil series present in the study.

Study site	Soil series	Texture	Permeability	Drainage
Cloverleaf	Troup	loamy	moderately	excessive
Home	Ailey	loamy	slowly	well
Home	Dothan	fine-loamy	moderately slow	well
Home	Varina	fine-loamy	slowly	well
Burma	Fuquay	loamy	moderate to low	well
Reactor	Udorthent	loamy	slowly	poor to moderate

¹ Each block of this study had different soil series. Soil composition should be considered before any herbicide application. Permeability and drainage of soils may favor groundwater contamination and/or off site movement of herbicides which could result in non-target vegetation damage.

APPENDIX D

CROWN COVER RESPONSES

Table D1. Orthogonal contrasts and significance levels (*P*) for cover (%) of kudzu, blackberry, herbs, and pine in response to five herbicide treatments and broadcast burning at the Savannah River Site, South Carolina.

Contrast I: Untreated check (U) versus herbicide treatments (H)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	U	H	<i>P</i>	U	H	<i>P</i>	U	H	<i>P</i>	U	H	<i>P</i>
7-97	68.1	88.4	<0.001	12.0	6.2	<0.001	8.6	2.4	<0.001	---	---	---
8-97	88.1	5.1	<0.001	7.8	6.9	0.002	5.0	0.4	<0.001	---	---	---
6-98	65.7	4.1	<0.001	14.1	6.7	<0.001	18.4	20.0	0.882	1.1	1.4	0.276
8-98	72.0	0.6	<0.001	5.6	5.0	<0.001	26.1	26.7	0.671	0.2	1.2	<0.001
8-99	94.1	0.4	<0.001	10.0	11.2	0.161	8.1	55.1	<0.001	0.1	6.1	<0.001

Contrast II: Tebuthiuron (granular-G) versus spray-applied herbicides (S)												
mo-yr	Kudzu			Blackberry			Herbs			Pine		
	G	S	<i>P</i>	G	S	<i>P</i>	G	S	<i>P</i>	G	S	<i>P</i>
7-97	88.3	88.5	0.858	3.8	6.8	0.042	3.7	2.0	0.178	---	---	---
8-97	23.7	0.4	<0.001	4.6	7.4	0.145	0.3	0.4	0.993	---	---	---
6-98	3.5	4.3	0.966	2.4	7.8	0.038	4.4	23.8	<0.001	0.4	1.7	<0.001
8-98	1.1	0.5	0.010	1.2	5.9	0.015	5.7	31.9	<0.001	0.3	1.5	<0.001
8-99	0.5	0.3	0.375	3.1	13.2	<0.001	25.4	62.5	<0.001	0.3	7.5	<0.001

Table D1 continued

Contrast III: Pine tolerant (T) versus pine intolerant (I) herbicides

mo-yr	Kudzu			Blackberry			Herbs			Pine		
	T	I	P	T	I	P	T	I	P	T	I	P
7-97	92.1	84.9	0.005	5.3	8.3	0.034	2.0	2.0	0.764	---	---	---
8-97	0.8	0.1	0.098	14.8	0.1	<0.001	0.6	0.2	0.142	---	---	---
6-98	4.9	3.7	0.040	14.8	0.7	<0.001	20.5	27.1	0.002	1.6	1.8	0.394
8-98	0.9	0.1	0.013	0.4	11.5	<0.001	28.9	34.9	0.007	1.3	1.7	0.069
8-99	0.6	0.1	0.037	22.1	4.4	<0.001	45.4	79.6	<0.001	8.3	6.8	0.074

Contrast IV: Picloram (P) versus triclopyr (T)

mo-yr	Kudzu			Blackberry			Herbs			Pine		
	P	T	P	P	T	P	P	T	P	P	T	P
7-97	87.6	82.2	0.189	10.3	6.4	0.073	0.7	3.2	0.061	---	---	---
8-97	0.0	0.1	0.938	0.0	0.1	0.617	0.1	0.2	0.603	---	---	---
6-98	0.3	7.2	<0.001	0.7	0.7	0.999	22.7	31.5	0.005	1.7	1.9	0.619
8-98	0.1	0.0	0.784	0.6	0.1	0.141	38.1	31.7	0.094	1.5	1.8	0.430
8-99	0.1	0.0	0.570	6.6	2.2	0.008	86.7	72.5	0.005	5.5	8.0	0.027

Table D1 continued

Contrast V: Metsulfuron (M) versus clopyralid (C)

mo-yr	Kudzu			Blackberry			Herbs			Pine		
	M	C	P	M	C	P	M	C	P	M	C	P
7-97	90.3	93.8	0.241	3.8	6.9	0.091	1.8	3.2	0.729	---	---	---
8-97	0.0	1.5	0.002	0.2	29.4	<0.001	0.4	0.7	0.548	---	---	---
6-98	2.6	7.1	0.004	0.3	29.4	<0.001	26.1	15.0	<0.001	1.7	1.4	0.038
8-98	0.0	1.8	<0.001	0.0	23.0	<0.001	43.6	14.2	<0.001	1.3	1.3	0.946
8-99	0.4	0.7	0.509	0.6	43.5	<0.001	21.8	69.1	<0.001	9.9	8.0	0.013

APPENDIX E

EXPERIMENTAL DESIGN

I. Prediction Equations

1997 and 1998 log (biomass) values were predicted from the following equations:

$$\text{Kudzu } (r^2=0.9154)=\log 2.206653+ 0.775695*\log(\text{cover})$$

$$\text{Blackberry } (r^2=0.8204)=1.775289+0.943282*\log(\text{cover})$$

$$\text{Herbaceous } (r^2=0.8710)=2.338989+0.977834*\log(\text{cover})$$

$$\text{Pine } (r^2=0.7198)=1.623753+0.365059*\log(\text{cover})$$

1999 log (biomass) values were predicted from the following equations:

$$\text{Kudzu } (r^2=0.8298)=1.624832+ 0.894554*\log(\text{cover})$$

$$\text{Blackberry } (r^2=0.5954)=1.155220+1.003488*\log(\text{cover})$$

$$\text{Herbaceous } (r^2=0.6862)=2.119325+1.023109*\log(\text{cover})$$

$$\text{Pine } (r^2=0.7029)=1.016489+1.014199*\log(\text{cover})$$

Log (leaf area index) equations for are as follows:

$$1997 \text{ and } 1998 (r^2=0.6488)=-2.357727+0.762843*\log(\text{cover})$$

$$1999 (r^2=0.6272)=-2.394916+0.774221*\log(\text{cover})$$

Pine log (biomass) weights in January 1999 was estimated from a regression on height and ground line diameter ($r^2=0.7736$):

$$\log(\text{weight}) = -2.414017 + 0.46224112 * \log(\text{height}) + 1.637720 * \log(\text{ground line diameter}).$$

II. Orthogonal Contrasts

The different main treatment herbicides were chosen from a variety of herbicides on the market labeled to control kudzu. Differentiating features such as translocation method and selectivity were the basis of selection. Orthogonal contrasts were only used on the main treatment tests (Dowdy and Weardon 1991, Ott 1993). The orthogonal contrast matrix is shown in Table E1.

The first contrast involves all main treatments. This contrast distinguishes between the untreated check and the herbicide treatment effects.

The second contrast differentiates between soil-applied and spray-applied herbicides. This contrast involves only the herbicide treatments and not the untreated check. Tebuthiuron (Spike) was the only herbicide used in granular form. The effects of this herbicide may appear to be slower acting because it must be incorporated by rain into the soil. It will enter the plant by the roots and translocated in the xylem, thus

moving with water and minerals. This will cause a delay in effects in comparison to the spray-applied herbicides, which enter the plant almost immediately and will be translocated in the phloem. There may be some question of better coverage with granular herbicides in dealing with kudzu. The granules contact with the soil or wash with rainwater into the soil evenly. With spray applied herbicides, coverage of kudzu leaves in the under-canopy may not be as consistent.

A third contrast is only between the herbicides tolerated by pines, clopyralid (Transline) and metsulfuron (Escort), and the herbicides not tolerated by pines, picloram (Tordon) and triclopyr (Garlon). This contrast will show if efficacy is being sacrificed by choosing herbicides safe to spray over pines. Any differences will be useful in recommendations to prepare landowners as to what to expect.

The last two contrasts distinguish between herbicides in these groups (Table E1). Efficacy differences in herbicides with similar traits may be helpful in recommending chemicals in specific situations.

Table E1: All main treatment orthogonal contrasts.

Contrast	Matrix					
	CH	ES	GA	SP	TO	TR
untreated check versus all herbicide treatment plots	+5	-1	-1	-1	-1	-1
tebuthiuron versus spray applied herbicide plots	0	-1	-1	+4	-1	-1
pine tolerant herbicides versus pine intolerant herbicides	0	+1	-1	0	-1	+1
Picloram versus triclopyr	0	0	-1	0	+1	0
Metsulfuron versus clopyralid	0	+1	0	0	0	-1

Abbrev.: CH: untreated check TR: Transline (clopyralid)
 GA: Garlon (triclopyr) ES: Escort (metsulfuron)
 TO: Tordon (picloram) SP: Spike (tebuthiuron)

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APPENDIX E

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