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INSECT DIVERSITY AND PEST STATUS ON SWITCHGRASS GROWN FOR BIOFUEL IN SOUTH CAROLINA

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INSECT DIVERSITY AND PEST STATUS ON SWITCHGRASS GROWN FOR BIOFUEL IN SOUTH CAROLINA

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ABSTRACT

Switchgrass (*Panicum virgatum* L.) has tremendous potential as a biomass and stock crop for cellulosic ethanol production or combustion as a solid fuel. The first goal of this study was to assess diversity of insects in a perennial switchgrass crop in South Carolina. A three-year study was conducted to sample insects using pitfall traps and sweep nets at the Pee Dee Research and Education Center in Florence, SC, from 2007-2009. Collected specimens were identified to family and classified by trophic groups, and predominant species were identified. The diversity and density of weeds in the field during the establishment year (2007) were greater than the following years. Insect diversity at the family level varied significantly across sampling dates only for sweep net samples, with diversity peaks in May of each year. Diversity at the trophic-group level showed significant differences for predators in pitfall traps and for predators and herbivores in sweep net samples across sampling dates. The second goal was to determine the potential impact of insect herbivores on switchgrass yield. Selected plots received applications of 1,3-dichloropropene and chloropicrin soil fumigation before planting and foliar applications of acephate during the season. Dry weight biomass was not significantly affected ($P > 0.05$) by treatments and visible herbivory was limited to sporadic grasshopper feeding. The most abundant herbivore family collected in pitfall traps was Gryllidae and in sweep net samples Cicadellidae. Chewing, sucking and boring feeding guilds were negatively correlated with the biomass of switchgrass in sweep net samples and sucking insects for pitfall traps. Predominant herbivore species were

Draeucolacephala sp. and *Melanoplus* possibly *sanguinipes* and an undetermined species of Tettigoniidae. The predominant predator was *Solenopsis invicta* Buren. Assessing arthropod diversity in switchgrass is a first step in identifying potential pests and beneficial insects in this crop. The results of this study provide important information related to the pest status of insects in switchgrass in South Carolina.

DEDICATION

This thesis is dedicated to my father, who had an accident two weeks before my arriving in the US to do my M.S. program and passed away a month later.

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LITERATURE REVIEW

Biofuel Overview

Biofuel is a renewable fuel, solid, gas or liquid, made from plant sources rather than fossil fuels. It can be produced from plants such as sugarcane (*Saccharum* spp.) and sugar beet (*Beta vulgaris* L.), and from starchy crops such as corn (*Zea mays* L.), wheat (*Triticum* spp.), potato (*Solanum tuberosum* L.) and sorghum (*Sorghum bicolor* L.), which are fermented and distilled to produce ethanol or butanol. Plant oils from soybeans (*Glycine max* (L.) Merr.), sunflowers (*Helianthus annuus* L.), coconut (*Cocos nucifera* L.), palm (*Elaeis* spp.) and jatropha (*Jatropha curcas* L.), recycled cooking oil or animal fats can be used to produce biodiesel. Ethanol and biodiesel are currently the primary source of biofuel and are known as the first generation biofuels made mainly from crops traditionally used for food (Dufey 2006, Reiinders and Huijbregts 2007, Plieninger and Bens 2008).

Biofuels can also be produced from lignocellulosic biomass, such as crop residues, woody crops or energy grasses (grasses that are grown to generate power) (McLaughlin and Walsh 1998). In this case, as the starting feedstock is lignocellulose, different processing steps are required to generate biofuel. Many of these thermochemical fuels are already being produced from fossil fuels such as coal and natural gas using methods similar to biofuel production. These biofuels obtained from lignocelluslosic biomass of non food plants are called second-generation (Gwehenberger et al. 2007, Himmel et al. 2007, Plieninger and Bens 2008).

Although biofuel has been produced since 1975 in Brazil from sugarcane, its global importance increased considerably five years ago because of the rising prices of petroleum-based products, the dependence on imported petroleum in many countries and the negative impact of burning fossil fuels on the environment (Dufey, 2006). Today, Brazil leads the world in ethanol production, mainly for domestic consumption (although exports have increased in recent years), followed by the U.S. which produces ethanol mainly from corn. Countries such as France, Spain, China, Thailand, Canada and India are also producing biofuels in large scale derived from corn, cassava (*Manihot esculenta* C.), rice (*Oryza sativa* L.), wheat, sugarcane and straw. Also, large scale production of biofuel was recently initiated in Australia and in some countries of South America and Africa from sugarcane and cassava (Dufey 2006, Gwehenberger et al. 2007, Larson 2008).

Among environmental benefits of using biofuels rather than fossil fuel, biofuels sequester carbon during the development of the feedstock, are a potential low-carbon energy source and consequently reduce greenhouse gas effects (Lemus and Lal 2005, Tilman et al. 2008). However, others (Fargione et al. 2008, Scharlemann and Laurance 2008, Searchinger et al. 2008) suggest that converting native ecosystems to biofuel production generates high carbon emissions because the energy consumed is higher than when native ecosystems are converted to intensive crop production. For example, Fargione et al. (2008) attributed 13, 61, and 17% of carbon debt to palm, soy beans, and corn, respectively when they are planted in native ecosystems. Searchinger et al. (2008) affirm that, if corn fields with average yield were replaced with switchgrass for ethanol production, greenhouse emissions would increase considerably. Nevertheless, these authors also say that marginal lands planted with a mixture of perennial grasses and legumes and monocultures of perennial grasses such as switchgrass and woody species cause only a limited carbon debt (Fargione et al. 2008, Searchinger et al. 2008), and economically are less expensive than replacing food crops (Scharlemann and Laurance 2008). Other advantages of cellulosic ethanol crops are their efficient growth on degraded soils, minimal competition with food production and provision of wildlife habitat (Lemus and Lal 2005, Tilman et al. 2008).

Switchgrass Generalities

Switchgrass, *Panicum virgatum* L., is a warm-season, perennial grass that ranges in height from 0.5 to 3 m and has a strong and well-developed root system that can reach depths of up to 3 m (Surrency et al. 2003, Parrish and Fike 2005, Jensen et al. 2007). Switchgrass is native to North America, with a wide geographical distribution that covers most of the U.S. and some parts of Canada and Mexico (McLaughlin and Walsh 1998). Switchgrass grows on different type of soils and in areas where annual precipitation oscillates between 38 and 76 cm. It has the maximum growth period from June through August (Ryan and Marks 2005, Rinehart 2006).

Switchgrass is classified into two major types, upland and lowland, based on genetics rather than per location. The two types maintain their own characteristics if planted in different environments (Parrish and Fike 2005). Moreover, constant genetic differences between the two major types were detected by Hultquist et al. (1996), with the lowland type being tetraploid while upland type being hexaploid (Sanderson et al.

1996, Parrish and Fike 2005). The lowland types are smaller, with longer and wider leaves, larger panicles, are better adapted to heavy soils and produce more dry matter than the upland types (Parrish and Fike 2005, Rinehart 2006).

The selection of a switchgrass variety should be based on type and latitude of origin. Studies demonstrated that there is a direct association between latitude and yield, which determine the performance of a cultivar and adaptability (Parrish and Fike 2005, Rinehart 2006). ‘Alamo’ is a lowland variety well adapted to heavy soils especially in the Southeast, while ‘Blackwell’ is an upland variety poorly adapted to conditions in the lower southeastern United States. Other upland varieties include ’Trailblazer,’ ‘Cave in Rock,’ ‘Pathfinder’ and ‘Caddo’ (Surrency et al. 2003, Rinehart 2006).

Switchgrass is established from seed and the initial development is slow because of seed dormancy that can be broken after stratification (period of wet weather) or after ripering (period of warm weather) (Parrish and Fike 2005, Rinehart 2006). Switchgrass is a C4 species; therefore it has a faster photosynthesis than C3 plants under high light intensity and high temperatures. For this reason, switchgrass uses water and nitrogen efficiently, and is tolerant to stress conditions (McLaughlin et al. 1999, Parrish and Fike 2005).

Switchgrass is mainly grown as a forage crop or cultivated in association with other grasses and legumes to control erosion (Gettle et al. 1996, Parrish and Fike 2005). The long root system and dense foliage of switchgrass renders the plant useful for soil conservation and stabilization, protection of native wildlife and addition/supplementation of organic matter to soils (McLaughlin and Walsh 1998, Surrency et al. 2003).

Insects in Grasses

In general, grasses (Poaceae) host insects that belong to the orders Orthoptera, Lepidoptera, Coleoptera, Hemiptera, Hymenoptera, Diptera and Phasmidae, although the richness of grass feeders depends on grass species, shoot length and host abundance (Mowat 1974, Prestidge and Mcneill 1983, Hansen et al. 1985, Tscharntke and Greiler 1995). Tscharntke and Greiler (1995) found species of Hemiptera (leafhoppers and planthoppers, Diptera: Cecidomyiidae (gall midges), Hymenoptera: Eurytomidae (chalcidoid) and Hymenoptera: Cephidae (sawflies) more frequently in tall and abundant grass communities than in scarce and small grasses.

Turfgrasses are more widely used and intensively managed than other grasses and can host insects from a wide range of taxa. Soilborne insects such as scarabaeid grubs (Scarabaeidae), mole crickets (Orthoptera: Gryllotalpidae) and billbugs (Coleoptera: Curculionidaae) are usually pests that attack the root system of the plant. Leaves and stems are affected by cutworms (Lepidoptera: Noctuidae), armyworms (Lepidoptera: Noctuidae), skippers (Lepidoptera: Hesperiidae) and some species of sod webworms (Lepidoptera: Pyralidae). Chinch bugs (Hemiptera: Lygaeidae), mites, spittle bugs (Hemiptera: Cercopidae), aphids (Hemiptera: Aphididae) and mealybugs (Hemiptera: Pseudococcidae) are leaf feeders that can be serious pests at high densities (Potter and Braman 1991).

In a study on different perennial grasses in Germany, the smallest grasses (*Corynepherus canescens* L. and *Agrostis capillaries* L.) were attacked only by one species of Chalcidae (Hymenoptera), one gall midge and one mealybug (Homoptera: Pseudococcidae), while the taller species were attacked by chloropid flies (Diptera:

Chloropidae), sawflies (Hymenoptera), moths (Lepidoptera), beetles (Coleoptera), and small flies (Diptera: Schizophora) (Tscharntke 1993). This pattern occurred because the diversity of plant structures provides more food supply than rare plants with simple architecture (Strong et al. 1984). However, Scherber et al. (2006) evaluated the relationship between plant diversity and the damage caused by herbivorous insects in experimental grassland in Central Europe and concluded that herbivore damage is independent of the number of plant species. The authors reported *Longitarsus pratensis* (Panzer) (Chrysomelidae), three *Chaetocnema* species (Coleoptera: Curculionidae) and three typical grassland leafhopper species (Homoptera: Auchenorrhyncha) including (*Philaenus spumarius* (L.), *Arthaldeus pascuellus* (Fallén) and *Javesella pellucid* (F.)) as the main herbivore species. Herbivory tended to increase with plant species richness but the damage of leaves was rarely significant (less than 5% of leaf area).

Other studies of insect diversity in grasses refer to specific groups. Zurbrugg and Frank (2006) explored true bugs (Heteroptera) in Switzerland in three types of habitats: wildflower areas, meadows and grazed pastures. The authors chose Heteroptera because the group is very diverse, larvae and adults live in the same habitat, and the species richness has a correlation in cultivated landscapes. Bugs species were less abundant in pastures than in meadows and wildflower areas. Generalist species such as the mirids *Notostira elongate* (Geoffroy), *N. erratica L. and Lygus rugulipennis* Poppius were more common in pastures and meadows while predatory bug species were more frequent in the wildflower areas (Zurbrugg and Frank 2006). Other Miridae that are abundant in grasses are tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), and alfalfa plant bug, *Adelphocoris lineolatus* (Goeze) (Mack Un and Baker 1990).

Studies of butterflies (Lepidoptera) in mixed grass areas have shown variation in species depending on the height of grass. In tall grasses such as *Andropogon gerardii* (big bluestem), *Sorghastrum nutans* (indian-grass), *Aster falcatus*, *Sporobolus asper* (dropseed) and *Panicum virgatum* (switchgrass), *Hesperia ottoe* Edwards, *Hesperia leonardus pawnee* Dodge, *Euphyes bimacula* (Grote & Robinson) and *Speyeria idalia* (Drury) are commonly found (Panzer et al. 1995, Swengel 1996, Collinge et al. 2003); while *Cercyonis pegala* (F.), *Speyeria aphrodite ethne* (Hemming), *Pontia protodice* (Boisduval & Leconte), and species of *Colias* and *Pieris* are more abundant in grasses of smaller size such as *Bouteloua gracilis* (blue grama), *Bouteloua curtipendula* (side-oats grama), *Liatris punctata* (blazing star) and *Carex heliophylla* (sedge) (Collinge et al. 2003). Beetles are also a typical group in grasslands. Families Scarabaeidae, Carabidae, Staphylinidae, Tenebrionidae are frequently found. The scarab *Adoryphorus couloni* (Burmeister), the tenebrionid *Saragus catenulatus* Blackburn and the carabid *Promecoderus concolor* Germar are some of the important species (Gibson and New 2007).

Orthopteran insects such as crickets, grasshoppers and locusts are commonly found in grass ecosystems. A list of common species in the U.S. include *Melanoplus femurrubrum* (DeGeer), *M. bivittatus* (Say), *Phoetaliotes nebrascensis* (Thomas), *Eritettix simplex* (Thomas) and *Aulocara elliotti* (Thomas), *Phlibostroma quadrimaculatum* (Thomas), *Psoloessa deliculata* and *Trachyrhachys aspersa* (Welch et al. 1991, Craig et al. 1999). High densities of grasshoppers can cause a significant economic impact in the production of forage. Out of the approximately 400 known grasshopper species just 12 are known to be economically important in crops and forages in the western U.S. (Pfadt 2002, Branson et al. 2006).

Stem borers (Lepidoptera) are also some of the most serious pests in grasses and are problematic in graminaceaous plants in general (e.g. White et al. 2005, Reay-Jones et al. 2008). Grass loopers (*Mocis* spp.) and fall armyworm (*Spodoptera frugiperda* [J.E. Smith]) (Lepidoptera) are major pests in different grasses species, and annually may cause important economic losses for beef cattle and hay producers (Meagher et al. 2007).

Some Hemiptera have been reported as injurious in grasses as well. Families Cercopidae (spittlebugs), Cicadellidae (leafhoppers), Delphacidae (planthoppers) and Aphididae (aphids) in high populations can cause significant injury in forage crops (Mack Un and Baker 1990).

Although grass flowers are pollinated by wind and do not produce nectar to attract insects, species of Halictidae, Apidae, Anthophoridae (Hymenoptera), Syrphidae (Diptera) and Coccinellidae (Coleoptera) are found to be grass flower visitors (Tscharntke and Greiler 1995, Ngamo et al. 2007). Genus *Halictus*, *Lipotriches* and *Xylocopa* (Hymenoptera: Apidae), *Platycheirus* and *Melanostoma* (Diptera: Syrphidae) are the more predominant (Ngamo et al. 2007).

Management of pests in grasses involves mainly chemical control. Outbreaks of grasshoppers and crickets in the United States can cause important economic (Branson et al. 2006) losses. With high densities of these pests, applications of broad spectrum insecticides such as malathion and carbaryl can reduce the damage significantly (Branson et al. 2006).

To control *Dallaca pallens* (Lepidoptera: Hepialidae), an important pest in grasslands of South America, conventional insecticides such as insect growth regulators and pyrethroids are applied. Although effective in controlling this pest, such insecticides are also expensive and have the potential of reducing beneficial insect populations. Biological agents such as *Beauveria bassiana* were evaluated by Devotto et al. (2007). The authors compared applications of *B. bassiana* and lambda-cyhalothrin on non-target insects, and found that *B. bassiana* spores did not affect grassland diversity in the short-term (40 days), while the opposite was found with lambda-cyhalothrin.

Crop rotation is the most common cultural tactic and helps to interrupt pest dynamics and therefore limit damage by insect dispersal from field to field by separating crop species. Also, altering harvest schedules in forages production can reduce insect pest populations (Lamp et al. 2007)

Insects in Switchgrass

Few studies have been published on insects and their pest status in switchgrass. Insects, along with weed competition and seed dormancy, could potentially limit the establishment and therefore the yield of switchgrass (Parrish and Fike 2005). In a study in the United Kingdom (Semere and Slater 2004), the relative biodiversity of insects was determined in three grass crops (*Miscanthus*, reed canary and switchgrass) grown for biofuel. The most common insects found were Coleoptera (Curculionidae, Chrysomelidae, Carabidae, Staphylinidae, Elateridae), Hemiptera (Heteroptera and

Homoptera), Diptera, and Hymenoptera. The authors also monitored pests in these crops by visual inspection of the plants and reported only leafminers and stem borers but with minimal injury (Semere and Slater 2004). In Germany, thrips were found feeding on switchgrass (Gottwald and Adam 1998). The yellow sugar cane aphid (*Sipha flava*) and grasshoppers have also been reported to feed on switchgrass, but not as preferred hosts such as *Bothriochloa caucasica* (Trin.), *Dichanthium* sp., *Sorghum bicolor* (L.) and *Digitaria ciliaris* (Retz.) (Kindler and Dalrymple 1999, Parrish and Fike 2005).

Another study (Ward and Ward 2001) compared the diversity and abundance of carabid beetles in short-rotation plantings of sweetgum (*Liquidambar styraciflua* L.) with and without cover crops such as switchgrass and maize. The highest number of species collected was in switchgrass plots. The genera *Amara* and *Anisodactylus* were the most predominant. The authors suggested that switchgrass possibly provided a greater quantity and variety of food resources for these carabids (Ward and Ward 2001).

In this study, we aimed to determine changes in insect diversity as the switchgrass plant grows and weed diversity was modified and also determine the impact of pests on switchgrass yield and identify the potential species responsible. The research was conducted during 2008 and 2009 in a swtchgrass field planted in the spring of 2007 at the Pee Dee Research and Education Center in Florence, South Carolina.

The main objectives of this study were

1. To assess changes in insect diversity in switchgrass associated with switchgrass growth and changes in weed diversity and abundance.

2. To determine the impact of insect injury on switchgrass yield and to relate insect injury to pest species.

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INTRODUCTION

Interest in agricultural products grown for biofuel has increased drastically in recent years because of concerns over energy security and climate change (Farrell et al. 2006). Fossil fuels (oil, coal and natural gas) currently represent more than 85% of energy consumed in the United States (Parrish and Fike 2005). The use of biofuel not only slows the depletion of fossil fuel resources, but also reduces the release of fossil carbon (Lynd et al. 1991). Ethanol production (mainly from corn, *Zea mays* L.) represents 99% of the biofuels produced in the United States (Farrell et al. 2006). However, the net energy yield of corn (80-100 GJ/ha of crop) is less than those of perennial crops and grasses (200-300 GJ/ha of crop) and sugarcane, *Saccharum* spp. (400 GJ/ha of crop) (Rogner 2000). In addition, increasing demands on grain supplies and prices can limit the expansion of ethanol biofuel produced from monoculture crops grown on fertile soils (Schmer et al. 2008).

Native to North America, switchgrass (*Panicum virgatum* L.) has good potential for biomass production because of its wide geographic distribution and great adaptability to diverse environmental conditions (Sanderson et al. 1996, Parrish and Fike 2005). Perennial grasses such as switchgrass can reduce erosion and runoff, increase incorporation of carbon in the soil and reduce the use of pesticides compared to annual crops (Vaughan et al. 1989, Hohenstein and Wright 1994, Sanderson et al. 1996). Switchgrass also requires relatively low amounts of water and nutrients, grows on marginally productive land, provides habitat for wildlife and can be used for conservation buffers, streambank stabilization and filter strips (Sanderson et al. 1996, McLaughlin and

Walsh 1998, Parrish and Fike 2005). On the Coastal Plain in South Carolina, frequent droughts can decrease yield and increase production costs of traditional crops and the drought tolerant switchgrass provides an alternative crop for farmers.

Research on the production of switchgrass as a biofuel crop has centered on breeding for improved biomass yield and developing practices for nitrogen fertilization, weed control, and harvest (Sanderson et al. 1996, Parrish and Fike 2005). Insects, however, have been sparsely studied (Parrish and Fike 2005). The few insects reported to feed on switchgrass are grasshoppers, the yellow sugarcane aphid, *Sipha flava* (Forbes) (Kindler and Dalrymple 1999), thrips (Gottwald and Adam 1998) and an unidentified armyworm species (Barnhart et al. 2007). Insect pests may not become a threat to the production of biofuel from energy plants such as switchgrass until they are grown as an extensive monoculture (Parrish and Fike 2005).

Intensive agriculture with extensive use of monocultures may reduce the diversity of insects (Bourn and Thomas 2002). With the anticipated widespread planting of switchgrass as a monoculture crop, the diversity of insects in switchgrass fields may be considerably reduced compared to the smaller-scaled plots currently planted mainly as wildlife habitats. In addition, competition from weeds in a switchgrass field is most intense during the establishment year (Parrish and Fike 2005). The weed community in a perennial crop can change substantially from year to year (Parrish and Fike 2005); the impact of such a shift in plant diversity on insect diversity has not yet been quantified in switchgrass. However, arthropod responses can be functional group/feeding guild specific (Nickel and Hildebrandt 2003). For instance, densities of herbivores are often higher in monocultures where host plants are concentrated (Root 1973, Koricheva et al. 2000). In contrast, natural enemies of herbivores are often more abundant in polycultures having increased prey diversity and abundance of alternative food sources such as pollen and nectar (Root 1973). Therefore, insect outbreaks typically are more frequent in systems with reduced plant diversity (Andow 1991).

To better understand the insect dynamics in a switchgrass agroecosystem in South Carolina, we evaluated insect diversity and host plant diversity over three years and assessed potential changes over time in the densities of major insect trophic groups, in particular potential pests and natural enemies. In addition, we determined the potential impact of insect herbivores on switchgrass yield.

MATERIAL AND METHODS

Eight ha of switchgrass (lowland cultivar 'Alamo') were planted on 3 May 2007 at the Clemson University Pee Dee Research and Education Center in Florence, SC. Land preparation included double disking, broadcast planting at a seeding rate of 8.9 kg of pure live seed per ha, and deep tilling with a 6-shanked ParaTill equipped with a roller bar that firmed the seed into the soil. No nitrogen was applied in 2007 and weeds were controlled by mowing twice (19 June 2007 and 6 August 2007) at switchgrass canopy height.

Fertilizer was applied on 6 May 2008 (67 kg N/ha), 15 April 2009 (258 kg P/ha and 775 kg K/ha), and 29 April 2009 (67 kg N/ha). The entire field was previously mapped for soil type on a 15-m grid basis for soil characteristics such as depth to clay, thickness of the E soil horizon, and soil organic matter in the upper 15 cm of soil. The field contains large areas of Bonneau sand (loamy, siliceous, thermic Arenic Paleudults having organic matter less than 0.5%), Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Kandiudults having organic matter around 1.0%), and Rains sandy loam (fine-loamy, siliceous,thermic Typic Paleaquults with organic matter near 1.5%). The Bonneau soil series has relatively little clay in the upper soil profile and the argillic horizon (horizon of clay accumulation) as deep as 91 cm or more, while in the Norfolk series the depth to the argillic is about 38 cm (Darlington Co. Soil Survey Report, 2007). The Rains sandy loam is similar to the Norfolk loamy sandy except the Rains is usually higher in organic matter and moisture. Although diverse in soil characteristics, these three soil types are very common in the Pee Dee region of the Coastal Plain (see website for Darlington Co. Soil Survey Report, 2007). No herbicide or insecticide was applied.

To assess the impact of insect injury on switchgrass yield, prior to planting, the field was divided into 20 plots (24.4 m x 24.4 m) separated by 1.2 m mowed alleys with four treatments assigned in a randomized complete block design with five replications: (a) 1,3-dichloropropene (nematicide) and chloropicrin (soil fumigant used to control diseases that also has insecticidal properties) soil fumigation before planting, (b) 1,3-dichloropropene and chloropicrin soil fumigation before planting and monthly foliar applications of acephate during the season, (c) untreated plots, and (d) foliar applications of acephate during the season. Fumigated plots received applications of 1,3-dichloropropene and chloropicrin soil fumigation on 1 March 2007. A positive pressure pump was used to inject 2.25 ml 1,3-D/m row and chloropicrin (113 liters/ha) 30 cm deep with a single sub- soiling chisel placed with a 30 cm row spacing. A field cultivator was used to seal the chisel trace and prevent premature fumigant release. Acephate was applied (1.09 kg a.i./ha) in treatments b and d on 20 July 2007, 24 August 2007 and 3 July 2008. Additional samplings were conducted in the untreated plots to determine changes in diversity and abundance of insects and weeds associated to switchgrass growth.

Plant sampling

In treated and untreated plots, densities of switchgrass and weed plants (identified to species or genus) were measured in nine randomly selected 30.5-cm^2 areas in each plot on 21 June 2007, 18 June 2008 and 24 July 2009. Dry weight of switchgrass and combined weed species were determined in each plot in four randomly selected 0.3-m^2 areas on 2 August 2007 (switchgrass only) and in two 1-m^2 samples on 30 January 2008, 31 July 2008, 10 January 2009 and 29 July 2009. Plants were cut at ~5 cm above soil level and were dried for 5 days at 60ºC. Switchgrass height, defined as the distance from soil level to the top of the tallest tiller of the plant, was recorded in 20 randomly selected plants per plot on 19 June 2007, 23 May 2008, 18 June 2008, 21 August 2008 and 16 July 2009. To determine potential insect herbivore injury, plants were inspected for feeding injury in each plot in one randomly selected square meter monthly during the growing season.

Insect sampling and identification

For both treated and untreated plots, insects were monitored monthly from May to August of 2007, 2008 and 2009 using pitfall traps and sweep nets. Two pitfall traps (plastic cups, diameter: 10 cm and depth: 7.5 cm) containing antifreeze (ethylene glycol) were randomly placed in each plot once a month and left in the field for 14 days. The traps were collected, the antifreeze removed and insect samples preserved in vials with 75% ethanol. Two 25-sweep net samples per plot were also taken once a month. Insects collected were transferred to plastic bags and placed in a freezer in the laboratory. For soil insect density estimation, five samples were taken in each plot near the root of the plant on 12 June 2008 using a post hole digger (diameter: 10 cm and depth: 15 cm). Samples were processed using a soil sieve with a mesh size of 1.7 mm. All insects were counted and identified morphologically to family, using the keys of Johnson and Triplehorn (2004). Arthropods such as spiders and springtails were identified to order using Johnson and Triplehorn (2004), and mites were identified to suborder using Krantz (1978).

To determine changes in diversity and abundance of insects associated with switchgrass growth and to understand the potential role each taxon may have in a switchgrass agroecosystem, all arthropods collected in untreated plots were classified by trophic levels according to the feeding habit and functionality in the switchgrass agroecosystem: herbivores, predators, scavengers and parasitoids (Siemann et al. 1998, Koricheva et al. 2000, Johnson and Triplehorn 2004). When possible, groups that contain two feeding habits were identified to genus or species for insects and to suborder for mites. Groups for which a specific guild was difficult to assign were classified in the different possible guilds and data were analyzed for each guild. To determine the potential impact of herbivorous insects on switchgrass yield and to identify the basic functional roles and organization of feeding guilds in the switchgrass agroecosystem, without referencing to any explicit species (Root 1973), in the four treatments, insect herbivores were divided into feeding guilds: chewing, sucking and boring. Chewing insects can feed on the entire plant (roots, stems, leaves, flowers and/or seeds). These insects tear or cut plants, leaving ragged tissue and, in most cases, most of the plant tissue is eaten (Johnson and Triplehorn 2004). The characteristic damage of chewing insects can be holes in the leaves, cuts around the edges and defoliation. Sucking insects cause damage by inserting the mouthparts into the leaf and sucking sap from the plant, and, as a result, the leaves can turn yellow, curl and stunt and in some cases the plant can reduce growth. Other sucking insects can rasp the tender tissues of the plant and suck the exuding sap resulting in deformed plants, and others can also transmit diseases (Johnson and Triplehorn 2004, Cabrera-La Rosa et al. 2008). Boring insects can cause damage by boring into the stem or roots, resulting in the destruction of vascular tissue. High densities of such insects can weaken the root system and can cause the death of the plant (Johnson and Triplehorn 2004).

In addition, for treated and untreated plots, the most frequent insects were identified to species, using the reference collection in the insect museum at the Clemson University Pee Dee Research and Education Center. Families such as Acrididae, Carabidae, Curculionidae, Scarabaeidae, Pentatomidae, Lygaeidae, Tenebrionidae, Thripidae, some Cicadellidae, Miridae and Reduviidae were identified to species by taxonomic specialists. Target species were selected based on their consistent presence in sampling over time, as these species appeared to be well established in the switchgrass agroecosystem. A collection with representative specimens found in this study was also created and deposited at the Pee Dee Research and Education Center.

Data analyses

In untreated plots, the diversity of plant species, insect families, non-insect orders and trophic groups was estimated by sampling method for each date during the three years of study using the Shannon index (*H*) (Southwood and Henderson 2000) (eq. 1):

$$H = -\sum_{i=1}^{s} p_i \, ln \, p_i \qquad (1)$$

Where p_i = the proportional abundance of i-th species (n_i /N); *i* = i-th species; n_i = abundance of each species; N= the total number of all individuals and S = observed number of species (species richness).

To estimate changes in diversity and abundance of weeds and insects and dry weight in plots receiving no pesticide (treatment c), a one-way ANOVA was used with date as a fixed effect and a repeated measures statement with a first order autoregressive covariance structure (PROC MIXED SAS Institute 1999). To estimate the impact of pesticides on diversity and abundance of weeds, insect herbivores and dry weight (for each of the four treatments), a two-way ANOVA was used with pesticide treatment and sampling dates as factors (PROC MIXED, SAS Institute 1999). A repeated measures statement was used with a first order autoregressive covariance structure. Tukey's HSD (Tukey 1953) was used for mean separation. Densities of plants, weeds and insects were transformed ($\sqrt{x+\frac{3}{8}}$) prior to ANOVA to normalize their distribution (Zar 1999).

Across treated and untreated plots, associations between abundance of herbivores, feeding guilds and dry weight of switchgrass obtained in August of 2008 and 2009 were determined using correlation analyses (PROC CORR, SAS Institute 1999).

RESULTS

Plant diversity

A total of 16 weed species were found in the five untreated plots (receiving no pesticide) across the three years of this study. In the first growing season (2007), *Mollugo verticillata* L. (carpetweed) was the dominant species, followed by *Helenium* sp. (sneezeweed) (Table 1). Pigweed, *Amaranthus* sp., was one of the more prevalent species in 2007, but was not found in following years. Only *Oxalis corniculata* L. (creeping woodsorrel) was found in both 2007 and 2008. The overall density of weeds present in 2007 was greater than in 2008 and 2009 (Table 1). The density of switchgrass in 2007 was greater compared to 2009 and increased substantially relative to density of weeds (Table 2). In addition, the height of switchgrass increased significantly over time (Table 2).

The diversity of plant species (switchgrass and weeds) expressed by Shannon's index, decreased significantly from 2007 to 2008 and 2009 (F = 102.1; df = 2,8; P = 0.0001) (Fig. 1). However, when only weed diversity was estimated, the Shannon index did not vary significantly across the three years of study (F = 1.34; df = 2,8; P = 0.3149).

Insect diversity

A total of 13,746 arthropods were collected in untreated plots from 2007 to 2009 across all sampling methods and dates from three classes: Arachnida (spiders and mites), Entognatha (Collembola) and Insecta (Table 3). All mites belonged to the suborder Oribatida. Insects belonged to seven orders and 41 families. In pitfall trap sampling, 9,363 individuals were found across the three years, comprising six orders and 31 families. In sweep net samples, fewer individuals were found (1,927), representing five orders and 27 families (Table 4).

Insect diversity in untreated plots based on pitfall trap sampling (Fig. 2) did not show significant differences among sampling dates (F = 1.04; df = 6,27; *P* = 0.4244), while diversity based on sweep net sampling differed significantly among dates (F = 5.54, df = 6,27; *P* = 0.0007). In sweep net samples, diversity was higher in May and decreased in the following months in 2008 and 2009 (Fig 2). For non-insect orders (Acari, Araneae and Collembola) in pitfall traps, the Shannon diversity index was significantly different across sampling dates (F = 5.90; df = 6,27; *P* = 0.0005), with the greatest diversity in May 2007 (Fig. 3).

Arthropod abundance in untreated plots also varied significantly ($P < 0.05$) among sampling dates. In pitfall traps, Araneae, Collembola, Formicidae and Gryllidae were the most abundant and consistently present groups over time (Table 5). In sweep net samples, Cicadellidae was the most abundant group and Cicadellidae, Acrididae and Tettigoniidae were the most consistently captured groups for this sampling method (Table 6). Flies such as Sciaridae, Phoridae and Chloropidae and beetles such as Carabidae in pitfall traps and Curculionidae in sweep net samples were collected in most dates although at low abundance. Anthicidae, Tenebrionidae, Cydnidae and Gryllotalpidae were most numerous in 2007, decreased in 2008 and were not collected in 2009 for pitfall traps, and Geocoridae and Berytidae were present only in 2007 and 2008 for sweep net samples. Lygaeidae showed the same trend for both sampling methods (Tables 5 and 6). Other groups of insects, however, were found only in 2009. These groups included Reduviidae and Cercopidae for pitfall traps and Pipunculidae, Dolichopodidae, Syrphidae and Coenagrionidae for sweep net samples. Families such as Elateridae for pitfall traps and Pentatomidae and Reduviidae for sweep net samples were collected in 2007 and in 2009, but not in 2008 (Tables 5 and 6). Other families of insects were found only once or twice across sampling dates at low abundance; these included Tipulidae, Alydidae, Membracidae, Platystomatidae and Chrysomellidae for both sampling methods and Coccinellidae for sweep net samples (Tables 5 and 6).

Among the four trophic groups (Table 7), insects that belonged to the families Lygaeidae, Pentatomidae, Miridae, Carabidae and Cecidomyiidae can be either predators or herbivores. As a result, Lygaeidae, Pentatomidae, Carabidae and a species of Miridae (the most predominant in this group) were identified to genus or species (Tables 9 and 10) and classified as herbivores. We were not able to identify specimens of Cecidomyiidae to genus or species; however, due to the low abundance of individuals we collected, the trophic group was arbitrarily assigned as herbivore. The same criteria were used for another undetermined species of Miridae. The genus *Gryllus* can be a predator or can feed on seedling plants (Walker 1986) or dead material (Gangwere 1961). Gangwere (1961) suggests that field crickets prefer plant material; however, Carmona et al. (1999)

reported that *Gryllus pennsylvanicus* Burmeister had high densities and activity in switchgrass used as a filter strip, but its specific role was undetermined. Because the function of this field cricket is unknown in the present study, the family Gryllidae was classified in two trophic groups, herbivores and predators. Mites were classified as scavengers because the individuals collected belonged to the suborder Oribatida and are mycophagous and saprophagous, acting as decomposers of organic material in the soil (Krantz 1978, Jordan 2001).

In pitfall traps, the diversity of only herbivores differed significantly across sampling dates [herbivores (F = 3.74; df = 6,28; P = 0.0074); predators (F = 1.21; df = 6,28; P = 0.3308); scavengers (F = 2.04; df = 6,28 P = 0.0936)] (Fig. 4). Diversity of herbivores showed a peak in May 2008 and tended to decrease across time. For sweep net samples, herbivores and predators were the only groups found (Fig. 5). The diversity of these groups varied significantly over time [predators (F = 9.25; df = 6,28; P = 0.0001); herbivores (F = 3.28; df = 6,28; P = 0.0143)]. Diversity of herbivores was lowest in June 2009 and highest in May 2009. Diversity of predators did not show a clear pattern but a tendency to decrease across sampling dates was observed.

The abundance of trophic groups in pitfall traps in untreated plots varied significantly over time only for herbivores and predators (Table 8). For both groups, abundance was higher in June of each year and abundance of predators was higher than abundance of herbivores. For sweep net samples, herbivores and predators were also the only groups that varied significantly over time (Table 8). Both groups decreased from 2007 to the end of 2008 and increased in 2009 in June. In contrast to pitfall traps, abundance of herbivores was always greater than the abundance of predators sampled with sweep nets.

In untreated plots, some of the more abundant and consistently sampled species (referred to as target species) in pitfall traps were *Solenopsis invicta* Buren (predator) and *Gryllus* sp (undetermined trophic role) (Table 9). In sweep net samples, target species were *Draeucolacephala* sp. (herbivore), *Melanoplus* possibly *sanguinipes* (herbivore) and two undetermined species of Tettigoniidae. In 2008 and 2009, *Gryllus* sp. and *Draeucolacephala* sp. showed a peak in June and then decreased at the end of the season (Table 10), while *Melanoplus* and a species of Tettigoniidae were less abundant than the other herbivores selected as target species across the three years of sampling.

Impact of pesticides on switchgrass and weed growth

Dry weight of switchgrass did not show significant differences neither by treatment (F = 0.67; df = 3,76; *P* = 0.5703) nor by the interaction treatment and sampling date (F = 0.73; df = 12,76; *P* = 0.7168). Across sampling dates dry weight of switchgrass varied significantly (F = 268.87; df = 4, 76; *P* = 0.0001) with a general increase over time, and was substantially higher than the dry weight of weeds (Fig. 6). Dry weight of weeds did not show differences by date (F = 2.23; df = 3, 66; *P* = 0.0940), treatment (F = 2.53; df = 3, 66; *P* = 0.0660) and interaction (F = 1.95; df = 9, 60; *P* = 0.0621). The ratio of the dry weight of switchgrass divided by the dry weight of weeds increased from 2.4 in 2007 to 23.7 in August 2009.

Impact of pesticides on herbivorous insects

A total of 6,027 individuals and 20 families of herbivores were collected in pitfall trap samples across the four treatments during the three years of this study. The total insect herbivores collected in this sampling method showed significant differences across sampling dates (F = 16.56; df = 6, 108; *P* = 0.0001), but neither treatment nor interaction effects were significant (treatment: F = 0.74; df = 3,108; *P* = 0.5356; interaction: F = 0.71; df = 18,108; *P* = 0.7897).

In sweep net samples, a total of 6,309 individuals and 17 families of herbivores were collected during the three years of study. As in pitfall traps, the total insects collected showed significant differences across sampling dates (F = 44.79; df = 6, 108; *P* = 0.0001) but not for treatments or interaction (treatment: F = 0.39; df = 3,108; *P* = 0.7611; interaction: F = 0.54; df = 18,108; *P* = 0.9306).

In the analysis by feeding guilds, none of the feeding guilds showed significant differences for the effect of treatments or interaction in pitfall traps [chewing (treatment: F = 0.48; df = 3,108; *P* = 0.6913; interaction: F = 0.61; df = 118,108; *P* = 0.8888); sucking (treatment: F = 0.59; df = 3,108; *P* = 0.6257; interaction: F = 1.04; df = 118,108; *P* = 0.4270); boring (treatment: F = 1.27; df = 3,108; *P* = 0.2684; interaction: F = 0.65; df = 118,108; *P* = 0.8500). Chewing insects were the most predominant feeding guild in pitfall traps (Fig. 7). Abundance of this group was significantly higher in June 2008 and June 2009 (F = 30.35; df = 6,108; *P* = 0.0001). Sucking insects were significantly more abundant in the first three dates of sampling (F = 17.40; df = 6,108; *P* = 0.0001). Abundance of boring insects did not show significant differences across sampling dates (F = 1.27; df = 6,108; *P* = 0.2795). For sweep net samples, none of the feeding guilds showed significant differences among treatments or interaction as for pitfall traps [chewing (treatment: F = 0.95; df = 3,108; *P* = 0.8642; interaction: F = 0.25; df =

118,108; P = 0.5181); sucking (treatment: F = 0.28; df = 3,108; P = 0.8388; interaction: F = 0.50; df = 118,108; P = 0.9526); boring (Treatment: F = 1.93; df = 3,108; P = 0.1283; interaction: F = 1.43; df = 118,108; P = 0.1103)]. Sucking and boring herbivores showed significant differences across time, with peaks of abundance in August 2007 and June 2009 for sucking insects (F = 54.43; df = 6,108; P = 0.0001) and for boring insects, densities were significantly higher in May 2007 (F = 9.09; df = 6,108; P = 0.0001) (Fig. 8).

The correlation analysis for pitfall traps showed that the abundance of herbivores and dry weight of switchgrass were positively correlated (Table 11), while a negative correlation was determined for sweep net samples. For pitfall traps, the abundance of boring insects did not show a significant correlation with the dry weight of switchgrass. Abundance of chewing insects was positively correlated while sucking insects showed a negative correlation. For sweep net samples, abundance of herbivores and the three feeding guilds showed negative correlations with dry weight of switchgrass.

Of 12,336 herbivore specimens collected in the treated plots**,** approximately 9,000 were identified to genus and 4,950 were identified to species with the help of experts (Tables 12 and 13). In pitfall traps, 40% of the genus showed significant differences (P < 0.05) across sampling dates (Table 12). The genus *Gryllus* sp. (chewing) was persistent across sampling dates. Boring species (Curculionidae) were rarely collected. In sweep net samples 37% of genus also showed significant differences across sampling dates (Table 13). The predominant and persistent species were the sucking insects

Draeucolacephala sp. and *Stirellus bicolor* Van Duzee (Cicadellidae) and chewing insect *Melanoplus* sp.

In pitfall traps, the only species that showed significant differences among treatments was the sucking insect *Ptochiomera nodosa* Say (Lygaeidae) (F = 2.93; df = 3,108; *P* = 0.0368). This species was absent in plots received only foliar applications of acephate, and significantly higher in plots with 1,3-dichloropropene and chloropicrin soil fumigation before planting combined with foliar applications of acephate (1.1±0.6a). However, these values were not significantly different from the control (0.4±0.2ab). In sweep net samples *Melanoplus* sp., a chewing genus, had the lowest density in plots fumigated with 1,3-dichloropropene and chloropicrin plus foliar applications of acephate (0.4±0.2b) and the highest was observed in plots treated with only foliar applications of acephate (2.0±0.8a) (F = 5.08; df = 3,108; *P* = 0.0025). No significant differences were observed between treatments and control (0.9±0.3ab). In addition, *Stirellus bicolor*, a sucking insect, showed differences among treatments (F = 3.00; df = 3,108; *P* = 0.0339), being significantly more abundant in untreated plots (2.6±0.8a) than in plots treated with only foliar applications of acephate (0.8±0.3b).

DISCUSSION

Plant diversity

A total of 16 species of weeds were found in the switchgrass field used in our study. Weed species that can compete with switchgrass vary from region to region and are in general perennial forbs and warm season grasses (Parrish and Fike 2005). In our switchgrass plots, *M. verticillata*, *Helenium* sp. and *Amaranthus* sp. were the most abundant species and were mainly collected in the first year after planting (2007) (Table 1). Weed competition can be a major limiting factor for switchgrass growth in the year of establishment (Martin et al. 1982, Parrish and Fike 2005). However, Martin et al. (1982) also found that switchgrass, along with big bluestem grass (*Andropogon gerardii* Vitman), excluded weeds more efficiently during the establishment year than other grasses such as Indiangrass (*Sorghastrum* sp.) and side-oats grama (*Bouteloua curtipendula* (Michx.)). Moser and Vogel (1995) also indicated that switchgrass is more competitive than other warm-season grasses. In our study, the weed species found in the first year did not always persist in subsequent years (Table 1). In addition, as the density of switchgrass increased relative to the density of weeds (Table 2). Plant diversity (weeds and switchgrass) estimated by the Shannon index was also significantly higher in the establishment year compared to years two and three (Fig 1). These results suggest that switchgrass out-competed weeds after the establishment year and there was not a dominant weed species associated with switchgrass in our study in years two and three. The disturbed habitat after switchgrass was planted may explain the high densities of weeds in 2007, particularly of the dominant species *M. verticillata*. Parrish and Fike (2005) affirm that new weed species can appear in well-established switchgrass stands, mainly because of management practices. However, our work was conducted in a single field, and further work is necessary under a wider range of conditions to confirm these results in South Carolina.

Insect diversity

Three different methods of estimating insect abundance and diversity were used in this study. Pitfall traps are inexpensive and easy to manipulate in the field and have been extensively used to sample active ground-dwelling arthropods from a wide range of taxa (Luff 1975, Thomas and Marshall 1999, Ward et al. 2001), particularly Coleoptera and Araneae (Luff 1975). In our unrtreated plots, spiders, springtails and ants were the most abundant and consistent groups collected with this method. Sweep net sampling can be a fast and easy method to measure relative abundance and relative species richness of insects, and has been widely used for sampling aerial insects (Siemann et al. 1998, Southwood and Henderson 2000). In our study, the dominant families of insects collected using sweep nets were Cicadellidae, Lygaeidae and Tettigoniidae. Soil sampling is usually used to estimate arthropod densities in a specific area, for instance, near the roots of plants (Missa et al. 2009). Although only limited sampling was conducted with this method, the absence of soil herbivores suggests that switchgrass may not be impacted by root feeding insects. The combined use of these three methods enabled the sampling of a broad range of insects, such as ants, crickets and ground beetles with pitfall traps, and leafhoppers and grasshoppers with sweep nets**.** Future work may evaluate other sampling methods more appropriate for certain insects, which may include direct counting of insects on the lower leaf surface for thrips, leaf miners and aphids or using a white cloth or enamel pan under the plant for plant hopper sampling (Wilson and Wheeler 2005).

Shannon's diversity index using family-level classification did not differ significantly across sampling dates for pitfall traps, but peaks of diversity were observed in May of each year for sweep net samples (Fig. 2). Diversity analysis using trophic groups allowed the detection of trends that were not observed at family-level classification (Koricheva et al. 2000). In pitfall traps, herbivore diversity showed significant differences over time, indicating that trophic group classification may be more informative when studying temporal changes in diversity. In sweep net samples, herbivores and predators varied significantly over time with a peak in May 2007 and 2008, respectively (Fig. 5). These results support the findings using family-level classification that also showed peaks in May of each year (Fig. 2). This pattern may be explained by greater emergence of insect adults in early summer (Unsicker et al. 2006).

Many authors have found a positive correlation between plant diversity and arthropod diversity (Andow 1991, Siemann et al. 1998, Borges and Brown 2001). In our study, the higher insect diversity observed in May was usually followed by a decline across sampling dates for herbivores in both sampling methods and for predators in sweep net samples (Fig. 4 and 5), despite a significant decrease in plant diversity in 2008 and 2009 (Fig. 1). Numerous studies have demonstrated that intensive agriculture with widespread use of monocultures has a negative effect on the insect diversity (e.g., Bourn and Thomas 2002). In our study, several families were collected only in the establishment year before weed diversity declined (Table 5 and 6). Some of these families may have been associated with weed species present in 2007. For example, species of *Amaranthus* are hosts of weevils and leaf beetles (Burki et al. 2001) that were mostly found in our study in 2007. Thrips were also collected mainly in 2007, although appropriate sampling methods were not used. High densities of species of the genus *Frankiniella* have been found on *Amaranthus palmieri* S.Wats and *M. verticillata* in North Carolina (Kahn et al. 2005).

Root (1973) stated that herbivores are more likely to find and remain on host-plants in pure stands than in polycultures because monocultures provide concentrated resources of food. Many other authors have corroborated this concept (Letourneau 1987, Borges and Brown 2001, Midega et al. 2004, Unsicker et al. 2006). In this study, although herbivore diversity tended to decrease with plant diversity in 2008 and 2009, herbivore abundance increased in June 2009 for both sampling methods (Table 8). Plant diversity could potentially have affected insect diversity in our switchgrass plots. Root (1973) also stated that higher plant diversity has a positive correlation with the densities of generalist natural enemies; consequently, there is often better control of specialist herbivores by natural enemies in more diverse plant communities (Root 1973). In addition, Siemann et al. (1998) reported that reduction in plant diversity directly affects the diversity of higher trophic levels, because the food sources for many predators or parasites are reduced too. In our study, however, plant diversity declined after 2007 without a corresponding decline in predator diversity.

Siemann et al. (1998) affirmed that parasitoid and predator diversity can be positively correlated with the diversity of herbivores, which helps to prevent competitive exclusion and allows more species of herbivores to coexist. Although our study was not designed to test this hypothesis, our findings suggest that this affirmation is partially true, because diversity of herbivores and predators was higher in May and showed significant differences across sampling dates in sweep net samples (Fig. 5). This may indicate an interaction effect between those two trophic groups. In addition, families of predators such as Geocoridae, Berytidae, Anthicidae and Formicidae decreased over time; and families of herbivores such as Lygaeidae, Cydnidae and Gryllotalpidae also decreased. However, some families that appeared in 2009 were predators and parasitoids, such as Reduviidae, Pipunculidae, Dolichopodidae, Syrphidae and Coenagrionidae, although some were in low abundance. The predominant group of predators observed in this study was Formicidae, collected in pitfall traps (Table 9). The main species, *S. invicta*, showed a substantial decrease in 2008 and 2009 compared to 2007. Ants in general are susceptible to habitat changes, disturbance and agriculture intensification (Andersen et al. 2002, Bruhl et al. 2003; Philpott and Armbrecht 2006). In our switchgrass plots, the recently disturbed habitat in the first year after planting may explain the high densities of this species found in 2007. Canopy closure in subsequent years likely caused a reduction in fire ant densities.

In this study, switchgrass out-competed weeds after the establishment year and there was not a dominant weed species in years two and three. Peaks of diversity of insects were found in May of each year. Herbivores and predators were the only groups that showed significant differences across sampling dates. Large-scale commercial planting of switchgrass may lead to a reduction of natural diversity of insects across the landscape than that observed in the small plots used in our work. The reduction in ecological diversity in monocultures can lead to increased pest problems because food, hosts, prey and overwintering sites of many natural enemies are reduced (Mensah 1999). Unless natural enemies are present before colonization, pests can rapidly migrate into crops before control can be achieved by natural enemies. Future work should investigate farmscape dynamics of insects in and around switchgrass crops to quantify the impact of this new crop on the sustainability of pest management systems. This study has provided the basis for identifying pest and beneficial insects in switchgrass in South Carolina.

Impact of pesticides on herbivore insects and switchgrass growth

The pesticides 1,3 dichloropropene, a nematicide that controls some soilborne insects (Unruh et al. 2002) and chloropicrin, a fungicide that provides effective control of soilborne pathogens (Martin 2003) are commonly used in crop production. These two chemicals are usually applied in combination to optimize the control of diseases, insects and also weeds applied as pre-plant fumigants (Ajwa et al. 2002, Unruh et al. 2002, Martin 2003, Shrestha et al. 2008). Acephate is an orgonophosphate insecticide that provides control of a wide range of insects (Bull 1979). In several crops such as strawberry, tomato, potato, cotton, soy bean and sorghum, applications of these chemicals have been widely used with effective results and significant increase in yields (Ajwa et al. 2002, Duniway 2002, Westphal et al. 2004, Collins et al. 2006).

In our study, the chemical treatments applied did not elicit significant differences for the dry weight of switchgrass and weeds, total abundance of herbivore families and feeding guilds. Environmental factors not considered in this study may explain the low efficiency of the treatments, such as evaporation and degradation during the application of the pesticides. In addition, applications of acephate to control insects were made regardless of insect densities in the switchgrass field, so timing of applications may have hindered their effectiveness. The low abundance of insects observed in this study may also explain the lack of significant effect of pesticides that did not permit the detection of significant differences. However, differences between treatments were detected in three herbivores species: *P. nodosa, Melanoplus* sp. and *S. bicolor*. Plots treated with acephate did not show significant differences with the control for *P. nodosa* and *Melanoplus* sp. For *S. bicolor,* differences with the control were observed when acephate was applied topically but not when this insecticide was applied in combination with the soil fumigation. However, due to the low number of species that presented differences in abundance by treatments, it is more likely that the low densities of insect species observed in this study did not permit detection of significant differences from the control.

The ratio of dry weight of switchgrass to weeds increased from 2.4 in 2007 to 23.7 in August 2009 (Fig. 6). The dry weight of switchgrass also tended to increase across sampling dates, with the exception of January 2009, where a slight reduction was observed. This reduction in dry weight in January 2009 may have an impact on determining the best time to harvest switchgrass. The highest value of dry weight in our switchgrass plots (12 Mg ha^{-1}) was reached in August 2009 (Fig. 7). This yield is similar to recent studies with values higher than 10 Mg^{-1} (Parrish and Fike 2005). Maximum yields of 20 Mg ha^{-1} have been reported by the same authors in systems managed for maximum sustainable dry weight with later harvests. In a study of dry weight production in the eastern United States (Kentucky, North Carolina, Tennessee, Virginia, and West Virginia) an average of 14.7 Mg ha^{-1} across the region was reported (Fike et al. 2006). Dry weight yield comparisons should be taken with caution since yield depends greatly upon environmental conditions and harvest times.

In plots that received application of pesticides, insect herbivores collected were divided into feeding guilds to identify the basic functional roles and organization of these guilds in the switchgrass agroecosystem without referencing to any explicit species (Root 1973). Chewing insects were more abundant in pitfall traps than in sweep net samples (Fig. 7 and 8). The most abundant chewing insect belonged to family Gryllidae (Table 12). In sweep net samples, grasshoppers of family Acrididae were the more abundant and persistent chewing insects (Table 13). Sporadic leaf feeding was observed in each year of our study; although we did not directly observe grasshoppers feeding on switchgrass, we attribute the majority of this type of feeding to grasshopper herbivory. In contrast, sucking insects were more abundant in sweep net samples (Fig. 8) with insects that belong to family Cicadellidae being the most predominant (Table 13). In our study we did not observe injury caused by leafhoppers. Boring insects were less abundant than chewing and sucking insects in both sampling methods (Fig. 8 and 9). The only family collected was Curculionidae. Although none of the species collected showed persistence across sampling dates in our study, many species have been reported as pests of grasses (Lamp et al. 2007). In this study, we did not detect injury caused by weevils, possibly due the low density of boring insects observed.

The results of the correlation analysis indicated a negative relationship between herbivores collected in sweep net samples and dry weight of switchgrass (Table 11). All feeding guilds in this sampling method showed similar correlations, with insects of the sucking guild with the stronger correlation (Table 11). In pitfall traps, herbivores in general and chewing insects showed a positive correlation with the dry weight of switchgrass. However, sucking insects as in pitfall traps showed a significant negative correlation with the dry weight of switchgrass. The consistent and significant negative correlation between switchgrass dry weight and sucking insect abundance in both sampling methods may indicate that many of these species were associated with weeds that were less abundant in the second and third years of this study.

In treated and untreated plots, the predominant families of herbivores collected using sweep net samples were Cicadellidae, Acrididae, and Tettigoniidae (Tables 10 and 13). For family Cicadellidae, the dominant genus found in our study was *Draeucolacephala* sp. This sharpshooter is common in grasses and as a phloem feeder can cause yellow and curling leaves (Cabrera-La Rosa et al. 2008). It is recognized as an important pest in grasses and is also associated with the transmission of some diseases (Hewitt et al. 1946, Cabrera-La Rosa et al. 2008). Koricheva et al. (2000) and Nickel and Hildebrandt (2003) showed that Cicadellidae was more abundant in monoculture stands rather than in more diverse habitats. Leafhoppers are specialized herbivores and might find the host plant more readily in monocultures (Joshi et al. 2000, Koricheva et al. 2000, Nickel and Hildebrandt 2003). This may explain the higher abundance of *Draeucolacephala* in June 2009, although we did not observe this leafhopper feeding on switchgrass (Table 10 and 13).

Other herbivores found consistently in our study were orthopterans (Tettigoniidae and Acrididae). Grasshoppers have also been reported in switchgrass but not as frequently as on preferred hosts such as *Bothriochloa caucasica* Trin., *Dichanthium* sp., *Sorghum bicolor* and *Digitaria ciliaris* (Retz.) (Kindler and Dalrymple 1999, Parrish and

Fike 2005). In our study, the species of Acrididae collected was *Melanoplus* possibly *sanguinipes,* and the species of Tettigoniidae were undetermined (Tables 6 and 10). These species are typical of grass ecosystems (Welch et al. 1991, Craig et al. 1999). Craig et al. (1999) classifies grasshoppers as residents or accidentals based on the incidence of individuals caught rather than by densities to determine the stability of a species in an ecosystem. In our study, although the densities were low compared to other herbivores, grasshoppers were considered a target group because of the persistence of these families across sampling dates.

Gryllidae was also a predominant family collected in pitfall traps in treated and untreated plots (Tables 5 and 12). In the classification by trophic groups in untreated plots, these crickets were considered as both herbivores and predators due to its undetermined trophic role. Crickets showed peaks of abundance in June 2008 and 2009 (Table 5). Carmona et al. (1999) studied the abundance of *G. pennsylvanicus* in soybean and two adjacent filter strips, alfalfa and switchgrass. The highest activity and densities of *G. pennsylvanicus* were found in switchgrass rather than in soybean or alfalfa, but the role of the insect was undetermined. Further studies are recommended to identify the function of crickets in a switchgrass agroecosystem. In our switchgrass plots, only one genus was identified (*Gryllus* sp.) (Tables 9 and 12). This genus is recognized for causing damage mostly at night, and can reduce the stand of a melon crop by feeding on newly emerged seedlings (Palumbo and Kerns 1998). Injury caused by crickets was not observed in our switchgrass study.

Many of the insect species sampled in the switchgrass plots are recognized as pests in grasses, for instance: *Phyllophaga* sp., *Sehira cinctus,* chinch bugs *Blissus* sp., stink bugs *Euschistus* sp., *Thyanta* sp., tarnished plant bugs *Lygus lineorales* and thrips *Frankiniella tritici* (Lamp et al. 2007). Although these species were collected in low densities, future studies should continue to monitor such insects associated with switchgrass. In this study, we did not see significant injury caused by herbivores across the three years. The lack of differences in dry weight of switchgrass when treatments were compared may be explained by inadequate timing of insecticides to suppress herbivore populations or that the low densities of insect species observed in this study did not permit detecting significant differences. The only species that showed differences with the untreated control was *S. bicolor* when plots were only treated with acephate, being significantly more abundant in untreated plots. High densities and persistence of potential pests such as *Draeucolacephala* sp., and *Melanoplus* possibly *sanguinipes* can possibly cause injury to switchgrass. The results of this study provide important information related to the pest status of insects in switchgrass in South Carolina. This work will help in determining potential pest problems associated with switchgrass in this region.

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TABLES

Table 1. Density (± SEM) of weed species per square meter in untreated switchgrass plots in Florence, SC, 2007-2009.

Plant species	Plant density per square meter			F[a]	*P* > F
	2007	2008	2009		
Amaranthus sp.	15.3±5.7	0	0	-	-
Cyperus esculentus	3.6±2.0	0	0	-	-
Mollugo verticillata	47.4±29.0	0	0	-	-
Helenium sp.	21.9±11.0 a	0 b	0.2 ±0.2 b	7.93	0.013
Digitaria sp.	4.8±4.5	0	0	-	-
Oxalis corniculata	2.6±2.6 a	1.7±1.7 a	0	0.52	0.614
Silene antirrhina	0	2.4±1.3	0	-	-
Conyza canadensis	0 a	1.0±1.0 a	4.3±3.2 a	1.78	0.229
Rumex acetosella	0	0.7±0.7	0	-	-
Solidago sp.	0	2.6±1.3	0	-	-
Oenothera sp.	0 b	2.6±1.3 a	0.2±0.2 b	7.07	0.017
Richardia brasiliensis	0	0	0.5±0.5	-	-
Senna obtusifolia	0	0.2±0.2 a	0.5±0.3 a	1.2	0.350
Croton glandulosus var. septentrionalis	0	0	1.0±0.7	-	-
Unidentified species	0	5.7±5.7	0	-	-
Acer rubrum	0	0	0.2±0.2	-	-
Total	95.4±21.4 a	11.2±4.3 b	11.2±4.3 b	23.73	0.0004

[a] df = 2,8

Means within the same row followed by the same letter are not significantly different ($P < 0.05$; Tukey's [1953] HSD).

Table 2. Switchgrass density and height (± SEM) in untreated switchgrass plots in Florence, SC, 2007-2009.

Dates	Density(plants per square meter)	Dates	Height (cm)
21 June 2007	166.7 ± 41.1 b	19 June 2007	5.6 ± 40.3 e
18 June 2008	542.5 ± 36.3 a	23 May 2008	46.3 ± 4.1 d
24 July 2009	396.8 ± 26.3 a	18 June 2009	70.3 ± 4.0 c
		21 August 2008	127.4 ± 4.6 b
		16 July 2009	145.4 ± 8.7 a
F	23.6[a]	F	250.2[b]
P > F	0.0004	*P* > F	0.0001

[a] df = 2,8

[b] df = 4,16

Means within the same column followed by the same letter are not significantly different ($P < 0.05$; Tukey's [1953] HSD)..

Table 3. Arthropods pooled from all sampling methods and dates in untreated switchgrass plots in Florence, SC, 2007-2009.

Class	Order	Number of individuals
Arachnida	Araneae	280
	Acari	389
Entognatha	Collembola	1,637
Insecta	Coleoptera	625
	Diptera	301
	Hemiptera	1,650
	Hymenoptera	7,471
	Odonata	2
	Orthoptera	1,311
	Thysanoptera	80
Total		13,746

Table 4. Insects pooled from all sampling methods and dates in untreated switchgrass plots in Florence, SC, 2007-2009.

Order	Family	Sampling method	
		Pitfall	Sweep net
Coleoptera	Anthicidae	82	5
	Carabidae	94	1
	Coccinelidae	1	17
	Chrysomelidae	4	25
	Curculionidae	2	24
	Elateridae	13	
	Lampyridae		1
	Tenebrionidae	103	
	Scarabaeidae	6	
	Staphylinidae	188	
Diptera	Cecidomyiidae	7	
	Chironomidae	28	
	Chloropidae	27	4
	Dolichopodidae	11	61
	Phoridae	56	
	Pipunculidae		3
	Platystomatidae	1	1
	Sciaridae	59	
	Syrphidae		3
	Tipulidae	6	1
Hemiptera	Alydidae	1	
	Aphididae		10
	Berytidae		4
	Cercopidae	5	3
	Cicadellidae	20	1,080
	Cydnidae	7	5
	Geocoridae	18	27
	Lygaeidae	82	267
	Membracidae		2
	Miridae		38
	Nabidae		28
	Pentatomidae		15
	Reduviidae	2	36
Hymenoptera	Formicidae	7,394	
	Proctotrupidae	19	
Odonata	Coenagrionidae		2
Orthoptera	Acrididae	2	91
	Gryllidae	1,038	
	Gryllotalpidae	3	
	Tettigoniidae	4	173
Thysanoptera	Thripidae	80	
Total		9,363	1,927

Table 5. Groups of arthropods collected in pitfall traps (± SEM) (2 per plot, n = 5 replications) across sampling dates in untreated switchgrass plots in Florence, SC, 2007-2009.

Order/Family	31 May 2007	6 May 2008	30 June 2008	22 July 2008	31 May 2009	30 June 2009	23 July 2009	F [a]	*P*>F
Araneae	21.6±2.5 a	6.2±2.7b	9.4±2.6 ab	6.6±2.5 b	3.4±1.0 b	5.4±1.0 b	1.7±1.0b	33.15	0.0001
Acari									
Oribatida	17.6±5.1 a	0a	0a	0a	30.0±10.1a	15.6±8.7 b	18.2±3.3a	8.76	0.0001
Collembola	42.2±9.7a	65.2±43.8a	34.8±12.7a	28.4±11.1a	41.4±4.4a	49.2±25.1a	82.7±20.5a	0.76	0.6061
Coleoptera									
Anthicidae	15.6±3.7a	0.8±0.6 b	0b	0b	0b	0b	0b	33.15	0.0001
Carabidae	6.8±0.7a	11.0±5.4a	0b	0b	0.6±0.2b	0.2±0.2b	0.2±0.2b	9.34	0.0001
Coccinelidae	0.2±0.2	0	0	0	0	0	0	-	-
Chrysomelidae	0.8±0.8	0	0	0	0	0	0	-	-
Curculionidae	0a	0.2±0.2a	0a	0.2±0.2a	0a	0a	0a	0.79	0.5840
Elateridae	0.4±0.4a	0a	0a	0a	0a	1.4±1.2a	1.0±0.7a	1.41	0.2516
Tenebrionidae	6.6±3.9a	6.2±5.0a	5.2±4.7a	1.4±1.2a	1.2±0.8a	0a	0a	1.25	0.3163
Scarabaeidae	0a	0a	0a	0a	0.4±0.4a	0.8±0.6a	0a	1.43	0.2462
Staphylinidae	34.2±14.0a	0b	0b	0b	3.4±2.7b	0b	0b	12.16	0.0001
Diptera									
Cecidomyiidae	0b	0.4±0.2b	0b	1.0±0.5a	0b	0b	0b	3.32	0.0167
Chironomidae	5.6±3.4	0	0	0	0	0	0	-	-
Chloropidae	0a	0.6±0.4a	0.2±0.2a	2.2±2.2a	0.2±0.2a	1.6±0.5a	0.7±0.5a	1.14	0.3689
Dolichopodidae	2.2±0.9	0	0	0	0	0	0	-	-
Phoridae	0.8±0.5a	1.2±1.2a	2.0±1.4a	5.4±3.0a	0.6±0.4a	0a	1.5±0.5a	1.83	0.1376
Platystomatidae	0	0	0.2±0.2	0	0	0	0	-	-
Sciaridae	0a	9.0±6.8a	0.2±0.2a	0.2±0.2a	0.6±0.2a	0.8±0.6a	1.2±0.6a	2.41	0.0589
Tipulidae	1.2±1.0	0	0	0	0	0	0	-	-
Hemiptera									
Alydidae	0	0	0	0	0	0.2±0.2	0	-	-
Cercopidae	0a	0a	0a	0a	0a	1.0±0.2a	0.7±0.1a	1.77	0.1510
Cicadellidae	3.4±2.9a	0.2±0.2a	0a	0a	0.4±0.2a	0a	0a	1.46	0.2349
Cydnidae	1.0±1.0a	0.4±0.4a	2.4±2.4a	0a	0a	0a	0a	0.82	0.5654
Geocoridae	1.2±0.8a	0a	7.8±3.0a	0a	0a	0a	0a	1.05	0.4197
Nabidae	0	0.6±0.6	0	0	0	0	0	-	-
Lygaeidae	0b	6.8±1.5a	0b	1.8±1.3b	0b	0b	0b	13.07	0.0001
Reduviidae	0a	0a	0a	0a	0a	0.2±0.2a	0.2±0.2a	0.96	0.4704
Hymenoptera									

Formicidae	345.2±190.8a	225.6±195.5a	651.2±397.0a	135.0±88.9ab	46.4±15.5a	41.4±18.5a	42.5±28.8a	3.68	0.0104
Proctotrupidae	0a	0a	1.0±1.0a	0a	2.2±1.5a	0.6±0.6a	0a	1.53	0.2126
Orthoptera									
Acrididae	0.2±0.2a	0a	0a	0a	0a	0.2±0.2a	0a	0.79	0.5840
Gryllidae	0.8±0.2c	18.0±6.6abc	72.6±26.3ab	8.2±1.2ab	16.8±6.3bc	72.6±24.6a	23.2±8.3abc	8.27	0.0001
Gryllotalpidae	0.4±0.a	0.2±0.2a	0a	0a	0a	0a	0a	1.84	0.1352
Tettigoniidae	0	1.02±0.2	0	0	0	0	0	-	-
Thysanoptera									
Thripidae	12.8±6.4a	0.6±0.4b	0b	0b	0b	0b	2.6±1.9ab	1.18	0.0069
Total	524.0±169.1 ab	359.0±186.5 ab	800.4±367.2 a	191.0±96.0 b	147.6±1.1 b	191.0±32.3 ab	141.6±42.5 b	4.36	0.0041

[a] df = 6,23

Table 6. Groups of arthropods collected in sweep net samples (± SEM) (2-25 samples per plot, n = 5 replications) across sampling dates in untreated switchgrass plots in Florence, SC, 2007-2009.

Order/Family	14 Aug. 2007	16 May 2008	20 June 2008	24 July 2008	27 May 2009	24June 2009	25 July 2009	F [a]	*P*>F
Araneae	0b	0b	0b	0b	0b	1.4±0.4a	0.6±0.2b	9.36	0.0001
Coleoptera									
Anthicidae	0.6±0.4a	0a	0a	0.4±0.2a	0a	0a	0a	2.10	0.0905
Carabidae	0	0.2±0.2	0	0	0	0	0	-	-
Coccinelidae	0.2±0.2b	0.80±0.4b	0b	0b	2.2±0.4a	0.2±0.2b	0b	12.38	0.0001
Chrysomelidae	4.8±1.4a	0b	0b	0b	0b	0.2±0.2b	0b	12.91	0.0001
Curculionidae	4.0±2.3a	0.2±0.2ab	0.2±0.2ab	0b	0.2±0.2ab	0.6±0.2b	0.2±0.2ab	3.2	0.0190
Lampiridae	0	0	0	0	0	0.2±0.2	0	-	-
Diptera									
Chloropidae	0a	0a	0a	0a	0.6±0.6a	0.2±0.2a	0a	0.87	0.5284
Dolichopodidae	0c	0c	0c	0c	3.2±1.3b	8.6±1.4a	0.4±0.2c	24.7	0.0001
Pipunculidae	0a	0a	0a	0a	0a	0.4±0.4a	0.2±0.2a	0.85	0.5429
Platystomatidae	0	0	0.2±0.2	0	0	0	0	-	-
Syrphidae	0a	0a	0a	0a	0.2±0.2a	0.4±0.4a	0a	0.85	0.5429
Tipulidae	0	0	0	0	0.2±0.2	0	0	-	-
Hemiptera									
Aphididae	0b	1.8±0.9a	0b	0b	0.2±0.2b	0b	0b	4.21	0.0050
Berytidae	0.2±0.2b	0.6±0.2a	0b	0b	0b	0b	0b	3.86	0.0078
Cercopidae	0.4±0.4a	0a	0a	0a	0a	0.2±0.2a	0a	0.85	0.5429
Cicadellidae	78.2±20.8a	3.0±1.0bc	1.4±0.5c	1.4±0.9c	9.8±1.9bc	100.8±21.5a	21.4±4.2b	27.32	0.0001
Cydnidae	0a	0.6±0.4a	0a	0a	0.4±0.2a	0a	0a	2.10	0.0905
Geocoridae	4.6±2.1a	0.4±0.2b	0.4±0.2b	0b	0b	0b	0b	10.29	0.0001
Lygaeidae	12.6±6.1a	40.4±40.4a	0.2±0.2a	0a	0.2±0.2a	0a	0a	1.46	0.2331
Membracidae	0	0.4±0.2	0	0	0	0	0	-	-
Miridae	3.4±1.2a	3.8±3.1ab	0b	0.2±0.2ab	0.2±0.2ab	0b	0.6±0.3b	3.8	0.0087
Nabidae	3.4±1.3a	1.2±1.2ab	0b	0b	0b	0.2±0.2b	0.8±0.4ab	3.7	0.0096
Pentatomidae	1.8±1.1a	0a	0a	0a	0.4±0.2a	0.6±0.4a	0.2±0.2a	2.21	0.0773
Reduviidae	6.6±2.7a	0b	0b	0b	0b	0.2±0.2b	0.4±0.4b	10.7	0.0001
Odonata									
Coenagrionidae	0a	0a	0a	0a	0.2±0.2a	0a	0.2±0.2a	0.83	0.5561
Orthoptera									
Acrididae	1.4±0.7a	1.8±0.5a	4.2±3.2a	2.4±1.5a	3.0±1.8a	4.0±1.6a	1.4±0.7a	0.99	0.4518
Tettigoniidae	3.0±1.8a	8.0±2.6a	1.4±0.2a	9.2±3.5a	1.6±0.5a	2.0±0.6a	9.4±2.9a	4.93	0.0038

Total	125.2±21.0 a	69.2±44.3 ab	8.2±2.9 b	13.8±4.5 b	22.8±2.8 b	120.0±19.7 a	34.6±4.9 b	10.44	0.0001

[a] df = 6,23

Table 7. Classification by trophic groups of arthropods collected in untreated switchgrass plots in Florence, SC, 2007-2009.

Herbivores	Predators	Scavengers	Parasitoids
Alydidae	Anthicidae	Acari	Proctotrupidae
Acrididae	Aracnida	Chironomidae	Pipunculidae
Aphididae	Berytidae	Chloropidae	
Cecidomyiidae	Carabidae	Collembola	
Cercopidae	Coccinellidae	Phoridae	
Cicadellidae	Coenagrionidae	Sciaridae	
Chrysomelidae	Dolichopodidae	Tenebrionidae	
Curculionidae	Formicidae	Tipulidae	
Cydnidae	Geocoridae		
Elateridae	Gryllidae		
Gryllidae	Lampyridae		
Gryllotalpidae	Nabidae		
Lygaeidae	Reduviidae		
Membracidae	Staphylinadae		
Miridae	Syrphidae		
Pentatomidae			
Platystomatidae			
Scarabaeidae			
Tettigoniidae			
Thripidae			

Table 8. Abundance (± SEM) of arthropods by trophic groups found in pitfall traps (2 per plot, n = 5 replications) and sweep net samples (2 25 samples per plot, n= 5 replications) in untreated switchgrass plots, Florence, SC. Columns with the same letter by each sampling method are not significantly different (*P* < 0.05; Tukey's [1953] HSD).

Date	Sampling method	Herbivores	Predators	Parasitoids	Scavengers
31 May 2007	Pitfall	19.8±5.8 ab	427.8±179.1ab	0a	74.0±14.0a
6 May 2008	Pitfall	27.6±7.85 ab	261.6±192.4 abc	4.4±1.8a	82.2±45.3a
30 June 2008	Pitfall	80.6±28.3 a	735.6±376.7 a	6.2±3.3a	42.4±13.7a
22 July 2008	Pitfall	11.2±2.1 b	149.8±89.1 bc	0.2±0.2a	37.6±11.2a
31 May 2009	Pitfall	17.6±6.2 ab	70.6±13.5 bc	2.2±1.5a	74.0±13.1a
30 June 2009	Pitfall	76.0±25.5 a	119.8±22.0 bc	0.6±0.6a	67.2±26.5a
23 July 2009	Pitfall	22.2±8.1 ab	54.4±19.7 c	0a	83.6±26.8a
F		3.92[a]	4.82	3.48	0.61
P > F		0.0072	0.0023	0.0129	0.7176
14 Aug. 2007	Sweeping	109.6±18.5 a	15.6±5.2 a	0a	0a
16 May 2008	Sweeping	60.2±43.5 ab	3.2±1.3 bc	1.8±1.2a	0a
20 June 2008	Sweeping	7.4±3.2 b	0.4±0.2 c	0a	0a
24 July 2008	Sweeping	13.2±4.5 b	0.4±0.2 c	0a	0a
27 May 2009	Sweeping	16.0±2.1 b	6.0±1.1 ab	0a	0.8±0.6a
24 June 2009	Sweeping	107.6±19.4 a	11.8±0.9 a	0.4±0.4a	0.2±0.2a
25 July 2009	Sweeping	32.8±5.2 ab	1.6±0.5 bc	0.2±0.2a	0a
F	Sweeping	8.27	14.67	2.03	1.82
P > F	Sweeping	0.0001	0.0001	0.1004	0.1369

[a] df = 6,24

Table 9. Summary of densities (±SEM) of species collected in pitfall trap samples during three years of sampling in untreated switchgrass plots Florence, SC, 2007-2009. Rows with the same letter are not significantly different (P < 0.05; Tukey's [1953] HSD).

Insect species	14 Aug. 2007	16 May 2008	20 June 2008	24 July 2008	27 May 2009	24 June 2009	25 July 2009	F [a]	*P*>F
Herbivores									
Coleoptera									
Curculionidae									
Sitophilus zeamais	0	0	0	0.2±0.1	0	0	0	-	-
Naopactus peregrines	0	0	0.2±0.1	0	0	0	0	-	-
Scarabaeidae									
Phyllophaga sp.	0	0	0	0	0.4±0.1	0	0	-	-
Onthophagus sp.	0	0	0	0	0	0.6±0.2	0	-	-
Onthophagus sp.	0	0	0	0	0	0.2±0.1	0	-	-
Martineziana dutertrei	0	0	0	0	0	0	0.2±0.1	-	-
Hemiptera									
Alydidae									
Alydus sp.	0	0	0	0	0	0.2±0.1	0	-	-
Cercopidae									
Prosapia bicincta	0a	0a	0a	0a	0a	0.8±0.2a	0.2±0.2a	1.77	0.1471
Cydnidae									
Sehirus cinctus	1.0±1.4	0	0	0	0	0	0	-	-
Lygaeidae									
Ptochiomera nodosa	0a	0.8 ±0.8a	0.8± 0.4a	1.0±0.8a	0a	0a	0a	1.40	0.2543
Orthoptera									
Acrididae									
Melanoplus pos. *sanguinipes*	0	0	0	0	0	0.2±0.2	0	-	-
Gryllidae									
Gryllus sp.	0.6±0.2b	18±6.6ab	72.6±14.3ab	8.2±1.2a	16.8±63ab	72.6±14.3a	27.6±6.6abc	8.98	0.0001
Thysanoptera									
Thripidae									
Pos. *Frankliniella tritici*	12.8±6.4a	0.6±0.4b	0b	0b	0b	0b	2.6±1.9ab	1.18	0.0069
Predators									
Coleoptera									

Anthicidae									
Notoxus sp.	15.6±3.7a	0.8±0.6 b	0b	0b	0b	0b	0b	33.15	0.0001
Carabidae									
Megacephala carolina Carolina	1.2±1.2a	0	0.2±0.2a	0.2±0.2a	0.4±0.4a	0.2±0.2a	1.4±1.2a	0.60	0.7264
Pasimachus subsulcatus	0	0	0	0	0.2±0.2	0	0	-	-
Galerita janus	0	0	0	0.2±0.1	0	0	0	-	-
Harpalus protactus	1.8±0.5a	1.8±1.6ab	0b	0b	0b	0b	0b	3.83	0.0081
Amara litoralis	0.2±0.2b	2.4±1.0a	0b	0b	0.2±0.2b	0b	0b	6.57	0.0003
Agonum punctiforme	0.2±0.2a	2.4±0.4a	0a	0a	0.2±0.2a	0a	0a	0.83	0.5561
Anisodactylus rusticus	0.6±0.2a	0.4±0.2ab	0b	0b	0b	0b	0b	3.67	0.0100
Tetragonoderus intersectus	0	2.0±2.0	0	0	0	0	0	-	-
Selenophorus palliates	0.2±0.2a	0.4±0.4a	0.2±0.2a	0a	0a	0a	0a	0.75	0.6160
Calathus opaculus	0.4±0.2a	0.4±0.2a	0a	0a	0a	0a	0a	2.67	0.0398
Harpalus katiae	0	0	0.2±0.2	0	0	0	0	-	-
Amara sp.	0.8±0.6a	0.2±0.2a	0.4±0.2a	0a	0a	0a	0a	1.57	0.1984
Amara sp.	0.4±0.2a	5.4±5.1a	0.2±0.2a	0a	0a	0a	0a	1.29	0.2973
Diptera									
Dolichopodidae									
Condylostylus sp.	1.6 ± 1.0	0	0	0	0	0	0	-	-
Hemiptera									
Geocoridae									
Geocoris sp.	1.0±0.9a	0a	2.4±2.4a	0a	0a	0a	0a	1.07	0.4052
Nabidae									
Nabis sp.	0	0.6 ± 0.6	0	0	0	0	0	-	-
Hymenoptera									
Formicidae									
Solenopsis invicta	345.2±190.7a	225.4±195.5a	786.2±544.9a	135.0±88.9a	46.4.±14.2a	41.4±18.5a	41.6±16.1a	2.98	0.0255

[a] df = 6,24

Table 10. Summary of densities (±SEM) of species of insects collected in sweep net samples during three years of sampling in untreated switchgrass plots, Florence, SC, 2007-2009. Rows with the same letter are not significantly different (*P* < 0.05; Tukey's [1953] HSD).

Insect species	14 Aug. 2007	16 May 2008	20 June 2008	24 July 2008	27 May 2009	24 June 2009	25 July 2009	F[a]	*P*>F
Hebivores									
Coleoptera									
Chrysomelidae									
Diabrotica undecimpunctata	0	0.4±0.1	0	0	0	0	0	-	-
Curculionidae									
Naupactus pereginus	0.4±0.1	0	0	0	0	0	0	-	-
Hemiptera									
Cercopidae									
Clastoptera sp.	0.4±0.1	0	0	0	0	0	0	-	-
Cicadellidae									
Stirellus bicolor	11.8 ± 3.4a	0b	2.6 ± 0.6b	1.2 ± 0.6b	0.8 ± 0.6b	1.0±0.3b	1.0 ± 0.5b	10.18	0.0001
Cuerna sp.	0	0	0	0	0	0.4±0.4	0	-	-
Draeucolacephala sp.	2.0±1.0bc	1.0±0.4c	0.8±0.4c	0.2±0.2c	1.8±0.7bc	93.4±19.9a	14.6±5.4b	35.86	0.0001
Texananus exultus	1.6±0.6	0	0	0	0	0	0	-	-
Cydnidae									
Sehirus cinctus	0b	1.0±0.5a	0b	0b	0.2±0.2ab	0b	0b	3.36	0.0150
Lygaeidae									
Ptochiomera nodosa	0	0	0.2±0.2	0	0	0	0	-	-
Neoparema bilobata	0b	1.0±0.5a	0b	0b	0.2±0.2ab	0b	0b	3.36	0.0150
Nysius raphanus	2.8±1.1a	40.4±40.4a	0.2±0.2a	0a	0a	0a	0a	1.00	0.4459
Blissus sp.	3.0±1.1	0	0	0	0	0	0	-	-
Miridae									
Lygus lineoralis	2.2±0.8a	2.6±1.9a	0a	0a	0.2±0.2a	0a	0a	4.08	0.0559
Pentatomidae									
Oebalus pugnax	1.8±1.1a	0a	0a	0.2±0.2	0a	0a	0a	3.54	0.0118
Orthoptera									
Acrididae									
Melanoplus pos. *sanguinipes*	0b	0b	0.2±0.2b	0.6±0.4b	0.2±0.2b	3.6±0.9a	0b	14.92	0.0001

Predators									
Coleoptera									
Anthicidae									
Notoxus sp.	0.6±0.4a	0a	0a	0.2±0.2a	0a	0a	0a	1.93	0.1173
Coccinellidae									
Coleomegilla maculata	0a	0a	0a	0a	0.4±0.2a	0.2±0.2a	0a	1.93	0.1175
Coccinella septempuncunctata	0	0	0	0	0.6±0.2	0	0	-	-
Diptera									
Dolichopodidae									
Condylostylus sp.	0c	0.2±0.2c	0c	0c	3.2±1.3b	11±2.3a	0.4±0.2bc	22.53	0.0001
Hemiptera									
Geocoridae									
Geocoris sp.	4.6±2.1a	0.4±0.2b	0.2±0.2b	0b	0b	0b	0b	10.76	0.0001
Nabidae									
Nabis sp.	3.4±1.3a	0.4±0.2b	0b	0b	0.2±0.5b	0.6±0.4b	0b	5.65	0.0009
Reduviidae									
Barce fraterna	2.4±0.8	0	0	0	0	0	0	-	-
Zelus sp.	2.8±1.7a	0a	0.2±0.2a	0a	0a	0a	0a	2.48	0.0522

[a] df = 6,24

Table 11. Pearson correlation coefficients and p-values among herbivore feeding guilds and switchgrass yield by sampling method. ($P < 0.05$)

Sampling methods	Feeding guild			
	Herbivores	**Chewing**	**Sucking**	**Boring**
Pitfall	0.27284	0.62986	-0.56294	0.12076
	0.0316	0.0001	0.0001	0.3580
Sweep nets	-0.58496	-0.07209	-0.71881	-0.37882
	0.0001	0.5841	0.0001	0.0028

Table 12. Summary of densities (±SEM) of species collected in pitfall trap samples during three years of sampling (2007-2009) across treated and untreated plots, Florence, SC. Rows with the same letter are not significantly different (*P* < 0.05; Tukey's [1953] HSD).

Insect species	31 May 2007	6 May 2008	30 June 2008	22 July 2008	31 May 2009	30 June 2009	23 July 2009	F	*P*>F
<u>Chewing</u>									
Coleoptera									
Chrysomelidae									
Altica sp.	0.2 ±0.1	0	0	0	0	0	0	-	-
Scarabaeidae									
Canthon depressipennis	0	0	0	0.1±0.1	0	0	0	-	-
Dichotomius carolinus	0	0	0	0	0	0.1±0.1	0	-	-
Dyscinetus morator	0.1 ±0.1a	0	0.1 ±0.1a	0a	0a	0.1 ±0.1a	0.1 ±0.1	1.24	0.2926
Onthopahgus sp	0a	0.1±0.1a	0.1±0.1a	0a	0a	0.30±0.2a	0a	1.35	0.2396
Phyllophaga sp.	0.1 ±0.1	0	0	0	0	0	0	-	-
Orthoptera									
Acrididae									
Melanoplus pos. *sanguinipes*	0.1±0.1ab	0b	0.3±0.1a	0b	0b	0.1±0.1ab	0b	3.58	0.0029
Gryllidae									
Gryllus sp.	0.8±0.2d	15.6±3.5bc	79.8±15.0a	7.6±1.5cd	19.4±2.7bc	75.2±11.6a	26.8±3.8b	31.55	0.0001
<u>Sucking</u>									
Hemiptera									
Alydidae									
Alydus sp.	0a	0.1±0.1a	0.1±0.1a	0a	0a	0.1±0.1a	0a	1.08	0.3770
Cercopidae									
Prosapia bicincta	0b	0b	0b	0b	0b	0.4±0.2a	0.1±0.1ab	4.32	0.0006
Cicadellidae									
Draeucolacephala sp.	0	0	0	0	0	0.1±0.1	0	-	-
Cydnidae									
Sehira cinctus	0.6±0.3a	0.2±0.1ab	0b	0.2±0.1ab	0b	0b	0b	3.75	0.0020
Lygaeidae									
Blissus sp.	0	0	0	0	0.1±0.1	0	0	-	-
Neoparema bilobata	0c	9.4±3.2a	7.8±1.6ab	3.6±1.1b	0c	0c	0.2±0.1c	18.89	0.0001
Ptochiomera nodosa	0a	0.7±0.3a	1.6±1.1a	0.6±0.3a	0.3±0.3a	0.1±0.1a	0.1±0.1a	2.49	0.0269

Rhyparochromidae									
Myodocha serripes	0b	0.6±0.3a	0.3±0.1ab	0b	0b	0b	0b	3.87	0.0015
Thysanoptera									
Thripidae									
Pos. *Frankliniella tritici*	18.0±4.0a	0.8±0.3c	4.8±1.9bc	10.8±10.8bc	0c	0.4±0.2c	12.3±3.9ab	7.78	0.0001
Boring									
Coleoptera									
Curculionidae									
Aramigus tessellatus	0.6±0.5	0	0	0	0	0	0	-	-
Sitophilus zeamais	0	0	0	0.1±0.1	0	0	0	-	-
Naupactus peregrinus	0	0	0.1±0.1	0	0	0	0	-	-

[a] df = 6,108

Table 13. Summary of densities (±SEM) of species collected in sweep net samples during three years of sampling (2007-2009) across treated and untreated plots, Florence, SC. Rows with the same letter are not significantly different (*P* < 0.05; Tukey's [1953] HSD).

Insect species	14 Aug. 2007	16 May 2008	20 June 2008	24 July 2008	27 May 2009	24 June 2009	25 July 2009	F	*P*>F
Chewing									
Coleoptera									
Chrysomelidae									
Dysonycha sp.	0.3±0.3a	0.1±0.1a	0a	0a	0a	0a	0a	0.91	0.4906
Altica sp.	0.7±0.7a	0.1±0.1a	0a	0a	0a	0a	0a	0.95	0.4610
Diabrotica undecimpunctata	0	0.3±0.1	0	0	0	0	0	-	-
Oulema sp.	0.1±0.1	0	0	0	0	0	0	-	-
Orthoptera									
Acrididae									
Melanoplus pos. *sanguinipes*	0b	0.4±0.3b	0.7±0.3b	0.2±0.1b	0.3±0.1b	5.1±1.3a	0.2±0.1b	25.93	0.0001
Sucking									
Hemiptera									
Cercopidae									
Clastoptera sp.	0.4±0.2	0	0	0	0	0	0	-	-
Prosapia bicincta	0.1±0.1a	0a	0a	0a	0a	0.1±0.1a	0a	0.83	0.5467
Cicadellidae									
Cuerna sp	1.1±0.5a	0b	0b	0b	0b	0.2±0.1b	0.1±0.1b	5.48	0.0001
Draeucolacephala sp.	2.4±0.6c	0.9±0.2c	1.0±0.2c	0.1±0.7c	1.4±0.3c	87.8±10.2a	14.3±1.9b	110.03	0.0001
Stirellus bicolor	8.1±2.0a	0.3±0.2c	1.7±0.3b	0.4±0.2bc	0.7±0.2bc	0.5±0.1bc	1.0±0.2bc	22.98	0.0339
Texanus sp.	0.5±0.4a	0a	0.1±0.1a	0a	0.1±0.1a	0a	0a	1.71	0.1266
Cydnidae									
Sehira cinctus	0b	0.9±0.2a	0b	0b	0.3±0.1b	0b	0b	15.46	0.0001
Lygaeidae									
Blissus sp.	0.8±0.7a	0a	0a	0a	0.1±0.1a	0a	0a	1.61	0.1503
Neoparema bilobata	7.0±1.8a	0b	0.1±0.1b	0.1±0.1b	0.1±0.1b	0b	0b	32.73	0.0001
Neortholomus scolopax	0	0	0	0	0.1±0.1	0	0	-	-
Nysius sp.	1.3±0.4ab	17.3±11.2a	0.1±0.1b	0.1±0.1b	0.1±0.1b	0b	0b	3.05	0.0085
Ptochiomera nodosa	0a	0a	0.1±0.1a	0a	0a	0.1±0.1a	0a	0.83	0.5467
Miridae									

Lygus lineoralis	1.0±0.3ab	1.8±0.6a	0c	0c	0.3±0.2bc	0c	0c	10.44	0.0001
Pentatomidae									
Euschistus sp.	0.4±0.4	0	0	0	0	0	0	-	-
Oebalus pugnax	1.5±0.5a	0b	0b	0.1±0.1b	0b	0b	0b	12.28	0.0001
Thyanta sp.	0.2±0.1	0	0	0	0	0	0	-	-
Rhyparochromidae									
Myodocha serripes	0	0	0.1±0.1	0	0	0	0	-	-
Boring									
Curculionidae									
Aramigus tessellates	0.1±0.1a	0a	0a	0.1±0.1a	0a	0a	0a	0.83	0.5467
Naupactus peregrinus	0.5±0.2	0	0	0	0	0	0	-	-

[a] df = 6,10

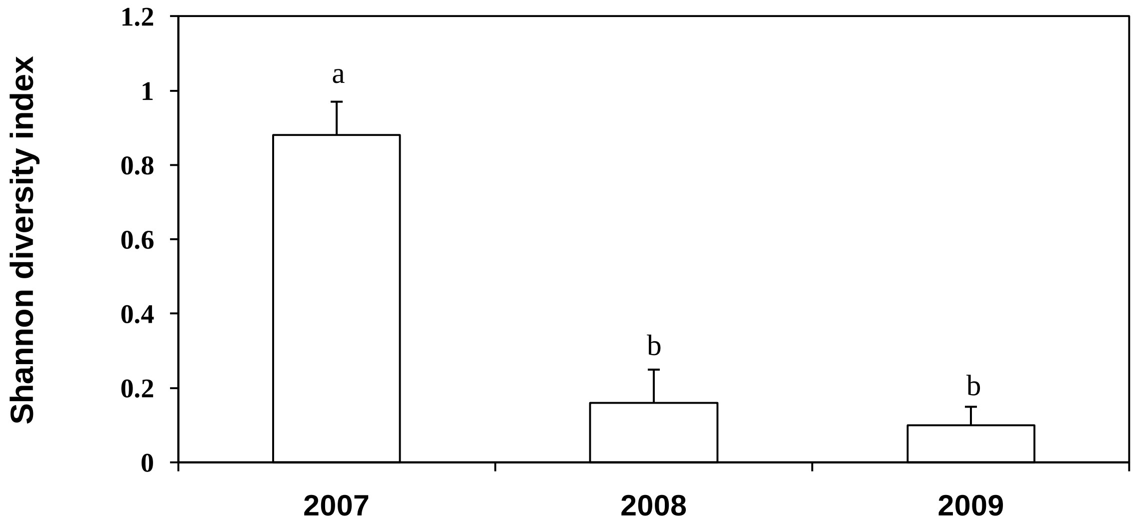

Fig. 1. Plant diversity (switchgrass and weeds) in untreated switchgrass plots in Florence, SC, 2007-2009. Bars with the same letter are not significantly different (P < 0.05; Tukey's [1953] HSD).

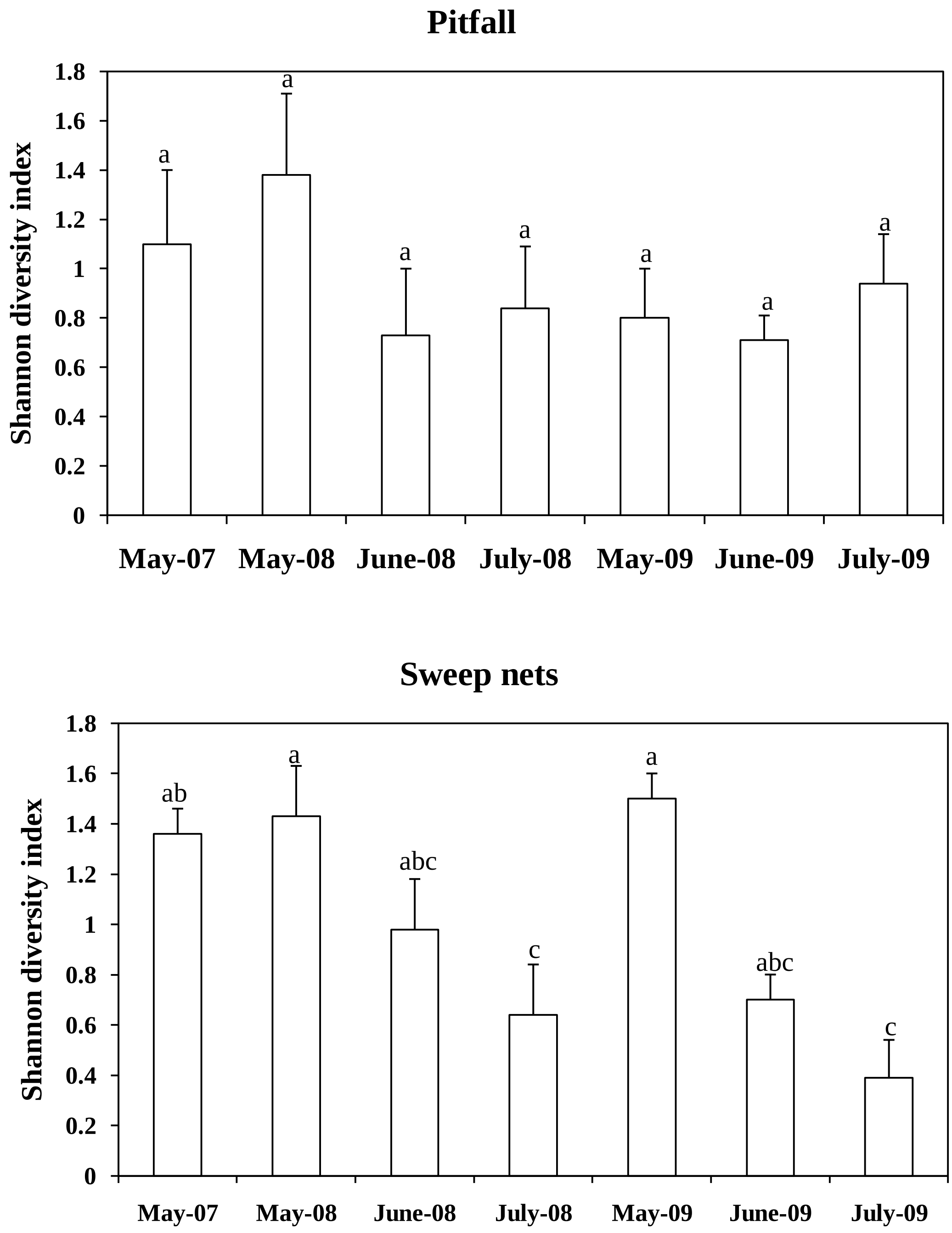

Fig. 2. Diversity (±SEM) of insects classified by family from pitfall traps and sweep net samples in untreated switchgrass plots, Florence, SC, 2007-2009. Bars for each sampling method with the same letter are not significantly different ($P < 0.05$; Tukey's [1953] HSD).

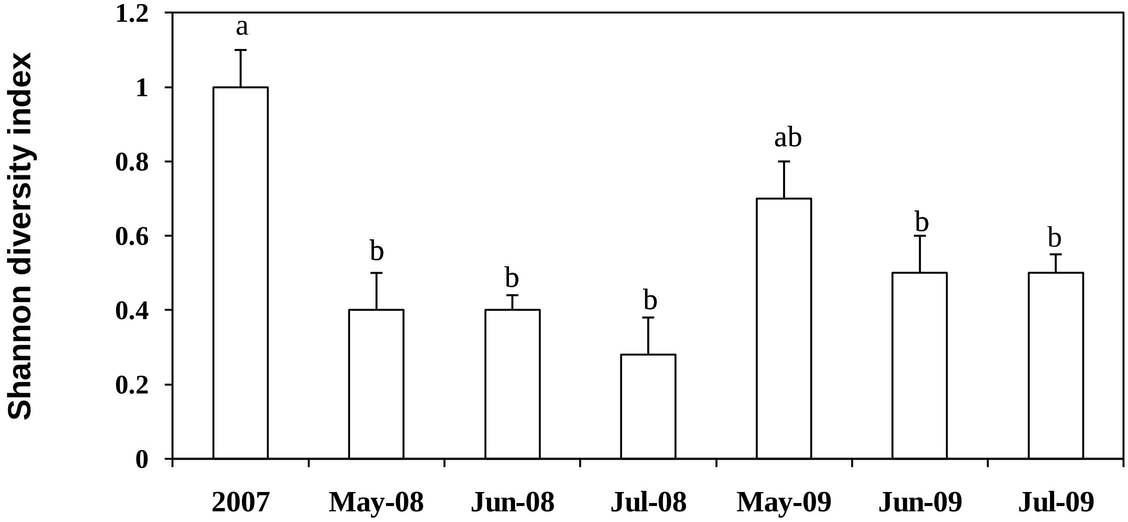

Fig. 3. Diversity of non-insect orders (Araneae, acarae, collembola) estimated by pitfall trap samples in untreated switchgrass plots, Florence, SC, 2007-2009. Bars with the same letter are not significantly different ($P < 0.05$; Tukey's [1953] HSD).

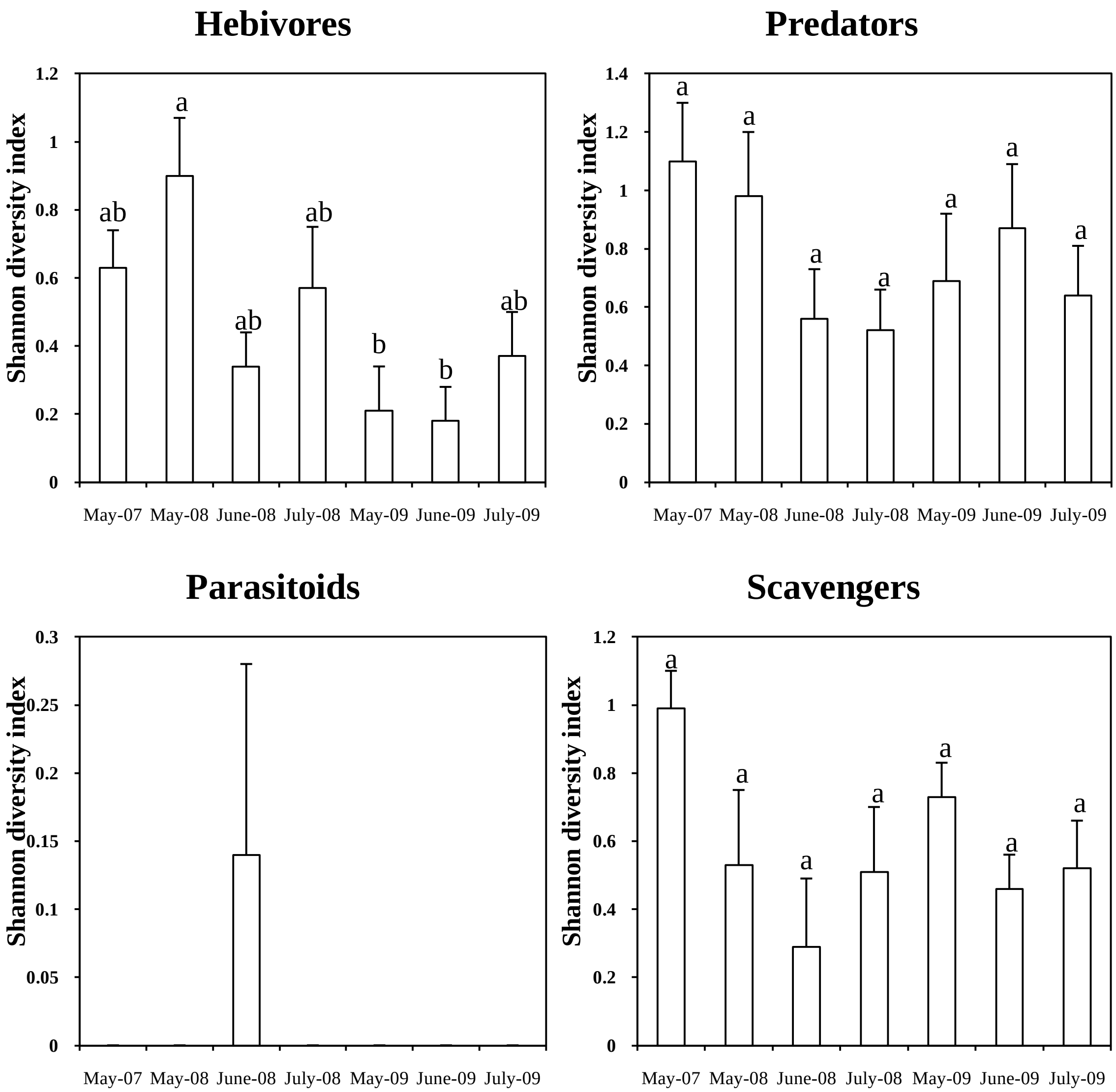

Fig. 4. Trophic group diversity (±SEM) estimated by pitfall traps in untreated switchgrass plots, Florence, SC, 2007-2009. Bars with the same letter for each trophic group are not significantly different ($P < 0.05$; Tukey's [1953] HSD).

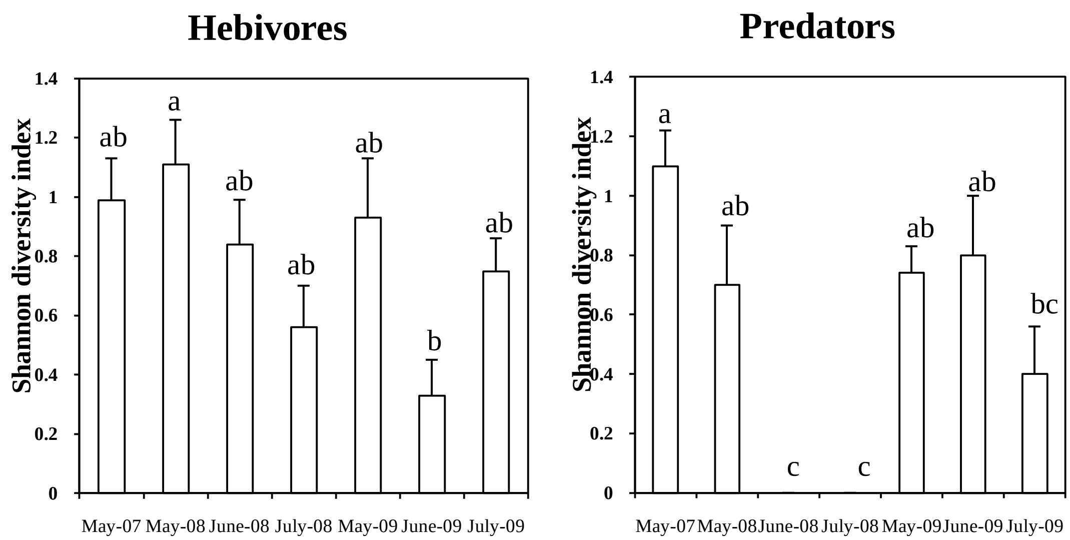

Fig. 5. Trophic groups diversity (±SEM) estimated by sweep net samples in untreated switchgrass plots, Florence, SC. Bars with the same letter are not significantly different ($P < 0.05$; Tukey's [1953] HSD).

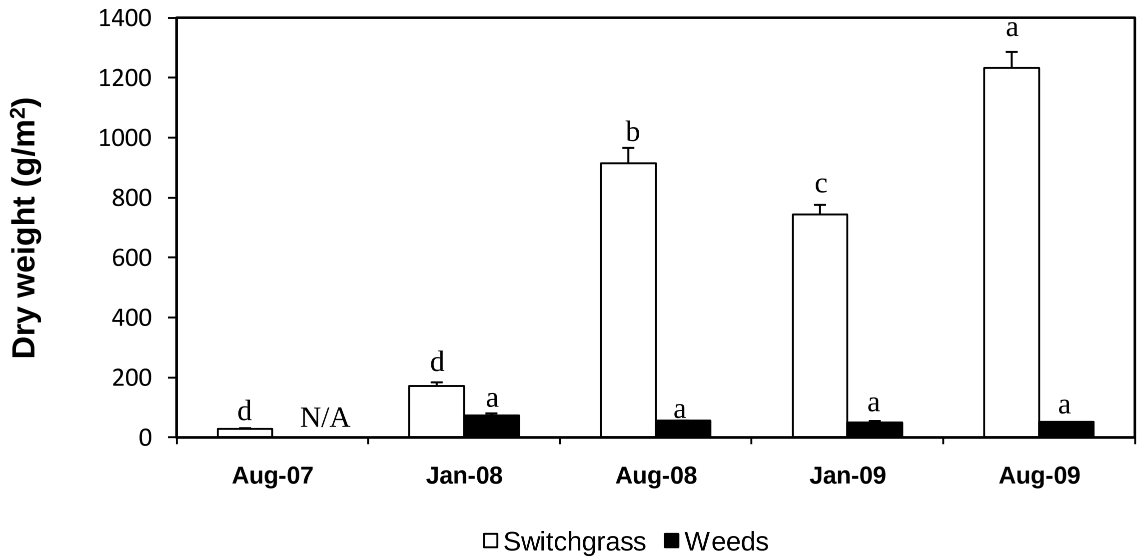

Fig. 6. Dry weight of switchgrass and weeds across treated and untreated switchgrass plots in Florence, SC, 2007-2009. For each variable, bars with the same letter are not significant different (P < 0.05; Tukey's [1953] HSD).

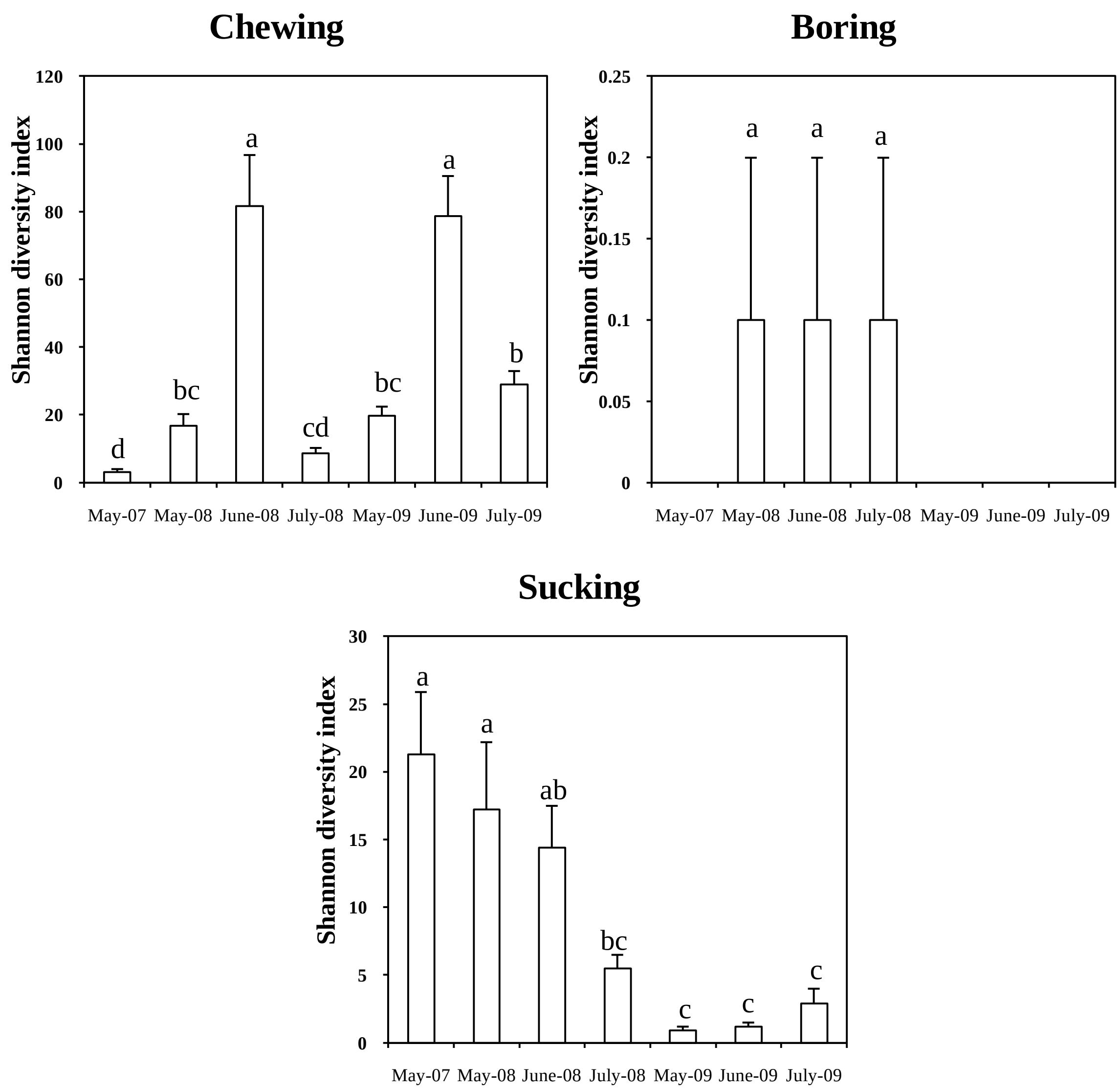

Fig. 7. Abundance (± SEM) of herbivores feeding guilds collected in pitfall traps across treated and untreated switchgrass plots, Florence, SC, 2007-2009. Bars with the same letter for each trophic group are not significantly different ($P <$ 0.05; Tukey's [1953] HSD).

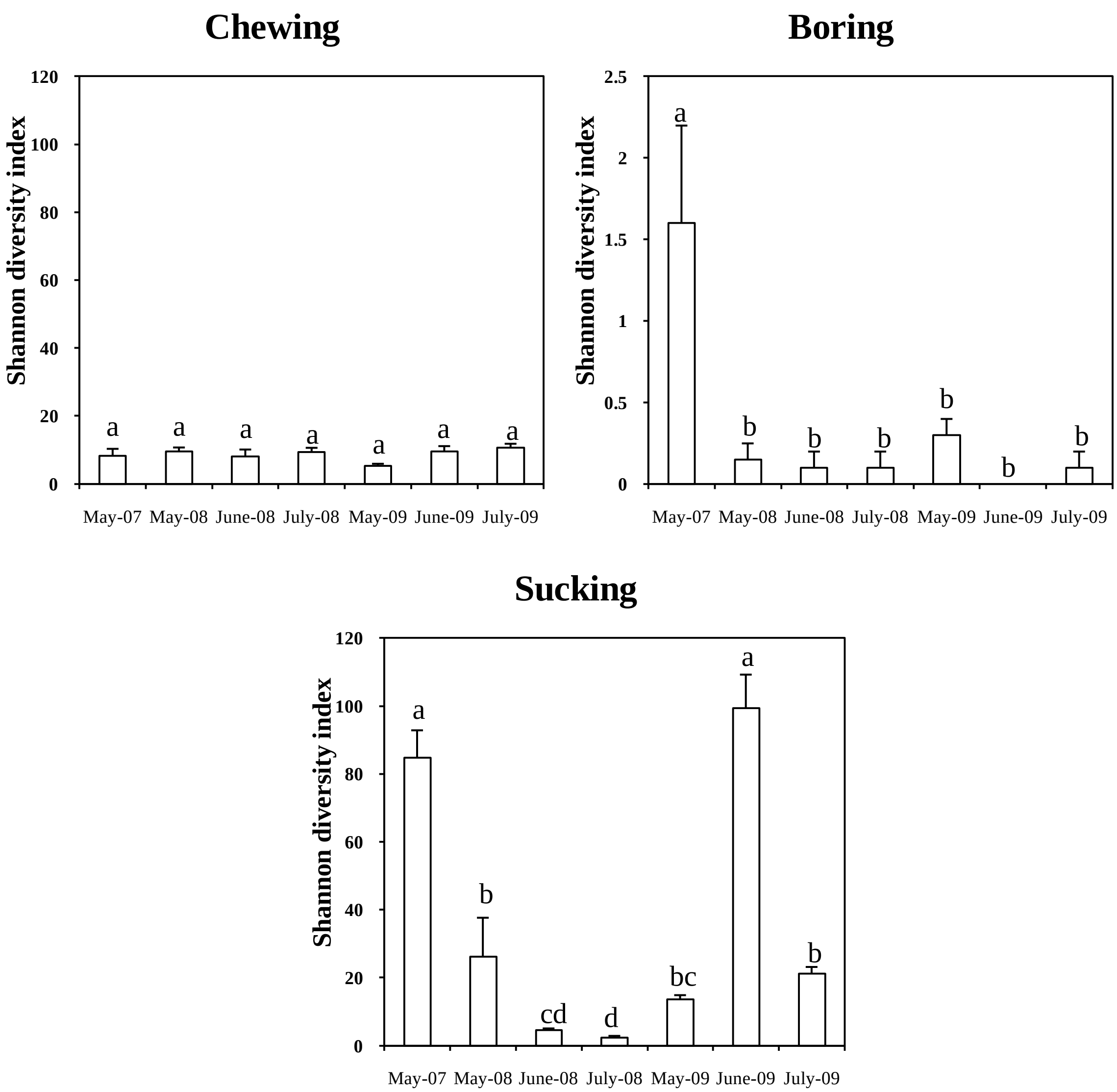

Fig. 8. Abundance (± SEM) of herbivores feeding guilds collected in sweep net samples across treated and untreated switchgrass plots, Florence, SC, 2007-2009. Bars with the same letter for each trophic group are not significantly different (*P* < 0.05; Tukey's [1953] HSD).

CONCLUSIONS

Switchgrass out-competed weeds after the establishment year and there was not a dominant weed species associated with switchgrass in years two and three. The ratio of the dry weight of switchgrass to weeds increased from January 2008 to January 2009 from 2.4 to 15.3. Plant diversity decreased after 2007 and peaks of diversity of insects were found in May of each year. Insect diversity based on family-level identification varied significantly across sampling dates only for sweep net samples, with peaks in May of each year and decreased within years. Herbivores and predators were the only groups that showed significant differences across sampling dates. *Gryllus* sp., *Melanoplus* sp. and an undetermined species of Tettigoniidae were the predominant herbivores. *S. invicta* was the predominant predator found in this study.

Switchgrass yield did not show significant differences among pesticide treatments. Differences in dry weight were observed across the three years of the study and the highest yield was reached (12 Mg ha^{-1}) in the last year (2009). We did not see significant injury caused by herbivores across the three years. The predominant herbivore species were *Draeucolacephala* sp., and *Melanoplus* possibly *sanguinipes.* The predominant predator was *S. invicta.* Our work has provided the basis for identifying pest and beneficial insects in switchgrass in South Carolina and provides important information related to the pest status of insects in switchgrass in South Carolina. Although further work is needed, our data suggest that insecticides may not always be needed to maximize switchgrass growth. Limited pesticide applications are important for a crop to be low carbon producing or carbon neutral.