A COMPARISON OF CONVENTIONAL AND ALTERNATIVE CROPPING SYSTEMS USING ALFALFA (*MEDICAGO SATIVA*) AND WINTER WHEAT (*TRITICUM AESTIVUM*): AN AGROECOSYSTEM ANALYSIS

by

LAURA ELIZABETH SKELTON

(under the direction of Dr. Gary W. Barrett)

ABSTRACT

Natural Systems Agriculture is based on an understanding that natural systems are self-sustaining due to regulatory mechanisms resulting from natural selection that ensure the long-term maintenance of all components of the ecosystem. The objective of this study was to determine if agroecosystems modeled after nature exhibit advantages over conventional agroecosystems.

Five treatments were examined: wheat monoculture, alfalfa monoculture, strip-cropped alfalfa and wheat, and two alfalfa-wheat intercrops (one no-till and one conservation-till). Monocultures produced high yields, as did strip-crop and conservation-till intercrop treatments. Although yields for no-till intercrops were low, protein values were high. Soil fertility was enhanced by the presence of alfalfa. Surface decomposition decreased under conventional tillage. Insect pests preferred alfalfa and were more abundant in treatments containing high percentages of alfalfa, as were predator groups. Benefits to yield, fertility, decomposition, and pest control were observed for the alternative agroecosystems, compared to the conventional monoculture systems, studied.

INDEX WORDS: *Medicago sativa*, *Triticum aestivum*, agroecology, Natural Systems Agriculture, The Land Institute

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LAURA ELIZABETH SKELTON

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LAURA ELIZABETH SKELTON

Major Professor:	Gary W. Barrett
Committee:	John N. All Carl F. Jordan

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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DEDICATION

to Thomas, my biggest fan

and to my parents, who have always had full faith in my every endeavor

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Wes Jackson has continuously urged scientists to examine the *problem of agriculture*, making sure to distinguish this problem from the *problems in agriculture* (Jackson and Piper 1989). Conventional farming, for example, is a problem plaguing humanity, biotic diversity, and the quality of the land that is cultivated. Modern agriculture encourages increased production and yield maximization without examining long-term consequences (NRC 1989, Piper 1999). One cannot simply modify parts of current modes of production and expect major changes to occur. Instead, political, socio-cultural, and economic mechanisms pertaining to agriculture must also be changed.

Although a paradigm shift in agriculture is needed, current infrastructure is not equipped to handle this monumental change. Therefore, smaller steps must be taken to move modern agricultural practices away from subsidies and toward sustainability based on naturally-occurring ecological processes. Processes of ecosystems selected through millions of years of evolution (e.g., pollination biology, use of indicator species, and nutrient recycling to name a few) need to be applied in the design of agroecosystems so that they become more self-sustaining (Barrett and Skelton 2002). Sustainability includes not only preservation of the health of agricultural lands in order to continue bountiful primary production and yield indefinitely, but also a decreased need for external subsidies (Barrett et al. 1990).

Today, agricultural practices threaten soil productivity, air and water quality, and biotic diversity. Alternative cropping strategies are urgently needed to enhance soil quality, combat pest infestation, and reduce the use of chemical inputs, among other reasons. Sustainable agriculture seeks to promote beneficial relationships, such as the interchange of insects between agricultural and surrounding landscapes (Ekbom 2000). Ecologically-sound agriculture is based on enhancing or coupling processes found in nature with the design of sustainable systems (Jackson 1984, Barrett 1990).

Two ecosystem-stabilizing mechanisms found in natural grassland ecosystems are species and functional diversity. These two types of diversity can be integrated into cropping systems by planting more than one plant species in a field simultaneously and by using crop species from different functional groups. Vandermeer (1989) defines an intercrop as an agricultural system in which “two or more crops [are] grown in association with one another.” The use of species from different functional groups may enhance the growth and yield of each individual species. One mechanism for this facilitation is that of interspecific competition being weaker than intraspecific competition (Vandermeer 1989). In a diverse cropping system, plants of different species have different resource requirements distributed differentially through time (Tilman et al. 1996).

Soil disturbance

Farms in the United States rely heavily on modern technology and intensive cultivation. For example, tractors are used to disk the ground several times before seeds are planted. This disturbance of soil frequently leads to increased soil loss, decreased soil biotic diversity, and decreased water-holding capacity (Coleman and Crossley 1996). More sustainable methods include the use of alternative cropping systems, such as strip- or intercropping, to facilitate greater cycling of nutrients throughout the soil, rather than relying on traditional methods of tillage. This study examines the effects of different cropping systems, as well as several levels of tillage, on parameters indicative of agroecosystem structure (e.g., biotic diversity and soil fertility) and agroecosystem function (e.g., primary productivity and rates of decomposition).

Lal (1999) found that soil not tilled for 25 years had more desirable physical properties than conventionally tilled soil. Reduced tillage, frequently referred to as conservation tillage, minimizes soil erosion (Lal 1999, Schomberg and Steiner 1999) and the loss of topsoil (Doran 1980). Soils that have been subjected to reduced tillage or no-till regimes retain more water (Schomberg and Steiner 1999), remain cooler (Coleman and Crossley 1996), and have a lower pH than soils that have been tilled in the fashion typical of conventional agriculture (Doran 1980). Although the elimination of tillage may require an herbicide to combat weeds, Carter et al. (1991) found it economically beneficial to reduce tillage. While yields may be lower for no-till, less energy is spent tilling soils before planting, less fertilizer is needed, and less water is necessary for sufficient irrigation (Carter et al. 1991). As a result, there may be net energetic and economic benefits to the system as a whole.

Soils subjected to less tillage, and therefore less burial of plant residues, also experience a cycling of nitrogen that extends over a longer time period than does the N cycle in conventionally tilled systems (Coleman and Crossley 1996). The slow release of nutrients from decomposing residues helps to retain soil organic matter (Holland and Coleman 1987). Nutrient conservation is more common in no-till soils than in tilled soils due to greater numbers of fungi and fungivorous nematodes (Hendrix et al. 1986). Thus, soil organic matter increases over time in no-till soils (Hendrix et al. 1986, Unger 1991). This results in higher total carbon in no-till fields than in tilled fields (Stine and Weil 2002), higher macroaggregate stability (Bruce et al. 1995), and increased crop yield in some cases (e.g., Stine and Weil 2002). No-till soils also leach less nitrate than conventionally tilled soils (Stinner et al. 1984), thus decreasing agricultural pollution.

Decomposition

The microbial populations of no-till soils resemble those of naturally occurring ecosystems more than populations in conventionally tilled soils (Doran 1980). Nutrient cycling, facilitated by soil populations, is considered more efficient in no-till fields than in conventionally plowed fields because fewer nutrients are lost from no-till systems (Stinner et al. 1984).

Decomposition of plant residues is greatly affected by their placement relative to the soil (Holland and Coleman 1987). Tilled residues tend to decompose rapidly (Holland and Coleman 1987) because tillage buries litter below the soil surface where it is more quickly decomposed by bacteria (Beare et al. 1992), presumably due to microhabitat conditions favoring constant moisture and temperature. Therefore, tilling encourages increased rates of plant decomposition compared to no-till systems (Hendrix et al. 1986).

While burying residues has demonstrated benefits, retention of litter aboveground may be desirable. For example, surface litter helps to keep the soil cool and moist by protecting it from direct sunlight (Coleman and Crossley 1996), and increased cover combats soil erosion (Altieri and Nicholls 2000). Mulch left to decompose on the soil surface increases soil carbon and soil organic matter, leading to increased water use efficiency and decreased soil erosion (Bruce et al. 1995). Also, more surface litter provides more substrate available to microbial organisms that aid in nitrification and denitrification. While denitrification, which is increased in no-till systems (Gooding and Davies 1997), leads to losses of N from agroecosystems, volatilization of NH4 and leaching of NO3, both of which are encouraged by tilling, lead to large losses of N from tilled systems (Gooding and Davies 1997).

It is important to note that while maintaining organic matter on the soil surface has aforementioned benefits, efficient and fairly rapid cycling of nutrients from that organic matter is essential for crop plants that demand nutrients for optimal growth. In climates where rainfall is low or variable, such as the Great Plains, surface residues will likely decompose more slowly than they would in a more humid climate (Ofori and Stern 1987, Drury et al. 1999). Several researchers have also found that release of legume N is more of a long-term rather than a short-term benefit, as much of the N during the initial year of legume growth or immediately following incorporation of residues into the soil is unavailable for plant uptake (Ladd et al. 1981, Peoples et al. 2001). Fungi and other decomposers initially immobilize N from decomposing residues, and mineralization may proceed slowly, especially in untilled soils (Hendrix et al. 1986).

Fungi are more abundant in soils under reduced tillage than under conventional tillage (Norstadt and McCalla 1969, Hendrix et al. 1986). No-till soils also exhibit greater biotic diversity (Hendrix et al. 1986) and higher densities of invertebrates, such as earthworms and arthropods, than tilled soils (House and Parmelee 1985). Thus, biotic soil organisms provide ecosystem services (Daily et al. 1997) in undisturbed soils, encouraging the breakdown of crop residues which contributes recycled nutrients to succeeding crops.

One important aspect of this biotic breakdown of crop residues is nitrogen mineralization. Carbon in crop residues is used for respiration, thus lowering the C:N ratio of plant material (House and Parmelee 1985). Beare et al. (1992) found that soil respiration rates were greater in no-till than in conventional-till soils, suggesting increased rates of microbial activity in the no-till environment. Holland and Coleman (1987) demonstrated that more efficient nitrogen immobilization occurred when straw was left on the surface than when it was incorporated into the soil.

In my study, alfalfa stems and leaves were placed on the soil surface to estimate rates of plant decay. Young alfalfa hay has a low C:N ratio and, therefore, should decompose fairly quickly (Brady and Weil 1999). Surface litter decay has been found to be faster in no-till than in conventionally tilled soils (Beare et al. 1992). Because it is already well-known that burial of residues speeds decomposition (Holland and Coleman 1987, Beare et al. 1992), only rates of surface litter decay were examined. By this method we can see which system has a more active decomposer community. I examined the rate at which alfalfa residues decomposed on surface soil subjected to three different levels of tillage (i.e., within three agroecosystem treatments). Higher rates of decomposition of aboveground residues indicate greater functioning of soil decomposer fauna near the soil surface.

Contribution of legume to ecosystem nitrogen

Increased biotic diversity provides benefits for plant communities, including higher primary production per unit area of land (Vandermeer 1989). A proposed mechanism for this increased productivity is higher resource-use efficiency in diverse stands (Tilman et al. 1996, Hooper and Vitousek 1998). If plant species having sufficiently different resource requirements are grown together, interspecific competition is weaker than intraspecific competition (Vandermeer 1989, Haynes 1980). Hooper and Vitousek (1998) found higher plant diversity to be correlated with greater resource use. Plants from different functional groups required peak nutrients in different seasons, and different groups dominated different resources (Hooper and Vitousek 1998).

Root morphologies and physiologies of alfalfa (*Medicago sativa* L.) and wheat (*Triticum aestivum* L.) are significantly different so that uptake of water and nutrients may be maximized. Legumes, for example, have long roots that are efficient to obtain water and nitrate at greater depths than fibrous wheat roots (Entz et al. 2001). Therefore, alfalfa can obtain water and nutrients that are leached below wheat roots, increasing resource uptake. Through complementary use of these resources, overyielding may occur. Overyielding occurs when two species grown together produce a higher combined yield per unit area than would be expected based on monoculture yields (Vandermeer 1989). Mead and Willey (1980) analyzed land-use efficiency (or production per unit area) of pigeonpea (*Cajanus cajan* L.)-sorghum (*Sorghum bicolor* L.) and pigeonpea-maize (*Zea mays* L.) intercrops and found that overyielding occurred in many cases.

Facilitation is another mechanism for overyielding, whereby the presence of one species enhances the growth of another species (Vandermeer 1989). One mechanism contributing to facilitation in a legume-grass intercrop is the legume's input of nitrogen into the soil. *Rhizobium* bacteria nodulate in legume roots and release fixed nitrogen into the system for uptake by non-legumes via decomposition of vegetative tissue, nodule senescence, root sloughing, or mycorrhizae. Because legumes compete poorly with grasses for mineral soil N (Haynes 1980), they appear to be ideal companion species for intercropping with grasses (i.e., legumes are able to obtain atmospheric N when soil N is not adequately available).

The concept that legumes contribute to available soil nitrogen used by other crop species has been well documented (e.g., Brophy et al. 1987, Ofori and Stern 1987). However, the overall effect of a legume-nonlegume association on crop yields and vegetative quality is less clear. According to Ofori and Stern (1987), overyielding in a legume-nonlegume intercrop is a function of the legume yield; because legumes are typically weaker competitors, their success determines the success of the intercrop and, consequently, the amount of overyield. In a study of a lentil-wheat intercrop, Carr et al. (1995) found that while wheat yield was unaffected by intercropping, yield of lentil (*Lens culinaris* Medik.), a legume, was lower.

Intercropping provides benefits other than overyielding, such as suppression of weed growth (Carr et al. 1995). For example, Moynihan et al. (1996) noted that in a barley-medic intercrop, weeds were reduced 65% in intercrops compared to fertilized barley monocultures. Lesoing and Francis (1999) studied corn-sorghum-soybean intercrops. Although they found no consistent economic advantages to strip intercropping, they suggested that strip cropping could reduce soil erosion (Lesoing and Francis 1999). Intercropping can also improve nutritive quality of some crops (Abdel Magid et al. 1991).

I investigated the contribution of intercropped alfalfa to soil nitrogen and wheat grain nitrogen. Yields of intercropped and monoculture wheat and alfalfa were also used to determine if yield advantage occurred in any of the intercropped treatments.

Arthropods

Alternative cropping systems are often designed to combat insect pest infestation and reduce damage caused by herbivory, thus decreasing the need for insecticides (Kemp and Barrett 1989, Holmes and Barrett 1997). Cultural control of pests in agroecosystems includes designing cropping systems in such a way as to avoid pest outbreaks (All 1999). Focus has recently turned to cultural methods to control pests because pesticides are expensive and frequently have adverse impacts on ecosystem health, including the elimination of beneficial insects. One form of cultural control is intercropping, or increasing diversity of crop species, to lower pest pressure or maintain populations of natural enemies (All 1999).

Pest damage has been shown to be worse in monocultures than in diverse stands of vegetation (e.g., Bach 1980, Letourneau and Altieri 1983). Low arthropod diversity is characteristic of monocultures (Root 1973). Only a few specialist species typically dominate simplified agroecosystems or monocultures, whereas more arthropod species have been found in systems where several plant or crop species are present (i.e., as found in natural systems). More diverse, natural systems have regulatory mechanisms created by stable populations of predators that prohibit herbivorous species from dominating agroecosystems (Root 1973).

Root (1973) proposed the “resource concentration” hypothesis to explain higher numbers of arthropod pests in monocultures. His work on collards suggested that specialist herbivores whose requirements are fulfilled by plants in a simple environment tend to remain and reproduce in that environment. Specialist herbivores often rely on chemical and visual cues from their host plants to feed and reproduce (Vinson 1981). Findings suggest that chemical signals from non-host plants interfere with the ability of herbivores to find suitable food and reproduce (e.g., Roda et al.1997, Degooyer et al. 1999). The phenomenon of interference with herbivore selection by a non-host plant is termed "associational resistance" (e.g., Root 1975).

Strip-cropping or adding corridors in crop fields has been shown to reduce movement of insect species (e.g., Kemp and Barrett 1989). Aphids and leafhoppers, both vectors of numerous plant diseases, must physically touch a plant to determine if it is a suitable host plant (Backus 1985). The probability of encountering non-host plants is certainly increased with strip- or intercropping. Thus, the decrease in insect pest numbers in heterogeneous agroecosystems may be attributed to greater movement, possibly due to the need to move farther in search of a host plant (e.g., Roda et al. 1997), whereby herbivorous insects are more likely to emigrate from the field and be susceptible to predation.

Heterogeneous agroecosystems also tend to attract more generalist predators and parasitoids, which could potentially control herbivore populations. Root (1973) formulated the "enemies" hypothesis as another possible mechanism explaining reduced injury from pests in complex vegetation. This hypothesis focuses on the contention that predators are more likely to remain in heterogeneous systems due to diversity of food and refugia. Although it has received less support than the resource concentration hypothesis, it continues to be researched as a potential mechanism of pest control. Karel (1991), for example, found that natural bean fly predators, such as *Opius melanagromyzae* Fischer, preferred abiotic conditions created by intercropping beans with corn than those found in bean monocultures. Letourneau and Altieri (1983) suggest that predators immigrate quickly into stands of diverse vegetation, which provide a greater diversity of refugia than found in monocultures. However, the presence of predators may not significantly affect herbivore populations in polycultures (Bach 1980).

Because some of the most important wheat and alfalfa pests in the mid-western United States are aphids and leafhoppers, I focused on these as indicator species to quantify differences among treatments. Pest numbers were quantified for several herbivorous families: aphids (Hemiptera: Aphididae), leafhoppers (Hemiptera: Cicadellidae), and grasshoppers (Orthoptera: Acrididae). Abundances of several generalist predator groups, including ladybird beetles (Coleoptera: Coccinellidae), wolf spiders (Araneae: Lycosidae), and crab spiders (Araneae: Thomisidae), were also investigated. I predicted that the more diverse cropping systems would exhibit lower abundance of specialist herbivores due to lower concentration of host plants, interference from non-host plants, or higher numbers of natural enemies.

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CHAPTER 2

A COMPARISON OF CONVENTIONAL AND ALTERNATIVE CROPPING SYSTEMS USING ALFALFA (*MEDICAGO SATIVA*) AND WINTER WHEAT (*TRITICUM AESTIVUM*): AN AGROECOSYSTEM ANALYSIS[1]

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Introduction

Modern agriculture encourages increased production and yield maximization without examining long-term consequences (Piper 1999), such as soil degradation, pesticide contamination of groundwater, and declining biotic diversity. Although a major revision of the agricultural system is needed, current infrastructure is not equipped to handle this monumental change. Therefore, smaller steps must be taken to move modern agricultural practices away from increased subsidies (pesticides, fossil fuels, and fertilizers) and toward sustainability based on naturally-occurring ecological processes. If we can apply components of functioning ecosystems chosen by natural selection through millions of years (e.g., pollination biology, use of indicator species, and nutrient recycling to name a few), then we should be able to design agroecosystems that are more self-sustaining (Barrett and Skelton 2002). The idea of sustainability includes not only preservation of the health of agricultural lands in order to continue bountiful primary production and yield indefinitely, but also a decreased need for external subsidies to maintain the system (Barrett et al. 1990).

Ecologically-sound agriculture is based on enhancing or coupling processes found in nature with the design of sustainable systems (Jackson 1984, Barrett 1990). One ecosystem-stabilizing mechanism found in natural grassland ecosystems is diversity, both of species and function. These two types of diversity can be integrated into cropping systems by planting more than one species in a field simultaneously and by using crop species from different functional groups.

Soil disturbance. Farms in the United States rely heavily on modern technology and intensive cultivation. This constant disturbance of soil frequently leads to increased soil loss, decreased soil biotic diversity, and decreased water-holding capacity (Coleman and Crossley 1996). More sustainable methods include the use of alternative cropping systems, such as strip- or intercropping, to facilitate cycling of nutrients throughout the soil, rather than conventional tillage.

Reduced tillage, frequently referred to as conservation tillage, minimizes soil erosion and the loss of topsoil. Soils that have been subjected to reduced tillage or no-till regimes retain more water (Schomberg and Steiner 1999), remain cooler (Coleman and Crossley 1996), and have a lower pH than soils that have been tilled in the fashion typical of conventional agriculture (Doran 1980). Although the elimination of tillage may require an herbicide to combat weeds, Carter et al. (1991) found it economically beneficial to reduce tillage. Yields may be lower for no-till; however, less energy is spent tilling soils before planting, and less fertilizer and water are needed (Carter et al. 1991). There appear to be net energetic and economic benefits to the overall system.

Soils subjected to less tillage, and therefore less burial of plant residues, also experience a cycling of nitrogen that extends over a longer time period than does the N cycle in conventionally tilled systems (Coleman and Crossley 1996). This strategy helps to retain soil organic matter (Holland and Coleman 1987). Increased soil organic matter corresponds to higher total carbon in no-till fields than in tilled fields (Stine and Weil 2002), higher macroaggregate stability (Bruce et al. 1995), and increased crop yield in many cases (e.g., Stine and Weil 2002).

No-till soils also leach less nitrate than conventionally tilled soils (Stinner et al. 1984), decreasing agricultural pollution.

Decomposition. Microbial populations found in no-till soils resemble those of naturally occurring ecosystems more than populations in conventionally-tilled soils (Doran 1980). Nutrient cycling facilitated by soil populations is generally more efficient in no-till fields than in conventionally plowed fields because less leaching occurs (Stinner et al. 1984).

Although burial of plant residues increases rates of plant decomposition (Hendrix et al. 1986), retention of litter aboveground may be desirable. For example, surface litter helps to keep the soil cool and moist by protecting it from direct sunlight (Coleman and Crossley 1996), and increased cover combats soil erosion (Altieri and Nicholls 2000). Mulch left to decompose on the soil surface increases soil carbon and soil organic matter (Bruce et al. 1995), while providing substrate for microbial organisms that aid in nutrient cycling.

Fungi (Norstadt and McCalla 1969, Hendrix et al. 1986) and invertebrates such as earthworms (House and Parmelee 1985) are more abundant in soils under reduced tillage than under conventional tillage. No-till soils also exhibit greater biotic diversity than tilled soils (Hendrix et al. 1986). Biotic soil organisms provide ecosystem services (Daily et al.1997) such as nutrient cycling in undisturbed soils, encouraging the breakdown of crop residues.

In our study, alfalfa stems and leaves were placed on the soil surface to estimate rates of decay. Because it is already well-documented that burial of residues enhances decomposition (Holland and Coleman 1987, Beare et al.

1992), only surface litter decomposition was observed in this study. I examined the rate at which alfalfa residues decompose on surface soil subjected to three different levels of tillage (i.e., within three agroecosystem treatments). Higher decomposition rates of aboveground residues indicate greater functioning of soil decomposer fauna near the soil surface. It is expected that soil disturbance from tillage will decrease functioning of the decomposer community. It is important to note that while retention of litter on the soil surface has demonstrated benefits, fairly quick nutrient cycling from litter decomposition benefits crop plants by providing nutrients for growth. Therefore, a balance between extremely slow and extremely rapid decomposition may be key for long-term nutrient availability.

Plant interactions. Increased biotic diversity provides benefits for plant communities, including higher rates of primary production per unit area of land (Vandermeer 1989). A proposed mechanism for this increased productivity is higher resource-use efficiency in diverse stands (Hooper and Vitousek 1998). Plants from different functional groups require peak nutrients in different seasons (Tilman et al. 1996), and different groups dominate different resources (Hooper and Vitousek 1998). If plant species having sufficiently different resource requirements are grown together, interspecific competition is weaker than intraspecific competition (Vandermeer 1989, Haynes 1980).

Root morphologies and physiologies of alfalfa and wheat are quite different so that uptake of water and nutrients may be maximized. Legumes, for example, have long roots that are efficient to obtain water and nitrate at greater depths than fibrous wheat roots (Entz et al. 2001). Therefore, alfalfa can obtain water and nutrients that are leached below wheat roots, increasing resource uptake. Through complementary use of resources, overyielding may occur. Overyielding occurs when two species grown together produce a higher combined yield per unit area than would be expected based on monoculture yields (Vandermeer 1989). Mead and Willey (1980) analyzed land-use efficiency (or production per unit area) of pigeonpea-sorghum and pigeonpea-maize intercrops and found that overyielding occurred in many cases.

Facilitation is another mechanism for overyielding, whereby the presence of one species enhances the growth of another species (Vandermeer 1989). One mechanism contributing to facilitation in a legume-grass intercrop is the legume’s input of nitrogen (N) into the soil. *Rhizobium* bacteria nodulate in legume roots and release fixed N into the system for uptake by non-legumes via decomposition of vegetative tissue, nodule senescence, root sloughing, or mycorrhizae. Because legumes compete poorly with grasses for mineral soil N (Haynes 1980), they appear to be ideal companion species for intercropping with grasses (i.e., legumes are able to obtain atmospheric N when soil N is not adequately available).

I investigated the contribution of intercropped alfalfa to soil, wheat grain, and hay nitrogen concentrations. Yields of intercropped and monoculture wheat and alfalfa were also used to determine if yield advantage occurred in any of the intercropped systems.

Arthropods. Alternative cropping systems are often designed to combat insect pest infestation and reduce damage caused by herbivory, thus decreasing the need for insecticides (Kemp and Barrett 1989, Holmes and Barrett 1997). Focus has recently turned to cultural methods to control pests because pesticides are expensive and frequently have adverse impacts on ecosystem health, including the elimination of beneficial insects. Cultural control of pests in agroecosystems includes designing cropping systems to avoid pest outbreaks (All 1999). One form of cultural control is intercropping, or increasing the diversity of crop species (All 1999).

Insect pest damage has been shown to be more harmful in monocultures than in more diverse stands of vegetation (Bach 1980, Letourneau and Altieri 1983). Root (1973) proposed the “resource concentration” hypothesis to explain higher numbers of arthropod pests in monocultures. His work on collards (*Brassica oleracea*) suggested that specialist herbivores whose requirements are fulfilled by plants in a simple environment tend to remain and reproduce in that environment. Specialist herbivores often rely on chemical and visual cues from their host plants to feed and reproduce (Vinson 1981). Findings suggest that chemical signals from non-host plants interfere with the ability of herbivores to find suitable food and reproduce (e.g., Roda et al.1997, Degooyer et al. 1999).

Aphids and leafhoppers must physically touch a plant to determine if it is a suitable host plant (Backus 1985). The probability of encountering non-host plants is certainly increased with strip- or intercropping. Thus, the decrease in insect pest numbers in heterogeneous agroecosystems may be attributed to greater movement, possibly due to the need to move farther in search of a host plant (e.g., Roda et al. 1997), whereby herbivorous insects are more likely to emigrate from the field and be susceptible to predation.

Heterogeneous agroecosystems may also attract more generalist predators and parasitoids, which could potentially control herbivore populations. Root (1973) formulated the “enemies” hypothesis as another possible explanation for lower pest numbers in complex agroecosystems. This hypothesis suggests that predators are more likely to remain in heterogeneous systems due to diversity of food resources and refugia. Although it has received less support than the resource concentration hypothesis, it continues to be researched as a potential mechanism of pest control. Karel (1991), for example, found that natural bean fly predators, such as *Opius melanagromyzae* Fischer, preferred abiotic conditions created by intercropping beans with corn than those found in bean monocultures. Letourneau and Altieri (1983) suggested that predators immigrate quickly into stands of diverse vegetation, which provide a greater diversity of refugia than found in monocultures.

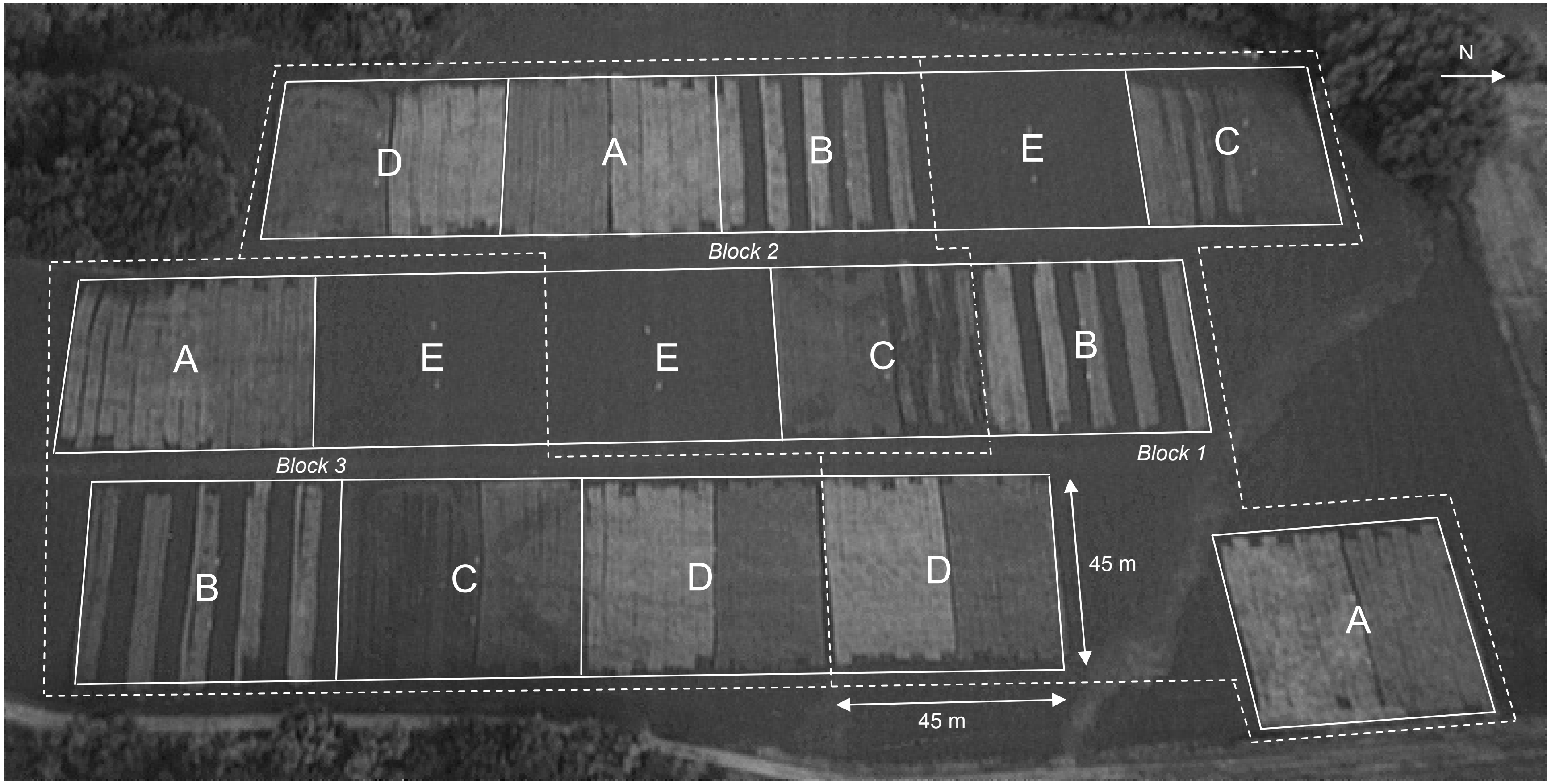
Arthropod pest numbers were quantified for several herbivorous families: aphids (Hemiptera: Aphididae), leafhoppers (Hemiptera: Cicadellidae), and grasshoppers (Orthoptera: Acrididae). Abundances of several generalist predator groups, including ladybird beetles (Coleoptera: Coccinellidae), wolf spiders (Araneae: Lycosidae), and crab spiders (Araneae: Thomisidae), were also investigated. I predicted that the more diverse cropping systems would exhibit lower abundance of specialist herbivores due to lower concentration of host plants, interference from non-host plants, or higher numbers of natural enemies.

Materials and Methods

This investigation was conducted during the growing season (April-September) in 2001 and 2002. The field site was located at the Land Institute in Saline County, Kansas (97°36'W, 38°46'N). Figure 1 is a visual layout of the experimental plots. Prior to this experiment, the field site had been in continuous alfalfa cultivation since 1996. Soil type was Hord silt loam (fine-silty, mixed, mesic Cumulic Haplustoll) (Soil Survey of Saline Co., KS). Average annual rainfall is approximately 76 cm, with 46.6 cm occurring from April through August. Only 31.3 cm of rain fell from April through August, 2002, resulting in a drought year that severely affected wheat production.

Plots were established in a randomized block design consisting of 3 blocks and 5 treatments (Figure 1). Treatments were as follows: wheat monoculture (conventional till), alfalfa-wheat strip crop (wheat strips till; alfalfa strips no-till), alfalfa-wheat row intercrop (no-till), alfalfa-wheat row intercrop (conservation-till), and alfalfa monoculture (no-till). Strips in the strip-crop treatment were 12 feet (3.64 m) wide. Conservation tillage entailed lightly disking the plots once prior to planting. No-till treatments were planted using a no-till drill to seed wheat into the alfalfa stand. In all treatments except alfalfa monoculture, two varieties of hard red winter wheat (Ike and Jagger) were planted in a split-plot design. Each plot was 45m x 45m, separated by a 1-m buffer of alfalfa. No

Figure 1. Aerial photograph of experimental site located in Salina, KS, illustrating 3 blocks and 5 treatments. A = wheat monoculture; B = alfalfa-wheat strips; C = no-till alfalfa-wheat; D = conservation-till alfalfa-wheat; E = alfalfa monoculture.


N
D
A
B
E
C
Block 2
A
E
E
C
B
Block 3
Block 1
B
C
D
D
45 m
A
45 m

fertilizers or pesticides were applied to any of the plots prior to or during the experiment.

Agroecosystem parameters quantified include aboveground biomass, plant and soil nitrogen, plant and soil C:N ratios, rates of soil surface plant decomposition, and arthropod pest and predator abundances. One-way analyses of variance were used when possible (SAS Institute software, SAS version 8.2). Extreme outliers were removed from analyses. Means were separated by pairwise comparisons (Fisher's protected least significant difference) with the α level of probability at $p \leq 0.05$.

***Estimating yield*.** Mean yield values during 2001 and 2002 were based on three random 0.75m x 0.75m samples per sample period. The first alfalfa harvests occurred on 14 May 2001 and 26 May 2002; alfalfa was only harvested in alfalfa monocultures and alfalfa strips in the strip-cropped bicultures. For the second harvest, samples were clipped in all treatments on 28 June 2001 and 2 July 2002. Alfalfa and wheat straw were clipped simultaneously. All vegetation was dried to constant mass. Percent wheat, percent alfalfa, and percent weeds were determined by separating wheat, alfalfa, and weeds in each treatment. Based on the percent alfalfa values, alfalfa yield was estimated for the second hay cutting which included wheat straw in all plots containing wheat.

To estimate wheat grain yield in 2001, all plots except alfalfa monocultures were harvested with a combine on 25 June 2001; the head of the combine was set just above the top of the alfalfa plants. One strip running the length of each replicate plot was harvested, bagged, and weighed. Weight due to moisture and debris (green material) was subtracted from gross harvest weights in order to obtain a final dry weight estimate.

In 2002, wheat growth was stunted due to drought conditions in both the no-till row intercrop and the conservation-till row intercrop; thus the alfalfa was taller than both wheat varieties during the entire growing season. Therefore, wheat was harvested on 19 June 2002 by hand rather than with a combine. Three 0.75m x 0.75m samples were cut per wheat variety per plot. Then wheat seeds were harvested using a hand thresher. Debris was removed from harvested grain by hand, and wheat grain was dried to constant mass to obtain a final yield estimate.

Mean yield values per treatment, including wheat, alfalfa, weeds, and total aboveground biomass, were compared using a one-way ANOVA. Relative yields were also analyzed using the Land Equivalent Ratio, or LER (Mead and Willey 1980, Vandermeer 1989). LER values are a measure of land-use efficiency of intercrops; efficiency refers to harvestable biomass per unit land area. A farmer or crop manager evaluating intercropping would want to know if two crops grown together produce more total combined biomass than each crop when grown alone. The formula is as follows:

$$LER = RY_w + RY_a,$$

where RY_w is the relative wheat yield and RY_a is the relative alfalfa yield. Relative yields are obtained by comparing intercrop yields to monoculture yields. Thus,

$$RY_w = P_w / M_w,$$

where P_w is the polyculture wheat yield and M_w is the monoculture wheat yield. I used the best sole monoculture alfalfa and wheat yields as the divisor in the LER calculations to estimate overyielding because the best single yield is considered the optimal monoculture yield. Because this method underestimates intercrop yield advantage (Vandermeer 1989), I also calculated LERs a second way by comparing intercrop yields to averaged monoculture yields. If LER values are greater than one, intercrops exhibit yield advantage over monocultures. If LER values are less than one, monocultures were more efficient in land-use production per unit area. LER values were fitted to a general linear model to determine whether values were significantly different among treatments.

Soil nitrogen analysis. As a gauge of long-term soil fertility, total soil nitrogen was determined for all five treatments. Soils were sampled at 6-week intervals over the growing season during both 2001 and 2002. Samples were collected during both growing seasons in mid-April, early June, and mid-July. Five soil cores were extracted in an “X” pattern from all plots excluding the strip-cropped treatment plots. In the strip-cropped treatment, 4 samples were collected each from wheat strips (till) and from alfalfa strips (no-till) in a grid pattern. Soil cores were extracted from the top 10 cm of soil.

In 2001 each soil core was analyzed individually. Data are missing for the no-till alfalfa-wheat intercrop treatment due to sampling error. Due to low variance among the 5 samples collected from the same replicate plots on the same date, three cores from each plot per sampling date were randomly selected for analysis during 2002.

Chemical analysis was performed using the Micro-Dumas combustion method (Association of Organic and Analytical Chemists 2000). Soils were initially air-dried at approximately 33°C. Soils were next sieved to pass through 2-mm mesh. After sieving, samples were dried for 24 hours at 60°C. Dried samples were ground to powder consistency using a ball mill (Spex Industries 8000D) to homogenize sample material. Following grinding with a Spex mill, samples were again dried at 60°C for 24 hours. Homogenized soil samples were weighed into tin capsules for analysis using the Carlo Erba C/H/N analyzer (NA1500 C/H/N Analyzer, Carlo Erba Strumentazione, Milan).

Percent nitrogen and percent carbon values were obtained. Total N (g N • kg soil^{-1}) and the C:N ratio were determined from these values. Percent N values were $\arcsin\sqrt{(x/100)}$ transformed prior to analysis. This standard transformation allows percentages to be analyzed with parametric statistics. Because repeated measures ANOVA revealed significant interactions between date and treatment, an ANOVA was performed on total N and C:N values for each individual sampling date.

Plant nitrogen analysis. Percent total nitrogen and C:N ratios were also determined for wheat grain and wheat and alfalfa hay. Preparation for analysis was similar to that for soil analysis. Three hay samples from each variety of wheat (Ike and Jagger) in each plot were collected for analysis in 2001. Three alfalfa monoculture samples were analyzed to compare hay from intercropped plots with pure alfalfa hay. Prior to grinding in the Spex ball mill, wheat straw and alfalfa hay were ground using a Wiley mill to homogenize alfalfa and wheat plants for analysis. Mulched plant samples were then ground with the ball mill and weighed into tin capsules.

Wheat grain from both years was analyzed for percent N and C:N ratios. Grain was originally air-dried in a greenhouse at approximately 33°C. Grain was then dried at 60°C for 24 hours and ground using the Spex ball mill prior to being weighed into tin capsules for analysis with the Carlo Erba auto-analyzer.

Percent crude protein was determined for both hay and grain samples. To determine percent crude protein for wheat grain, percent total N was multiplied by 5.7. To determine percent crude protein in hay, percent total N was multiplied by 6.25 (Association of Organic and Analytical Chemists 2000).

Total percent N and C:N values were analyzed using one-way ANOVA. Percent N values were $arcsin\sqrt{(x/100)}$ transformed prior to analysis. Statistical values are not reported for crude protein data because percent crude protein trends were identical to percent total N trends.

Estimating rates of decomposition. Differences in rates of surface litter decomposition among treatments were estimated using 20 cm x 30 cm litter bags. Decomposition of alfalfa residues in bags corresponds to the activity of decomposer organisms, which is thought to be strongly linked to tillage regimes. Litter bags were made of 1-mm nylon mesh. This small mesh size excludes most macroinvertebrates. Approximately 30 g of alfalfa dried at 80°C for 24 hours were initially placed in each bag. Eight bags were placed in each of the 15 plots during May of 2001 and 2002. Two bags were collected from each plot (i.e., a total of 6 per treatment) at 30-day intervals up to 120 days (May to September). Retrieved bags were dried for 24 hours at 80°C prior to weighing. Each bag was weighed to the nearest 0.01 g.

Differences in percent mass remaining among treatments were analyzed per date. Litter bags from the wheat monoculture treatment were excluded from analysis of the final 2001 sampling date because litter bags on this date weighed higher than bags from this treatment weighed 30 days earlier, perhaps due to excessive moisture or soil contamination. A one-way ANOVA was performed for each 30-day period. Data were $\arcsin \sqrt{(x/100)}$ transformed in order to analyze relative percentage values. Also, the negative exponential decay model (Olson 1963) was used to determine daily rates of decay (*k*) among different treatments. The model is as follows:

$$N_f = N_o e^{-kt},$$

where N_f is the final weight, N_o is the initial weight, and t is time in days. Decomposition constants were calculated for each experimental plot by regressing the natural logarithm of percent mass remaining against time. These *k* values were compared with an ANOVA.

Abundance of selected arthropod pests and predators. Two trapping locations were situated near the center of each plot. A pan trap and a pitfall trap were located at each trapping site, (i.e., 6 pan and 6 pitfall traps per treatment). Pan traps consisted of yellow plastic bowls affixed to wooden posts that were adjusted when needed to maintain the bowl rims level with the canopy of the crops. A mixture of water and ethylene glycol was used to cover the bottom of each pan trap. Pitfall traps were placed even with the soil surface.

Pan and pitfall traps were emptied five days after the ethylene glycol-water mixture was added. Traps were checked on a weekly basis during June and early July. No trapping occurred immediately prior to and post wheat harvest, but arthropods were collected following harvest. Collection dates for 2001 were 4 June, 8 June, 14 June, 18 June, 22 June, 8 July, and 12 July; collection dates for 2002 were 2 June, 9 June, 17 June, 24 June, and 15 July. Collected arthropods were preserved in 70% ethanol for later identification. Because counts of individual species were low, results are presented for abundance at the family level.

Arthropods were also collected with a sweep net in 2002 twice prior to (25 May and 13 June) and once following (18 July) wheat harvest. Samples consisted of 25 sweeps along a randomly selected transect in each experimental plot. The first sweep collection occurred prior to the first alfalfa cutting and thus included alfalfa weevils (*Hypera postica* Gyllenhal). Their numbers are typically greatly reduced by the first cutting; thus they are only injurious early in the growing season.

Insect pests collected in all traps during 2001 and 2002 included aphids (Hemiptera: Aphididae) and leafhoppers (Hemiptera: Cicadellidae). Grasshoppers (Orthoptera: Acrididae) were also collected from all traps in 2002. Grasshopper abundance was not quantified in 2001 because numbers were quite low. However, due to a mild winter followed by a summer drought, grasshoppers were ubiquitous in the 2002 growing season (Joern and Gaines 1990).

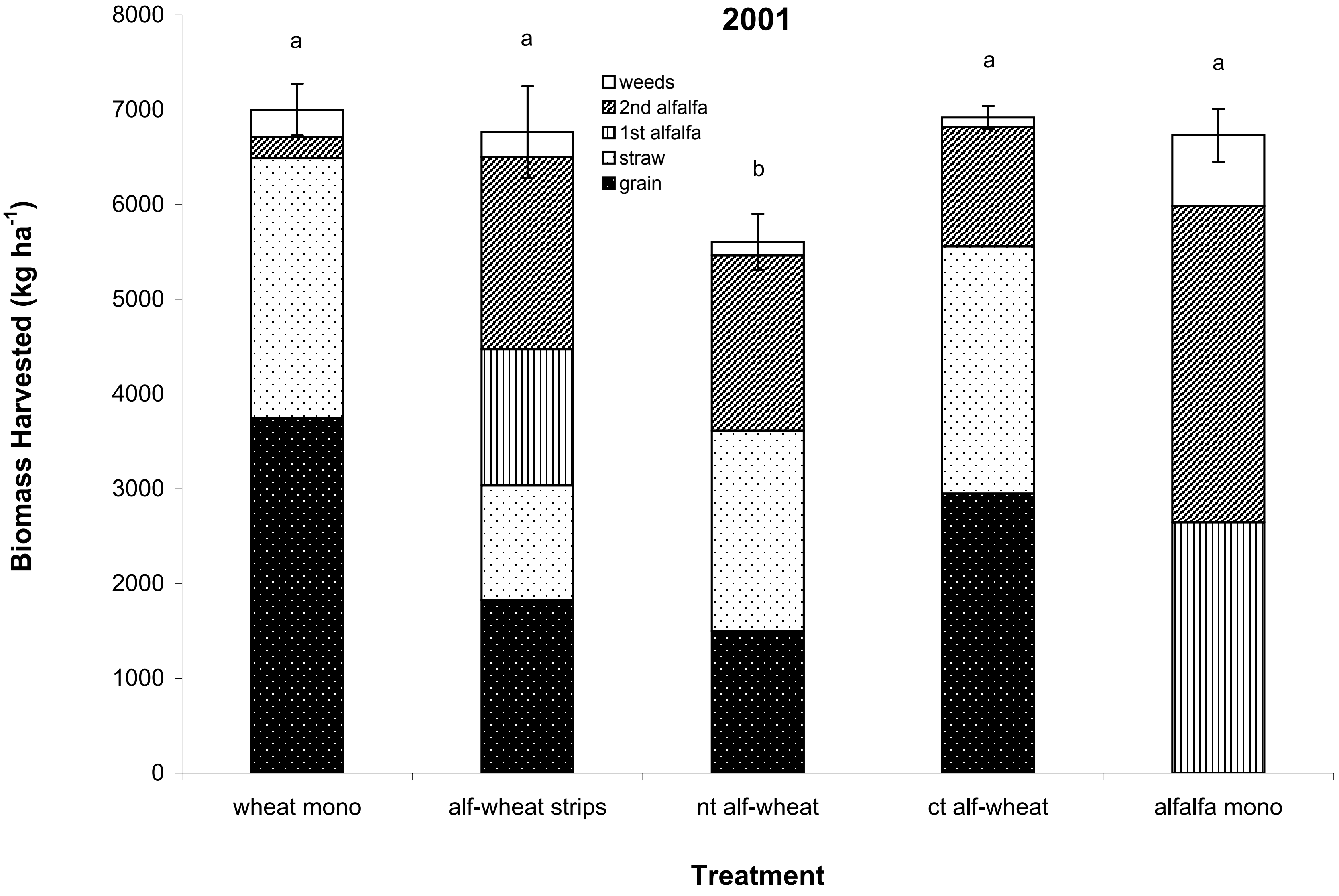
Two main groups of predators were counted for analysis: ladybird beetles (Coleoptera: Coccinellidae) and spiders (Araneae). Wolf spiders (Araneae: Lycosidae) were the dominant spiders in pan and pitfall traps, whereas crab spiders (Araneae: Thomisidae) were the most common spiders in sweep samples.

Differences in mean abundances of aphids, leafhoppers, grasshoppers, ladybird beetles, and spiders among treatments for pan and pitfall traps were analyzed by repeated measures ANOVA for each season. Abundances in most cases were too low to analyze for individual sampling dates. Arthropod data were square-root transformed prior to analysis to normalize data and homogenize variances (Sokal and Rohlf 1973). Because the *year x treatment* interaction term was significant for most arthropod groups, data are presented for means within each season. ANOVAs were also performed on data collected from sweep nets. Sweep sample data were analyzed separately for the three sampling dates. These 3 dates represent three distinct stages of the growing season; population sizes of arthropods were therefore quite variable among dates.

Results

Yield. Total aboveground biomass for 2001 is shown in Figure 2. Total biomass was similar for all treatments excluding the no-till alfalfa-wheat intercrop,

Figure 2. Mean total biomass (x ± 1 SE) for 2001. Different letters above SE bars indicate significant differences among treatments ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.



2001
Biomass Harvested (kg ha^{-1})
8000
7000
6000
5000
4000
3000
2000
1000
0
a
a
b
a
a
weeds
2nd alfalfa
1st alfalfa
straw
grain
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
alfalfa mono
Treatment

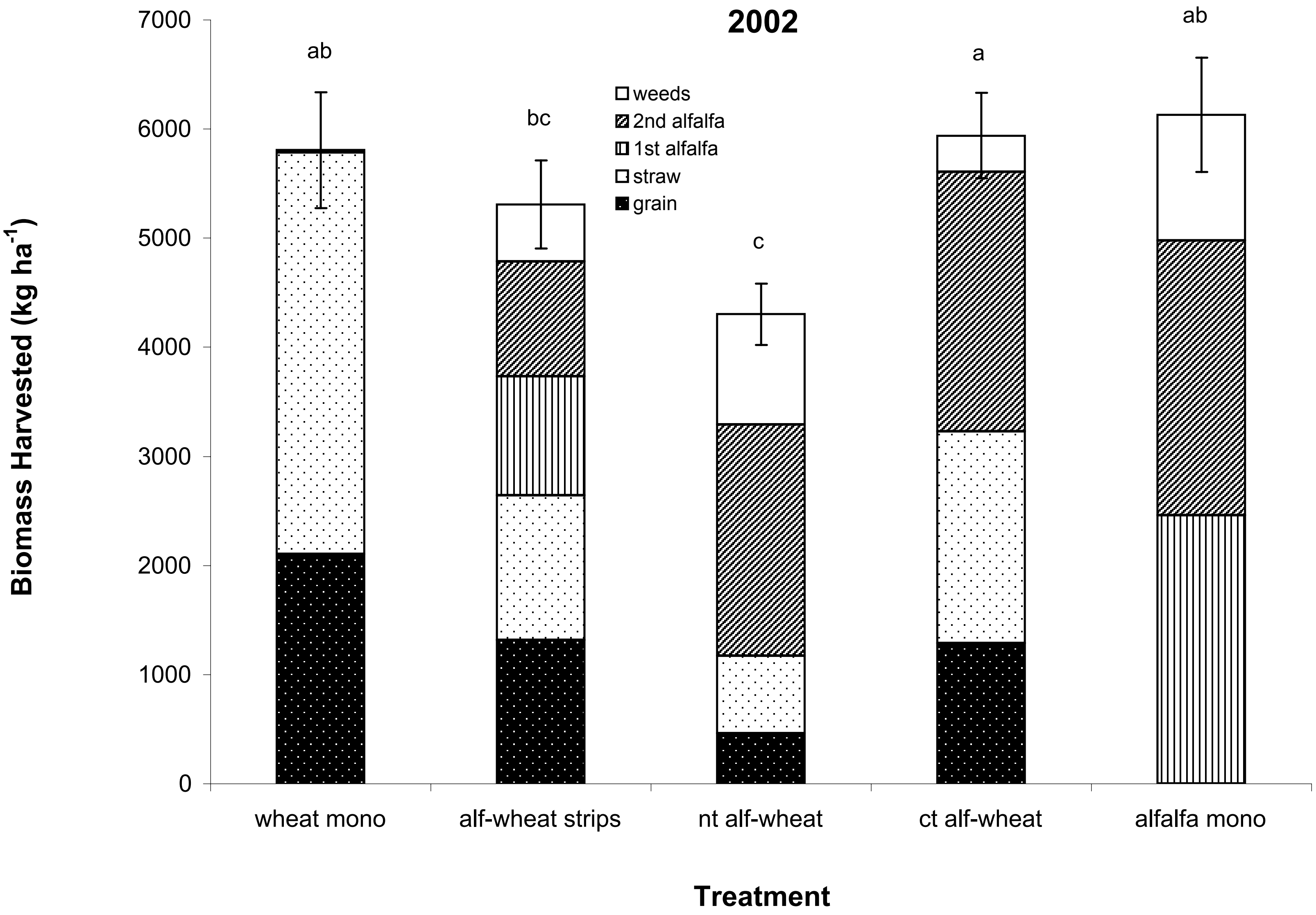
which exhibited significantly lower total biomass ($F_{4,22}$=4.85, $P<0.01$). Significant differences in wheat grain yields were observed among different treatments ($F_{3,20}$=45.51, $P<0.001$). Wheat monoculture and alfalfa-wheat strip-crop treatments had similar grain yields (3749 and 3644 kg ha^{-1}, respectively). The conservation-till alfalfa-wheat intercrop yielded significantly lower than wheat monoculture and wheat strips. The no-till alfalfa-wheat intercrop yielded significantly lower than all other treatments containing wheat. The no-till alfalfa-wheat intercrop was also the only treatment that did not exceed the 2001 average Kansas winter wheat yield (2757 kg ha^{-1}). There was no significant difference between wheat yields of Ike and Jagger ($P>0.05$).

Total alfalfa harvested in 2001 was greatest in alfalfa strips (in alfalfa-wheat strip-crop) and alfalfa monocultures ($F_{5,24}$=270.31, $P<0.001$). The no-till alfalfa-wheat intercrop had the next highest yield. Negligible amounts of alfalfa were harvested in wheat strips and wheat monocultures.

Mean weed biomass was fairly small in 2001. Species found included foxtail (*Setaria viridis, S. glauca*), dandelion (*Taraxacum officinale*), Japanese brome (*Bromus japonicus*), and prickly lettuce (*Lactuca seriola*). Weed biomass was greatest in the alfalfa monoculture ($F_{4,22}$=5.21, $P<0.01$). All other treatments had similar mean weed masses.

Total aboveground biomass for 2002 is shown in Figure 3. Total biomass was greatest in the conservation-till alfalfa-wheat intercrop, wheat monoculture, and alfalfa monoculture treatments ($F_{4,22}$=3.40, $P<0.05$). The alfalfa-wheat strip-crop treatment had the next highest total biomass. The no-till alfalfa-wheat

Figure 3. Mean total biomass (x ± 1 SE) for 2002. Different letters above SE bars indicate significant differences among treatments ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop*; nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.


2002
Biomass Harvested (kg ha^{-1})
7000
6000
5000
4000
3000
2000
1000
0
ab
bc
c
a
ab
weeds
2nd alfalfa
1st alfalfa
straw
grain
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
alfalfa mono
Treatment

intercrop had the lowest mean biomass, largely due to very small wheat yields in this treatment. Wheat monoculture produced the highest grain yield ($F_{3,68}$=30.82, P<0.001). Wheat strips (in alfalfa-wheat strip-crop) and conservation-till alfalfa-wheat produced similar yields. No-till alfalfa-wheat had the lowest grain yield. In 2002, an unknown disease affected several plots of wheat; researchers failed to identify this likely soil-borne pathogen. In all cases it affected Ike and not Jagger. Mean yield between the two varieties was therefore significantly different ($F_{1,70}$=4.25, P<0.05). Jagger yielded an average of 1293 kg ha^{-1}, whereas Ike yielded an average of 924 kg ha^{-1}. All grain yields were significantly lower in 2002 than in 2001, presumably due to drought conditions in 2002.

Total alfalfa harvested in 2002 was greatest in alfalfa monoculture ($F_{5,24}$=51.37, P<0.001). Conservation-till alfalfa-wheat intercrops, alfalfa strips (in alfalfa-wheat strip-crop), and no-till alfalfa-wheat intercrops yielded significantly lower alfalfa biomass than did alfalfa monocultures.

Mean weed biomass in 2002 was greatest in the alfalfa monoculture and no-till alfalfa-wheat intercrop treatments ($F_{4,22}$=11.42, P<0.001). The wheat monoculture treatment had the lowest weed biomass, presumably due to two years of continuous tillage. Cheat grass (*Bromus tectorum*) was prevalent throughout the field during 2002, which led to higher mean weed biomass values for most treatments in 2002 compared to 2001.

Land equivalent ratios (LER) were calculated two ways; the first is a more conservative calculation because intercrop yields were compared to the best single wheat and alfalfa monoculture yields. That is, monoculture yields were not averaged prior to comparison. Table 1a presents the results of the conservative LER calculations. In 2001, the strip-cropped alfalfa-wheat intercrop had the highest land use efficiency, with a mean LER value of 0.91 ($F_{2,15}$=41.52, $P<0.001$). LER values for the conservation-till alfalfa-wheat intercrop were significantly lower than those for the strip-crop treatment. No-till alfalfa-wheat intercrop LERs were significantly lower than all other mean values. There was no significant difference ($P>0.05$) between the two wheat varieties. Trends for LERs calculated with monoculture averages were identical to those for the conservative LERs. However, the strip-cropped alfalfa-wheat intercrop LER value was greater than 1.0 when calculated using monoculture average yields, suggesting that this treatment had higher land-use efficiency than if the land was divided into two monocultures. The less conservative LER values are reported in Table 1b.

In 2002 during drought conditions, intercrop advantage was more visible. The conservation-till alfalfa-wheat intercrop treatment showed an intercrop advantage (i.e., LER>1.0) when LERs were calculated both conservatively and using average monoculture yields. The alfalfa-wheat strip-crop treatment also exhibited high land-use efficiency when compared to the mean wheat and alfalfa monoculture yields. LER values for the conservation-till alfalfa-wheat intercrop were significantly greater than those for the no-till alfalfa-wheat intercrop ($F_{2,15}$=4.75, $P<0.05$). Again, no significant differences were found between LER values for the two wheat varieties.

Table 1a. Land equivalent ratio (LER) values calculated using best single wheat and alfalfa monoculture yields. RY_i represents the relative yield of an individual component crop. Treatment *SC* is strip-cropped alfalfa and wheat. Treatment *NT* is no-till alfalfa-wheat row intercrop. Treatment *CT* is conservation-till alfalfa-wheat row intercrop. Yields per hectare were halved for the alfalfa-wheat strip-crop treatment because in any given hectare, only half is devoted to each crop.

Treatment	Wheat variety	RY_a		RY_w		LER	
		2001	2002	2001	2002	2001	2002
SC	Ike	0.48	0.71	0.41	0.20	0.89	0.91
	Jagger	0.48	0.71	0.45	0.27	0.93	0.98
NT	Ike	0.18	0.81	0.35	0.05	0.53	0.86
	Jagger	0.21	0.59	0.36	0.19	0.57	0.78
CT	Ike	0.11	0.76	0.70	0.34	0.81	1.10*
	Jagger	0.11	0.80	0.70	0.52	0.81	1.32*

Table 1b. Land equivalent ratio (LER) values calculated using average wheat and alfalfa monoculture yields.

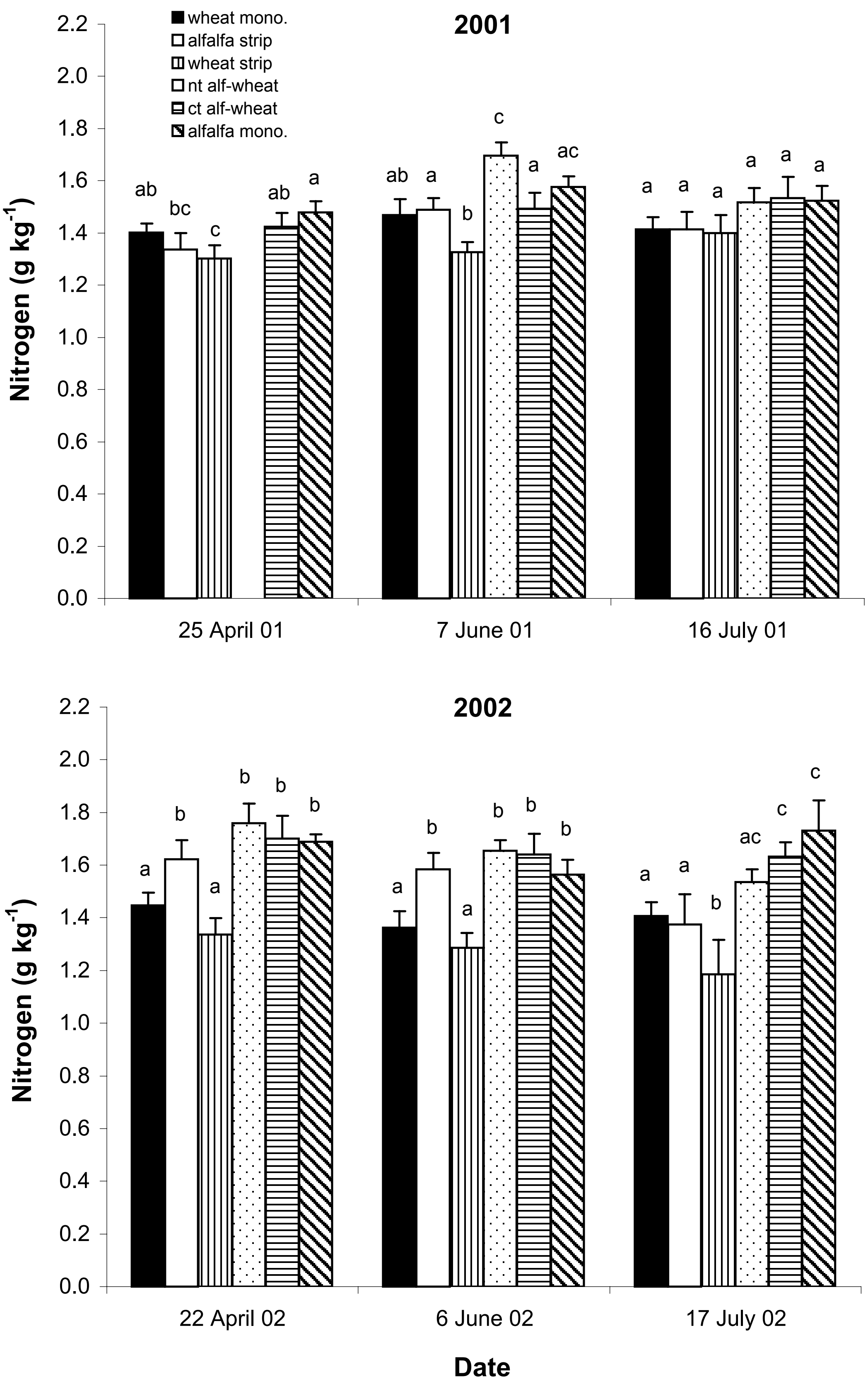
Treatment	Wheat variety	RY_a		RY_w		LER	
		2001	2002	2001	2002	2001	2002
SC	Ike	0.55	0.85	0.46	0.38	1.01*	1.23*
	Jagger	0.55	0.85	0.51	0.34	1.06*	1.19*
NT	Ike	0.21	0.98	0.39	0.06	0.60	1.04*
	Jagger	0.24	0.71	0.41	0.24	0.65	0.95
CT	Ike	0.13	0.92	0.79	0.43	0.92	1.35*
	Jagger	0.13	0.97	0.79	0.66	0.92	1.63*

* indicates overyielding.

Soil nitrogen. Figure 4 shows soil nitrogen (g kg^{-1}) over six sampling dates. Because the entire field was in continuous alfalfa for four years prior to this experiment, soil nitrogen (N) was fairly high in all treatments. In April 2001 soils of alfalfa monoculture, conservation-till alfalfa-wheat, and wheat monoculture treatments had the highest percent N ($F_{4,53}$=5.72, P<0.001). Data from the no-till alfalfa-wheat intercrop are not available for this date. In June 2001 treatments containing a high percentage of alfalfa had high percent soil nitrogen. No-till alfalfa-wheat and alfalfa monoculture treatments had the highest mean soil N content ($F_{5,78}$=5.71, P<0.001). Nitrogen content of wheat monocultures and wheat strips (in alfalfa-wheat strip-crop) was lower than mean soil N in the no-till alfalfa-wheat intercrop. In July 2001, no significant differences among treatments were observed. In both April and June, the *treatment x block* interaction term was significant; Block 2 had higher percent soil nitrogen. This finding may be partly explained by the Smoky Hill River, which is adjacent to several of the plots in Block 2. It is likely that the river deposited silt when its banks overflowed in previous years.

In 2002 trends in soil N were fairly static. In April and June, wheat monoculture and wheat strips in the alfalfa-wheat strip-crop had significantly lower soil nitrogen than did soil from all other treatments (April $F_{5,36}$=9.71, P<0.001; June $F_{5,36}$=8.92, P<0.001). In July 2002 wheat monoculture and wheat and alfalfa strips in the alfalfa-wheat strip crop had lower mean soil N than the alfalfa monoculture and two row-intercrop treatments ($F_{5,40}$=8.29, P<0.001).

Figure 4. Mean soil nitrogen concentration (x ± 1 SE) presented as (g N • kg soil^{-1}). Different letters above treatment means indicate significant differences ($P \leq 0.05$) on a particular sampling date. *Wheat mono* = wheat monoculture; *alfalfa strip* = alfalfa strip in alfalfa-wheat strip-crop; *wheat strip* = wheat strip in alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.


2001
2002
wheat mono.
alfalfa strip
wheat strip
nt alf-wheat
ct alf-wheat
alfalfa mono.
Nitrogen (g kg^{-1})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
ab
bc
c
ab
a
ab
a
b
c
a
ac
a
a
a
a
a
a
25 April 01
7 June 01
16 July 01
a
b
a
b
b
b
a
b
a
b
b
b
a
a
b
ac
c
c
22 April 02
6 June 02
17 July 02
Date

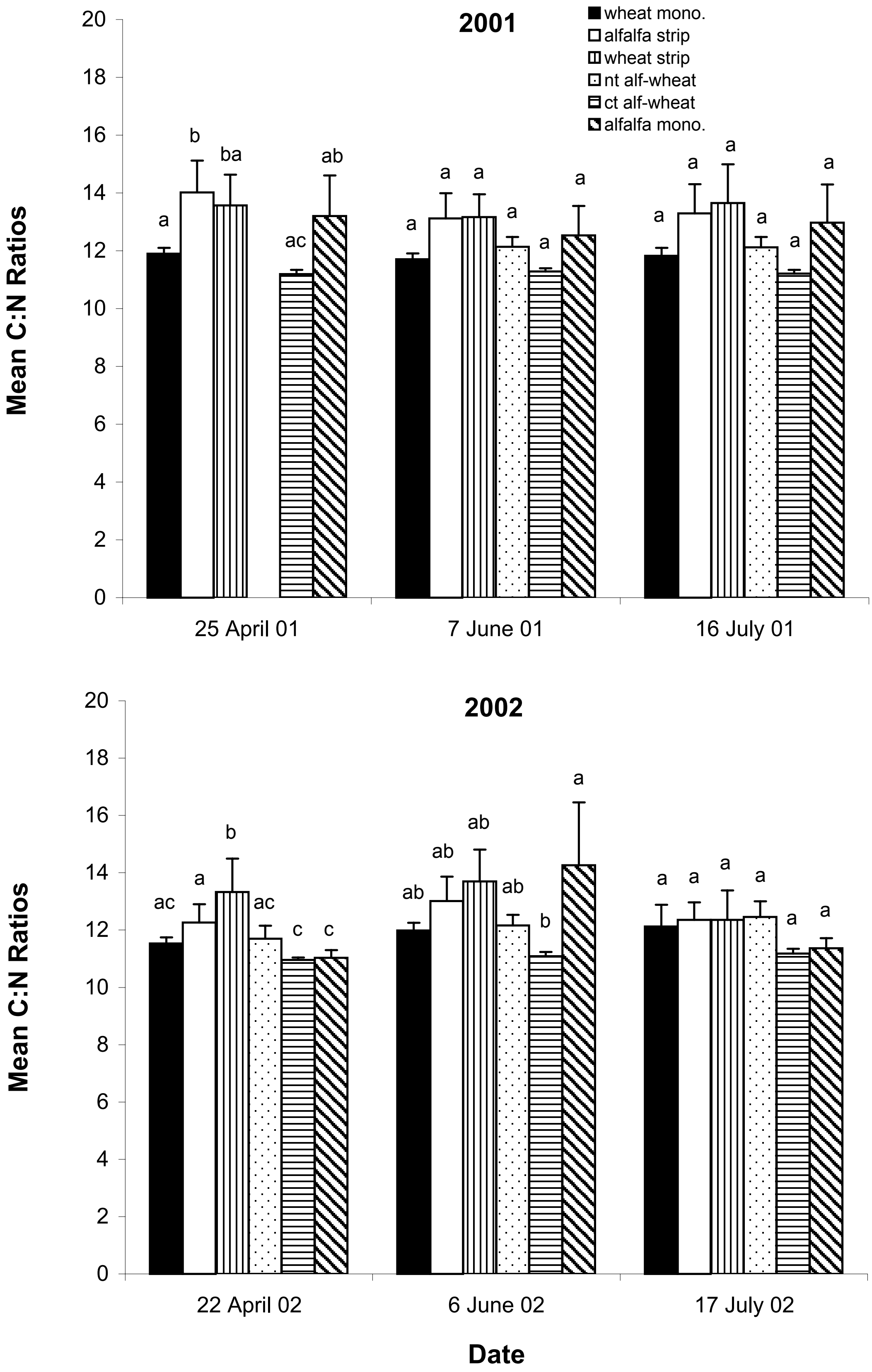
Throughout the growing season, soils in Block 2 again had significantly high nitrogen concentrations.

Trends in C:N ratios are represented by Figure 5. Differences among C:N ratios per treatment are significant for April 2001 ($F_{4,53}$=5.3, P<0.001). Wheat and alfalfa strips in the alfalfa-wheat strip-crop treatment had the highest C:N ratios, which was expected based on their low soil N content. No significant differences in C:N ratios occurred for June and July 2001. Thus, soils containing higher amounts of nitrogen also had high carbon content so that the C:N ratios do not reflect fluctuations in N.

In April 2002, wheat strips in the alfalfa-wheat strip-crop had significantly higher C:N ratios than all other treatments ($F_{5,36}$=6.47, P<0.001). The two row intercrop and the two monoculture treatments had the lowest C:N ratios. This finding is a result of high N values for the row intercrops and alfalfa monoculture and low C values for the wheat monoculture, which exhibited low N on this date. There were no significantly different C:N ratios among treatments in June or July.

Plant nitrogen. Grain quality as measured by total percent nitrogen is depicted in Figure 6. In 2001, grain from the conservation-till alfalfa-wheat intercrop had significantly lower N than all other treatments ($F_{3,68}$=9.58, P<0.001). Percent N values were used to calculate percent crude protein values (Table 2). These protein values are well within the range of acceptable grain protein values. The average percent value for the past ten years in Kansas is about 12% (KASS 2001). Grain percent nitrogen was higher in 2002, but differences among treatments and varieties were not significant.

Figure 5. Mean soil carbon:nitrogen ratios (x ± 1 SE). Different letters above treatment means indicate significant differences ($P \leq 0.05$) on a particular sampling date. *Wheat mono* = wheat monoculture; *alfalfa strip* = alfalfa strip in alfalfa-wheat strip-crop; *wheat strip* = wheat strip in alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.



2001
wheat mono.
alfalfa strip
wheat strip
nt alf-wheat
ct alf-wheat
alfalfa mono.
Mean C:N Ratios
0
2
4
6
8
10
12
14
16
18
20
a
b
ba
ac
ab
a
a
a
a
a
a
a
a
a
a
a
a
25 April 01
7 June 01
16 July 01
2002
Mean C:N Ratios
0
2
4
6
8
10
12
14
16
18
20
ac
a
b
ac
c
c
ab
ab
ab
ab
b
a
a
a
a
a
a
a
22 April 02
6 June 02
17 July 02
Date

Figure 6. Mean total percent nitrogen (x ± 1 SE) for wheat grain harvested in 2001 and 2002. Different letters above different treatment means indicate significant differences among treatments for a particular year ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; and *ct alf-wheat* = conservation-till alfalfa-wheat intercrop.

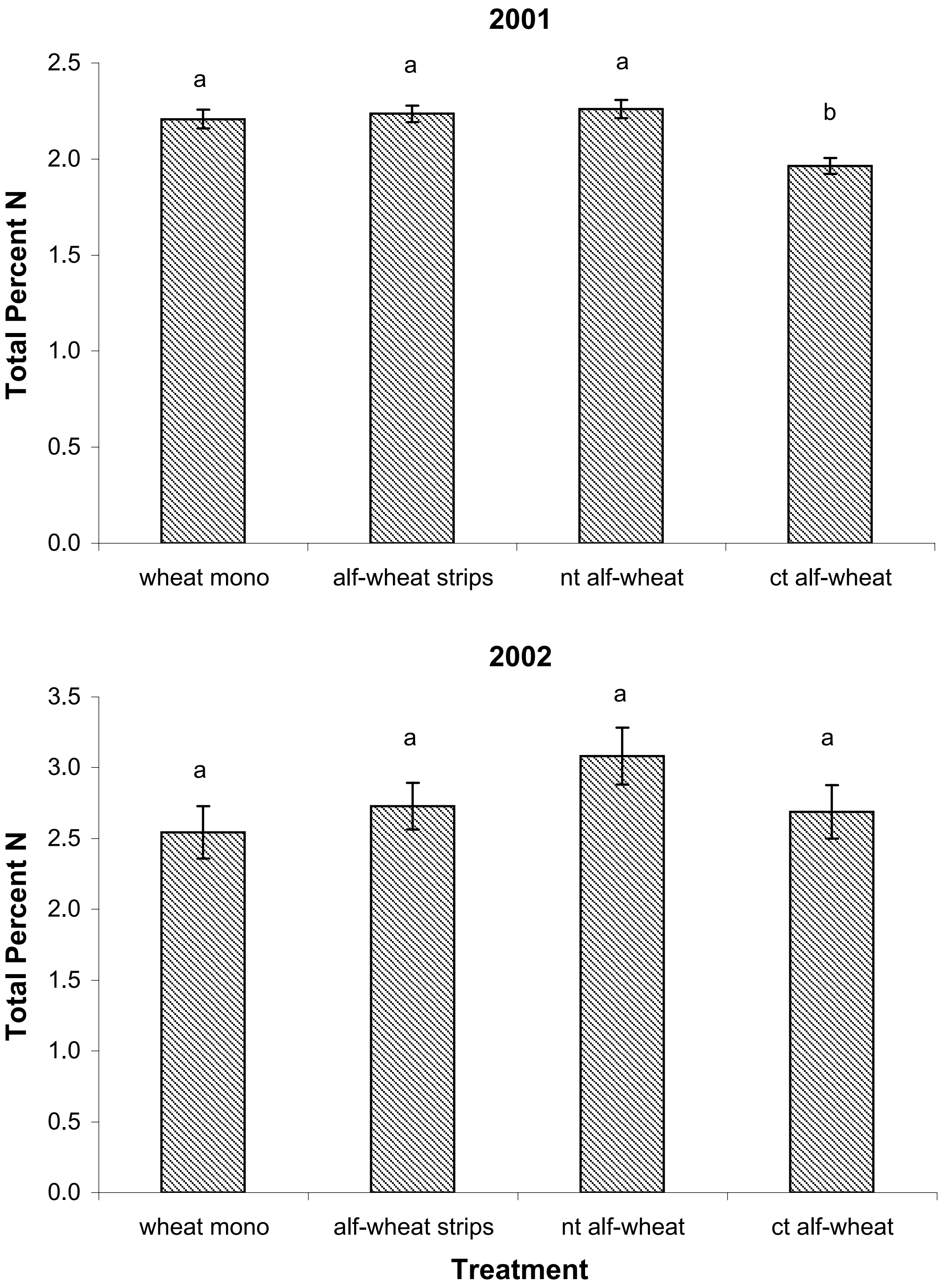

2001
Total Percent N
0.0
0.5
1.0
1.5
2.0
2.5
a
a
a
b
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
2002
Total Percent N
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
a
a
a
a
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
Treatment

Table 2. Mean (x ± 1 SE) crude protein values for wheat grain.

Treatment	Percent Crude Protein	
	2001	2002
Wheat monoculture	12.6 ± 0.3	14.5 ± 1.1
Wheat strip (in strip-crop)	12.7 ± 0.3	15.6 ± 0.9
No-till alfalfa-wheat	12.9 ± 0.3	17.6 ± 1.1
Disked alfalfa-wheat	11.2 ± 0.2	15.3 ± 1.1

Grain C:N ratios are shown in Figure 7. In 2001, the conservation-till alfalfa-wheat intercrop had a significantly greater C:N ratio than other treatments ($F_{3,68}$=11.03, P<0.001). This corresponds to trends seen in total N. No significant differences in C:N ratios were observed during 2002.

Total percent N for hay is shown in Figure 8. Nitrogen content of hay from alfalfa monoculture was significantly higher ($F_{4,70}$=118.7, P<0.001) than hay from other treatments, which included varying proportions of wheat stubble. No-till alfalfa-wheat hay had significantly higher percent N than all treatments other than alfalfa monoculture. Wheat strips (in alfalfa-wheat strip-crop) and wheat monocultures produced hay with the lowest mean N content. This finding was expected since hay in these two treatments consisted primarily of wheat straw. Both alfalfa hay and wheat straw had slightly higher N concentrations than expected; Brady and Weil (1999) reported typical values of 0.50% N for wheat straw and 1.80% N for mature alfalfa hay. Values found in this experiment were 0.67% and 2.43%, respectively. Percent crude protein values are reported in Table 3.

Figure 9 shows C:N ratios for hay among treatments. Trends in C:N ratios mirrored those of total percent N. Therefore, hay from wheat monocultures and wheat strips had significantly higher C:N values than those for the conservation-till alfalfa-wheat, no-till alfalfa-wheat, and alfalfa monoculture treatments ($F_{4,70}$=46.01, P<0.001).

Decomposition. Patterns of decomposition of alfalfa litter placed on the soil surface are shown in Figure 10. In 2001, after 30 days, the two reduced-

Figure 7. Mean carbon:nitrogen ratios (x ± 1 SE) for wheat grain harvested in 2001 and 2002. Different letters above different treatment means indicate significant differences among treatments for a particular year ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; and *ct alf-wheat* = conservation-till alfalfa-wheat intercrop.

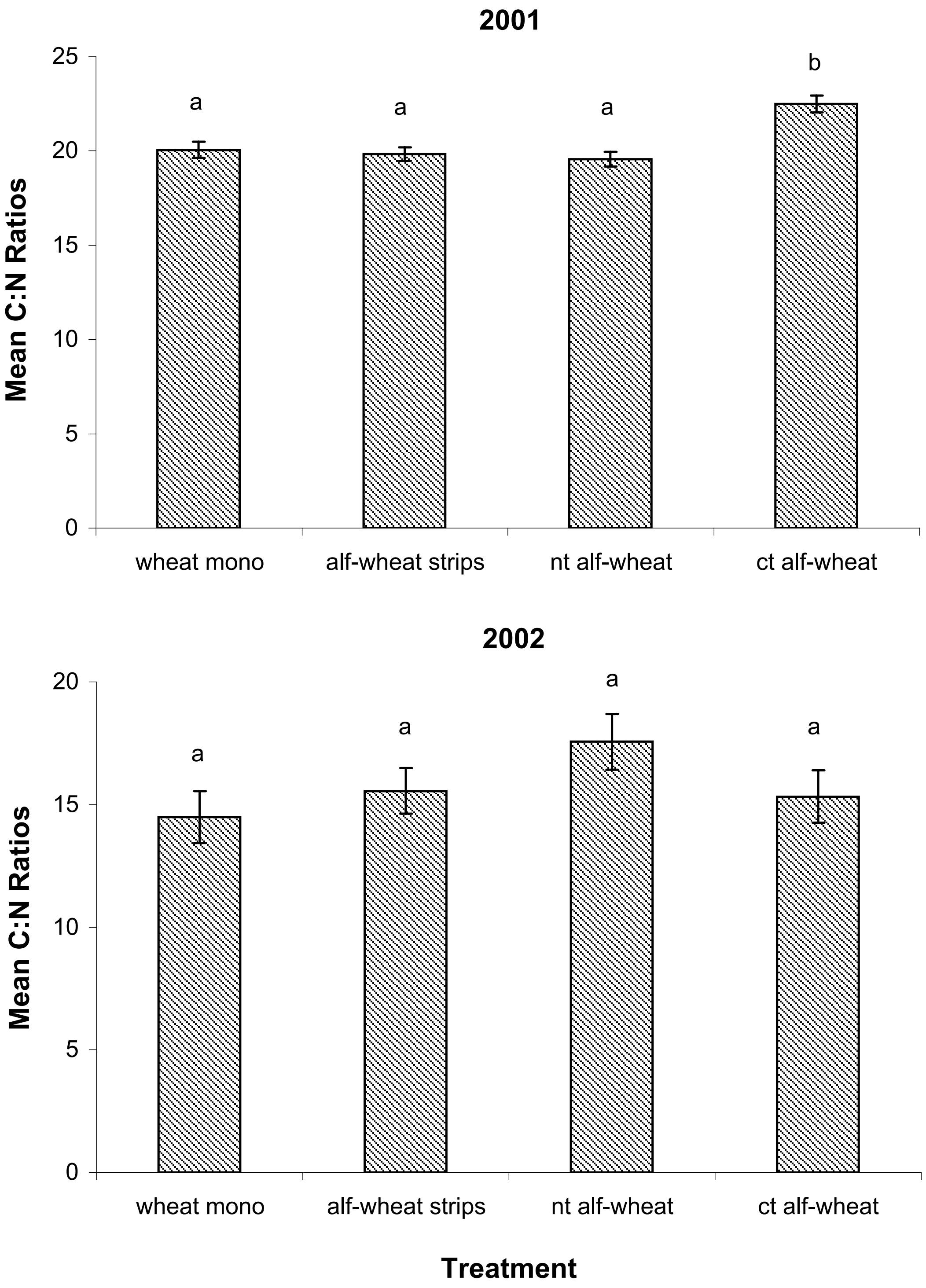
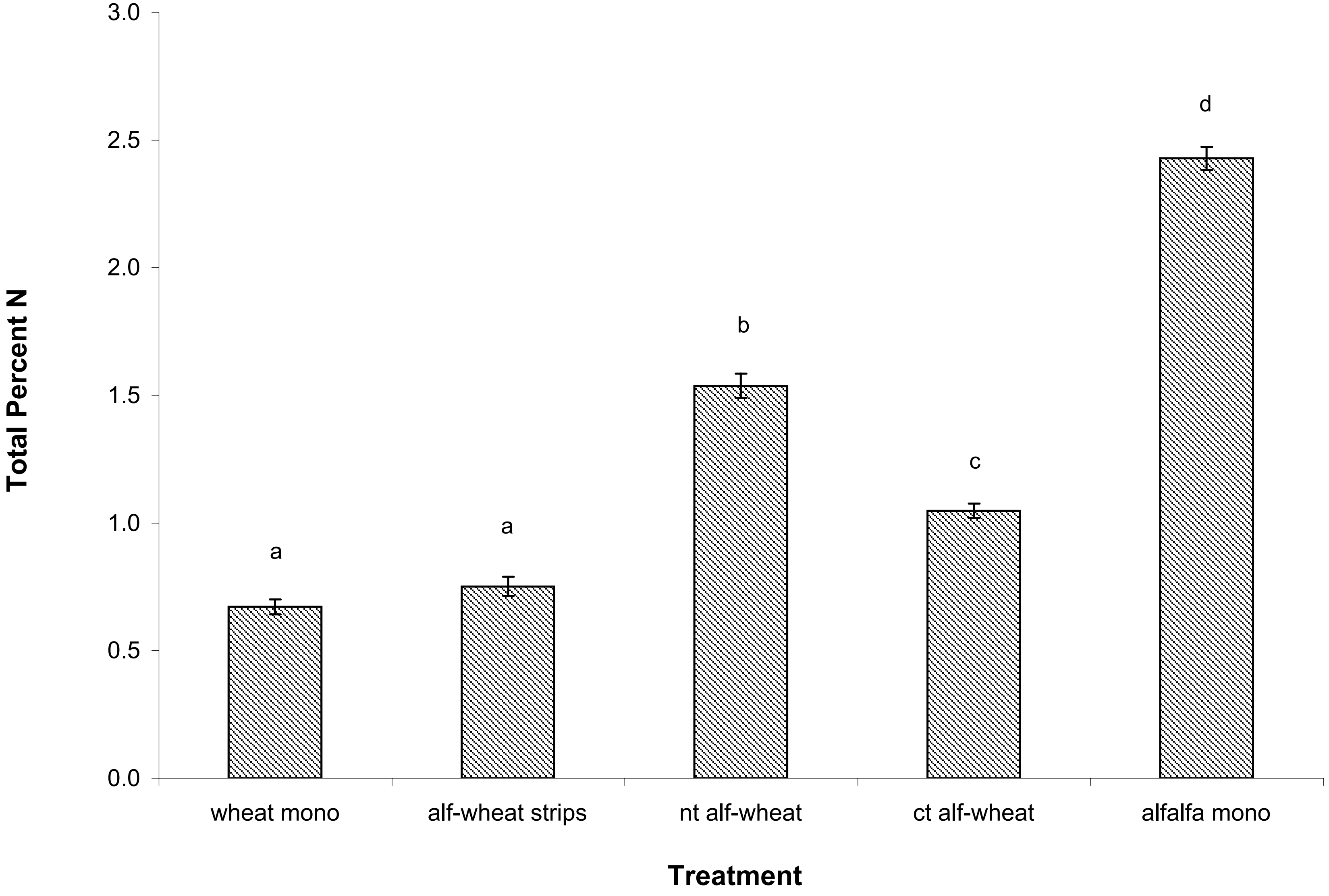

2001
25
20
15
10
5
0
Mean C:N Ratios
a
a
a
b
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
2002
20
15
10
5
0
Mean C:N Ratios
a
a
a
a
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
Treatment

Figure 8. Mean total percent nitrogen (x ± 1 SE) for hay harvested in 2001. Different letters above treatment means signify differences in percent nitrogen among treatments ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Total Percent N
a
a
b
c
d
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
alfalfa mono
Treatment

Table 3. Mean (x ± 1 SE) crude protein values for hay. Hay from wheat monoculture, alfalfa-wheat strip-crop, no-till alfalfa-wheat intercrop, and conservation-till alfalfa-wheat intercrop treatments includes wheat straw and alfalfa. Hay from alfalfa monoculture consists of alfalfa only.

Treatment	Percent Crude Protein
Wheat monoculture	4.2 ± 0.2
Wheat strip (in strip-crop)	4.7 ± 0.2
No-till alfalfa-wheat	9.6 ± 0.3
Disked alfalfa-wheat	6.6 ± 0.2
Alfalfa monoculture	15.2 ± 0.3

Figure 9. Mean carbon:nitrogen ratios (x ± 1 SE) for hay harvested in 2001. Different letters above treatment means signify differences in percent nitrogen among treatments ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.

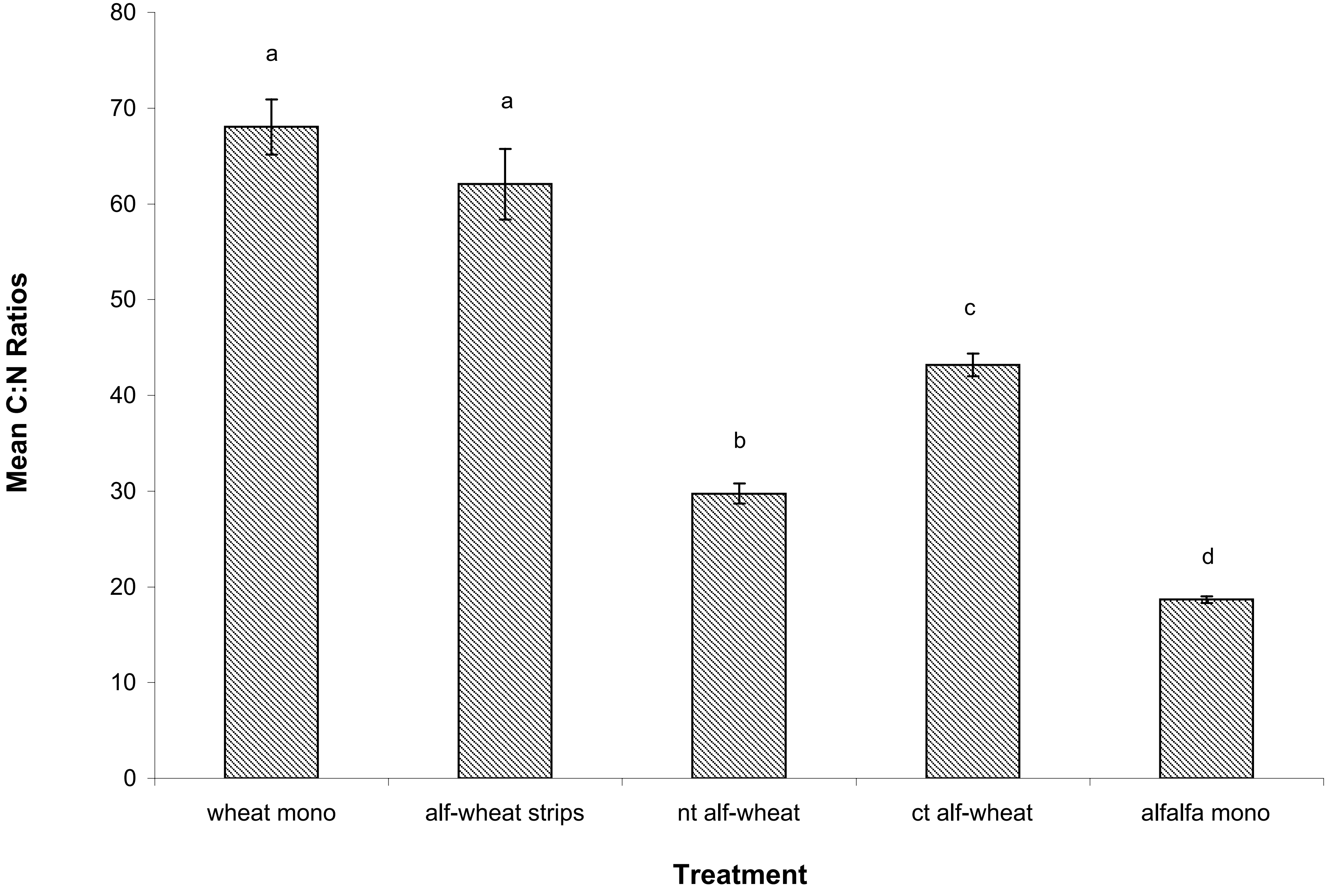
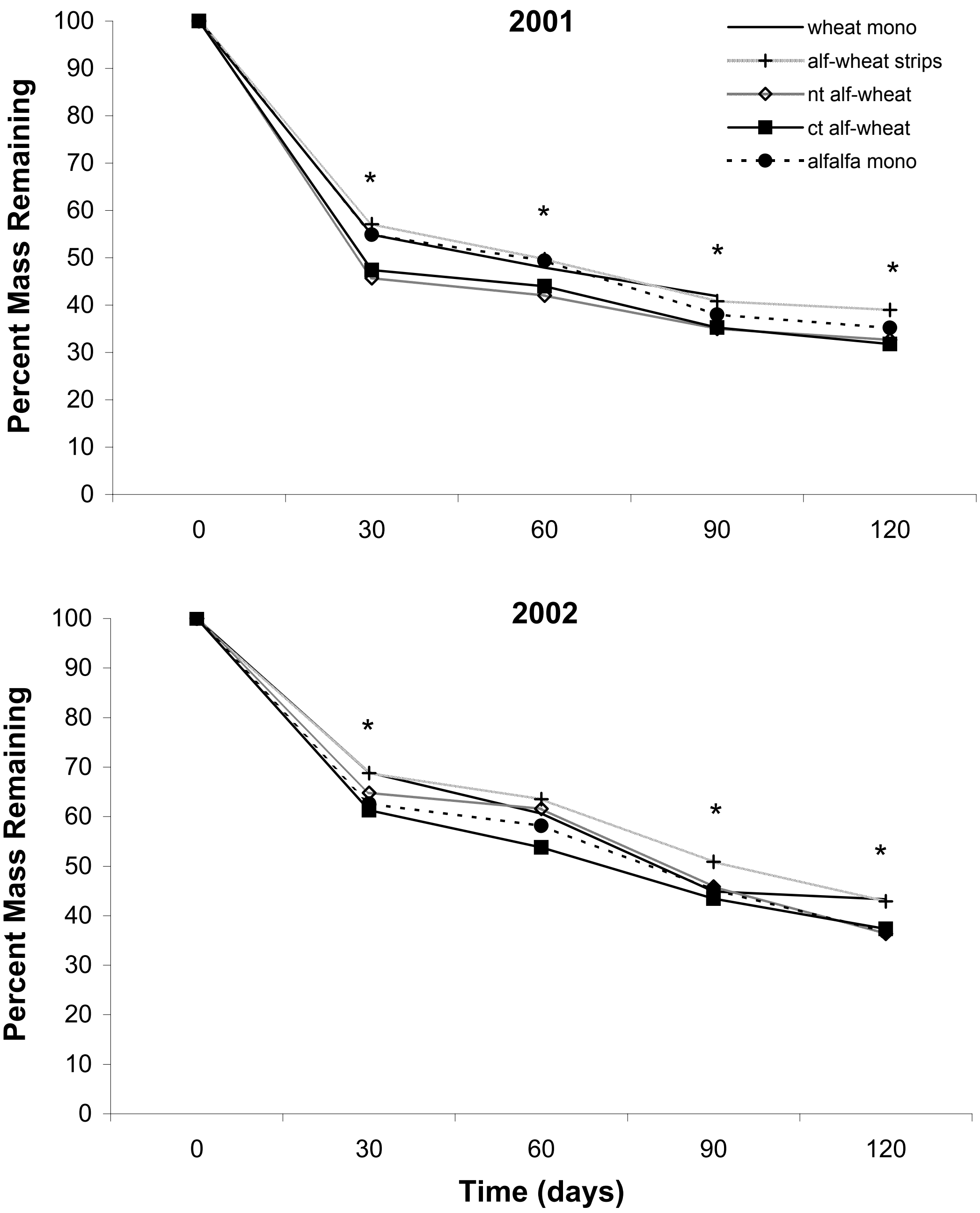

Mean C:N Ratios
80
70
60
50
40
30
20
10
0
a
a
b
c
d
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
alfalfa mono
Treatment

Figure 10. Percent mass remaining in alfalfa litter bags over time. * indicates significant differences ($P \leq 0.05$) for a particular date.


2001
2002
Percent Mass Remaining
Time (days)
wheat mono
alf-wheat strips
nt alf-wheat
ct alf-wheat
alfalfa mono
0
10
20
30
40
50
60
70
80
90
100
0
30
60
90
120
*

tillage row intercrop treatments had significantly less mass remaining than all other treatments ($F_{4,25}$=5.77, P<0.01). After 60 days, litter in the no-till alfalfa-wheat intercrop treatment was decomposing significantly faster than all other treatments excluding the conservation-till row intercrop ($F_{4,25}$=3.59, P<0.05). After 90 days, litter in the no-till and conservation-till alfalfa-wheat intercrops was again decomposing significantly quicker than litter in other treatments ($F_{4,22}$=3.55, P<0.05). After 120 days, the conservation-till alfalfa-wheat intercrop had the least biomass remaining, followed by the no-till alfalfa-wheat intercrop. These two intercrop treatments, along with the alfalfa monoculture (also a no-till treatment), exhibited significantly faster rates of decomposition than the alfalfa-wheat strip-crop treatment ($F_{3,18}$=7.63, P<0.01), which was subjected to tillage.

In 2002 conservation-till alfalfa-wheat intercrop and alfalfa monoculture treatments exhibited significantly faster rates of decomposition than strip-cropped alfalfa-wheat and wheat monoculture treatments after 30 days ($F_{4,25}$=5.05, P<0.01). After 60 days, less litter remained in conservation-till alfalfa-wheat than in wheat monoculture, no-till alfalfa-wheat, and strip-cropped alfalfa-wheat treatments, although these differences were not quite significant at a probability level of 0.05 ($F_{4,25}$=2.64, 0.05<P<0.10). After 90 days, decomposition in strip-cropped alfalfa-wheat was significantly slower than decomposition in all other treatments ($F_{4,25}$=4.67, P<0.01). After 120 days, all reduced-tillage treatments (no-till alfalfa-wheat, alfalfa monoculture, and conservation-till alfalfa-wheat) had significantly less litter remaining than did wheat monoculture and alfalfa-wheat strip-crop treatments ($F_{4,20}$=17.71, $P<0.001$), signifying quicker rates of decomposition for reduced-tillage soils.

Daily rates of decomposition were calculated by regressing the natural logarithm of mean mass remaining against time. Table 4a shows calculated *k*'s for 2001; Table 4b includes *k*'s from 2002. For 2001, *k* rates were calculated two ways, once with the final 120-day weights included and once without. Because litter bags from the wheat monoculture treatment weighed heavy on the final date, ANOVAs were run on *k*-values for both 0-90 day data (all treatments included) and 0-120 data (with wheat monoculture data excluded). Results of analyses run both ways reveal no significant differences among daily rates of decay among treatments. The same trend was observed for 2002 data. Although daily decay constants are not statistically different, daily decay rates for both years were slightly smaller for tilled treatments, possibly indicating lower functioning of natural (i.e., biotic) decomposition processes.

Arthropods. Statistical results of arthropod data from pan and pitfall traps are shown in Table 5. Data from sweep samples are presented in Table 6. Results presented are for square-root transformed arthropod data.

Leafhoppers *Ceratagallia agricola* Hamilton, *Ceratagallia uhleri* Van Duzee, and *Paraphlepsius irroratus* (Say) were common both years. Leafhoppers in pan traps (Figure 11a) were significantly more abundant in the alfalfa monoculture in 2001 ($F_{4,8}$=5.85, $P<0.05$) and 2002 ($F_{4,8}$=18.97, $P<0.001$). Numbers were also fairly high in no-till alfalfa-wheat intercrops in 2001 and 2002 and in the conservation-till alfalfa-wheat intercrops during 2002. Leafhopper

Table 4a. Decomposition rates (k) presented using 0-90 day and 0-120 day litter bag data, 2001. No data were available for 120-day wheat monocultures during the 2001 growing season. Means followed by different letters indicate significant differences among treatments (Fisher's PLSD, P ≤ 0.05).

Treatment	90-day k	120-day k
Wheat monoculture	0.0092 (a)	-------
Alfalfa-wheat strips	0.0090 (a)	0.0068 (a)
No-till alfalfa-wheat	0.0108 (a)	0.0083 (a)
Disked alfalfa-wheat	0.0107 (a)	0.0090 (a)
Alfalfa monoculture	0.0099 (a)	0.0081 (a)

Table 4b. Decomposition rates (k) presented using 0-120 day litter bag data, 2002. Means followed by different letters indicate significant differences among treatments (Fisher's PLSD, P ≤ 0.05).

Treatment	120-day k
Wheat monoculture	0.0073 (a)
Alfalfa-wheat strips	0.0071 (a)
No-till alfalfa-wheat	0.0079 (a)
Disked alfalfa-wheat	0.0077 (a)
Alfalfa monoculture	0.0077 (a)

Table 5. Arthropod data (square-root transformed) from pan and pitfall samples for 2001 and 2002. Data presented are seasonal means for each arthropod group. “n/a” indicates that no statistical analyses were performed due to extremely low abundances.

Arthropod Group	Sampling Regime	Repeated Measures (F, P)	2001 (F, P)	2002 (F, P)
Cicadellidae	pan	2.06 * (16.82, < 0.01)	2.04 * (5.85, 0.02)	2.07 * (18.97, < 0.01)
	pitfall	1.72 * (4.26, 0.04)	1.93 * (4.05, 0.04)	1.51 (3.30, 0.07)
Aphididae	pan	1.55 (3.53, 0.06)	1.56 (3.69, 0.05)	1.54 * (5.05, 0.03)
	pitfall	1.90 * (7.91, 0.01)	2.09 * (6.28, 0.01)	1.71 (0.90, 0.51)
Acrididae	pan	0.88 (2.45, 0.13)	n/a	0.88 (2.45, 0.13)
	pitfall	1.78 (2.91, 0.09)	n/a	1.78 (2.91, 0.09)
Coccinellidae	pan	0.97 * (6.03, 0.02)	0.98 (3.03, 0.09)	0.97 (1.13, 0.41)
	pitfall	0.84 (1.99, 0.19)	0.90 (1.39, 0.32)	0.77 (0.17, 0.95)
Lycosidae	pan	0.83 (1.33, 0.34)	0.83 (0.52, 0.72)	0.83 (2.08, 0.18)
	pitfall	1.50 (1.68, 0.25)	1.71 (0.54, 0.71)	1.30 (0.45, 0.77)
Total Araneae	pan	1.37 (2.39, 0.14)	1.19 (0.73, 0.60)	1.55 * (5.45, 0.02)
	pitfall	1.99 (2.08, 0.18)	2.27 (0.60, 0.68)	1.72 (0.60, 0.67)

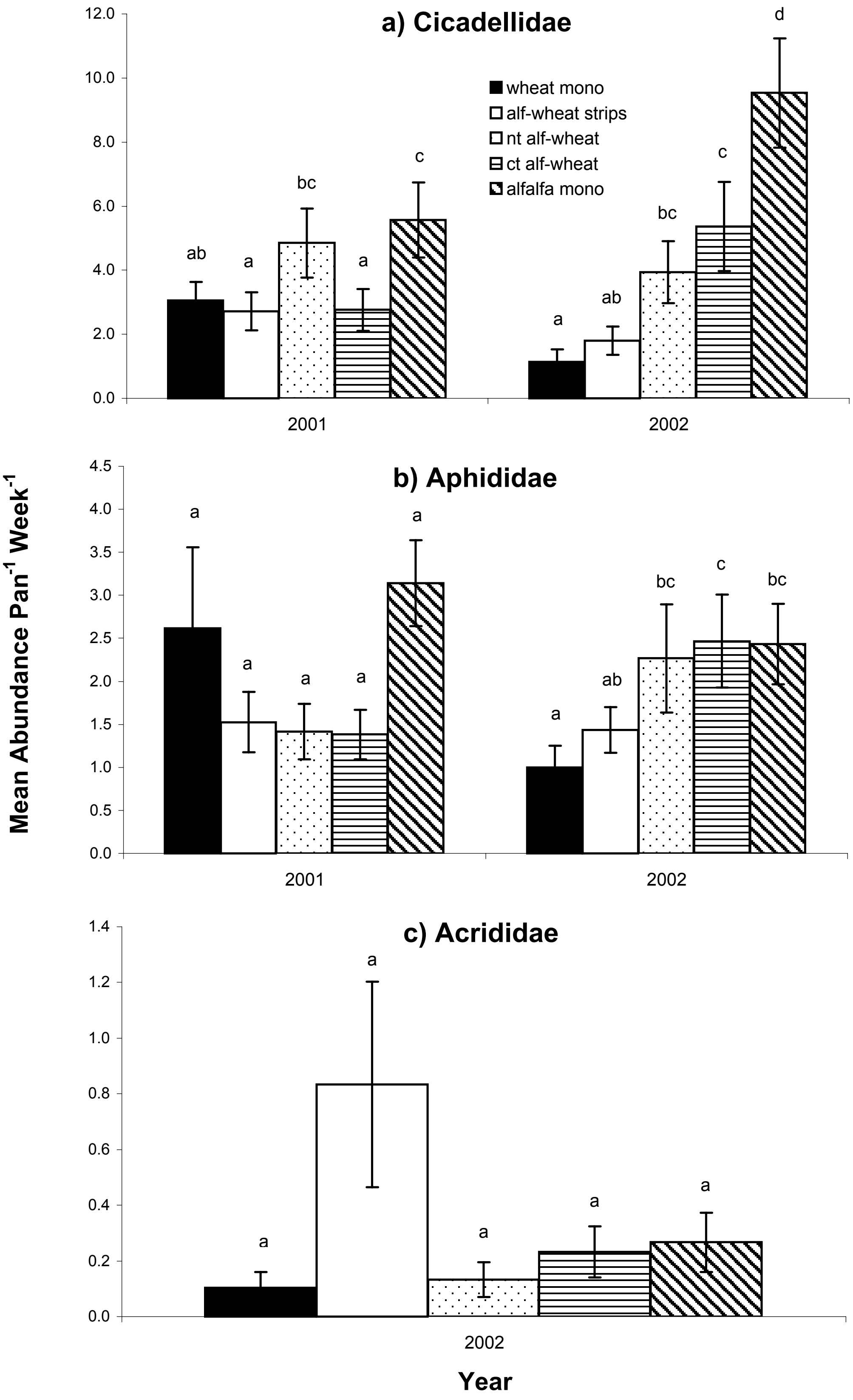
* indicates that treatments have significantly different abundances (Fisher’s PLSD, $P \leq 0.05$).

Table 6. Arthropod data (square-root transformed) collected with a sweep net. Data presented are seasonal means for a particular sampling date. “n/a” indicates that no analysis was performed due to extremely low abundances.

Arthropod Group	25 May 2002 (F, P)	13 June 2002 (F, P)	18 July 2002 (F, P)
Cicadellidae	4.43	4.50 *	3.67
	(1.85, 0.19)	(7.36, < 0.01)	(0.84, 0.55)
Aphididae	13.18 *	1.68 *	7.63 *
	(6.75, 0.01)	(3.94, 0.03)	(11.65, < 0.01)
Acrididae	2.34	2.08	3.39
	(2.05, 0.16)	(1.04, 0.45)	(1.87, 0.19)
Hypera postica	2.87 *	n/a	n/a
	(11.82, < 0.01)		
Coccinellidae	2.54	1.00	n/a
	(0.60, 0.70)	(0.38, 0.85)	
Thomisidae	4.00	2.39 *	1.67
	(1.87, 0.19)	(7.91, < 0.01)	(1.10, 0.42)
Total Araneae	4.50	2.90 *	3.14
	(2.73, 0.08)	(4.53, 0.02)	(2.50, 0.10)

* indicates significant differences in abundance among treatments (Fisher’s PLSD, $P \leq 0.05$).

Figure 11. Means (x ± 1 SE) for herbivorous arthropod groups, leafhoppers (a), aphids (b), and grasshoppers (c), collected in pan traps. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). Note that scale of y-axes differs. *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.


a) Cicadellidae
12.0
10.0
8.0
6.0
4.0
2.0
0.0
■ wheat mono
☐ alf-wheat strips
☐ nt alf-wheat
☐ ct alf-wheat
▧ alfalfa mono
ab
a
bc
a
c
a
ab
bc
c
d
2001
2002
b) Aphididae
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a
a
a
a
a
a
ab
bc
c
bc
2001
2002
c) Acrididae
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
a
a
a
a
a
2002
Mean Abundance Pan-1 Week-1
Year

catches in pitfall traps were much lower than the pan traps (Figure 12a). Leafhoppers in pitfall samples were again most numerous in no-till alfalfa-wheat intercrop, alfalfa monoculture, and conservation-till alfalfa-wheat intercrop treatments for 2001. The only significant differences from sweep net catches were found in June 2002 (Figure 13a) when the no-till alfalfa-wheat intercrop had more leafhoppers than did any other treatment ($F_{5,10}$=7.36, P<0.01).

Aphids were most abundant in the same treatments as were leafhoppers. The most common aphid species during 2001 was the spotted alfalfa aphid, *Therioaphis trifolii* forma *maculata* (Buckton). This species recurred in 2002, but pea aphids, *Acyrthosiphon pisum* (Harris), were also in fairly large numbers. Both *T. trifolii* and *A. pisum* feed on alfalfa phloem (Blackman and Eastop 2000); *T. trifolii* tends to feed near the roots, whereas *A. pisum* feeds on shoots and leaves. Other aphids occurring less frequently, such as *Acyrthosiphon kondoi* Shinj. and *Sitobion avenae* (Fabricius), were also included in analyses. The 2002 canopy catches (Figure 11b) were greater for no-till alfalfa-wheat intercrop, conservation-till alfalfa-intercrop, and alfalfa monoculture treatments than other treatments ($F_{4,8}$=5.05, P<0.05). Pitfall aphid catches were higher than were pan traps. No-till alfalfa-wheat intercrops had larger aphid numbers than did all other treatments (Figure 12b) excluding alfalfa monocultures ($F_{4,8}$=6.28, P<0.05). Aphids caught by sweep net (Figure 13b) were most abundant for May 2002 in alfalfa monocultures and alfalfa strips in alfalfa-wheat strip-crops ($F_{5,10}$=6.75, P<0.01). Numbers were much lower for June sweeps but revealed that aphids were significantly more abundant in alfalfa monoculture than in wheat

Figure 12. Means (x ± 1 SE) for herbivorous arthropod groups, leafhoppers (a), aphids (b), and grasshoppers (c), collected in pitfall traps. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.

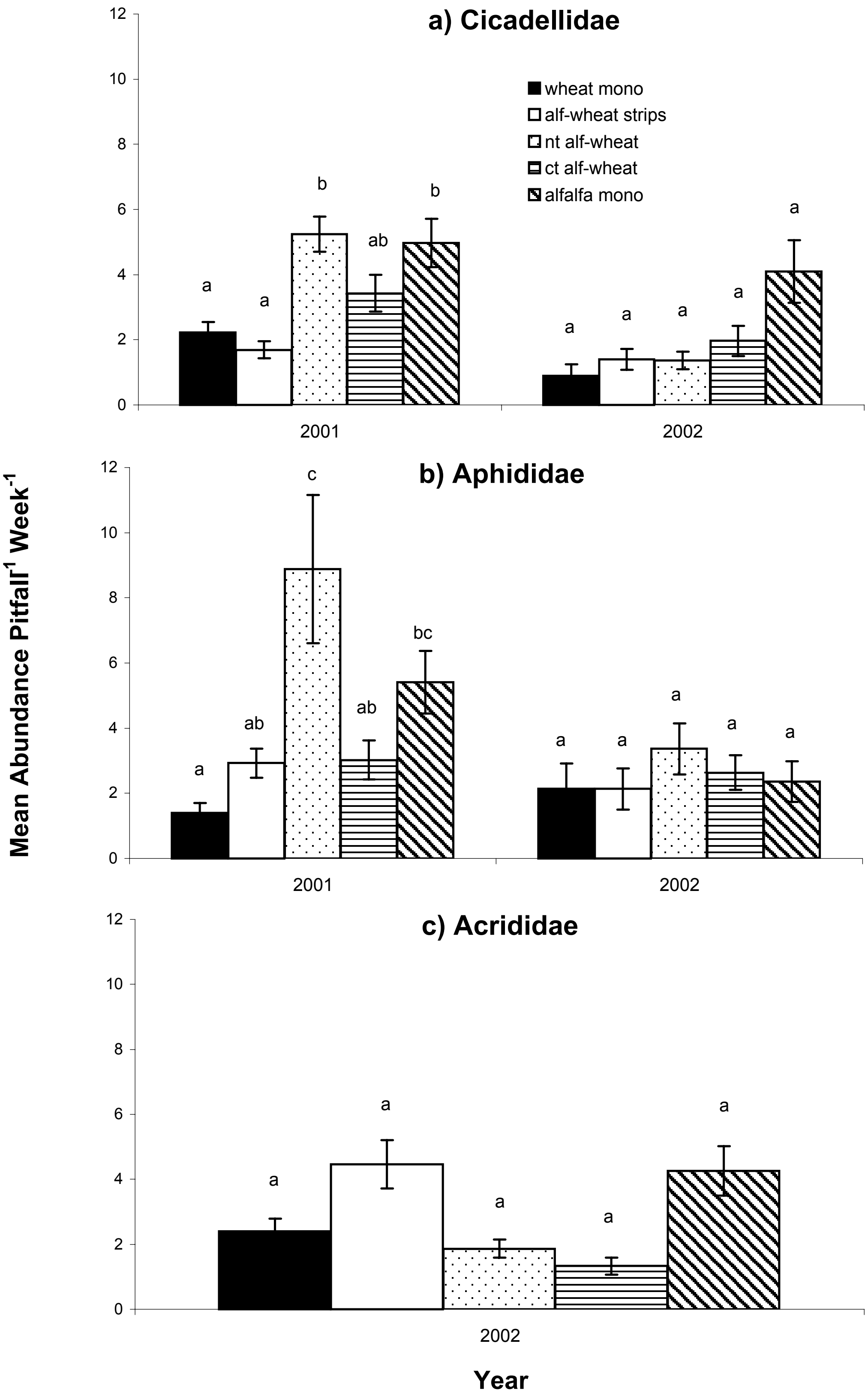
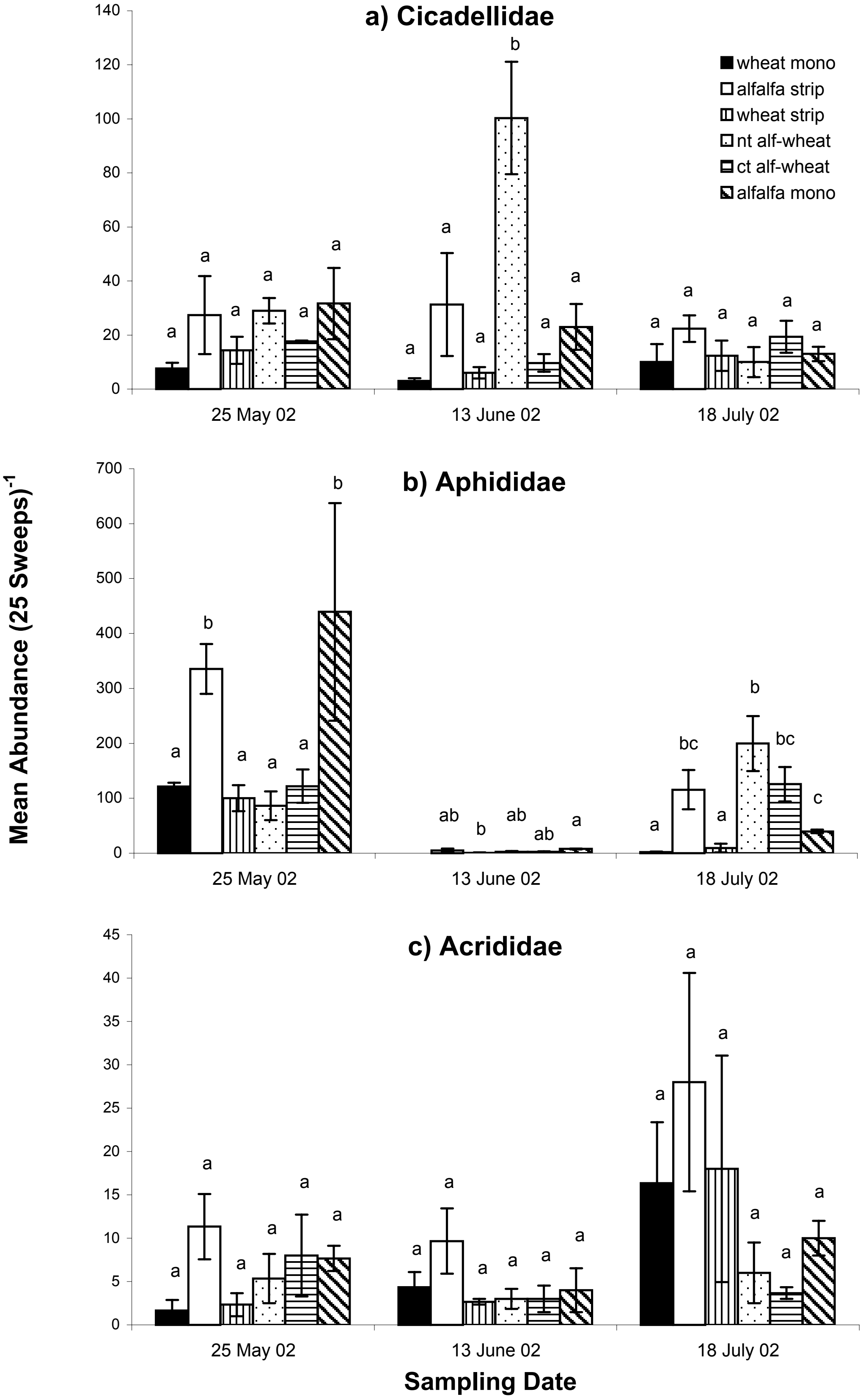

a) Cicadellidae
■ wheat mono
☐ alf-wheat strips
☐ nt alf-wheat
▤ ct alf-wheat
▧ alfalfa mono
a
a
b
ab
b
a
a
a
a
a
2001
2002
b) Aphididae
a
ab
c
ab
bc
a
a
a
a
a
2001
2002
c) Acrididae
a
a
a
a
a
2002
0
2
4
6
8
10
12
Mean Abundance Pitfall^{-1} Week^{-1}
Year

Figure 13. Means (x ± 1 SE) for herbivorous arthropod groups, leafhoppers (a), aphids (b), and grasshoppers (c), collected in sweep nets. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). Note that scale of y-axes differs. *Wheat mono* = wheat monoculture; *alfalfa strip* = alfalfa strip in alfalfa-wheat strip-crop; *wheat strip* = wheat strip in alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; *alfalfa mono* = alfalfa monoculture. No aphids were collected in wheat monoculture on 13 June.


a) Cicadellidae
b) Aphididae
c) Acrididae
wheat mono
alfalfa strip
wheat strip
nt alf-wheat
ct alf-wheat
alfalfa mono
Mean Abundance (25 Sweeps)$^{-1}$
Sampling Date
25 May 02
13 June 02
18 July 02
0
20
40
60
80
100
120
140
100
200
300
400
500
600
700
5
10
15
20
25
30
35
40
45
a
b
ab
bc
c

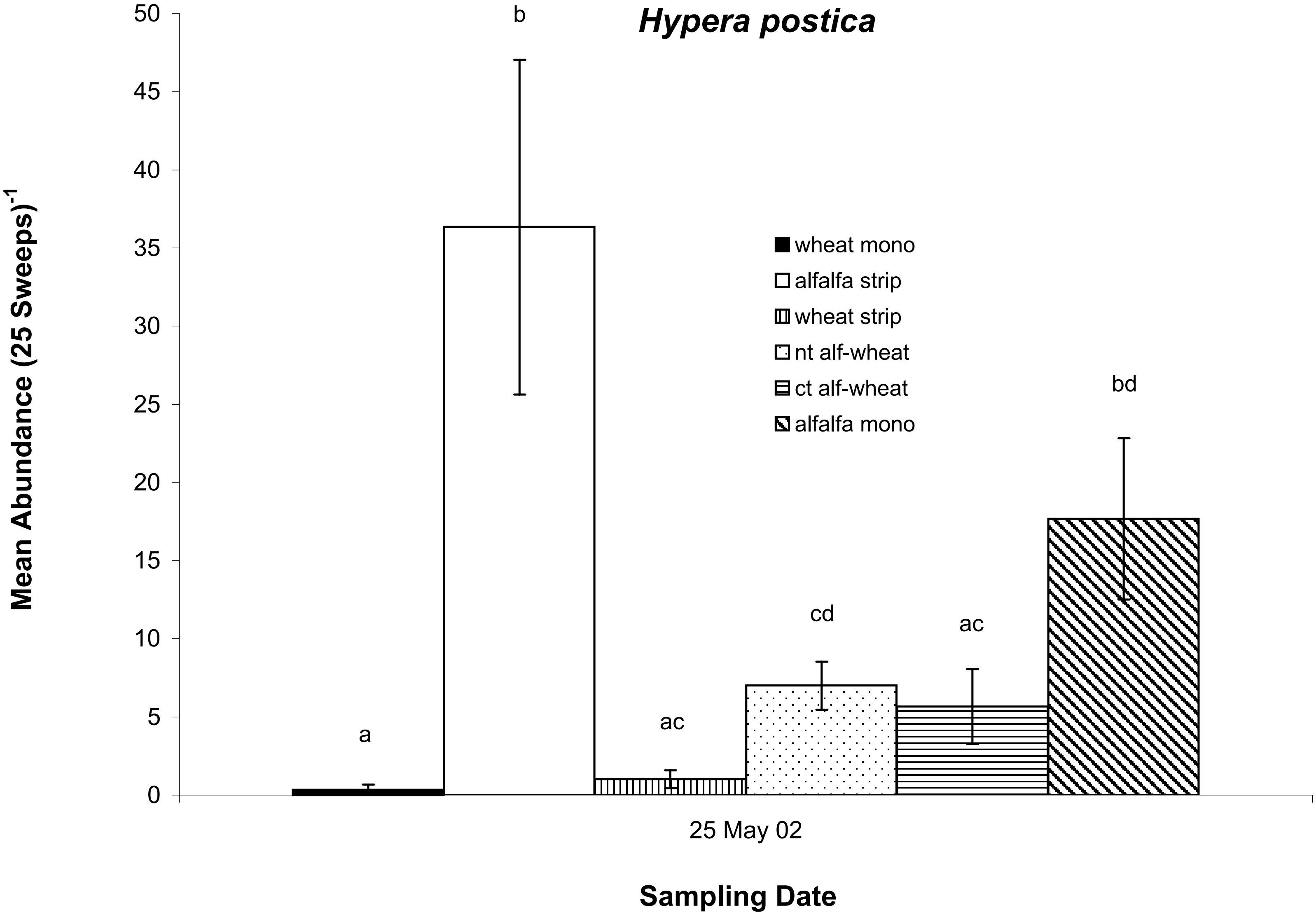
monoculture ($F_{5,10}$=3.94, $P<0.05$). Catches from July sweeps revealed similar trends; numbers were greatest in no-till wheat-alfalfa intercrops, alfalfa strips, and conservation-till alfalfa-wheat intercrops ($F_{5,10}$=11.65, $P<0.001$).

Grasshoppers were only examined during the second growing season, when their large numbers indicated that they were a potential pest problem. The most common grasshopper species found was *Melanoplus sanguinipes* (Fabricius). No significant differences in grasshopper abundance were observed among treatments for any of the three sampling regimes, although numbers tended to be slightly higher in alfalfa monoculture and in alfalfa strips in the alfalfa-wheat strip-crop.

The final herbivorous species included in this study is the alfalfa weevil (*Hypera postica* Gyllenhal), analyzed solely from the 25 May 2002 sweep samples (Figure 14). Alfalfa strips in the alfalfa-wheat strip-crop had higher densities than all other treatments with the exception of alfalfa monoculture, which also had a mean abundance similar to the no-till alfalfa-wheat intercrop ($F_{5,10}$=11.82, $P<0.001$).

Ladybird beetles are a common aphid predator and are therefore of interest for their potential to exert population control on aphids. The most common Coccinellid species found was *Coccinella septempunctata* L. Because numbers caught were very low (see Figures 15a, 16a, 17a), differences in most cases were not significant. However, it should be noted that repeated measures analysis for pan traps indicated that alfalfa-wheat strip-crop and conservation-till

Figure 14. Means (x ± 1 SE) for alfalfa weevils (*Hypera postica* Gyllenhal) collected in sweep nets. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alfalfa strip* = alfalfa strip in alfalfa-wheat strip-crop; *wheat strip* = wheat strip in alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.



Hypera postica
Mean Abundance (25 Sweeps)-1
0
5
10
15
20
25
30
35
40
45
50
a
b
ac
cd
ac
bd
wheat mono
alfalfa strip
wheat strip
nt alf-wheat
ct alf-wheat
alfalfa mono
25 May 02
Sampling Date

Figure 15. Means (x ± 1 SE) for predatory arthropod groups, ladybird beetles (a), wolf spiders (b), and total spiders (c), collected in pan traps. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.

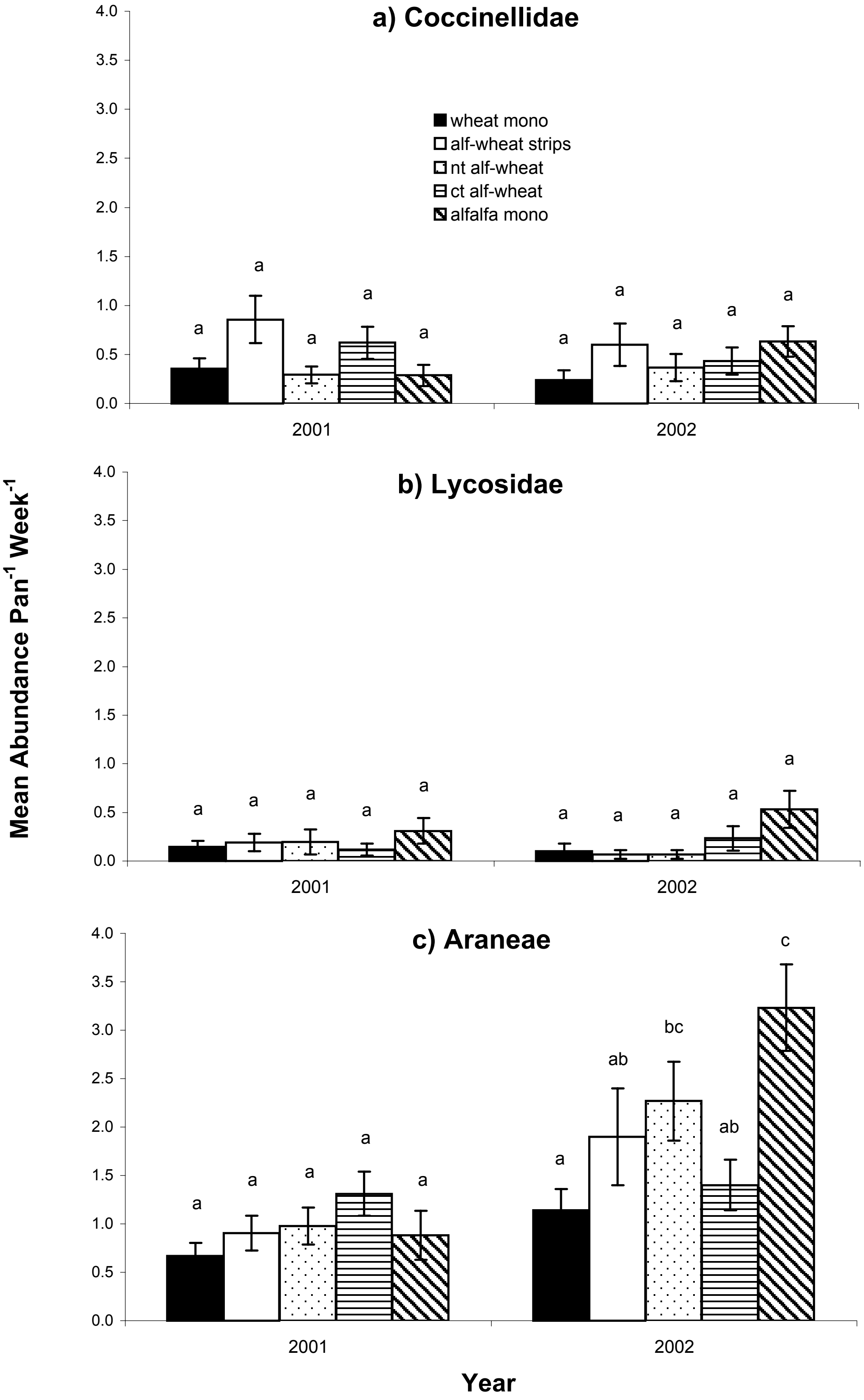

a) Coccinellidae
■ wheat mono
☐ alf-wheat strips
☐ nt alf-wheat
☐ ct alf-wheat
▨ alfalfa mono
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a
a
a
a
a
a
a
a
a
a
2001
2002
b) Lycosidae
a
a
a
a
a
a
a
a
a
a
2001
2002
c) Araneae
a
a
a
a
a
a
ab
bc
ab
c
2001
2002
Mean Abundance Pan^{-1} Week^{-1}
Year

Figure 16. Means (x ± 1 SE) for predatory arthropod groups, ladybird beetles (a), wolf spiders (b), and total spiders (c), collected in pitfall traps. No significant differences were detected ($p \leq 0.05$). Note that scale of y-axes differs. *Wheat mono* = wheat monoculture; *alf-wheat strips* = alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture.

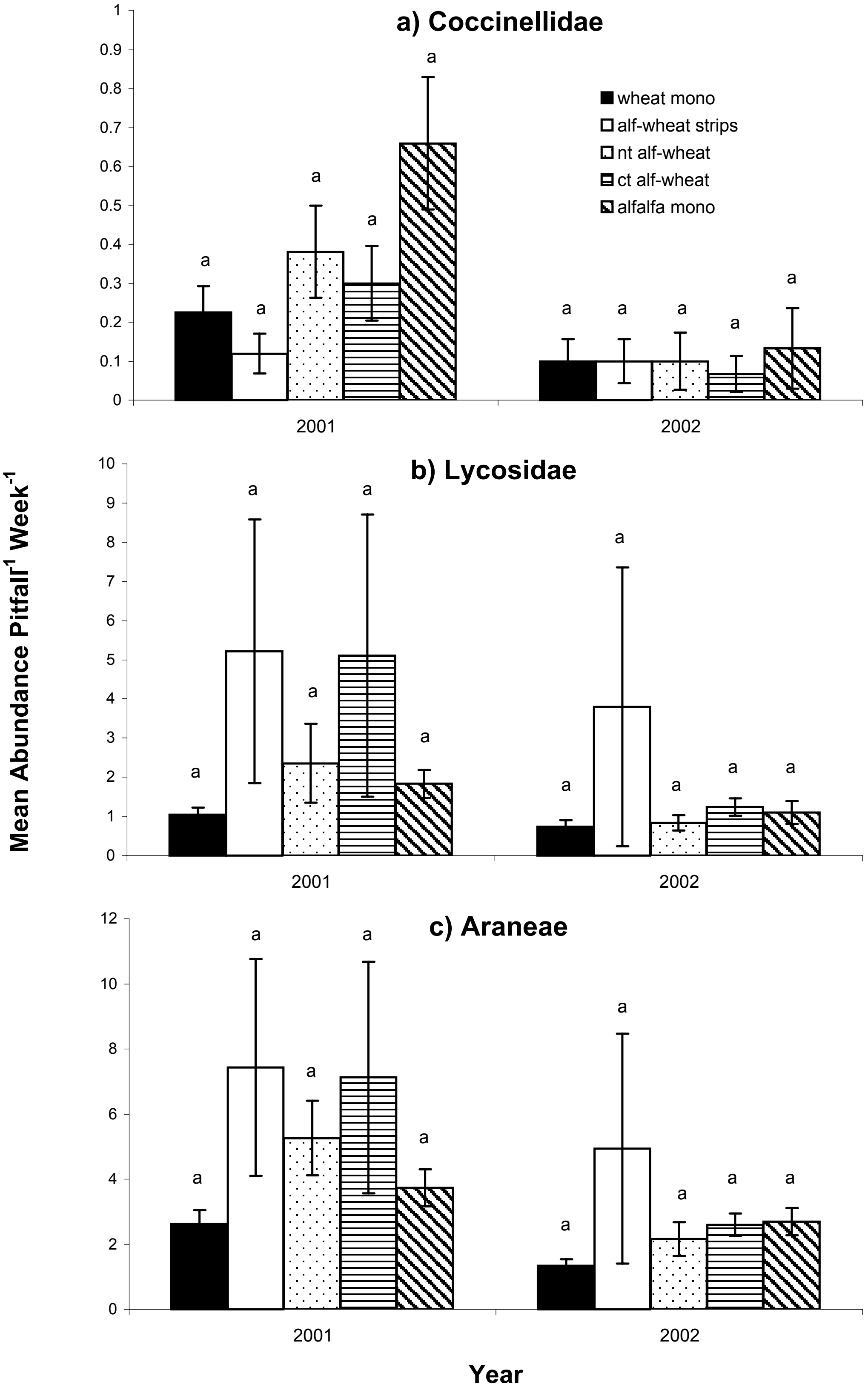
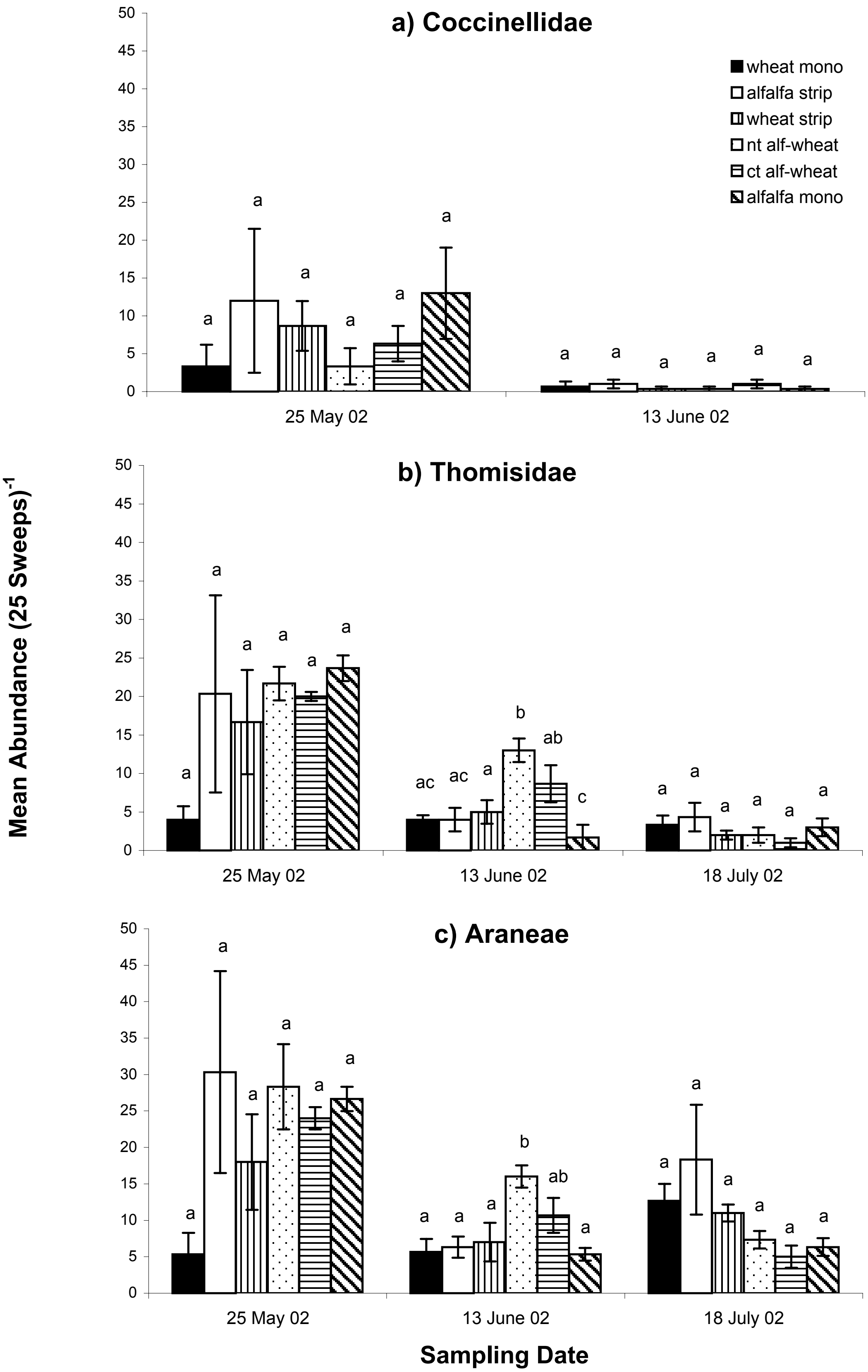

a) Coccinellidae
b) Lycosidae
c) Araneae
Mean Abundance Pitfall-1 Week-1
Year
2001
2002
■ wheat mono
☐ alf-wheat strips
☐ nt alf-wheat
☐ ct alf-wheat
▨ alfalfa mono
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
a

Figure 17. Means (x ± 1 SE) for predatory arthropod groups, ladybird beetles (a), crab spiders (b), and total spiders (c), collected in sweep nets. Different letters above means indicate that treatment means are significantly different ($P \leq 0.05$). *Wheat mono* = wheat monoculture; *alfalfa strip* = alfalfa strip in alfalfa-wheat strip-crop; *wheat strip* = wheat strip in alfalfa-wheat strip-crop; *nt alf-wheat* = no-till alfalfa-wheat intercrop; *ct alf-wheat* = conservation-till alfalfa-wheat intercrop; and *alfalfa mono* = alfalfa monoculture. Coccinellid means were not reported for 18 July due to low numbers.


a) Coccinellidae
b) Thomisidae
c) Araneae
Mean Abundance (25 Sweeps)$^{-1}$
Sampling Date
0
5
10
15
20
25
30
35
40
45
50
■ wheat mono
□ alfalfa strip
▥ wheat strip
□ nt alf-wheat
▤ ct alf-wheat
▧ alfalfa mono
25 May 02
13 June 02
18 July 02
a
ab
ac
b
c

intercrop treatments tended to have greater abundances of ladybug ($F_{4,8}$=6.03, P<0.05).

Wolf spiders (Lycosidae) were quantified for pan and pitfall samples, and crab spiders (Thomisidae) were quantified for sweep samples. Total spider abundance was also calculated for all sampling regimes. Wolf spider abundances were not significantly different for either pan or pitfall traps (Figures 15b, 16b). Significantly different numbers of crab spiders (Figure 17b) were only observed on 13 June 2002, when Thomisidae were most abundant in the no-till and conservation-till alfalfa-wheat intercrop treatments and significantly lower in alfalfa monoculture ($F_{5,10}$=7.91, P<0.01). Because all spiders are predators, calculating total abundance is important for estimating their relative contribution to trophic agroecosystem stability. Pan catches were significantly different among treatments in 2002 (Figure 15c), when total spider numbers were highest in alfalfa monoculture and no-till alfalfa-wheat intercrop treatments ($F_{4,8}$=5.45, P<0.05). Differences were also significant for 13 June 2002 sweep samples (Figure 17c), when no-till and conservation-till intercrop treatments had higher spider densities than all other treatments ($F_{5,10}$=4.53, P<0.05).

Discussion

This experiment was designed to represent an important intermediate step between conventional and alternative agricultural practices. Alternatives to modern agricultural practices are needed if farmers and resource managers are to decrease soil, water, and nutrient losses while minimizing environmental contamination by agricultural chemicals. Three alternative designs were studied, with varying levels of tillage and spatial association of two crop plants, alfalfa (*Medicago sativa*) and winter wheat (*Triticum aestivum*).

This study was also intended to better understand how cultural management practices affect ecosystem functioning in these agroecosystems. In the following discussion, ecosystem benefits and energetic (subsidy) costs will be examined. Groffman et al. (1986) suggested that low-input systems may be more productive than expected. This study attempts to quantify factors that compare crop productivity, systems sustainability, and ecosystem health among treatments to assess potential costs and benefits of alternative agricultural practices.

Aboveground biomass and intercrop advantage. Because crop productivity is the main goal of production agriculture (Zimdahl 2002), one of the factors receiving considerable attention is harvestable biomass. Total biomass harvested was similarly high for wheat monoculture, alfalfa monoculture, and conservation-till alfalfa-wheat intercrop treatments. This suggests that primary productivity of the conservation-till alfalfa-wheat intercrop rivals that of wheat and alfalfa monocultures. Both wheat monoculture and conservation-till alfalfa-wheat intercrop treatments had low weed mass. Full tillage in wheat monocultures disturbed the seed bed, resulting in low weed mass. This low competition from weeds probably contributed to the high seed yield. Low weed mass from the conservation-till alfalfa-wheat intercrop corresponds to experimental results from Carr et al. (1995). According to their study a wheat-lentil intercrop canopy intercepted much of the photosynthetically active radiation that would otherwise reach soil and weeds rather than crop plants.

Weeds were a higher proportion of harvested biomass in the alfalfa monoculture, perhaps because this treatment received no tillage. Groffman et al. (1986) found that growth and competitive ability of weeds were increased by fertilization; therefore, the excess N contributed by alfalfa in the alfalfa monoculture treatment may also have encouraged weed growth.

Total crop biomass was also fairly high for the alfalfa-wheat strip crop. Both alfalfa-wheat strip-crop and conservation-till alfalfa-wheat intercrop treatments exhibited intercrop yield advantage, as evidenced by high LER values. Thus, productivity per unit area in these two treatments is similar to that of monoculture treatments. High alfalfa and wheat yields for the alfalfa-wheat strip-crop treatment may be due to edge effects of dissimilar crop species (Putnam and Allan 1992). For example, water-conservation benefits of intercropping and reduced tillage (in the conservation-till alfalfa-wheat intercrop) may have contributed to the higher land use efficiency of these two intercrop treatments compared to monocultures.

Putnam and Allan (1992) suggested that border rows in a sunflower-mustard strip-crop benefited from excess N and water; mustard and sunflower had low interspecific competition due to temporal differentiation of resource requirements. Lesoing and Francis (1999) similarly found that nitrogen from soybean fixation conferred a positive edge effect on corn yields in a corn-soybean strip-crop. In the study at hand, nitrogen fixation by alfalfa in intercrops may have led to increased yields of neighboring wheat.

Total aboveground biomass in the no-till alfalfa-wheat intercrop was significantly low. Very little wheat grain was harvested from this treatment in 2002. Therefore, LER values were low, suggesting that no yield advantage (as measured by land use efficiency) exists for this system. This result contradicts findings of others who have reported higher yields for no-till than for conventionally-tilled systems (Wheatley et al. 1995, Horn et al. 1996). However, weeds were suppressed with herbicides in those studies, and interaction effects of intercropping and tillage were not considered. By 2002, alfalfa in no-till plots appeared dominant, suppressing growth of emerging wheat. Because the alfalfa was never tilled, it towered over wheat plants that therefore received reduced sunlight. Putnam and Allan (1992) reported that shading in a sunflower-mustard intercrop led to increased interspecific competition. Their results concur with ours: strip-cropping produced higher yields than did treatments in which alfalfa had a closer association with wheat plants (Putnam and Allan 1992).

An additional finding that should be highlighted is that intercropping appeared to confer an advantage to alfalfa growth during drought conditions. In 2002, alfalfa yields in no-till and conservation-till alfalfa-wheat intercrop treatments were actually higher than alfalfa yields for these treatments in 2001. Wheat production was reduced in these treatments, as it was for all treatments, in 2002. However, alfalfa production was reduced only for alfalfa monocultures and alfalfa strips within the alfalfa-wheat strip-crops. Because alfalfa’s long taproot can compete vigorously for water during a drought, perhaps decreased competition for water in intercrops led to higher forage yields (Haynes 1980).

Ecosystem nitrogen. Manufacture of nitrogen fertilizer uses more energy than all other parts of production agriculture (Keeney 1982), and much applied N is leached out of the system (Groffman et al. 1986). To create sustainable systems, natural and efficient means of fertilization, such as nutrient recycling and retention, must be used. Neely et al. (1987) found that legumes provide ample nitrogen for certain grain crops. Brophy et al. (1987) studied nitrogen transfer from legumes to grasses and found that maximum nitrogen transfer occurred where legume/grass ratios were high. Also, legumes nearest grasses fixed more nitrogen than legumes not surrounded by grass. Alfalfa-wheat intercrops have the potential for not only reduced interspecific competition via complementary resource use, but also facilitation of non-legume growth by the legume's contribution of nitrogen (Haynes 1980).

Percent soil N values were fairly high for a Mollisol (Brady and Weil 1999), probably due to four years of consecutive alfalfa growth. Over both growing seasons (2001 and 2002), soil nitrogen was lowest in wheat strips within the alfalfa-wheat strip-crop. Nitrogen tended to increase in treatments containing high percentages of alfalfa. No-till alfalfa-wheat intercrop and alfalfa monoculture treatments had high percent nitrogen both years, and N was also high in the conservation-till alfalfa-wheat intercrop and alfalfa strips within alfalfa-wheat strip-crops in 2002. The low soil N in wheat strips within alfalfa-wheat strip-crops indicates that alfalfa strips do not contribute significant N to wheat strips. Brophy et al. (1987) determined that the maximum distance of N transfer from legumes to grasses was only 20 cm. Strips in the alfalfa-wheat strip-crop were over 3.6 m wide so that beneficial edge effects were probably not realized for most of the wheat plants. Moderate soil disturbance (in the conservation-till alfalfa-wheat intercrop treatment) did not appear to negatively affect N fixation of alfalfa.

Soil N appeared to have little influence on wheat grain quality. Grain quality, as expressed by nitrogen concentration in wheat grain, was high for wheat monoculture, alfalfa-wheat strip-crop, and no-till alfalfa-wheat intercrop treatments. Perhaps high grain N in wheat monoculture and alfalfa-wheat strip-crop treatments is related to low competition with weeds and alfalfa. According to the Kansas Wheat Commission and the Kansas Department of Agriculture, typical Kansas winter wheat contains approximately 12% protein (KASS 2001). Protein content from wheat monoculture, alfalfa-wheat strip-crop, and no-till alfalfa-wheat intercrop treatments exceeded the Kansas average in both 2001 and 2002. High grain quality in the no-till alfalfa-wheat intercrop may offset economic losses from low grain yields. It is not uncommon for grain yield and protein values to be inversely related (Ladd et al. 1981, Olson and Kurtz 1982).

Grain quality was significantly lowest for the conservation-till alfalfa-wheat intercrop, revealing no advantage of intercropping conferred upon wheat quality. Hoflich et al. (1999), on the other hand, found that conservation tillage increases legume nodulation, contributing N to the system. However, excess soil N from association with a legume may not necessarily contribute to higher grain N or higher yields (Fillery 2001) because associated wheat generally takes up only a small percentage of N from legume residues (Ladd et al. 1981). Our findings confirm this observation.

Hay quality was influenced by wheat content in all treatments. For example, hay quality was low for wheat monocultures and wheat strips in alfalfa-wheat strip-crops because wheat straw was the sole component of the hay. Although such low-quality hay cannot be used for forage, straw is often used for livestock bedding and roadside erosion control. According to the Idaho National Engineering and Environmental Laboratory, in cooperation with the U. S. Department of Energy, there is evidence that this straw could also be used as biofuel (Anonymous 2002).

Hay quality for the alfalfa monoculture treatment was predictably high because hay harvested did not contain nutrient-deficient wheat straw. The C:N ratios were correspondingly low, which may increase the rate of nutrient cycling in this treatment because residues with low C:N ratios decompose quickly (Brady and Weil 1999). Hay quality was also high for the no-till alfalfa-wheat intercrop due to the high alfalfa content of this treatment. The lack of tillage led to higher alfalfa concentrations in no-till alfalfa-wheat intercrops than in conservation-till alfalfa-wheat intercrops. Conservation-till intercrop hay quality was moderate, corresponding to the moderate percentage of alfalfa present in the combined alfalfa-wheat hay.

Decomposition. Examining surface rates of decomposition allowed us to look at the abilities of each system to decompose residues without using mechanical means to bury residues and unnaturally speed decomposition.

Tillage had a notable effect on surface rates of decomposition of alfalfa residues. Decomposition was slow in wheat monoculture and alfalfa-wheat strip-crop treatments, the two treatments that received conventional tillage. Although daily decay rates were not significantly different, examination of percent mass remaining over time revealed fairly static trends of decomposition among treatments. Slow decay of alfalfa material placed on the soil surface in wheat monoculture and alfalfa-wheat strip-crop treatments appears to be the result of soil disturbance. Beare et al. (1992) also found that surface litter decay rates for no-till agroecosystems exceed those in conventionally-tilled agroecosystems. Tillage replaces the activity of soil fauna and decomposer organisms (House and Parmelee 1985). Human maintenance of nutrient cycling via tillage confers an energetic cost to conventionally tilled agroecosystems.

Decomposition, presumably facilitated by soil microorganisms, was fairly rapid in no-till alfalfa-wheat intercrop, conservation-till alfalfa-wheat intercrop, and alfalfa monoculture treatments. Importantly, fungal hyphal networks and decomposer soil fauna, such as microinvertebrates, apparently were not destroyed by minimal soil disturbance in these reduced-tillage treatments. Hyphal length is positively correlated with decay rates (Blair et al. 1990), suggesting the importance of fungi in surface decomposition. Higher numbers of soil arthropods, earthworms, fungi, and bacteria have been reported for no-till compared to conventionally-tilled systems (Doran 1980, House and Parmelee 1985, Hendrix et al. 1986). Because the small mesh size of litter bags used in this experiment excluded macroinvertebrates, and no-till soils are dominated by fungal rather than bacterial populations (Hendrix et al. 1986), fungi were considered primarily responsible for differences in rates of decay among treatments. Although short-term nutrient release is generally slower under no-till practices because residues are not buried, nutrient cycling is more efficient long-term in no-till systems because less nutrients leach out of the system (House and Parmelee 1985). Increased nutrient cycling efficiency is a potential benefit for reduced-tillage systems.

As evidenced by similar rates of mass loss in the no-till and conservation-till treatments, conservation tillage does not appear to harm soil decomposers, allowing natural processes to decompose plant residues and return nutrients to the soil (i.e., nutrient recycling processes remain intact). Norstadt and McCalla (1969) similarly found that conservation tillage led to increased abundances of bacteria, actinomycetes, and fungi than were found in conventionally tilled systems.

Arthropod pests and predators. There exists strong support for Root's resource concentration hypothesis (e.g., Root 1973, Bach 1980), which theorizes that specialist herbivores are more likely to feed and reproduce in stands of abundant host plants (i.e., monocultures) than in mixed vegetation. Therefore, it was expected that wheat and alfalfa monocultures would experience greater pest pressure than would intercrops. Because this field site was in continuous alfalfa for four years, alfalfa-feeding insects were already present in the field. Wheat-feeding insects, however, were much less abundant. Therefore, wheat monocultures had low leafhopper and aphid abundances. Conversely, alfalfa monocultures had much higher leafhopper and aphid abundances. Total spider counts seemed to mirror those of leafhopper and aphid abundances. Therefore, spiders were scarce in wheat monocultures, whereas they were more abundant in alfalfa monocultures, where prey were also more abundant. Another factor encouraging spider retention in alfalfa monocultures may be the perennial nature of this crop (Piper 1999). Wheat monocultures were tilled and replanted each fall, potentially discouraging a stable population of predatory insects (House and All 1981). Differences in spider densities were only significant in 2002, after wheat monocultures had been tilled for two consecutive years. Ladybird beetle numbers were low for all treatments; therefore no significant differences among treatments could be discerned on any sampling date.

Strips of alternating vegetation in the alfalfa-wheat strip-crop could be considered analogous to monocultures for pests in those individual strips. Migration has been found to be hindered by strips of non-host vegetation (Kemp and Barrett 1989), but host plants within a strip are easy to find. In general leafhopper and aphid numbers were low in the strip-crop treatment. Aphid numbers, collected with a sweep net in 2002, in alfalfa strips were higher in May than later in the season. Aphid and leafhopper numbers from sweep samples were significantly lower in wheat strips over all three sampling dates in 2002. Because the 3.6 m-wide strips are analogous to wheat monocultures, these results are not surprising based on wheat monoculture findings. Alfalfa weevil (*Hypera postica* Gyllenhal) abundance was very high in alfalfa strips. Because alfalfa weevils prefer to feed on and will reproduce only on alfalfa (Byrne 1969), incorporation of non-host plants into alfalfa strips should decrease weevil population densities. Spider numbers were modest for this treatment, suggesting an absence of biological control. Kemp and Barrett (1989) found predators to be more abundant in strips of uncultivated vegetation than in strips of soybeans. Uncultivated strips of native vegetation or strips of higher crop diversity would likely facilitate better biological control than do alternating monocrop strips.

In general, arthropod population trends in no-till alfalfa-wheat intercrops were similar to those in alfalfa monocultures. The high numbers of aphids and leafhoppers were attributed to the high amount of alfalfa present (Byers et al. 1999). Due to the close alfalfa-wheat association in the no-till intercrop treatment, wheat plants were not likely to deter alfalfa specialists from finding nearby alfalfa plants. Spider abundances in 2002 were also fairly high for this treatment. Stinner et al. (1984) suggested that predatory arthropods may inhabit no-till systems due to habitat created by the surface litter. While no-till fields may encourage invertebrate pests, high faunal diversity may also foster biological control (Warburton and Klimstra 1984). Because spiders were abundant in alfalfa monocultures, experimental results do not support Root’s enemies hypothesis, which states that predators are more likely to remain in diverse habitats due to increased diversity of food and habitats rather than monocultures (Root 1973).

The conservation-till alfalfa-wheat intercrop seemed to encourage neither pests nor predators. Alfalfa content of this treatment was lower than that of the no-till intercrop treatment because mild tillage set back alfalfa growth each year.

Therefore, it is not surprising that alfalfa specialists were more abundant in alfalfa monocultures, no-till alfalfa-wheat intercrops, and alfalfa strips within alfalfa-wheat strip-crops. There were low numbers of leafhoppers in 2001 and mid-June 2002 and high numbers of aphids in 2002; thus no general statement can be made about whether this treatment encourages or deters phloem-feeding arthropods. Spider numbers were also fairly low, suggesting that biological control was not an important regulatory mechanism in intercrop treatments. However, low arthropod (both herbivorous and predaceous) numbers could also indicate trophic balance.

It is important to note that in treatments where sap-feeding herbivores were particularly abundant (i.e., alfalfa monoculture and no-till alfalfa-wheat intercrop treatments), predator numbers were correspondingly higher. Two possible reasons for low spider numbers in wheat monocultures are low prey densities (Letourneau and Altieri 1983) and high disturbance from tillage (Stinner et al. 1987). Low predator numbers in wheat monocultures are of concern. If wheat-feeding herbivores were to emigrate from a nearby field into a wheat monoculture, there would be few natural population controls available. In addition, the lack of biotic diversity would make the wheat monoculture quite susceptible to specialist herbivores. Insecticide treatment to replace biotic controls would increase costs for this system. It should be noted that parasitic arthropods were not counted in this study and could therefore be exerting unobserved population control over herbivores.

The three alternative agroecosystems discussed here add to the growing body of research on intermediate steps between conventional agriculture and vastly new and different systems of production (see Table 7 for summary). In general, the no-till intercrop system was not advantageous when compared to the other treatments, mostly due to decreased yields and increased populations of herbivorous arthropods. The alfalfa-wheat strip-crop demonstrated advantages associated with alfalfa and wheat monocultures in this study, such as respectable alfalfa and grain yields and low weed biomass. However, benefits to ecosystem N from strip-cropping alfalfa and wheat were not apparent. Clearly, the conservation-till intercrop design has many demonstrated advantages over other experimental systems. This treatment was an intermediate intercrop arrangement between the alfalfa-wheat strip-crop and no-till alfalfa-wheat intercrop treatments. Benefits of the conservation-till intercrop include overyielding, high soil N, rapid decomposition (and therefore nutrient turnover), and low abundances of herbivorous arthropods. Therefore, it appears that moderate tillage combined with a close association of dissimilar crop species can be quite productive despite low inputs.

A rough estimate of nutrient input versus nutrient export from each system gives us another estimate of agroecosystem sustainability. I calculated that at current rates of production, the wheat monoculture can produce seed for about one more year without nutrient inputs. The soil in that treatment has approximately 1890 kg N ha^{-1} to a 10 cm depth. With adequate moisture, first-year yields removed 101 kg N ha^{-1} from the system. Second-year yields

Table 7. Relative costs and benefits of ecosystem parameters analyzed in this investigation. Costs (-), benefits (+), and neutral (o) findings indicate performance of an agroecosystem treatment relative to others. *WM* = wheat monoculture; *SC* = alfalfa-wheat strip-crop; *NT* = no-till alfalfa-wheat intercrop; *CT* = conservation-till alfalfa-wheat intercrop; *AM* = alfalfa monoculture.

Parameter	WM	SC	NT	CT	AM
Total biomass	+	o	-	+	+
Wheat	+	o	-	o	n/a
Alfalfa	n/a	o	o	o	+
Weeds	+	+	o	+	-
LER	n/a	+	-	+	n/a
Soil N	-	o alfalfa / - wheat	+	+	+
Soil C:N	+	-	o	+	o
Grain N	+	+	+	o	n/a
Hay N	-	-	o	o	+
Hay C:N	-	-	o	o	+
Decomposition	-	-	+	+	+
Leafhopper	+	+	-	o	-
Aphid	+	+ (- alfalfa, sweep sample)	-	o	-
Grasshopper	o	o	o	o	o
Alfalfa weevil	n/a	- alfalfa / + wheat	o	o	-
Ladybird beetles	o	o	o	o	o
Spiders	o	o	+	o (+ sweep sample)	+
Totals	7 + / 4 -	5 + / 4 -	4 + / 5 -	6 + / 0 -	7 + / 4 -

removed 78 kg N ha^{-1}. Assuming that only 1-2 % of the total soil N is in readily available forms of nitrate and ammonium (Brady 1990), this system will probably only survive one or perhaps two (if drought occurs again) more growing seasons. The other four agroecosystems appear to be able to sponsor all or most of their own fertility. Assuming that alfalfa fixes 150-250 kg N ha^{-1} $year^{-1}$ (Brady and Weil 1999), the agroecosystems containing alfalfa have enough soil N to continue current levels of production indefinitely, although alfalfa must be replanted after several years. Therefore, the experimental agroecosystems incorporating both alfalfa and wheat should be able to sustain fairly high wheat grain production without external inputs of nitrogen fertilizer.

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CHAPTER 3

CONCLUDING THOUGHTS

Consideration of sustainable alternatives to modern agriculture must consider both immediate and long-term environmental effects. Zimdahl (2002) asserted that sustainable agricultural production was the responsibility of society, not just of producers. While a new paradigm of agroecosystem management is needed, most farmers and crop managers do not want or are unable to push boundaries past slight modifications of current production systems (Zimdahl 2002). Society must work within the current framework; otherwise producers would not have the machinery, markets, and knowledge to survive. Consideration of external costs must also be addressed as this study suggests. Each of the three experimental intercrop systems has some ecological or economic advantage over monoculture systems. It is important that we keep modifying existing and examining new cropping systems to integrate ecological processes with sustainable systems designed for food production.

A fundamental switch from conventional agriculture to a natural systems agriculture will mean changing or modifying many agricultural processes and methods of production; it essentially entails undoing the past 10,000 years of agricultural practices (Pimm 1997). This change to sustainable agriculture would also entail revolutionary social and political policies (Altieri et al. 1983), not to mention a change in the way we view agroecosystems. Instead of being simply a new means of land exploitation for human needs (Altieri et al. 1983), alternative agriculture has the potential to restore degraded ecosystems (Piper 1999).

Current work being done at The Land Institute involves domestication of wild perennials, such as Illinois bundle flower (*Desmanthus illinoensis*) and eastern gamagrass (*Tripsacum dactyloides*), and increasing structural and functional diversity of agroecosystems (Piper 1999). These monumental changes will require years of future work (Piper 1999). Therefore, smaller changes, such as those proposed in this study, are urgently needed to minimize long-term consequences of agriculture on the landscape.

Although this study focused on ecosystem-level management, we must also look to landscape-level applications (Barrett 1992). A field-by-field approach does not address long-term maintenance of ecosystem services (Lowrance et al. 1986). Natural ecosystem services facilitated by sustainable agriculture (involving reduced tillage, intercropping, and integrated pest management) include nutrient retention and recycling, pollination biology, maintenance of natural enemy populations, and regulation of carbon and nitrogen cycles, among others (Daily et al. 1997). Alternative agricultural systems, like the ones proposed here, seek to take advantage of ecosystem services for the mutual benefit of human consumers and surrounding ecosystems.

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