# ABSTRACT

THORNTON, MELISSA ROSE. Arthopod Fauna Associated With Kudzu (*Pueraria montana* var. *lobata* Willd) In North Carolina. (Under the direction of David Orr.)

The purpose of this research was to obtain background information to aid the implementation of a biological control program against the weed, kudzu *(Pueraria montana* var. l*obata* Willd*).* This research had several specific objectives that examined: 1) potential insect pollinators and seed production of kudzu in NC; 2) phytophagous insects and insect herbivory of kudzu foliage, seeds, vines and roots in NC; 3) abundance and diversity of foliar, vine, and root feeding insect communities on kudzu in comparison with those found on soybeans, the closest North American relative of kudzu in the United States. Kudzu is pollinated by native and naturalized insects in NC, in a pattern that varies by flower apparency rather than density. Arthropod herbivory by native generalists almost eliminated kudzu seed viability, while a naturalized Asian specialist consumed a nominal proportion of seeds. These data indicate that seed feeding arthropods would be poor candidates for importation biological control. Kudzu and soybeans shared the same foliar feeding insect communities and levels of defoliation, suggesting that foliage feeders are also poor choices for importation. No kudzu vine or root feeding insects or damage were found during the two years of this study, suggesting that future importation biological control research should focus on such feeders from Asia.

# ARTHROPOD FAUNA ASSOCIATED WITH KUDZU (*PUERARIA MONTANA* VAR. *LOBATA* WILLD) IN NORTH CAROLINA

by

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# ABSTRACT

Potential insect pollinators of kudzu *(Pueraria montana* var. *lobata)* and kudzu seed production were studied in order to obtain background information for a biological control program against the weed. Ten species of potential pollinators, representing six families and 2 orders, were observed visiting kudzu flowers. Native Hymenoptera were the most diurnally and seasonally active potential pollinators. Activity was greatest in the morning (6.0 ± 5.0 flowers/raceme/hr) and early afternoon (6.4 ± 3.5 flowers/raceme/hr) and was reduced in late afternoon (2 ± 1.4 flowers/raceme/hr). An introduced species, the giant Asian resin bee, *Megachile sculpturalis* (Clark) (Hymenoptera: Megachilidae), and the native carpenter bee, *Xylocopa virginica* (L.) had the greatest pollen loads (100's - 1000's of pollen grains per insect). The average density of mature flowers in kudzu growing over shrubs 1.5 - 2.0 m in height (11.8 ± 4.84/$m^2$) was not significantly different from the density in plots where kudzu was growing over a flat surface (7.08 ± 2.12/$m^2$ ). However, there was a significant interaction between kudzu height and seed density. Seed density averaged 837 ± 445 in plots with kudzu growing over shrubs, while seed density in plots of prostrate kudzu was 3 ± 5.3. It may be inferred that pollination was strongly influenced by flower visibility and not by flower density.

**Key words:** *Pueraria montana var. lobata*, kudzu, pollinators, seed density.

# Introduction

Kudzu, *Pueraria montana* (Lour.) Merr. Var. *lobata* (Willd) Maesen and S. Almeida (Ward 1998), is an invasive exotic weed of primary concern in the southeastern United States, but with a range that spans from Massachusetts to Florida, and west to Oklahoma and Texas (Frankel 1989, Mitich 2000). Kudzu infestations have also recently been discovered in Oregon (Coste 2000). This perennial, semi-woody, climbing, leguminous vine is native to China but was subsequently introduced to Japan, and from there was first introduced to the United States in a display at the Japanese pavilion in the Philadelphia Centennial Exposition of 1876 (McKee and Stevens, 1943). Kudzu was first used as an ornamental "porch" vine during the late 19th century in the southeastern United States (Winberry and Jones, 1973), then was found to be nutritionally sound and palatable as a forage crop at the beginning of the 20th century (Piper, 1920). Widespread distribution of kudzu did not occur until the 1930's and 40's when the USDA Soil Conservation Service provided approximately 84 million seedlings for planting on roughly 120,000 acres of eroded or erodable land in the southeast (Tabor and Sussot, 1941).

By 1953, the USDA no longer recommended kudzu as a permissible cover plant for the Agricultural Conservation Program, then in 1970, listed it as a common weed in the southeastern United States (Everest et al. 1999), and finally in 1999 kudzu was declared a federal noxious weed (Mitich 2000). Estimates of the total spread of kudzu vary considerably from several hundred thousand acres to over 10 million acres (Fears and Frederick 1977, Miller and Edwards 1983, Everest et al. 1991, Corley et al. 1997, Britton et al. 2001, Mitich 2000). Many consider invasive species such as kudzu to be the second most important threat to biodiversity after habitat destruction (Kaiser 1997). Kudzu is widely believed to drastically reduce biodiversity, due to its tendency to smother other vegetation and exist as a monoculture.

Various management and eradication programs have been employed to control the spread of kudzu, from intensive herbicide application (Miller and Edwards 1983), to livestock grazing (Martin 1984, Bonsi et al. 1992), to industrial use of the plant (Tanner et al. 1979), but none have shown lasting results. Biological control of kudzu has only recently been considered as a possible management strategy. Kudzu appears to be a good candidate for a classical biological control project, since this naturalized weed appears to lack natural enemies capable of lowering its pest status in the United States (Britton et al. 2001). However, in order to successfully implement a classical biological control program, it is necessary to gain as much knowledge as possible about the biology and ecology of the target species (van Driesche and Bellows 1996).

As part of this effort, Thornton (2004) surveyed insects feeding on kudzu foliage, vines, roots, and seeds in North Carolina. It has frequently been stated that kudzu rarely produces viable seed in the United States (Pieters 1932, McKee and Stevens 1943, Everest et al. 1991, Hipps 1994). However, Mes (1953) observed that unidentified hymenopterans visited kudzu flowers in South Africa, and kudzu is believed to be cross pollinated by insects in the United States (Duke 1996). No quantitative analyses have been conducted on kudzu pollination or seed production by this plant in the United States. This information will be important to assess the impact of seed feeding insects on kudzu in the United States, and to assess the need for importation of natural enemies of kudzu seeds. The purpose of this study was to identify insects that are potential pollinators of kudzu and to assess kudzu seed production in North Carolina.

## Materials and Methods

**Potential insect pollinators.** Flowering kudzu racemes were observed at Centennial Campus, North Carolina State University, Raleigh, North Carolina, for evidence of diurnal pollination by arthropods. Observations were conducted on two consecutive days, every 2 weeks from 7 July 1999 to 9 September 1999. Data collected from each of the two consecutive days of observations were grouped to simplify analysis. Observations occurring after 24 August 1999 were omitted from analysis due to the low number of insect visits at this time. Five racemes, less than 0.3m apart from one another, were observed for insect visits from 8:00 AM to 9:00AM, 12:00 PM to 1:00 PM, and 4:00 PM to 5:00 PM. Flower visitation was defined for hymenopterous insects as the approach to one or more flowers of a raceme and contacting the pistil and stamen while imbibing nectar. A lepidopteran visit was defined as imbibing nectar from one or more flowers of a raceme without pistil and stamen contact necessarily occurring. The insect species visiting flowers, the number of flowers approached per visit, and the length of each visit were recorded for each raceme. The six species of indigenous hymenopterans identified were grouped into a single category, "native hymenoptera", due to the infrequency of visitation by several of these species, and to simplify analysis.

Voucher specimens of potential kudzu pollinators were collected and stored at -20°C in plastic cups (30 ml, Polar Rx, Polar Plastics Inc., Wilmington, DE) until curation and identification were conducted. Pollen grains were collected from voucher specimens and slide-mounted with fuchsin glycerin jelly, as described by Beattie (1971), and were compared to reference pollen samples from kudzu, also slide mounted with fuchsin glycerin jelly, under a compound microscope (Wild MZ8, Leica Microsystems Inc., Bannockburn, IL). A pollen atlas was also used to compare pollen samples collected from voucher specimens to pollen of common flowering plants in North Carolina (Bambara and Leidy 1991).

**Factors affecting seed density.** To assess any relationships between flower density and pollinator success, 10 plots (1m$^2$ soil surface) were set up over patches of kudzu that were expected to yield a range of flower densities. This was done while kudzu was in full bloom (13 August 1998, 28 July 1999). Half of the plots were in areas where there was no other notable vegetation or structures over which kudzu could grow, and the canopy ranged from 0.6 - 0.9 m deep. Remaining plots included kudzu that had grown over shrubs or small trees, ranging from 1.5 - 2.0 m in height. In flat plots, flower racemes were hidden from view beneath a closed canopy, while in the elevated plots, flowers were protruding from foliage and not obstructed from view.

Kudzu seed pods were harvested from plots at the end of the growing season (13 November 1998, 29 October 1999), when seeds were mature. Individual dried racemes were placed in plastic bags (15.9cm by 14 cm, Ziploc, S.C. Johnson & Son, Racine, WI) and stored at -20°C. The number of pods per raceme was tallied, then pods were hulled and the number of seeds per pod and total seed crop per m$^2$ of soil surface was determined.

**Insect identification.** Collected insects from all studies were identified with the assistance of David Stephan, Plant Disease and Insect Clinic, North Carolina State University. Voucher specimens of all collected insects were preserved and curated as described by Borrer et al. (1989), and deposited in the North Carolina State University Entomology Department museum collection.

**Data analysis.** Seasonal and diurnal activity data of potential insect pollinators were analysed using a mixed model analysis of variance (PROC MIXED) (SAS Institute 1998).

Least squares means for average number of flower visits per raceme and average visit length per flower were each separated using a mixed procedure (PROC MIXED) (SAS Institute 1998). Data for *Apis mellifera* were omitted from difference of least squares means analyses due to the low number of flower visits by this insect.

An analysis of variance (PROC ANOVA) (SAS Institute 1998) was used to test for differences between kudzu height and seed density and between flower density and seed density (SAS Institute 1998). An unpaired *t*-test was performed to analyze the effect of canopy height on flower density (Steel et al. 1997).

## Results

**Potential insect pollinators.** Ten species of potential pollinators from six families and 2 orders were observed visiting kudzu flowers (Table 1.1). Of the specimens collected, *Megachile sculpturalis* Smith and *Xylocopa virginica* (L.) had the greatest amount of kudzu pollen collected from their bodies. *Ceratina dupla* Say, *Bombus impatiens* Cresson, and *Apis mellifera* (L.) were found to carry smaller amounts of kudzu pollen, and no kudzu pollen was detected on *Conura amoena* (Say), *Dialictus* sp., *Megachile* sp., *Bombus fraternus* (Smith), and *Epargyreus clarus* (Cramer).

Observed insects varied in the number of flowers visited per raceme per hour ($F=56.33$; $df=3, 144$; $P<0.001$) and in the length of each visit ($F=12.17$; $df=3, 44$; $P<0.001$) (Figs. 1.1, 1.2). Time of day had a significant impact on the number of flowers visited ($F=14.57$; $df= 2, 32$ $p<0.001$) but not on the length of visit by observed insects ($F=0.32$; $df=2, 27$; $P=0.73$). The date within the season affected the number of flower visits per raceme per hour ($F=29.96$; $df=3,16$; $P<0.001$) but not the length of visit per flower ($F=3.79$; $df=3, 122$; $P=0.48$). The general trend was that the mean number of flower visits per raceme decreased with diurnal and seasonal progression for all insects observed, with the exceptions of native bees on 9 July 1999 and *E. clarus* on 27 July 1999, which both had peak flower visitations at 12:00 PM (Fig. 1.1). The mean length of visit per flower generally remained consistent with diurnal and seasonal progression for hymenopterans and decreased with seasonal progression for the lepidopteran, *E. clarus* (Fig. 1.2).

Averaged over all dates and times, native bees had the greatest number of flower visits per raceme (4.78 ± 5.40 visits), compared with *M. sculpturalis* ($t=-3.55$; $df=144$; $P<0.001$; 3.55 ± 4.98 visits). Because *A. mellifera* was an infrequent visitor, and *E. clarus* is considered a nectar thief rather than a pollinator, they were not compared statistically with native bees and *M. sculpturalis.* (Fig. 1.1). The average number (± SD) of flowers visited per raceme by native bees throughout the season was 6.0 ± 5.0 at 8:00 AM, 6.4 ± 3.5 at 12:00 PM, and 2 ± 1.4 at 4:00 PM. *Megachile sculpturalis* was moderately active, visiting 5.6 ± 6.8 flowers per raceme at 8:00 AM, 3.9 ± 3.8 flowers at 12:00 PM, and 1.2 ± 1.1 flowers per raceme at 4:00 PM. *Apis mellifera* had the least number of visits throughout the growing season with no flowers visited at 8:00 AM, 0.2 ± 0.3 flowers visited per raceme at 12:00 PM, and 0.7 ± 1.0 flowers visited per raceme at 4:00 PM. *E. clarus* was also a frequent visitor (3.6 ± 4.4 flowers per raceme at 8:00 AM, 5.3 ± 7.3 flowers per raceme at 12:00 PM, and 2.5 ± 3.1 flowers per raceme at 4:00 PM).

Native bees visited each flower for an average of 8.37 ± 9.46 s, which was not significantly different from *M. sculpturalis (t=-1.92; df=78; P=0.06;* 4.35 ± 2.67 s) (Fig. 1.2). Native bees' flower visits ranged from 11.2 ± 19.7 s per flower at 8:00 AM, to 7.6 ± 4.7 s per flower at 12:00 PM, and 7.9 ± 6.5 s per flower at 4:00 PM. *Megachile sculpturalis* visit lengths were 4.3 ± 1.7 s per flower at 8:00 AM, 4.1 ± 1.9 s per flower at 12:00 PM, and 4.5 ± 3.6 s per flower at 4:00 PM. *Apis mellifera* had the shortest visits overall with no flowers visited at 8:00 AM, only one visit at 12:00 PM which lasted 2.0 s, and three visits which lasted 6.2 ± 4.5 s at 4:00PM. *Epargyreus clarus* had the longest visits which were 16.3 ± 15.5 s at 8:00 PM, 12.9 ± 8.8 s at 12:00 PM, and 15.2 ± 14.4 s at 4:00 PM. *E. clarus* visit length decreased as the season progressed.

*Megachile sculpturalis* visited significantly more flowers than native hymenoptera only during one sampling period, at 8:00 AM on 8, 9 July 1999 *(t= 5.48; df= 24; P<0.001).*

Native hymenoptera had a significantly greater number of visits than *M. sculpturalis* at 4:00 PM 26, 27 July 1999 *($t= -2.02$; $df= 24$; $P=0.05$)*, 8:00 AM and 12:00 PM 11, 12 August *($t= -6.22$; $df=24$; $P<0.001$; $t=-3.57$; $df=24$; $P=0.002$)*, and at all three observation times on 23, 24 August *($t= -2.25$; $df= 24$; $P=0.03$; $t= 5.48$; $df=4, 24$; $P<0.001$; $t= -2.09$; $df= 24$; $P=0.047$)*.

**Factors affecting seed density.** Kudzu height in 1998 did not significantly affect flower density *($df=8$; $P>0.05$).* The average number of mature flowers in kudzu growing over shrubs 1.5 -2.0 m in height was 11.8 ± 4.84/$m^2$, and 7.08 ± 2.12/$m^2$ in plots where kudzu was not growing.

The density of mature flowers per $m^2$ of soil surface did not significantly affect seed density *($F=2.16$; $df=1,9$; $P>0.05$)*. However, kudzu height appeared to affect seed density *($F=20.13$; $df=1,9$; $P<0.005$).* The average seed density among the five 1 $m^2$ *P. montana* plots growing over shrubs was 837 ± 445 and the average number of racemes within these plots was 18 ± 8, while seed density was 3 ± 5.3 with an average of 9 ± 3 racemes /$m^2$ where kudzu was prostrate. Kudzu seed production was variable in North Carolina and ranged from 0 - 1800 seeds per $m^2$ of soil surface in kudzu in 1998.

## Discussion

Insects representing 10 species, 6 families, and 2 orders were observed imbibing nectar from kudzu flowers during the summer of 1999. These insects were evaluated for their potential to serve as pollinators of kudzu. Observed native species were the hymenopterans, *Conura amoena* (Say), *Dialictus* sp., *Megachile* sp., *Ceratina dupla* Say, *Xylocopa virginica* (L.), *Bombus impatiens* Cresson, *Bombus fraternus* (Smith), and the lepidopteran, *Eparygyreus clarus* (Cramer) (Table 1.1). Naturalized insects were also observed visiting kudzu flowers and were the hymenopterans, *Megachile sculpturalis* Smith, and *Apis mellifera* (L.) (Table 1.1).

The flower structure of kudzu is typical of insect pollinated flowers, such as those of *Lupinus* spp. (Mes 1953), which are in the same subfamily as kudzu, Papilionoideae (Polhill 1994). Papilionaceous flowers are characterized as having a large standard petal, two lateral wing petals, and 2 petals joined by their lower margins to form the keel, which houses the reproductive organs of the flower (Williams 1987). Pollen transfer occurs when a visiting insect exerts pressure on the wing petals, everting the stamens and stigma, which are then in contact with the abdominal surface of the insect (Knuth 1906, Williams 1987). Heavier and larger insects are said be more effective at tripping papilionaceous flowers (Williams 1987). The specimens that had the greatest number of pollen grains collected from their bodies in the current study were in fact some of the largest insects observed, whereas little or no pollen was collected from the smaller insects (Table 1.1). *Megachile sculpturalis* had the greatest average number of pollen grains and was the largest insect observed (Table 1.1). *Xylocopa virginica* also had a large pollen load (Table 1.1). Little pollen was collected from *Bombus* spp. (Table 1.1). It has been hypothesized that social insects, which must provision nonforaging individuals in the colony, should collect more resources when foraging than solitary insects, which only need to provide for their offspring (Heinrich 1983). However, *Bombus* spp. are social whereas *M. sculpturalis and X. virginica* are solitary insects.

Nectar production by plants results in fewer resources that can be allocated for seed production (Heinrich 1983). Furthermore, in order to increase fitness, cross-pollinating plants must produce enough nectar to be attractive to pollinators but must not produce so much nectar that visiting insects would not need to forage at more than one flower, thus impeding cross-pollination (Bohn and Mann 1960, Heinrich 1983). Therefore, plants generally only produce nectar and pollen during specific periods of the day (Waddington 1983). Insects have learned to forage when pollen and nectar production are optimal. Studies have shown that *Apis mellifera* has an internal clock which enables it to effectively time its visits to flowers (von Frisch 1967). In the current study, the greatest number of flower visits per raceme and the longest visits per flower primarily occurred during the 8:00-9:00 AM and 12:00-1:00 PM observations, indicating that nectar and pollen production are reduced by 4:00 PM.

The native bee species and *Megachile sculpturalis* were the predominant hymenopteran visitors of kudzu during the first two grouped dates of the study (Figs. 1.1A, 1.1B). The number of flowers visited by *M. sculpturalis* was greatly reduced during the last two grouped dates (Figs. 1.1C, 1.1D). Although flower visitation was also reduced in native bees during the last two grouped dates, these insects had the greatest number of visits per raceme and generally the longest visit length per flower of the hymenopterans observed (Figs. 1.1C, 1.1D, 1.2C, 1.2D). Pollinators have been found to forage longer on flowers that provide more resources (Pyke 1978, Best and Bierzychudek 1982, Gori 1983, Hodges 1985, Gori 1989), and a positive correlation exists between the size of a nectar resource and the number of flowers visited (Krell 1986). The native bees observed visiting kudzu flowers are generalist foragers (Mitchell, 1960, 1962) and appeared to frequently utilize kudzu nectar as an energy source. Native bees were the predominant potential pollinators of kudzu in North Carolina, since they consistently visited the greatest number of flowers and had the greatest visit length per flower throughout the season (Figs. 1.1, 1.2). The decline in flower visitation by all observed insects with seasonal progression may be due to the plant allocating more resources to seed production than nectar production. Kudzu flowers would be less rewarding to foragers late in the season, and would thus be visited less frequently and for shorter time periods.

*Megachile sculpturalis* was accidentally introduced to the United States from Asia within the past 30 years (Mangum and Brooks 1997), possibly in a shipment of wood (Mangum 1998). The currently confirmed range of *M. sculpturalis* is from Virginia south to Georgia and was believed to initially have been introduced to North Carolina, where the giant resin bee is wide spread (Mangum 1998). In Asia, *M. sculpturalis* forages on a wide variety of plant species and was recorded foraging on kudzu in Japan (Mangum and Brooks 1997). In North Carolina, *M. sculpturalis* also forages on kudzu and a wide variety of other plants, such as golden rain tree (*Koelreutaria paniculata*), and Chinese privet (*Ligustrum spp.),* (Mangum 1998), which are also of Asian origin (Dirr 1997). *M. sculpturalis* is said to be active from June to September. (Mangum 1998). It is not known why kudzu foraging activity by *M. sculpturalis* declined after 26, 27 July 1999 (Figs. 1.1, 1.2). Perhaps *M. sculpturalis* was foraging on alternate plant species for the latter half of the growing season.

Other plant species, such as *K. paniculata,* which blooms in mid summer (Dirr 1997), may be more attractive to *M. sculpturalis* than kudzu as the season progresses.

*Apis mellifera* only visited a small number of flowers from 12:00-1:00 PM on 8, 9 July 1999 (Figs 1.1A, 1.2A), and from 4:00-5:00 PM on 26, 27 July 1999 (Figs. 1.1B, 1.2B). Unlike the native bees and *M. sculpturalis*, *A. mellifera* was active toward the latter half of the day, when kudzu nectar production appeared to be reduced. Limited flower visitation by *A. mellifera* may have been due to expended nectar sources at this time. *A. mellifera* flower visitation was not recorded during the remainder of the observations throughout the season. *A. mellifera* is a generalist forager (Mitchell 1962), like the other hymenopterans observed, and appeared to utilize kudzu as nectar source. Like *M. sculpturalis*, *A. mellifera* may visit alternate nectar sources for the latter half of the season. Infrequent visitation by *A. mellifera* is also likely explained by the dramatic decline in populations of this species in recent years, due to the accidental introductions of the tracheal mite, *Acropsis woodi;* the varroa mite, *Varroa jacobsoni;* and the small hive beetle, *Aethina tumida* (Ambrose 1999a, 1999b, 2000). Within the past 15 years, since these invasive pests have been introduced to North Carolina, one third of the managed *A. mellifera* colonies and essentially all of the feral colonies have been eliminated (Ambrose 1999a). Habitat destruction has also contributed to *A. mellifera* population decline (Bambara 1993).

*Epargyreus clarus* generally had the greatest average visit length per flower of all insects observed. The average number of flowers visited per raceme per hour by *E. clarus* peaked on 26, 27 July 1999 (Fig. 1.1 B) and was the greatest from 12:00-1:00 PM. These findings are consistent with *E. clarus* life history and behavior. *E. clarus* is bivoltine throughout the eastern United States, and the first generation occurs from May to early July;

the second generation occurs from late July to September (Opler and Krizek 1984). Mating predominantly occurs at midday (Opler and Krizek 1984). Adult *E. clarus* would be present and mating by 27 July 1999 and peak activity would likely occur from 12:00-1:00. However, *E. clarus* does not seem to be a pollinator of kudzu. *E. clarus* did not appear to trip kudzu flowers during observations. Furthermore, no kudzu pollen was collected from *E. clarus* specimens (Table 1.1). Venables and Barrows (1985) concluded that *E. clarus* was more likely a nectar thief than a pollinator, due to its behavior during flower visitations. Kudzu appears to be an important energy source throughout the life history of *E. clarus;* larvae feed on kudzu foliage (Thornton 2004), while adults feed on kudzu nectar.

The closest relative to kudzu in the United States is the soybean, *Glycine max*, which also is of Asian origin (Britton et al.2001). The average soybean production for 1998 was 1557 seeds per $m^2$ of soil surface (American Soybean Association 1998). Kudzu seed production was highly variable. Seed density appeared to be independent of flower density. However, an interaction was found between seed density and flower height, where the number of seeds produced was greater among kudzu with elevated flowers than among prostrate kudzu with flowers growing closer to the ground. The reproductive output of both cultivated and wild cross-pollinated plants has been found to be pollinator limited (McGregor 1976, Bierzychudek 1981, Fenner 1985). Poor pollination may be caused by insufficient pollinator numbers or by pollinator inefficiency (Bierzychudek 1981). The racemes of elevated kudzu protruded above the canopy and may have been more apparent to pollinators than the racemes of prostrate kudzu which were below the canopy, resulting in reduced pollination and seed set among these racemes.

Kudzu does appear to be pollinated by insects in North Carolina, and native bees are likely the primary pollinators, due to their consistently high number of flower visits and visit lengths throughout the season. However, as this was a preliminary study, further research is needed to confirm these data. Although this study showed insects had pollen transferred to their bodies from kudzu flowers, a future study should be done to determine whether this pollen is then transferred from the bodies of visiting insects to the stigma of kudzu flowers, in order to truly establish that cross-pollination by insects occurs in kudzu. It is well known that kudzu out-competes native flora for resources (Fears and Frederick 1977, Miller and Edwards 1983, Everest et al. 1991). Another topic for investigation should be whether kudzu is able to out-compete native flora for pollinators and further reduce their competitive ability, due to the prevalence of kudzu flowers in infested areas.

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Table 1.1. Species observed visiting inflorescences of *P. montana* collected in 1999 and the approximate number of kudzu pollen grains obtained from each specimen with fuchsin glycerine jelly.

| Insect Species | N | Spp. origin | App. # of pollen grains/ insect |
|---|---|---|---|
| Hymenoptera | | | |
| Chalcididae | | | |
| *Conura amoena* (Say) | 1 | Indigenous | 0 |
| Halictidae | | | |
| *Dialictus* sp. | 1 | Indigenous | 0 |
| Megachilidae | | | |
| *Megachile sculpturalis* Smith | 2 | Naturalized (Asia) | 1000's |
| *Megachile* sp. | 1 | Indigenous | 0 |
| Anthophoridae | | | |
| *Ceratina dupla* Say | 1 | Indigenous | 10's |
| *Xylocopa virginica* (L.) | 4 | Indigenous | 100’s |
| Apidae | | | |
| *Bombus impatiens* Cresson | 3 | Indigenous | 10’s |
| *Bombus fraternus* (Smith) | 1 | Indigenous | 0 |
| *Apis mellifera* L. | 2 | Naturalized (Europe) | 10’s |
| Lepidoptera | | | |
| Hesperiidae | | | |
| *Epargyreus clarus* (Cramer) | 3 | Indigenous | 0 |

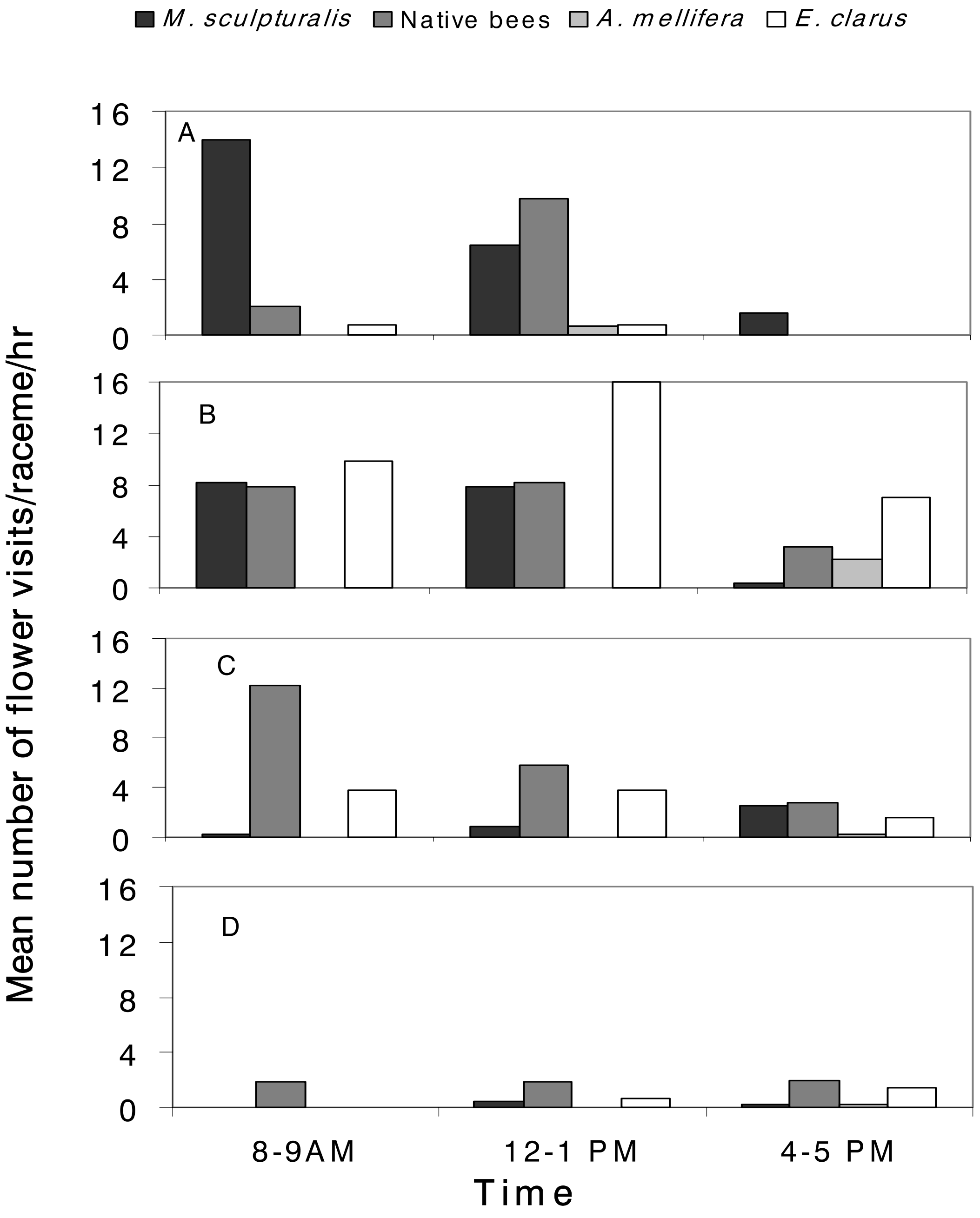

Figure 1.1. Mean number of flower visits per raceme per hour by potential insect pollinators, throughout the *P. montana* flowering period, Centennial Campus, NCSU, Raleigh, North Carolina, 1999, From 8:00 - 9:00 AM, 12:00 - 1:00 PM, and 4:00 - 5:00 PM. A - D = dates 9 July 1999, 27 July 1999, 12 August 1999, and 24 August 1999, respectively

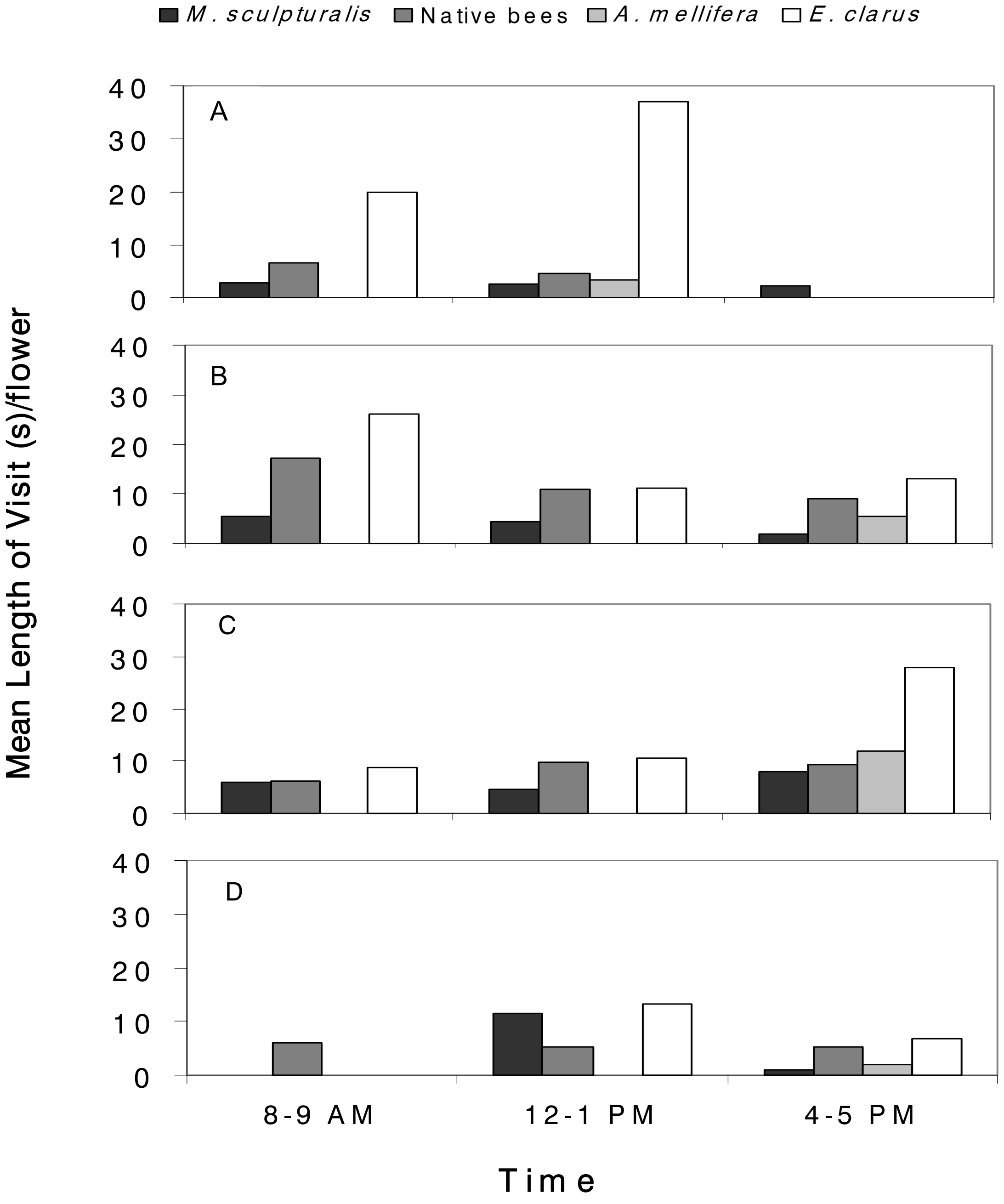

Figure 1.2. Mean length of visits per raceme in s, by potential insect pollinators, throughout the *P. montana* flowering period, Centennial Campus, NCSU, Raleigh, North Carolina, 1999, from 8:00 - 9:00 AM, 12:00 - 1:00 PM, and 4:00 – 5:00 PM. A - D = dates 9 July 1999, 27 July 1999, 12 August 1999, and 24 August 1999, respectively

# II. SEED HERBIVORY OF KUDZU *PUERARIA MONTANA VAR. LOBATA* BY ARTHROPODS IN NORTH CAROLINA

# ABSTRACT

Kudzu seed production and damage by arthropods were studied in order to obtain background information to aid the implementation of a biological control program against this weed in the United States. An exclusion cage study revealed that the viable seed yield of kudzu was low, ranging between 2% (1998) and 11% (1999). This low viability was primarily due to herbivory by native pentatomids during early seed development. A naturalized Asian bruchid (*Boroweicius ademptus* Sharp) was responsible for only 7 to 10% of the seed damage. The level of seed damage caused by both insects was density independent. Pentatomid seed damage was significantly influenced by Julian date but not by seed age. Conversely, the percentage of seeds with bruchid damage was not significantly affected by Julian date, but was affected by seed age. Pentatomids attacked seeds primarily later in the season, after Julian date 287, and bruchids preferentially attacked seeds aged 6 weeks and older. Results from this study suggest that seed feeding insects should not be targeted for importation in a biological control program against kudzu.

**Key words:** *Pueraria montana var. lobata*, kudzu, insect exclusion, *Acrosternum hilare*, *Boroweicius ademptus*, phenology, herbivory.

## Introduction

Kudzu, *Pueraria montana* (Lour.) Merr. Var. *lobata* (Willd) Maesen and S. Almeida is an invasive exotic weed of Asian origin (Ward 1998). Kudzu first appeared in the United States in 1876, in a garden display at the Japanese Pavilion of the Philadelphia Centennial Exposition and was in a similar display at the New Orleans World Exposition of 1883 (McKee and Stephens 1943). At the turn of the century, this perennial, semi-woody, leguminous vine was utilized for ornamental purposes in the southeastern United States (Winberry and Jones 1973). The first non-ornamental plantings of kudzu were for livestock forage, throughout the first half of the 20th century, due to the plant's high nutritive value and palatability to various domestic animals (Piper 1920, Corley et al. 1997). However, problems with maintaining kudzu stands during periods of heavy defoliation, producing sufficient yields, and harvesting kudzu hay precluded the use of kudzu as fodder (Miles and Gross 1939, Sturkie and Grimes 1939). Early in the 20th century, agricultural land in the southeastern United States was badly eroded due to poor agricultural practices (Bailey 1939). Kudzu was recognized as a suitable cover crop during the 30's and 40's, due to its rapid growth and extensive root system (Sturkie and Grimes 1939, McKee and Stephens 1943). At this time, the USDA Soil Conservation Service (SCS) produced 84 million kudzu seedlings (Tabor and Susott 1941, Tabor 1942) to be planted across approximately 120,000 acres of the southeastern United States for erosion control (Tabor and Susott 1941).

However, the growth characteristics of kudzu enabled the plant to spread rapidly in the climate of the southeast and its perceived value quickly diminished during the latter half of the 20th century. In 1953 the USDA removed kudzu from the list of permissible cover plants in the Agricultural conservation program (Everest et al. 1991). By 1970, kudzu was listed as a common weed of the southeastern United States by the USDA (Everest et al. 1991) and as a federal noxious weed in 1999 (Mitich 2000). Kudzu is estimated to currently infest from several hundred thousand acres to over 10 million acres of the Southeastern United States (Fears and Frederick 1977, Everest et al. 1991, Corley et al. 1997, Britton et al. 2001, Mitich 2000). The total range of the plant in the U.S. extends from Massachusetts to Florida, and west to Oklahoma and Texas (Frankel 1989, Mitich 2000). Kudzu infestations have also recently been discovered in Oregon (Coste 2000).

Kudzu appears to reproduce primarily vegetatively in Japan, with little or no reproduction occurring from seed (Tsugawa and Kayama 1985). Sexual reproduction does not appear to be important for kudzu propagation, and only 1 to 2% of the total plant biomass is allocated for seed production (Abramovitz 1983). New plants are established through the formation of roots at vine nodes in contact with the soil (Bailey 1939, Wechsler 1977). Infestations of kudzu are localized due to its apparent reliance on vegetative propagation, and seeds produced by the plant are not readily dispersed (Sasek 1985).

Although seed production does not appear to be critical for kudzu propagation, significant seed yields have been produced by kudzu grown commercially in Japan (Abramovitz 1983) for the production of starch products, textiles, and medicinal compounds (Shurtleff and Aoyagi 1977). Following a seven year erosion control planting program in the United States by the SCS , an attempt was made to develop a domestic seed source for kudzu when World War II prevented imports from Japan (Tabor and Sussott 1941,Tabor 1942). Members of the Civilian Conservation Corps and SCS collected approximately 2400 lbs. of kudzu seeds throughout the southeast in 1941(Tabor 1942). However, seed production and yields were deemed too low to continue the seed collections (Tabor 1942), and root crowns were then propagated to continue kudzu planting programs on erodable land in the southeastern U.S. until 1951 (Davis and Young 1951).

Several authors have reported that kudzu seed in the United States is generally non-viable (Tabor 1942, Mes 1953, Penfound 1966, Wechsler 1977, Sasek 1985) leading some to speculate this was due to a lack of pollinator activity. However, Thornton (2004) found that kudzu appears to be pollinated by native and naturalized insects in the United States and this did not explain the lack of viability. Other factors that may affect kudzu seed viability, such as arthropod herbivory, have not been examined. The purpose of this study was to examine seed herbivory by arthropods to assess its importance in limiting kudzu seed viability in NC. This information will aid in a determination of whether seed feeding insects should be examined as potential agents in a biological control program directed at kudzu.

## Methods and Materials

**Insect Exclusion.** Two exclusion treatments and a control were used to evaluate the impact of insect herbivory on *P. montana* seeds: closed cage over raceme; open cage over raceme, and non-caged raceme. The intent of the cage treatment was to completely exclude arthropods and thus prevent their seed damage, while the purpose of the cage control treatment was to closely simulate the environmental conditions of the cage treatment but to permit entrance and seed feeding by arthropods (van Dreische and Bellows 1996). The control was used to evaluate the natural level of arthropod seed herbivory in the absence of a cage. Should the cage control treatment and control be found to have similar levels of seed feeding, it could then be inferred that microclimate effects were absent.

Immediately before caging, all racemes selected for the study were prepared in the same manner. Newly formed pods were retained, older pods were removed, and racemes were cut just above the new pods to prevent further flowering. Cages were constructed of organdy cloth (64x80 threads per cm, 100% polyester), sewn into pockets (25 by 14 cm) with a 7 cm opening through which racemes were inserted. Cages were tied at their bases with plastic coated tie wire (Dispens-o-wire®, Anchor Wire Co., Goodlettsville, TN), then labeled with aluminum tags (Ben Meadows Company, Canton, GA). The cage control treatment consisted of identical cloth used in the cages (60 x 30 cm) which was draped over the raceme. The tip of the raceme was forced through the cloth with a sharp pencil tip, and the base of the raceme was tied and labeled, as previously mentioned, thus creating a cage that was partially open to the environment. Control racemes lacked cages and were labeled as mentioned. Ten replicates of each treatment were placed along a transect measuring approximately 75m, with the three treatments within each replicate less than 0.6m away from one another. New cohorts of pods were caged as above on 4 August, 21 August, and 7 September in 1998; and 29 July, 17 August, and 3 September 1999.

When seeds had reached maturity (approximately 8 weeks) the dried treatment racemes were removed from vines, placed in plastic bags (0.95L, Ziploc®, S.C. Johnson & Son, Racine, WI) and held without light at 4°C and 21% R.H. Seeds were hulled from pods and 10 seeds were randomly selected from each treatment and control raceme from each replicate. Hulled kudzu seeds were observed under a dissecting microscope (Wild MZ8, Leica Microsystems Inc., Bannockburn, IL) for insect feeding damage. Seed herbivory was classified into five damage categories: 1) no damage; 2) pentatomid feeding early in seed development; 3) pentatomid feeding late in seed development; 4) *Boroweicious ademptus* (Sharp) (Coleoptera, Bruchidae) damage; and 5) other types of infrequent and not clearly identifiable damage, which was apparently caused by one or more of the following: grasshoppers, rodents or lepidopterous larvae. Pentatomid feeding was confirmed by caging stinkbugs on racemes (see pentatomid inclusion study below).

To assess the impact of herbivory on seed viability, seeds of the 1998 insect exclusion study were subjected to a germination test. Ten randomly selected seeds for each replicate of each treatment and control, for each cohort, of the exclusion study were rolled in damp paper towel and placed on test tube racks inside a closed plastic container (34.3 cm by 21.6 cm by 14.0 cm; Rubbermaid®, Wooster, OH), which was filled with 1L of a 1.95 M NaCl solution to maintain 85% RH. Seeds were maintained at 25°C, 12L:12D, and were monitored daily for germination for 7d. The number of germinating seeds in each treatment and damage category was noted.

**Pentatomid Inclusion Study**. To conclusively ascribe damage in the above studies to stinkbugs, four replicates each consisting of two racemes were caged in the same manner as those of the cage treatment in the insect exclusion study (see above) on each of the following dates: 26 July, 11 August, 24 August 1999, and 9 September 1999. One of each pair of cages acted as a treatment, and one to three green stinkbug (*Acrosternum hilare* (Say); Hemiptera: Pentatomidae) adults or nymphs were placed inside each of these cages for one week on the following dates: treatment cage 1, 25 August; treatment cage 2, 9 September ; treatment cage 3, 29 September; Treatment cage 4, 8 October 1999. The other cage in each pair served as a control and did not have stinkbugs added. Stinkbugs removed from treatment cages were either pinned or preserved in 80% ethyl alcohol as voucher specimens. All caged racemes were collected on 29 October 1999, placed in plastic bags and stored at -20°C. Seeds were hulled from pods and observed for pentatomid damage as described in the insect exclusion study above.

**Seed Density.** To assess any relationships between seed density and herbivory, 10 plots (1$m^2$ soil surface) were established over patches of kudzu that were expected to yield a range of flower densities. This was done while kudzu was in full bloom (13 August 1998, 28 July 1999). Half the plots were in areas where there was no other notable vegetation or structures, and the canopy ranged from 0.6 - 0.9 m deep. Remaining plots included kudzu that was growing over shrubs or small trees, resulting in canopies ranging from 1.5 - 2.0 m deep.

All kudzu seed pods were harvested from each plot at the end of the growing season (13 November 1998, 29 October 1999), when seeds were mature. Individual dried racemes were placed in plastic bags (15.9cm by 14 cm, Ziploc®, S.C. Johnson & Son, Racine, WI) and stored at -20°C. Pods were hulled and the number of seeds per pod and total seed crop per $m^2$ of soil surface was determined. Insect damage was evaluated as described in the insect exclusion experiment above.

**Phenology of Insect Attack**. To study the phenology of insect attack on kudzu seeds, a cohort of newly formed pods on 20 racemes was established on each of the following dates in 1999: 28 July, 10 August, 25 August, and 8 September. Racemes were treated in the same manner as control racemes in the insect exclusion study.

Ten pods (one from each of ten randomly selected racemes) were collected from each cohort at two week intervals following cohort establishment, until pods were mature. One sample date (22 September 1999) was missed for all cohorts due to disruption from Hurricane Floyd. Pods were placed in plastic bags (15.9cm by 14 cm, Ziploc®, S.C. Johnson & Son, Racine, WI) and stored at - 20°C. Pods were then hulled and insect damage to seedswas categorized as described in the insect exclusion study above.

**Insect Identification.** Collected insects from all studies were identified with the assistance of David Stephan, director of the NC State University Plant Disease and Insect Clinic. *Boroweicious ademptus* (Sharp) specimens were identified by John Kingsolver, Research Associate, Florida Department of Agriculture, Gainsville, FL. Voucher specimens of all collected insects were preserved and curated as described by Borrer et al. (1989); and are located at the NC State University entomology department museum collection.

**Data Analysis.** Data from the insect exclusion study were subjected to general linear models procedure (PROC GLM) and means separated using LS means (SAS Institute 1998). Relationships between seed density and herbivory were examined using Pearson's correlation (PROC CORR) (SAS Institute 1998). The effect of Cohort, julian date, and seed age on insect damage in the phenology study were investigated using the general linear models procedure (PROC GLM) and means separated using LS means (SAS Institute 1998).

## Results

**Description of Damage.** Seeds free of insect damage were approximately 3.0 -3.5 mm in length when fully mature, and had a mottled black and white coloration. Pentatomid feeding during early seed development resulted in seeds between 2.0 - 2.9 mm in length, with a shriveled or flattened appearance and a puncture wound from the piercing of the insect's stylets on the surface of the seed coat. These seeds were generally brown or tan with darker discoloration surrounding the puncture wound. Seeds fed on late in development by pentatomids were approximately 3.0 - 3.5 mm in length and were mottled black and white, like non-damaged seeds, but a puncture wound, surrounded by discoloration, was evident on the seed coat.

Feeding by *B. ademptus* resulted in brown or tan seeds approximately 3mm in length with a lumpy appearance. These seeds had oviposition wounds, which were slightly larger than the pentatomid feeding wounds. Some seeds also had large circular exit wounds caused by emergence of *B. ademptus* adults. Seeds with apparent beetle damage were dissected and examined for *B. ademptus* presence. Larvae and pupae of *B. ademptus* were preserved in 80% ethyl alcohol, and adult beetles were frozen at -20°C.

Seeds in the "other damage" category lacked evidence of insect herbivory but were discolored, shriveled and only 2 mm long or less. Other seeds included in this category appeared to have been fed upon by a larval lepidopteran, based on silk-lined tunnels found in some pods. No larvae were collected, however.

**Exclusion Study.** The percentages of non-damaged seeds and of seeds attacked by pentatomids early in development were both significantly different between treatments in both years ($F = 22.35$; $df = 1, 16$; $P \leq 0.005$; and $F = 8.40$; $df = 1, 16$; $P \leq 0.05$). The percentages of seeds with pentatomid damage late in development, bruchid damage, and "other damage" were not significantly different between treatments in both years of the study (F = 0.01; df = 1, 16; P>0.05; F = 0.01; df = 1, 16; P>0.05; and F = 0.03; df = 1, 16; P>0.05, respectively).

The majority of caged seeds did not receive pentatomid damage (Table 2.1). Control seeds were primarily damaged early in development by pentatomids (Table 2.1). Control seeds damaged by pentatomids during late development, *B. ademptus*, and other factors accounted for a smaller degree of damage. Pentatomid damage during early seed development was the only significantly different damage category for control seeds for both the 1998 and 1999 field seasons (Table 2.1). Pentatomid damage during early seed development was also the only significant damage category for seeds in the open cage treatment for 1998, but was not significantly different during the 1999 field season (Table 2.1).

Approximately 4% of the observed seeds germinated. Roughly 2% of the seeds with pentatomid damage during early development and non-damaged seeds germinated. Germination occurred in approximately 33% of the seeds with pentatomid damage during late seed development. Seeds with bruchid and other damage failed to germinate.

**Pentatomid Inclusion.** Approximately 53 % of the seeds that had been caged with *A. hilare* nymphs or adults received puncture wounds that were identical in appearance to those of seeds described as damaged by pentatomids in the exclusion study. The other 47 % of the seeds enclosed with *A. hilare* were non-damaged. None of the seeds from the control cages had puncture wounds.

**Seed Density.** The insect herbivory did not appear to be correlated with seed density. The damage categories studied were damage by pentatomids during early development (r = 0.27, P = 0.45), damage by pentatomids later in development (r = 0.62, P = 0.06), *B. ademptus* damage (r = 0.06, P = 0.86), and no damage (r = 0.08, P = 0.83). N was equal to 10 for all damage categories.

**Phenology of Insect Attack.** The percentage of non-damaged seeds was significantly affected by Julian dates (F= 76.10; df=1, 18; P≤0.001); but was not significantly affected by seed age (F= 0.86; df=1, 18; P>0.05). The percentage of seeds with early pentatomid damage was significantly affected by julian dates (F= 35.46; df=1, 18; P≤0.001); but was not significantly affected by seed age (F= 0.87; df=1, 18; P>0.05). The percentage of seeds with pentatomid damage late in development was significantly affected by Julian dates (F= 18.05; df=1, 18; P≤0.001); but was not significantly affected by seed age (F= 0.07; df=1, 18; P>0.05). The percentage of seeds with bruchid damage was not significantly affected by Julian dates (F= 0.09; df=1, 18; P>0.05)., nor seed age (F= 35.98; df=1, 18; P≤0.0001).

The percentage of non-damaged seeds decreased as both seed age and Julian date increased. The total level of insect herbivory initially increased more rapidly with increasing seed age than with increasing Julian date.

## Discussion

Insect feeding damage dramatically reduced kudzu seed viability in this study. When damage was excluded by caging seeds throughout their development, most seeds were viable for both years of this study (Table 2.1). The majority of kudzu seed damage was comparable in appearance to soybean damage caused by the pentatomid, *Acrosternum hilare* (Say), which results in shriveled, discolored and malformed seeds (McPherson et al. 1994). The results of the inclusion study showed that pentatomids such as *A. hilare* were responsible for the pentatomid damage found on kudzu seeds. Most of this pentatomid damage occurred during early seed development, which has been found in other legumes, such as soybeans, where insect attack may be facilitated by the underdeveloped seed coat of young seeds (Panizzi 1985). The percentage of non-damaged seeds in the control was smaller in 1998 as compared to 1999. A possible explanation for this difference is that pentatomid populations were reduced in 1999. However, stinkbug populations on crop plants were reportedly larger in 1999 than 1998 (J.S. Bachelor, North Carolina State University, personal communication).

Although the intent of the cage treatment was to exclude insects from the treatment racemes and thus prevent seed herbivory, seed damage by insects did occasionally occur. It is possible that pentatomids may have been able to pierce the cage and seedpod to feed on seeds. Bruchid damage in the cage treatment may have been due to the inadvertent inclusion of these insects. The percentages of non-damaged seeds and seeds with "other damage" were not significantly different between the open cage treatment and control in 1998, implying that no microclimate effects were present to impact the results of the cage treatment.

Only 21 of the 524 seeds observed germinated. The majority of germinating seeds had damage during late seed development. Few non-damaged seeds and seeds with damage during early development germinated. These results indicate that kudzu seeds need to be scarified in order for germination to occur. The damage caused by pentatomids during late seed development may puncture the seed coat with out damaging the seed embryo and thus scarifying the seed. Conversely, damage done during early seed development appears to be injurious to the seed. In a qualitative study, 10 non-damaged seeds were sanded with 80 grit sandpaper and subjected to a germination test as previously described, and all seeds germinated. Scarification via pentatomid damage may cause these seeds to germinate prematurely during the cold months, resulting in seedling death.

Although a wide range of seed densities were examined in this study, the level of insect damage did not change. It therefore appears that kudzu seed herbivory is density independent. The percentage of seeds with pentatomid damage increased as the season progressed (Fig. 2.2), which could possibly be explained by pentatomid populations also increasing with seasonal progression. The percentage of seeds with bruchid damage increased with increasing seed age (Fig. 2.1). Perhaps bruchids select older seeds for oviposition sites in order to maximize the resources available for their developing offspring.

Although the percentage of non-damaged seeds was significantly affected by Julian date and not seed age, there was a trend for the percentage of non-damaged seeds to decrease both as seed age and Julian date increased. In fact, the total level of insect herbivory initially increased more with increasing seed age than with Julian date. Perhaps the lack of a significant relationship between total insect damage and seed age can be explained by the fact that pentatomid damage, which was more dependent on date, accounted for such a high percentage of the total seeds damaged.

In recent years, it has been proposed that a classical biological control program be implemented against kudzu in the United States. A cooperative project between the United States Forest Service, North Carolina State University, the Chinese Academy of Science, and the Chinese Academy of Forestry is ongoing to investigate the feasibility of classical biological control against kudzu (Britton et al. 2001). In order to successfully implement a classical biological control program, it is critical that basic information about the ecology and biology of the target species and its associated fauna be established both in its area of origin and newly invaded area (van Driesche and Bellows 1996).

The work presented in this study indicates that kudzu is capable of producing viable seeds in the United States. However, seed herbivory by native and naturalized insects greatly reduces kudzu seed viability. Yet even when seed viability is reduced by 98%, as was found in the 1998 exclusion study, the spread of kudzu did not appear to be hampered due to the vegetative nature of this weed. Kudzu vines grown from seed in the central piedmont of North Carolina were found to produce an average of 9.6 ± 3.8 nodes during their first year of growth, with each node capable of rooting (K. Kidd, North Carolina Dept. of Agriculture, personal communication). It is therefore clear the plant could spread vegetatively in the absence of seed production. Based on these findings it seems unlikely that seed feeding arthropods should be targeted as agents for use in a classical biological control program against kudzu.

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Table 2.1 Percentage of *P. montana* seeds damaged by arthropod herbivores following three levels of season long herbivore exclusion. Wake County NC, 1998, 1999.

| Damage Type | Treatment (% Damage) | | | | | |
|---|---|---|---|---|---|---|
| | 1998 | | | 1999 | | |
| | Cage | Open Cage | No Cage | Cage | Open Cage | No Cage |
| No Damage | $90^{a}$ | $21^{b}$ | $2^{b}$ | $85^{a}$ | $59^{b}$ | $11^{c}$ |
| Early Pentatomid[1] | $1^{a}$ | $54^{b}$ | $77^{b\ \ B}$ | $10^{a}$ | $19^{a}$ | $62^{b\ \ B}$ |
| Late Pentatomid[1] | $5^{a}$ | $12^{a}$ | $6^{a\ \ A}$ | $4^{a}$ | $9^{a}$ | $9^{a\ \ A}$ |
| *B. ademptus* | $2^{a}$ | $7^{a}$ | $7^{a\ \ A}$ | $1^{a}$ | $4^{a}$ | $10^{a\ \ A}$ |
| Other[2] | $2^{a}$ | $6^{a}$ | $8^{a}$ | $0^{a}$ | $9^{b}$ | $8^{ab}$ |

Values within a row, or within a column (uppercase), followed by the same letter are not significantly different (LS means; $P<0.05$).

[1] Hemiptera: Pentatomidae, *Acrosternum hilare*
[2] other damage was apparently caused by one or more of the following: grasshoppers, rodents, and lepidopterous larvae.

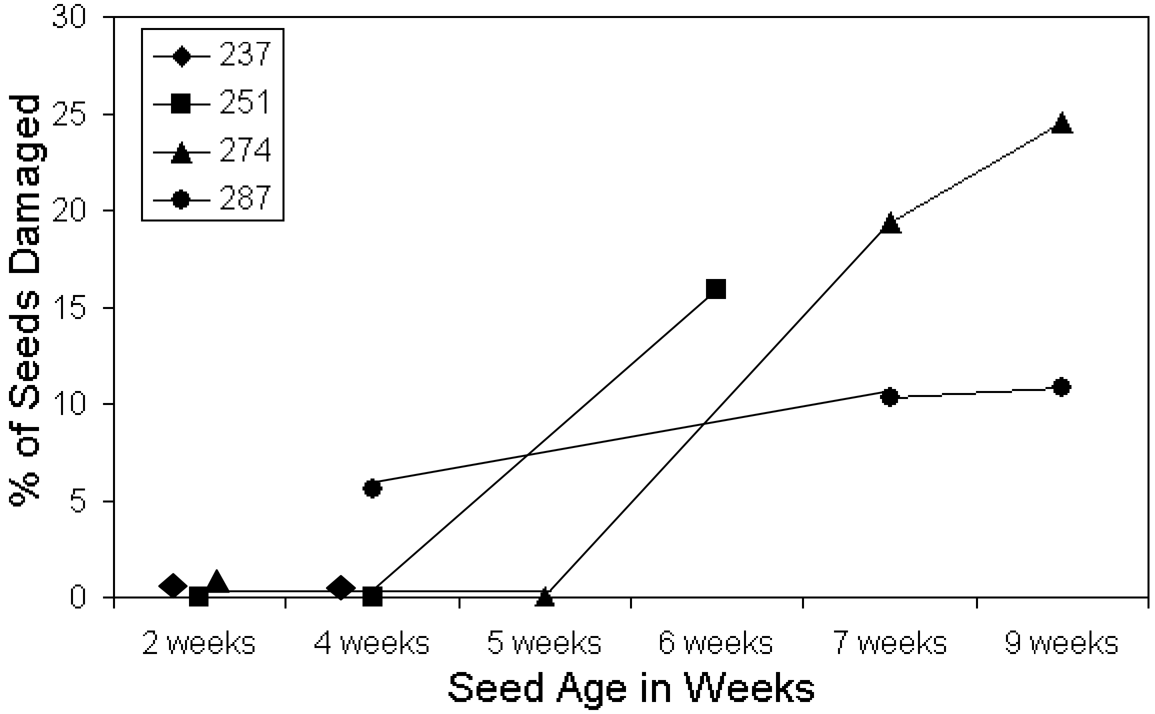

Figure 2.1. The phenology of attack of *P. montana* seeds with damage by *Boroweicius ademptus* (Sharp). Raleigh, NC, 1999. Julian dates 237, 251, 279, and 287 are the dates on which seeds from different cohorts of pods were collected

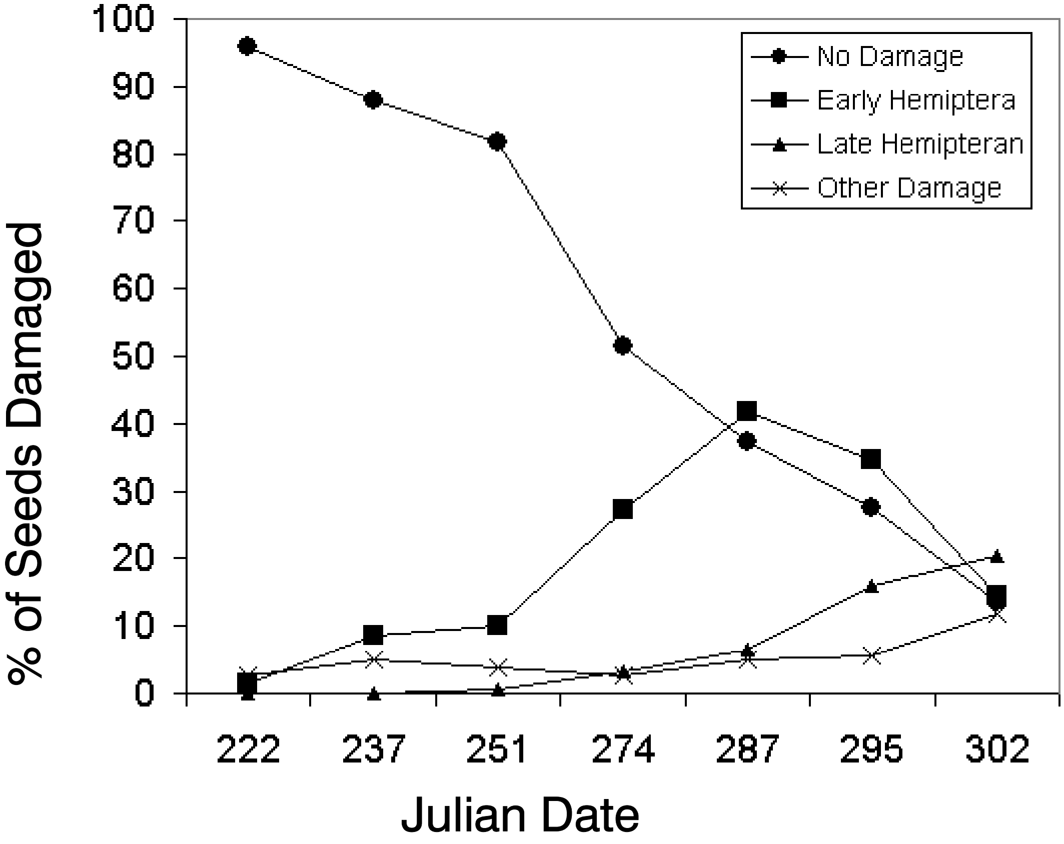

Figure 2.2. The phenology of attack on *P. montana* seeds by pentatomid. Raleigh, NC, 1999. Julian dates 237, 251, 279, and 287 are the dates on which seeds from different cohorts of pods were collected

# III.. COMPARISON OF ARTHROPOD DIVERSITY AND HERBIVORY OF KUDZU, *PUERARIA MONTANA VAR. LOBATA*, AND SOYBEANS IN NORTH CAROLINA

# ABSTRACT

Kudzu foliage, seeds, vines and roots were examined for phytophagous insects. Abundance, diversity, and herbivory of these insect communites were characterized for 1998 and 1999 and compared with those found on soybeans. Kudzu and soybeans had the same levels of defoliation (approx. 13% in 1998, 10% in 1999), and similar foliar feeding insect communities. All of these insects were generalist herbivores. No vine or root feeding insects or damage were recorded from kudzu. Results from this study suggest that seed and foliage feeding insects should not be targeted as agents in a classical biological control program, and instead, efforts should be targeted toward root and vine feeders. A companion project in China has identified several potential candidates for importation.

**Key words:** *Pueraria montana var. lobata*, kudzu, herbivory.

## Introduction

Kudzu, *Pueraria montana* (Lour.) Merr. Var. *lobata* (Willd) Maesen and S. Almeida (Ward 1998), was first brought to the United States from Japan, during the 1876 Philadelphia Centennial Exposition. Kudzu was initially planted as an ornamental vine (Winberry and Jones 1973), but was intermittently utilized as a forage crop for the first half of 20th century (Piper 1920, McKee and Stephens 1943). This perennial, semi-woody, leguminous vine was extensively planted in the southeastern United States to control erosion during the 1930's and 40's (Bailey 1939, Sturkie and Grimes 1939, McKee and Stevens 1943). However, the weed rapidly escaped cultivation and by 1953 was no longer recommended as a cover crop by the USDA (Everest et al. 1999). In 1970, kudzu was listed by the USDA as a common weed of the southeastern United States (Everest et al. 1999), and was declared a federal noxious weed in 1999 (Mitich 2000).

Although kudzu is more heavily utilized in Japan than the U.S., it has escaped cultivation in both countries, where it is a weed of fallow land, river banks, and roadsides (Sweet and Schaefer 1985, Tayutivutikul and Yano 1989), and of forestry in both nations (Sasek 1985, Tsugawa 1986, Miller and Edwards 1983). Various management and eradication programs have been employed to control the spread of kudzu, from intensive herbicide application (Miller and Edwards 1983), to livestock grazing (Martin 1984, Bonsi et al. 1992), to industrial use of the plant (Tanner et al. 1979), but none have shown lasting results. Biological control has only recently been considered as a possible management strategy.

A cooperative project was conducted in the U.S. and China, involving the United States Forest Service, North Carolina State University, the Chinese Academy of Science, and the Chinese Academy of Forestry, to evaluate the potential for a classical biological control program against kudzu in the United States. Although the majority of kudzu infesting the southeastern United States apparently originated from Japanese kudzu seed, this effort is focusing on the insects associated with kudzu in east-central China because that appears to be the center of the weed's natural range (Britton et al. 2001). Kudzu appears to be a good candidate for a classical biological control project, since this naturalized weed appears to lack natural enemies capable of lowering its pest status in the United States (Britton et al. 2001). However, in order to successfully implement a classical biological control program, it is necessary to gain as much knowledge as possible about the biology and ecology of the target species (Bellows and Fisher 2000).

Few studies have identified foliar feeding insects of kudzu in the United States. The velvetbean caterpillar, *Anticarsia gemmatalis* (Lepidoptera: Noctuidae) has been found to over-winter on kudzu in southern and central Florida (Buschman et al. 1977). No studies have examined kudzu vine or root feeding insects in the United States. The insect fauna of kudzu has been studied more extensively in China, where families from six feeding guilds have been reported to damage kudzu foliage, vines, roots, and seeds (Britton et al. 2002).

Many relatives of kudzu are of economic importance in the United States. Native American representatives of the subtribe Glycinae are *Amphicarpa bracteata* (American hogpeanut), and four species of the genus *Colgania*: *C. lemmonii, C. pallida,* and *C. pulchella*.. Other Native American relatives of kudzu are in the genera *Phaseolus, Strophostyles, and Vigna;* which are in the tribe Phaseolinae. The closest relative to kudzu in the United States is the soybean, *Glycine max*, which also is of Asian origin.

Soybeans are an important small grain crop in the United States and in North Carolina. Approximately 74 million acres of soybeans were planted in the United States in 1999 (USDA 2000) and 1.4 million acres were planted in North Carolina in 2000 (USDA 2000). Nearly 700 phytophagous insect species are associated with soybeans in the United States (Kogan 1980). The primary defoliating insects of soybeans in North Carolina are generalist herbivores of the orders Lepidoptera and Coleoptera (Deitz et al. 1976). Insect defoliation levels greater than 30% have been found to reduce soybean yields (Barry 1973). Soybean and kudzu patches are frequently within close proximity to one another in North Carolina. It is not known whether these closely related plants harbor the same insect species.

The purpose of this study was to survey insects associated with kudzu foliage, vines, and roots in North Carolina to establish basic information about the insect communities kudzu harbors in the United States. Foliar insects in nearby soybean fields were also surveyed to compare insect communities between the two plants. The degree of defoliation by insects on the two plants was also compared.

## Methods and Materials

**Field Plots.** Six paired kudzu patches and soybean fields were surveyed in 1998 and four paired sites were sampled in 1999. All sites were all in Wake County, NC. Each kudzu patch and soybean field contained five sample plots in 1998, and three sample plots in 1999. Plots were 7.30m by 9.14m wide, and were located equidistant from one another and the field border.

**Sampling.** Foliar arthropod fauna were collected from sample sites with a D-vac ( D-Vac Inc., Ventura, CA) vacuum sampler on 22 July, 1 September, 30 September 1998; and 28 July, 10 August, 25 August, 24 September, 8 October 1999. One 6.1m transect was sampled in each plot in 1998. Two 9.14m transects were sampled from each plot in 1999. Data from the plots were standardized to 10m, in order to make comparisons between years. Sampling was conducted between 11:00 AM and 3:00 PM when insects associated with soybeans are expected to be at their highest point in the soybean canopy (Kogan and Herzog, 1986). Collected insects were placed in plastic bags (3.75L, Ziploc®, S.C. Johnson & Son, Racine, WI) and stored in a cooler while en route to the lab. Cotton balls moistened with 10 ml of ethyl acetate were inserted into each bag to kill the arthropods. Soft bodied arthropods were placed in 80% ethyl alcohol, and hard bodied insects were stored in plastic cups (30ml; Polar Rx, Polar Plastics Inc.,Wilmington, DE ) at -20°C.

Vines and root crowns were examined for evidence of feeding and presence of arthropods in three 1 $m^2$ quadrants within each sample plot on each sampling date. Due to the difficulty of collecting lepidopteran larvae with the D-Vac sampler, separate counts of the number of lepidopteran larvae and sites of larval presence, such as the leaf shelters of *Epargyreus clarus*, was also noted for each quadrant**.**

**Specimen identification.** Voucher specimens of arthropods from samples were curated according to standard procedures (Borror et al., 1989). Specimens were identified to family and feeding guild was determined. The number of arthropod species found in each sample was tabulated.

**Estimation of defoliation.** On each sample date, a $0.09m^2$ sample of kudzu or soybean foliage was removed, with petioles intact, from each plot to assess the amount of defoliation from insect herbivory. Foliar samples were were placed in labeled plastic bags containing 0.24 $\ell$ of water then placed inside a cooler containing ice packs. The level of herbivory for each trifoliate of a sample was quantified using a visual rating scale. In 1998, the percentage of defoliation was estimated in units of 10; the percentage of defoliation was estimated in units of 5 in 1999. The leaf area was determined for individual trifoliates within each sample using an area meter (Model LI-3100, Li-Cor, Lincoln, NE). Foliar samples were collected on the dates of D-vac sampling.

**Vegetative Diversity.** The $1m^2$ quadrants sampled for vine and root feeding and lepidopteran larvae were also inspected for vegetative diversity. The percentage of the $1m^2$ quadrant occupied by plant species other than kudzu or soybeans was recorded.

Kudzu patches and soybean fields were surveyed to compare the diversity and abundance of arthropods in the following feeding guilds: herbivores, predators, and parasitoids.

**Data Analysis.**Vegetative diversity, leaf area, and estimation of defoliation data were each subjected to a general linear models procedure (PROC GLM) (SAS Institute 1998). The arthropod diversity and *Epargyreus clarus* data were analyzed with a paired *t*-test (SAS Institute 1998).

## Results

**Specimen Identification.** During the two years of study, herbivores in kudzu and soybeans were represented by members of six orders of arthropods (Table 3.1). Predatory Arthropods were found in six orders in kudzu and soybeans (Table 3.1). Parasitoids were composed of two orders in kudzu and soybeans (Table 3.1).

**1998 Analysis of Diversity and Composition.** Herbivore diversity did not differ between kudzu and soybeans based on Simpson's index, Shannon's index, Hill's N1 number, Hill's N2 number, and evenness, but family richness did differ (Table 3.2). Kudzu and soybeans also had comparable indices for parasitoid diversity, but differed by richness (Table 3.2). Predator diversity differed between the plant species when evaluated with Simpson's index, Shannon's index, Hill's N1 number, Hill's N2 number and richness, but did not differ by evenness (Table 3.2).

**1999 Analysis of Diversity and Composition.** Kudzu and soybeans had comparable herbivore diversity based on Simpson's index, Shannon's index, Hill's N1 number, Hill's N2 number, and richness, but evenness values differed (Table 3.3). Indices for predator diversity and evenness differed between kudzu and soybeans, but family richness was similar (Table 3.3). The diversity of parasitoids found in kudzu and soybeans was statistically equivalent, based on diversity indices, evenness, and richness.

***Epargyreus clarus* presence.** The mean number of *E. clarus* larvae collected, averaged over date and site was 1.46 ± 2.48 in kudzu and 0.33 ± 0.56 in soybeans, in 1999. The counts of E. clarus larvae in kudzu and soybeans were significantly different $(t_{46}=2.16, P=0.04)$.

**Percentage of weed coverage.** In 1998, weeds other than kudzu comprised 1.8 ± 2.3 % of soil surface in kudzu, while in soybeans, weeds including kudzu made up 22.2 ± 21.5 % of soil surface. In 1999, weeds composed 0.4 ± 1.4 % of soil surface in kudzu and 8.7 ± 10.2% in soybeans. Percent weed coverage significantly differed between kudzu and soybeans in 1998 ($t_{22}=-3.28, P=0.003$) and in 1999 ($t_{46}=-3.92, P<0.001$).

**Estimation of Defoliation.** *Leaf area.* The leaf area of kudzu and soybeans differed in both 1998 ($t_{29}=9.65, P<0.001$) and 1999 ($t_{46}=12.38, P<0.001$). In 1998, the mean leaf area for kudzu and soybeans was 186.0 ± 175.0 $cm^2$ and 59.5 ± 109.8 $cm^2$, respectively. The mean leaf area was 213.10 ± 119.9 $cm^2$ for kudzu and 68.1 ± 39.5 $cm^2$ for soybeans, in 1999.

*Defoliation.* The percentage of kudzu and soybean leaf defoliation by phytophagous insects was significantly different by date in 1998 ($F_{2,33}=3.28, P=0.05$). The percentage of kudzu and soybean defoliation also differed within dates 22 July and 29 September (Fig. 3.1). Date was also significant for percent defoliation in 1999 ($F_{5,41}=11.54, P<0.001$), but no differences were found between kudzu and soybeans within dates (Fig. 3.2).

## Discussion

Simpson's index is defined as "the probability that two individuals drawn at random from a population belong to the same species" (Ludwig and Reynolds 1988). Both richness and evenness of taxonomic groupings within a community are used to calculate diversity with this index, with more emphasis placed on the most abundant families than on the evenness of all families within the community (Krebs 1985). A community with a Simpson's index value of 1.00 would have no diversity, while one with an index approaching zero would be highly diverse. It has been shown that richness will increase with the number of individuals and amount of area sampled (Schulter and Ricklefs 1993). However, a rich but uneven community will be less diverse than one with fewer but more evenly abundant taxa (Begon et al. 1990).

Shannon's diversity index is "a measure of the average degree of 'uncertainty' in predicting to what species an individual chosen at random from a collection of S species and N individuals will belong" (Ludwig and Reynolds 1988). Like Simpson's index, both richness and evenness are used to calculate Shannon's index. Based on Shannon's index, diversity will increase with richness and also with evenness of abundance. Diversity measured by Shannon's index is at a maximum when all taxa are represented by the same number of individuals (Price 1997).

Hill's diversity number's, N1 and N2, are used to evaluate "the effective number of species present in a sample" (Ludwig and Reynolds 1988), or the number of taxa that make up the greatest number of individuals in a sample. N1, the exponent of Shannon's index, is defined as the number of equally abundant families that would give the same Shannon's Index value as the sample (Hill 1973, Ludwig and Reynolds 1988). N2, the reciprocal of

Simpson's index, gives the number of very abundant families in a sample (Hill 1973, Ludwig and Reynolds 1988).

Evenness is a measurement of how uniformly distributed individuals are among species (Ludwig and Reynolds 1988, Begon et al. 1990). This value increases from 0 to 1 as species become evenly abundant (Lloyd and Ghelardi 1964, Begon et al. 1990).

In 1998, herbivores on average were composed of more taxa in soybeans than in kudzu (Table 3.2). The distribution of individuals among taxa was statistically comparable in kudzu and soybeans, but the mean evenness values indicated that the distribution was slightly more uniform in kudzu (Table 3.2). Based on Hill's N1 number, the most abundant herbivores in kudzu were thrips (Thysanoptera), members of Cicadellidae (Homoptera), Miridae (Hemiptera), and Chrysomelidae (Coleoptera) (Table 3.2); while in soybeans, the most abundant herbivores were cicadellids, thrips, mirids, chrysomelids, and delphacid plant hoppers (Homoptera: Delphacidae). Composition of the most abundant taxa were nearly identical in kudzu and soybeans (Table 3.2). Although kudzu and soybean herbivore diversity did not statistically differ based on Simpson's and Shannon's indices, the trend was for diversity to be greater in soybeans, which was likely due to their greater richness (Table 3.2).

In 1998, the mean number of predatory arthropod taxa found in soybeans was greater than that of kudzu (Table 3.2). The distribution of predators among taxa was comparable in kudzu and soybeans (Table 3.2). Based on Hill's N1 diversity number, the most abundant predators in kudzu in were spiders (Araneae) and minute pirate bugs, *Orius insidiosus* (Say) (Hemiptera:Anthocoridae) (Table 3.1). The most abundant predators in soybeans were spiders, big-eyed bugs, *Geocoris* spp. (Hemiptera: Lygaeidae), damsel bugs, *Nabis* spp. (Hemiptera: Nabidae), and long legged flies (Diptera: Dolichopodidae). Predator diversity was significantly different between kudzu and soybeans, based on Simpson’s and Shannon's indices, the mean values of which indicated that soybeans were more diverse, which was likely due to their greater richness.

The mean number of taxa comprising parasitoids was greater in kudzu than in soybeans in 1998 (Table 3.2). According to the mean evenness index values, parasitoids were moderately uniform in their distribution across families in both kudzu and soybeans (Table 3.2). The most abundant parasitoid taxa in kudzu were Chalcidoidea and Braconidae (Hymenoptera). Chalcidoids were also the most abundant parasitoids in soybeans, based on Hill's N1 number. Parasitoid diversity was statistically comparable in kudzu and soybeans (Table 3.2), with a trend for the parasitoid assemblage in kudzu to be slightly more diverse, which again may be explained by the differences in richness.

In 1999, herbivores on average were represented by a comparable number of taxa in kudzu and soybeans (Table 3.3). Herbivores were more uniformly distributed among taxa in soybeans than in kudzu (Table 3.3). The most abundant taxa in kudzu, based on Hill's N1 number, were Thysanoptera, Cicadellidae, and Noctuidae, which also had the greatest representation in soybeans (Tables 3.1, 3.3). Kudzu and soybeans statistically had comparably diverse herbivore assemblages, although soybeans tended to be more diverse, which was probably due to their greater evenness (Table 3.3).

In 1999, predators were represented by an equivalent number of mean taxa in kudzu and soybeans (Table 3.3). Predators were significantly more evenly distributed across taxa in soybeans than in kudzu (Table 3.3). The most abundant predators were spiders and *O. insidiosus* in kudzu. Spiders were also the most abundant predators in soybeans, along with *Lygus* spp. and *Nabis* spp. Kudzu was significantly less diverse than soybeans according to

Shannon's index. Soybeans may have had a more diverse predator assemblage than kudzu due to greater evenness.

Parasitoids in 1999 were represented by equal mean numbers of taxa in kudzu and soybeans, and individuals were comparably distributed among taxa in both plant species (Table 3.3). The most abundant parasitoids in both kudzu and soybeans were chalcidoids. Parasitoid diversity in kudzu and soybeans was comparable based on Shannon's index.

Although kudzu had a significantly greater leaf area than soybeans, the level of defoliation was generally similar between these plants, except on dates 22 July and 29 September of 1998 (Figs. 3.1, 3.2). The percentage of defoliation in 1998 may have appeared to be more constant throughout the season than in 1999, due to the different defoliation rating scales used. However, in both years of study, a trend existed where kudzu was initially more defoliated than soybeans, but as the season progressed, soybeans became more defoliated. A possible explanation for this trend could be that herbivorous insects had a host preference for soybeans, as kudzu foliage was more developed than soybeans on the initial sampling dates of both years. Kidd and Orr (2001) found that feeding the soybean looper, *Pseudoplusia includens* (Walker) (Lepidoptera: Noctuidae) kudzu resulted in higher mortality, supernumerary molts and lower pupal weights than when this insect was fed soybeans. The soybean looper also deposited more eggs on soybeans than on kudzu in oviposition preference tests (Kidd and Orr 2001). In laboratory conditions, the soybean looper fed equally upon kudzu and soybeans and no nutritional differences were found between the two plant species (Kidd and Orr 2001). These data indicate that kudzu is an acceptable host for herbivorous arthropods, but soybeans may be the preferred host.

Kudzu and soybeans appeared to have similar arthropod communities in 1998 and 1999. Although the diversity of the predator assemblages in kudzu and soybeans differed, the diversity of the herbivore and parasitoid assemblages did not (Tables 3.2, 3.33). It is important to note that kudzu is a perennial while soybeans are grown as an annual crop in North Carolina. Kudzu may allocate more resources to its roots for energy storage, which would reduce the nutritive value of its foliage, with seasonal progression. Soybeans would allocate more resources to seed production as the growing season progressed. This difference in life strategies could also account for why there appeared to be a host preference for soybeans, based on the defoliation data, and why there was a trend for herbivore diversity to be greater in soybeans. It is not clear why the diversity of predators was not greater in kudzu than in soybeans, due to the more stable environment. However, it is also important to note that the soybean plots were significantly weedier than those of kudzu, which has long been known to exist as a monoculture. Although not quantitatively studied, it appeared that plant diversity was greater in the soybean plots, which could account for the statistically greater predator diversity and the trend for greater herbivore diversity, compared to the kudzu plots.

The composition of arthropods was generally similar in kudzu and soybeans (Table 3.1). The coleopteran family Chrysomelidae, which contains the occasional soybean pests, the spotted cucumber beetle, *Diabrotica undecimpunctata howardi*; the bean leaf beetle, *Cerotoma trifurcata* (Forster); and the grape colaspis, *Colaspis brunnea* (Fabricius) (Deitz et al. 1976), was one of the most abundant herbivore families in kudzu in 1998 (Table 3.1). The family Noctuidae (Lepidoptera), which contains one of the most economically important pests of soybeans in North Carolina, the corn earworm, along with the occasional pests the soybean looper, velvet bean caterpillar, and green clover worm (Deitz et al. 1976, Van Duyn

1998), was one of the most abundant herbivore families in both kudzu and soybeans in 1999 (Table 3.1). It is possible that the number of lepidopterans sampled during both years of study was reduced, due to the disturbance caused by the D-Vac sampler, which probably elicited a defensive response and caused the lepidopterans to drop from the plants and thus not be sampled. These findings coupled with the similar levels of defoliation in kudzu and soybeans, and the possibility that soybeans could be the preferred host of some herbivorous arthropods call into question the wisdom of importing defoliating arthropods as biological control agents of kudzu.

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Table 3.1. Mean numbers of arthropods collected in a 10 m transect of kudzu and soybeans with vacuum sampling. Wake County, NC.

| Order and Family | 1998 | | 1999 | |
|---|---|---|---|---|
| | Kudzu | Soybeans | Kudzu | Soybeans |
| | | Herbivores | | |
| Orthoptera | | | | |
| Acrididae | 0.27 ± 0.84 | 0.91 ± 1.88 | 0.31 ± 0.53 | 0.24 ± 0.51 |
| Gryllidae | 0.73 ± 2.33 | 0.18 ± 0.53 | 0.15 ± 0.39 | 0.41 ± 1.68 |
| Tettigoniidae | 0 | 0 | 0 | 0.55 ± 1.50 |
| Hemiptera | | | | |
| Tingidae | 0 | 0.27 ± 0.84 | 0.03 ± 0.17 | 0.07 ± 0.23 |
| Miridae | 12.00 ± 13.99 | 32.62 ± 38.58 | 1.71 ± 2.31 | 7.65 ± 8.32 |
| Berytidae | 0.18 ± 0.77 | 0.18 ± 0.53 | 0.03 ± 0.17 | 0.03 ± 0.17 |
| Lygaeidae | 0.64 ± 1.96 | 0.26 ± 0.61 | 0.21 ± 0.60 | 0.38 ± 0.94 |
| Coreidae | 0 | 0 | 0.14 ± 0.52 | 0.03 ± 0.17 |
| Cydnidae | 0.09 ± 0.39 | 0.09 ± 0.39 | 0.03 ± 0.17 | 0 |
| Pentatomidae | 0.35 ± 0.69 | 2.64 ± 4.36 | 0.24 ± 0.45 | 0.68 ± 1.02 |
| Homoptera | | | | |
| Membracidae | 0.64 ± 1.14 | 4.65 ± 6.12 | 0.68 ± 0.99 | 3.66 ± 3.43 |
| Cercopidae | 0 | 1.64 ± 5.28 | 0 | 0 |
| Cicadellidae | 24.78 ± 16.93 | 74.98 ± 41.45 | 33.14 ± 17.93 | 30.24 ± 23.01 |
| Delphacidae | 3.46 ± 5.27 | 15.12 ± 23.37 | 1.78 ± 3.37 | 5.33 ± 7.52 |
| Derbidae | 0 | 0 | 0.03 ± 0.17 | 0 |
| Achilidae | 0 | 0 | 0.03 ± 0.17 | 0 |
| Flatidae | 0.09 ± 0.39 | 0.55 ± 2.32 | 0 | 0 |
| Acanoloniidae | 0.36 ± 0.70 | 0 | 1.50 ± 3.35 | 0.10 ± 0.37 |
| Psyllidae | 0 | 0 | 0.07 ± 0.23 | 0 |
| Aphididae | 0.64 ± 2.33 | 0.55 ± 1.95 | 0.44 ± 1.41 | 0.07 ± 0.23 |
| Thysanoptera | 37.63 ± 43.66 | 32.80 ± 47.50 | 158.5 ± 111.3 | 141.0 ± 126.9 |
| Coleoptera | | | | |
| Scarabaeidae | 0 | 0.09 ± 0.39 | 0.03 ± 0.17 | 0 |
| Elateridae | 0 | 0.96 ± 2.84 | 0.03 ± 0.17 | 0.14 ± 0.46 |
| Melyridae | 0 | 0.18 ± 0.77 | 0.03 ± 0.17 | 0.49 ± 1.04 |
| Mordellidae | 1.37 ± 1.41 | 0.64 ± 1.14 | 0.92 ± 1.48 | 0.33 ± 0.49 |
| Meloidae | 0.09 ± 0.38 | 0 | 0.38 ± 0.76 | 0.03 ± 0.17 |
| Anthicidae | 0.18 ± 0.77 | 3.10 ± 3.42 | 0.14 ± 0.31 | 0.34 ± 0.76 |
| Cerambycidae | 0 | 0 | 0.03 ± 0.17 | 0 |
| Bruchidae | 0.27 ± 0.63 | 0.27 ± 0.63 | 0.85 ± 1.22 | 0 |
| Chrysomelidae | 5.47 ± 9.04 | 14.94 ± 19.75 | 1.21 ± 2.24 | 1.81 ± 2.95 |
| Curculionidae | 0.55 ± 0.80 | 0.66 ± 0.82 | 1.61 ± 1.58 | 1.06 ± 1.38 |

**Table 3.1 continued.**

| Order and Family | 1998 | | 1999 | |
|---|---|---|---|---|
| | Kudzu | Soybeans | Kudzu | Soybeans |
| Lepidoptera | | | | |
| Pyralidae | 0.09 ± 0.39 | 0.09 ± 0.39 | 0.10 ± 0.28 | 1.15 ± 0.73 |
| Geometridae | 0 | 0.09 ± 0.39 | 0 | 0 |
| Arctiidae | 0.09 ± 0.39 | 0.55 ± 1.13 | 0.07 ± 0.23 | 0.03 ± 0.17 |
| Noctuidae | 4.01 ± 4.91 | 3.64 ± 5.70 | 6.05 ± 6.77 | 8.23 ± 13.11 |
| | | Predators | | |
| Araneae | 27.97 ± 17.39 | 16.76 ± 10.74 | 33.07 ± 20.70 | 11.99 ± 7.52 |
| Odonata | | | | |
| Libellulidae | 0 | 0 | 0.03 ± 0.17 | 0 |
| Coenagrionidae | 0 | 0 | 0.03 ± 0.17 | 0 |
| Hemiptera | | | | |
| Nabidae | 0 | 5.65 ± 6.19 | 0.14 ± 0.39 | 4.41 ± 7.63 |
| Anthocoridae | 2.19 ± 2.45 | 1.64 ± 2.76 | 12.47 ± 16.67 | 3.59 ± 4.15 |
| Reduviidae | 0 | 0.18 ± 0.53 | 0.38 ± 1.67 | 0.10 ± 0.28 |
| Lygaeidae | 0.73 ± 1.16 | 13.48 ± 13.03 | 0.07 ± 0.23 | 4.54 ± 5.50 |
| Neuroptera | | | | |
| Chrysopidae | 0 | 0 | 0.21 ± 0.55 | 0.14 ± 0.31 |
| Myrmeleontidae | 0 | 0.18 ± 0.53 | 0 | 0 |
| Coleoptera | | | | |
| Carabidae | 0.09 ± 0.39 | 0.36 ± 0.70 | 0.03 ± 0.17 | 0.75 ± 2.37 |
| Staphylinidae | 0.09 ± 0.39 | 0.27 ± 1.16 | 0.14 ± 0.31 | 0.10 ± 0.28 |
| Lampyridae | 0 | 0 | 0 | 0.03 ± 0.17 |
| Cantharidae | 0.27 ± 1.16 | 0.09 ± 0.39 | 0.07 ± 0.23 | 0.03 ± 0.17 |
| Cleridae | 0 | 0.09 ± 0.39 | 0.10 ± 0.50 | 0.17 ± 0.54 |
| Cucujidae | 0.09 ± 0.39 | 1.18 ± 3.89 | 0.55 ± 0.89 | 0.07 ± 0.33 |
| Languriidae | 0 | 0 | 0 | 0.10 ± 0.28 |
| Coccinellidae | 0.18 ± 0.53 | 2.28 ± 2.88 | 0.34 ± 0.48 | 0.48 ± 0.99 |
| Mecoptera | | | | |
| Panorpidae | 0 | 0.18 ± 0.53 | 0.14 ± 0.67 | 0.58 ± 2.85 |
| Diptera | | | | |
| Dolichopodidae | 2.92 ± 3.35 | 2.19 ± 2.52 | 4.56 ± 6.53 | 0.92 ± 1.03 |
| Pipunculidae | 0 | 0.27 ± 0.84 | 0 | 0 |
| Hymenoptera | | | | |
| Mutilidae | 0 | 0 | 0 | 0.03 ± 0.17 |

**Table 3.1 continued.**

| Order and Family | 1998 | | 1999 | |
|---|---|---|---|---|
| | Kudzu | Soybeans | Kudzu | Soybeans |
| | Parasitoids | | | |
| Diptera | | | | |
| Phoridae | 0.27+0.63 | 0 | 0.11+0.28 | 1.20+4.85 |
| Hymenoptera | | | | |
| Braconidae | 5.10+4.05 | 2.08+2.10 | 2.97+3.33 | 1.74+1.35 |
| Ichneumonidae | 0.18+0.53 | 1.12+3.28 | 0.07+0.23 | 0.07+0.23 |
| Chalcidoidea | 36.81+29.67 | 28.06+24.34 | 27.16+20.42 | 22.00+19.33 |

**Table 3.2.** Mean values of diversity and evenness indices and richness for arthropod communities in kudzu and soybeans in Wake County, NC in 1998

| | Simpson | Shannon | N1 | N2 | Evenness | Richness |
|---|---|---|---|---|---|---|
| Herbivores | | | | | | |
| K | 0.33 ± 0.14 | 1.40 ± 0.33 | 4.25 ± 1.21 | 3.37 ± 1.03 | 0.26 ± 0.07 | 7.50 ± 2.09 |
| S | 0.31 ± 0.17 | 1.55 ± 0.41 | 5.02 ± 1.54 | 3.77 ± 0.14 | 0.22 ± 0.06 | 9.78 ± 3.10 |
| *t* | 0.41 | -1.22 | -1.68 | -1.01 | 1.86 | -2.58 |
| df | 34 | 34 | 34 | 34 | 34 | 34 |
| *P* | 0.68 | 0.23 | 0.10 | 0.32 | 0.07 | 0.01 |
| Predators | | | | | | |
| K | 0.68 ± 0.20 | 0.59 ± 0.36 | 1.91 ± 0.68 | 1.65 ± 0.67 | 0.34 ± 0.12 | 2.72 ± 1.36 |
| S | 0.35 ± 0.11 | 1.25 ± 0.26 | 3.63 ± 0.91 | 3.07 ± 0.90 | 0.34 ± 0.08 | 5.22 ± 1.17 |
| *t* | 5.93 | -6.43 | -6.42 | -5.39 | -0.08 | -5.91 |
| df | 34 | 34 | 34 | 34 | 34 | 34 |
| *P* | <0.001 | <0.001 | <0.001 | <0.001 | 0.94 | 0.01 |
| Parasitoids | | | | | | |
| K | 0.76 ± 0.18 | 0.38 ± 0.26 | 1.51 ± 0.41 | 1.40 ± 0.41 | 0.55 ± 0.21 | 2.00 ± 0.59 |
| S | 0.82 ± 0.23 | 0.25 ± 0.31 | 1.36 ± 0.47 | 1.36 ± 0.56 | 0.52 ± 0.19 | 1.56 ± 0.62 |
| *t* | -0.83 | 1.3 | 1.04 | 0.22 | 0.34 | 2.20 |
| df | 34 | 34 | 34 | 34 | 34 | 34 |
| *P* | 0.41 | 0.20 | 0.31 | 0.82 | 0.74 | 0.03 |

**Table 3.3.** Mean values of diversity and evenness indices and richness for arthropod communities in kudzu and soybeans in Wake County, NC in 1999

| | Simpson | Shannon | N1 | N2 | Evenness | Richness |
|---|---|---|---|---|---|---|
| | | | Herbivores | | | |
| K | 0.57 ± 0.17 | 0.90 ± 0.39 | 2.71 ± 1.59 | 2.05 ± 1.37 | 0.16 ± 0.07 | 9.41 ± 2.60 |
| S | 0.47 ± 0.21 | 1.12 ± 0.43 | 3.37 ± 1.53 | 2.63 ± 1.43 | 0.21 ± 0.09 | 8.96 ± 1.92 |
| *t* | 1.85 | -1.82 | -1.46 | -1.42 | -2.14 | 0.69 |
| df | 46 | 46 | 46 | 46 | 46 | 46 |
| *P* | 0.07 | 0.08 | 0.15 | 0.16 | 0.04 | 0.49 |
| | | | Predators | | | |
| K | 0.61 ± 0.17 | 0.72 ± 0.29 | 2.14 ± 0.60 | 1.78 ± 0.50 | 0.29 ± 0.07 | 4.25 ± 1.57 |
| S | 0.36 ± 0.14 | 1.16 ± 0.35 | 3.39 ± 1.26 | 3.24 ± 1.42 | 0.36 ± 0.12 | 4.91 ± 1.71 |
| *t* | 5.43 | -4.71 | -4.41 | -4.74 | -2.57 | -1.40 |
| df | 46 | 46 | 46 | 46 | 46 | 46 |
| *P* | <0.001 | <0.001 | <0.001 | <0.001 | 0.01 | 0.17 |
| | | | Parasitoids | | | |
| K | 0.79 ± 0.18 | 0.33 ± 0.24 | 1.43 ± 0.36 | 1.35 ± 0.38 | 0.55 ± 0.16 | 2.00 ± 0.51 |
| S | 0.77 ± 0.17 | 0.35 ± 0.24 | 1.46 ± 0.35 | 1.36 ± 0.35 | 0.49 ± 0.11 | 2.00 ± 0.59 |
| *t* | 0.21 | -0.30 | -0.27 | -0.07 | 1.5 | 0 |
| df | 46 | 46 | 46 | 46 | 46 | 46 |
| *P* | 0.84 | 0.76 | 0.79 | 0.94 | 0.14 | 1.00 |

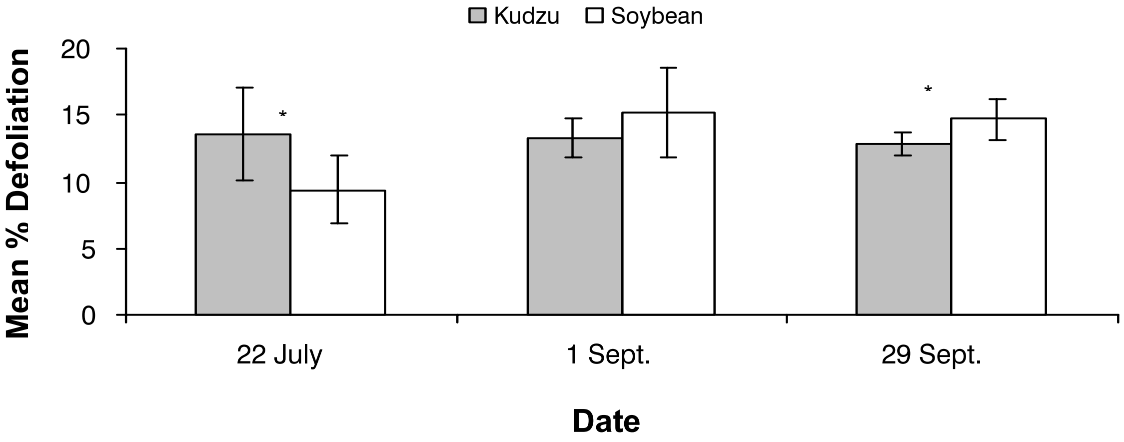

Figure 3.1. Mean percentage of kudzu and soybeans defoliated by herbivorous insects in Wake County, NC, on 22 July, 1 September, and 29 September of 1998. Means for kudzu and soybean defoliation that are significantly different (*t*-test, $P \leq 0.05$) within a date are indicated by an asterisk

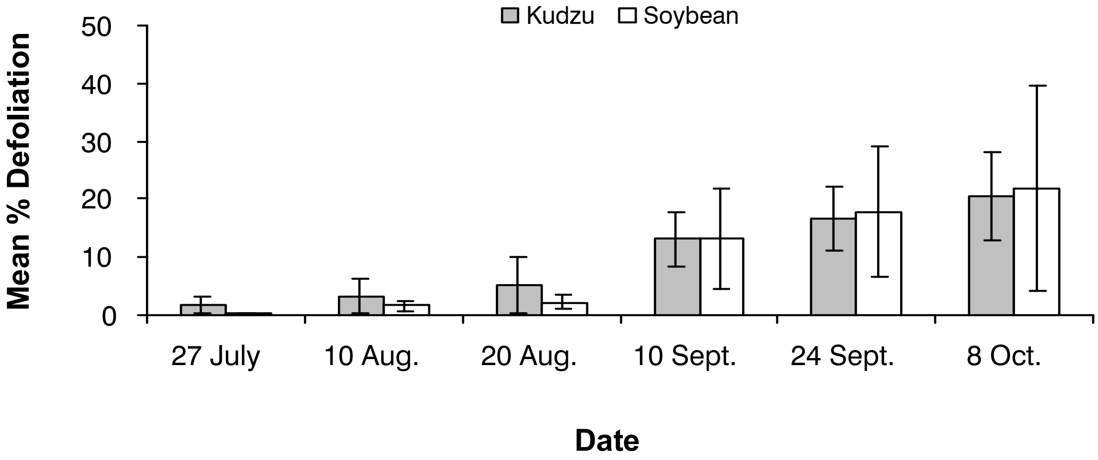

Figure 3.2. Mean percentage of kudzu and soybeans defoliated by herbivorous insects in Wake County, NC, on 27 July, 10 August, 20 August, 10 September, 24 September, and 8 October of 1999. Means for kudzu and soybean defoliation that are significantly different (*t*-test, $P \leq 0.05$) within a date are indicated by an asterisk