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A comparison of conventional and alternative agroecosystems using alfalfa (*Medicago sativa*) and winter wheat (*Triticum aestivum*)

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Abstract

Natural systems agriculture is based on an understanding that natural systems are self-sustaining due to regulatory mechanisms and processes that help to ensure the long-term maintenance of the ecosystem. An agroecosystem modeled after nature should encompass greater stability and biodiversity at all levels of organization than an agroecosystem based on conventional agricultural practices. The main objective of this study was to determine whether agroecosystems modeled after nature exhibit advantages over conventional agroecosystems. Five treatments were examined: winter wheat (*Triticum aestivum* L.) monoculture, alfalfa (*Medicago sativa* L.) monoculture, strip-cropped alfalfa and wheat, and two alfalfa–wheat intercrops (one no-till and one conservation-till). Indicators of ecosystem function studied included primary productivity, soil fertility, plant nitrogen (N) concentration, and abundances of arthropod pests and predators. No fertilizers or pesticides were used prior to or during this investigation. Monoculture, strip-crop and conservation-till treatments produced significantly higher yields than no-till intercropped alfalfa and wheat. Although yields from the no-till intercrop were low, wheat protein values were comparable to other treatments. Soil N concentrations tended to be high in treatments containing alfalfa. Insect pests preferred alfalfa and were, therefore, often more abundant in treatments containing high percentages of alfalfa, as were predators such as spiders. Researching alternatives to monoculture agroecosystems, such as the intercrop systems in this study, may provide us insight into a true natural systems agriculture.

Key words: agroecosystem ecology, alternative agriculture, *Medicago sativa*, natural systems agriculture (NSA), the Land Institute, *Triticum aestivum*

Introduction

Modern agriculture encourages increased production and yield maximization without examining long-term consequences, such as soil degradation, pesticide contamination of groundwater and declining biotic diversity[1]. Although a new model of the agricultural system is needed, current infrastructure is not equipped to handle this monumental change. Therefore, smaller steps must be taken now to move modern agricultural practices away from increased subsidies (pesticides, fossil fuels and fertilizers) and toward sustainability based on naturally occurring ecological processes[2].

If we incorporate basic ecosystem concepts, such as those in naturally occurring ecosystems (e.g., niche differentiation, use of keystone species and nutrient cycling) into management programs, then we may be able to design agroecosystems that are more self-sustaining and depend less on external energy inputs[3]. Diversity of species and function is a major component of, and regulatory mechanism in, natural grassland ecosystems[1]. These two types of diversity can be integrated into cropping systems by simultaneously cultivating more than one crop species in a field and by using crop species from different functional groups. The four main plant guilds in grassland ecosystems are perennial C_3 grasses, perennial C_4 grasses, nitrogen fixers and composites[1].

Another feature of natural grassland ecosystems is minimal soil disturbance (i.e., no mechanical tillage) compared to conventional agriculture, which has traditionally relied on tillage. By examining the effects of incorporating greater crop diversity and decreased tillage into agricultural systems, we can compare the relative advantages and disadvantages of alternative agroecosystems that incorporate the features of natural grasslands with more conventional agroecosystems.

Plant interactions

Increased biotic diversity provides benefits for plant communities, including higher rates of primary production per unit area of land[4]. A proposed mechanism for this increased productivity is higher soil resource-use efficiency in diverse stands compared to monocultures[5]. Plants from different functional groups require large amounts of nutrients at different times during the growing season[4], and different functional groups use different resources, resulting in niche differentiation[5].

We selected perennial alfalfa (*Medicago sativa*) and annual winter wheat (*Triticum aestivum*) to establish our cropping treatments. Because root morphologies and physiologies of alfalfa and wheat are quite different (i.e., they do not compete for the same resources), total uptake of water and nutrients may be improved when both species are grown together. Perennial alfalfa has a long tap root that is efficient for obtaining water and nitrate at greater depths than fibrous wheat roots[6]. Therefore, alfalfa may obtain water and nutrients that are leached below wheat roots, increasing total resource uptake. Complementary use of resources may result in a condition termed overyielding. Overyielding occurs when two species grown together are more productive per unit area than would be expected based on monoculture yields[7].

Facilitation is another mechanism that may result in increased net primary production in an intercrop, whereby the presence of one species enhances the growth of another species[7,8]. One mechanism contributing to facilitation in a legume–grass intercrop is the legume's input of nitrogen (N) into the soil. Because legumes compete poorly with grasses for mineral soil N[9], they can be used as companion species for intercropping with grasses (i.e., legumes are able to fix atmospheric N when adequate soil N is not available).

We investigated the contribution of intercropped alfalfa to soil and wheat-grain nitrogen concentrations. Yields of intercropped and monoculture wheat and alfalfa were also quantified to determine whether overyielding occurred in any of the intercropped systems.

Arthropods

We also sought to determine how ecosystem biotic diversity is related to different management practices. Focus has recently turned to cultural methods to control pests, because pesticides frequently have adverse impacts on ecosystem function, including the elimination of beneficial insects[10]. Cultural control of pests in agroecosystems includes designing cropping systems to avoid pest outbreaks. One form of cultural control is intercropping, or increasing the diversity of crop species[11].

Insect pest damage has been shown to be more harmful in monocultures than in diverse stands of vegetation[12,13]. Root[14] proposed the 'resource concentration' hypothesis as a possible explanation for higher numbers of arthropod pests in monocultures. He suggested that specialist herbivores whose requirements are fulfilled by plants in a less diverse 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[15]. Findings suggest that chemical signals from non-host plants interfere with the ability of herbivores to find suitable food and reproduce[16,17].

Multicropped agroecosystems may also attract more generalist predators and parasitoids, which could potentially control herbivore populations. Root[14] formulated the 'enemies' hypothesis as another possible explanation for lower pest numbers in heterogeneous agroecosystems. This hypothesis suggests that predators are more likely to remain in heterogeneous systems due to diversity of food resources and refugia. Although the enemies hypothesis has received less support than the resource concentration hypothesis, it continues to be researched as an important mechanism of pest control[18]. Our investigation sought to determine whether agricultural systems involving more than one crop species exhibited advantages over conventional monoculture systems.

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). Prior to this experiment, the field site had been in continuous alfalfa (variety Cimmaron VR) cultivation since 1996. Soil type was Hord silt loam (fine-silty, mixed, mesic Cumulic Haplustoll) (Soil Survey of Saline Co., Kansas). Average annual rainfall is approximately 76 cm, with 47 cm occurring from April through August. Only 31 cm of rain fell from April through August 2002, resulting in a drought that severely reduced wheat production.

Plots were established in a randomized block design consisting of 3 blocks and 5 treatments. Treatments were: 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 3.64 m (12 feet) wide. Both strip-crops and row intercrops can be considered more ecologically complex systems than traditional monocultures. Planting two crop species in close proximity may have effects on faunal diversity, soil nutrient dynamics and resource use.

Conservation tillage in the conservation-till alfalfa–wheat intercrops entailed coarsely disking the surface soil once prior to wheat seeding. No-till alfalfa–wheat intercrops were planted using a no-till drill to seed wheat into the alfalfa stand. The seeding rate of crop species was the same for each treatment. Each plot (45 m × 45 m) was separated from other plots by a 1 m buffer of alfalfa. No fertilizers or pesticides were applied to any of the plots prior to or during the experiment. Weed species found included foxtail (*Setaria viridis*, *S. glauca*), Japanese brome (*Bromus japonicus*), cheat grass (*B. tectorum*) and prickly lettuce (*Lactuca seriola*).

Agroecosystem parameters quantified included crop yields, grain and soil nitrogen, and arthropod pest and predator abundances. One-way analyses of variance were used when possible (SAS version 8.2, SAS Institute software, Cary, North Carolina, USA). Means were separated by pairwise comparisons (Fisher's protected least significant difference).

Estimating yield

Mean yield values during 2001 and 2002 were estimated from three random $0.75\,m \times 0.75\,m$ samples per harvest period. For the first alfalfa harvest in each season, alfalfa was harvested in alfalfa monocultures and alfalfa strips within the strip-cropped bicultures. For the second harvest each season, alfalfa and wheat straw were clipped simultaneously in all treatments. All vegetation was dried at $60^{\circ}C$ to constant mass.

To measure weed biomass, weeds were separated by hand from alfalfa and wheat samples. Although alfalfa in the wheat monoculture and wheat strips could be considered a weed, we kept alfalfa biomass separate from all other weed species. After 2 years of full tillage, alfalfa no longer grew in the wheat monoculture and wheat strips; therefore, no alfalfa was present in wheat strips or wheat monocultures in 2002.

Wheat was harvested with a combine in 2001 to estimate wheat grain yield. One strip running the length of each replicate plot was harvested with the head of the combine set just above the top of the alfalfa plants. In 2002, wheat growth was stunted due to drought conditions; thus the alfalfa in both the no-till row intercrop and in the conservation-till row intercrop was taller than both wheat varieties during the entire growing season. Therefore, three $0.75\,m \times 0.75\,m$ samples per wheat variety were harvested in 2002 by hand rather than with a combine. Grain was cleaned following harvest, dried to constant mass and weighed to the nearest gram.

Mean yield values per treatment, including wheat, alfalfa and weeds, were compared using one-way ANOVAs. Relative yields were also analyzed using the land equivalent ratio (LER)[19]. LER values are a measure of land-use efficiency of intercrops; efficiency refers to harvestable biomass per unit land area. The formula is as follows:

$$\mathrm{LER} = \mathrm{RY_w} + \mathrm{RY_a},$$

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,

$$\mathrm{RY_w} = \mathrm{P_w}/\mathrm{M_w},$$

where P_w is the polyculture wheat yield and M_w is the monoculture wheat yield.

We used mean monoculture alfalfa and wheat yields as denominators in the LER calculations[7]. To calculate LERs in the strip-crop treatment, the sum of the relative yields for alfalfa and wheat were halved, because only half of each strip-cropped plot was devoted to each species. If LER values are greater than one, intercrops are more productive per unit area than monocultures.

Nitrogen analyses

As a gauge of long-term soil fertility, total soil organic nitrogen (N) was determined for all five treatments. Soils were sampled at 6-week intervals over the growing season during both 2001 and 2002. Five cores were extracted from the top 10 cm of soil in an 'X' pattern from each plot, excluding plots in the strip-cropped treatment. In the strip-cropped treatment, four samples were collected each from wheat strips (till) and from alfalfa strips (no-till) in a grid pattern. Nitrogen concentrations were determined by the Micro-Dumas combustion method[20], using a Carlo Erba C/H/N analyzer (NA1500 C/H/N Analyzer, Carlo Erba Strumentazione, Milan, Italy). Nitrogen concentration values are presented on a nonvolumetric basis. Bulk density estimates in no-till wheat ($1.15\,g\,cm^{-3}$), no-till alfalfa ($1.25\,g\,cm^{-3}$) and tilled wheat ($1.10\,g\,cm^{-3}$) were so similar that the maximum error for not weighting nitrogen comparisons with bulk density estimates is 5% or less, and would underestimate any differences observed.

Percent N values were $\arcsin\sqrt{(x/100)}$ transformed prior to analysis. This standard transformation allows percentages to be analyzed with parametric statistics[21]. Because repeated-measures ANOVA revealed significant interactions between date and treatment, an ANOVA was performed on total N concentrations for each individual sampling date. Wheat grain from both years was also analyzed for protein concentration. To calculate crude protein concentration, we multiplied percent N values by constants, according to the methods of the Association of Organic and Analytical Chemists[20].

Abundance of selected arthropod pests and predators

Two trapping stations were situated near the center of each plot. A pan trap was located at each station (i.e., six 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 crop canopy. A mixture of water and ethylene glycol was used to cover the bottom of each pan trap.

Pan traps were emptied 5 days after the ethylene glycol–water mixture was added. Traps were collected seven times during 2001 and five times during 2002. Arthropods were also collected with a sweep net on three dates during 2002. Samples consisted of 25 sweeps along a randomly selected transect in each experimental plot. Most results are

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presented for abundance at the family level because counts of individual species were low.

Differences in mean abundances of herbivorous and predatory arthropod populations among treatments for pan traps were analyzed for each season by repeated-measures ANOVA. Arthropod count data were square-root transformed prior to analysis[21]. Because the year × treatment interaction was significant for most arthropod groups, data are presented as means for each season. ANOVAs were also performed on data collected from sweep nets. Sweep sample data were analyzed for each of three sampling dates (25 May, 13 June and 18 July). These three dates represent three distinct stages of the growing season (i.e., before the first alfalfa harvest, before the wheat harvest, and after the second alfalfa harvest); population sizes of arthropods were therefore quite variable among dates.

Results and Discussion

Above-ground biomass and intercrop advantage

Because crop productivity is the main goal of production agriculture[22], one of the factors in agroecology receiving considerable attention is harvestable biomass. In 2001, total above-ground biomass for all treatments, except the no-till alfalfa–wheat intercrop, averaged approximately 7000 kg ha^{-1}, and biomass for the no-till intercrop treatment was approximately 5500 kg ha^{-1}. Biomass values were lower in 2002, ranging from about 6000 kg ha^{-1} for wheat monoculture, alfalfa monoculture, and conservation-till alfalfa–wheat intercrop treatments to 4500 kg ha^{-1} for the no-till alfalfa–wheat intercrop treatment. According to Knapp et al.[23], tallgrass prairie biomass in North America has been estimated to be about 4000 kg ha^{-1}; one estimate for the Konza Prairie in Kansas was given as 5200 kg ha^{-1} [24]. Total biomass estimates from our experimental treatments were generally higher than these grassland values; the no-till intercrop was the only system that produced lower biomass than natural grassland ecosystems.

In 2001, significant differences in wheat grain yields (Table 1) were observed among different treatments ($P < 0.001$). Wheat monoculture and alfalfa–wheat strip-crop treatments had similar grain yields (3749 and 3644 kg ha^{-1}, respectively). The no-till alfalfa–wheat intercrop yielded significantly less than all other treatments containing wheat; it was also the only treatment that did not exceed the 2001 average Kansas winter wheat yield (2757 kg ha^{-1}). In 2002, wheat monoculture again produced the highest grain yield ($P < 0.001$). Both the wheat strips in the alfalfa–wheat strip-crop and the conservation-till alfalfa–wheat intercrop produced similar yields. No-till alfalfa–wheat again had the lowest grain yield. All grain yields were lower in 2002 than in 2001, presumably due to drought conditions in 2002.

Alfalfa harvested per unit area in 2001 (Table 2) was greatest in alfalfa strips (in alfalfa–wheat strip-crop) and alfalfa monocultures ($P < 0.001$) compared to other treatments. Small amounts of alfalfa were harvested in wheat strips and wheat monocultures, presumably due to the field being in continuous alfalfa cultivation for 4 years prior to planting wheat. Alfalfa biomass harvested in 2002 was greater in alfalfa monoculture ($P < 0.001$) than conservation-till alfalfa–wheat intercrops, alfalfa strips (in alfalfa–wheat strip-crop) and no-till alfalfa–wheat intercrops.

Alfalfa was more productive in 2002, during drought conditions, when intercropped. In 2002, alfalfa yields in the conservation-till alfalfa–wheat intercrop treatment were slightly higher than alfalfa yields for this treatment in 2001; alfalfa production was reduced during the drought only in the alfalfa monoculture and alfalfa strips within the alfalfa–wheat strip-crop. Perhaps decreased competition for water in intercrops led to higher forage yields[9] because alfalfa's long taproot can compete vigorously for water during a drought.

Mean weed biomass was small in 2001 compared to 2002 (Table 3). In 2001, weed biomass was significantly greater in the alfalfa monoculture ($P < 0.01$) compared to other treatments. Mean weed biomass in 2002 was significantly greater in the alfalfa monoculture and no-till alfalfa–wheat intercrop treatments ($P < 0.001$) compared to other treatments. The wheat monoculture treatment had the lowest weed biomass, presumably due to 2 years of continuous tillage. This low competition from weeds likely contributed to the high seed yield.

Table 1. Wheat grain biomass harvested ($x \pm$ SE).

Treatment	2001 Grain (kg ha^{-1})	2002 Grain (kg ha^{-1})
Wheat monoculture	3749 ± 163 a	2107 ± 229 A
Wheat strips (in strip crop)	3644 ± 212 a	1318 ± 127 B
No-till alfalfa–wheat	1497 ± 127 c	460 ± 92 C
Conservation-till alfalfa–wheat	2948 ± 83 b	1286 ± 97 B
Alfalfa monoculture	0	0

Mean yields were analyzed by year. Different letters indicate significant differences ($P < 0.001$).

Table 2. Alfalfa hay biomass harvested ($x \pm$ SE).

Treatment	2001 Alfalfa (kg ha^{-1})	2002 Alfalfa (kg ha^{-1})
Wheat monoculture	224 ± 67 d	0
Wheat strips (in strip crop)	351 ± 65 d	0
Alfalfa strips (in strip crop)	6773 ± 264 a	2147 ± 208 B
No-till alfalfa–wheat	1847 ± 197 b	2121 ± 316 B
Conservation-till alfalfa–wheat	1261 ± 73 c	2379 ± 103 B
Alfalfa monoculture	6298 ± 383 a	4978 ± 715 A

Mean yields were analyzed by year. Different letters indicate significant differences ($P < 0.001$).

Table 3. Weed biomass ($x \pm$ SE).

Treatment	2001 Weeds (kg ha^{-1})	2002 Weeds (kg ha^{-1})
Wheat monoculture	288 ± 127 (b)	24 ± 12 (C)
Alfalfa–wheat strip crop	267 ± 61 (b)	522 ± 70 (B)
No-till alfalfa–wheat	144 ± 29 (b)	1012 ± 150 (AB)
Conservation-till alfalfa–wheat	101 ± 29 (b)	334 ± 61 (BC)
Alfalfa monoculture	747 ± 173 (a)	1154 ± 309 (A)

Mean yields were analyzed by year. Different letters indicate significant differences ($P < 0.01$).

Table 4. Average land equivalent ratio (LER) values calculated using mean wheat and alfalfa monoculture yields.

	RY_a		RY_w		LER	
Treatment	2001	2002	2001	2002	2001	2002
SC	1.08	0.44	0.97	0.62	1.03[1]	0.53
NT	0.29	0.43	0.40	0.22	0.69	0.65
CT	0.20	0.48	0.79	0.61	0.99	1.09[1]

RY_a represents the relative yield of alfalfa, and RY_w, the relative yield of wheat.
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.
[1] LER values greater than 1 indicate overyielding.

Weeds represented a larger percentage of harvested biomass in the alfalfa monoculture, perhaps because this treatment received no tillage, compared to other treatments. Low weed mass from the conservation-till alfalfa–wheat intercrop corresponds to results reported by Carr et al.[25], who found that a wheat–lentil intercrop canopy intercepted much of the photosynthetically active radiation that would otherwise reach soil and weeds.

In 2001, the strip-cropped alfalfa–wheat intercrop had the highest land-use efficiency (Table 4) with a mean LER value of 1.03 ± 0.03, suggesting that this treatment was as productive as if the land was divided into two monocultures. Intercrop advantage was more visible in 2002, during drought conditions. The conservation-till alfalfa–wheat intercrop treatment showed a possible intercrop advantage with a mean LER of 1.09 ± 0.10. Thus, total productivity per unit area in this treatment is comparable to that of monocultures, perhaps due to complementary use of resources such as water and nitrogen. Putnam and Allan[8] suggested that border rows in a sunflower–mustard strip-crop benefitted from excess N and water; mustard (*Brassica hirta* Moench) and sunflower (*Helianthus annuus* L.) had low interspecific competition due to temporal differentiation of resource requirements.

Low yields and LER values in the no-till alfalfa–wheat intercrop contradict findings of others who have reported higher yields for no-till than for conventionally tilled systems[26,27]. However, weeds were suppressed with herbicides in those studies, and interaction effects of intercropping and tillage were not considered. Because alfalfa was never tilled in the no-till intercrop, this species was at least 0.25 m taller than wheat plants, especially in 2002. Wheat plants therefore received reduced sunlight.

Soil nitrogen

Manufacture of nitrogen fertilizer uses more energy than all other parts of production agriculture[28], and much applied N is leached out of the system[29]. To create less energy-intensive systems, nitrogen-use efficiency must be increased by management systems that improve efficient means of fertilization, such as nutrient recycling and retention. Alfalfa–wheat intercrops have the potential for not only reduced interspecific competition via complementary resource use, but also facilitation of wheat growth associated with the legume's contribution of nitrogen[9,30].

Blair et al.[31] reported that the upper 25 cm of soil at the Konza Prairie contains about 625 g N m^{-2}; assuming a bulk density of 1 g cm^{-3}, this is a concentration of about 0.25% N. Soils in our experimental treatments, although quite fertile, had much lower N concentrations than the soil at Konza Prairie.

Figure 1 depicts total soil N concentration (g kg^{-1}) over two growing seasons including six sampling dates. Because all treatments were in continuous alfalfa for 4 years prior to this experiment, concentrations of soil N were fairly high compared to non-nitrogen-fixing systems. Thus, fewer significant trends emerged during the first season than in the second season.

In contrast, significant differences were observed among treatments during 2002. Soil nitrogen concentration tended to increase from the previous year in those treatments containing high percentages of alfalfa. In April and June, wheat monoculture and wheat strips in the alfalfa–wheat strip-crop had significantly lower concentrations of mean soil N compared to other treatments (April, $P < 0.001$; June, $P < 0.001$). In July 2002, wheat monoculture and both wheat and alfalfa strips in the alfalfa–wheat strip crop had lower mean soil N concentrations than the alfalfa monoculture and two row-intercrop treatments ($P < 0.001$). The low soil N in wheat strips within the alfalfa–wheat strip-crop indicates that alfalfa strips do not contribute significant N to wheat strips. Brophy et al.[32] 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 soil in wheat strips.

Soil N concentrations in the wheat monoculture were maintained between years. Soil in the wheat monoculture contained approximately 1890 kg N ha^{-1} to a 10 cm depth. Assuming that only 1–2% of the total soil N is in readily available forms of nitrate and ammonium[33], and much of the N is removed when wheat is harvested, this system likely will not be able to support current levels of production for more than one or two additional growing

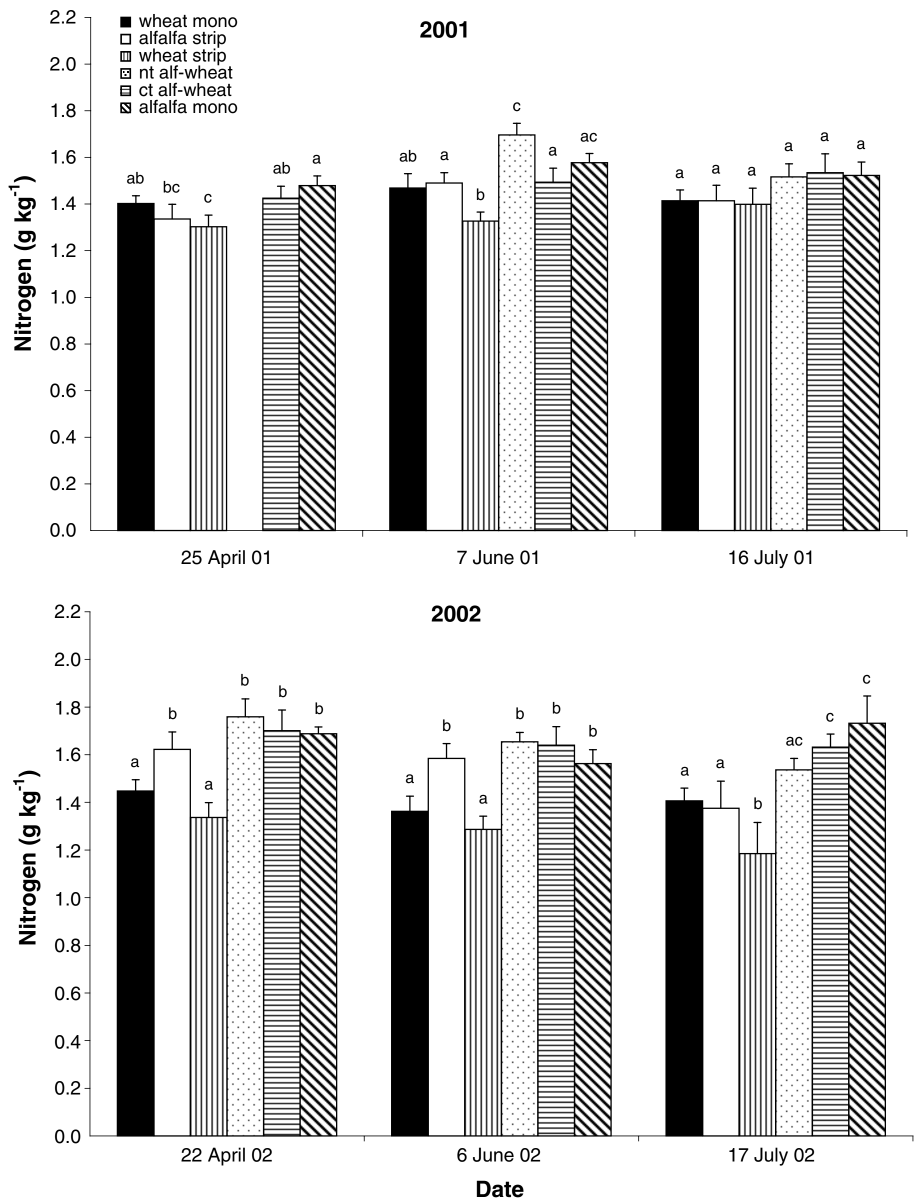

Figure 1. Mean soil nitrogen concentration ($x \pm$ SE) presented as ($g\,N \cdot kg\,soil^{-1}$). Different letters above treatment means indicate significant differences ($P \leq 0.05$) on a particular sampling date. Wheat monoculture is represented by black bars; alfalfa strip in alfalfa–wheat strip-crop, by white bars; wheat strip in alfalfa–wheat strip-crop, by vertically striped bars; no-till alfalfa–wheat intercrop, by dotted bars; conservation-till alfalfa–wheat intercrop, by horizontally striped bars; and alfalfa monoculture is represented by diagonally striped bars.

seasons, including mineralization of soil organic matter. In contrast, the alfalfa monoculture, no-till intercrop, and conservation-till intercrop treatments should be able to supplement their own fertility indefinitely without external N inputs, assuming that alfalfa fixes 150–250 kg N ha^{-1} year[33]. However, alfalfa monoculture is certainly not a sustainable system; increased temporal and spatial diversity should be incorporated to increase resilience against pest build-ups and autotoxicity.

The no-till intercrop treatment exhibited high soil N concentrations and low primary productivity, whereas the wheat monoculture and wheat strips (in the alfalfa–wheat strip-crop) were characterized by high grain production and lower soil N. Our results support conclusions drawn by other researchers who found that soil N and crop productivity may be unrelated[31,34]. We found, however, that total N appeared to be inversely related to net primary productivity.

Grain nitrogen

Percent crude protein values averaged 12.4% in 2001 and 15.8% in 2002. These protein values are well within the range of acceptable grain protein values. The average wheat protein concentration for the past 10 years in Kansas is about 12%[35].

No effect of treatment on grain protein concentration was observed. Soil N appeared to have little influence on wheat grain quality. Soil N concentrations throughout the field seemed to be sufficient for high wheat grain nitrogen concentrations without the use of fertilizers during the experiment. However, it should be noted that we measured total N and not plant-available nitrogen.

Arthropods

Insect pests collected in pan traps and sweep nets included leafhoppers (Hemiptera: Cicadellidae), aphids (Hemiptera: Cicadellidae), grasshoppers (Orthoptera: Acrididae) and alfalfa weevils (*Hypera postica* Gyllenhal). We expected that wheat and alfalfa monocultures would experience greater pest pressure than would intercrops, based on the strong support for Root's resource concentration hypothesis[12,14,36]. Because our field site was in continuous alfalfa for 4 years preceding the study, alfalfa-feeding insects were already present in the field. However, wheat-feeding insects were much less abundant. In this study, alfalfa may be considered the host plant and wheat the nonhost plant, or interference crop.

Leafhoppers *Ceratagallia agricola* Hamilton, *C. uhleri* Van Duzee and *Paraphlepsius irroratus* (Say), all of which feed on alfalfa and other legumes, were common in both years. Leafhoppers in pan traps were significantly more abundant in the alfalfa monoculture and no-till alfalfa–wheat intercrop treatments in 2001 ($P < 0.05$) and in the alfalfa monoculture in 2002 ($P < 0.001$) than in other treatments (Fig. 2a). No strong trends in leafhopper numbers were observed from samples collected by sweep net.

Aphid trends were not significant in 2001, but in 2002 they were similar to those for leafhoppers (Fig. 2b). 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. Differences among treatments were not significant for pan traps in 2001; in 2002 aphid abundances were greater for no-till alfalfa–wheat intercrop, conservation-till alfalfa–wheat intercrop, and alfalfa monoculture treatments than for wheat monoculture and alfalfa–wheat strip-crop treatments ($P < 0.05$). In general, the treatments with the largest concentrations of alfalfa also had the highest numbers of aphids. Few strong trends were exhibited by sweep net samples. However, aphid numbers from sweep samples were significantly lower in wheat strips than in alfalfa strips over all three sampling dates in 2002. If the 3.6 m-wide strips are analogous to wheat monocultures, these results are not surprising, based on wheat monoculture findings.

Grasshoppers were only examined during the second growing season, when large numbers indicated that they were a potential pest problem. Grasshoppers occur in great numbers when climatic conditions are hot and dry, as they were in 2002[37]. 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.

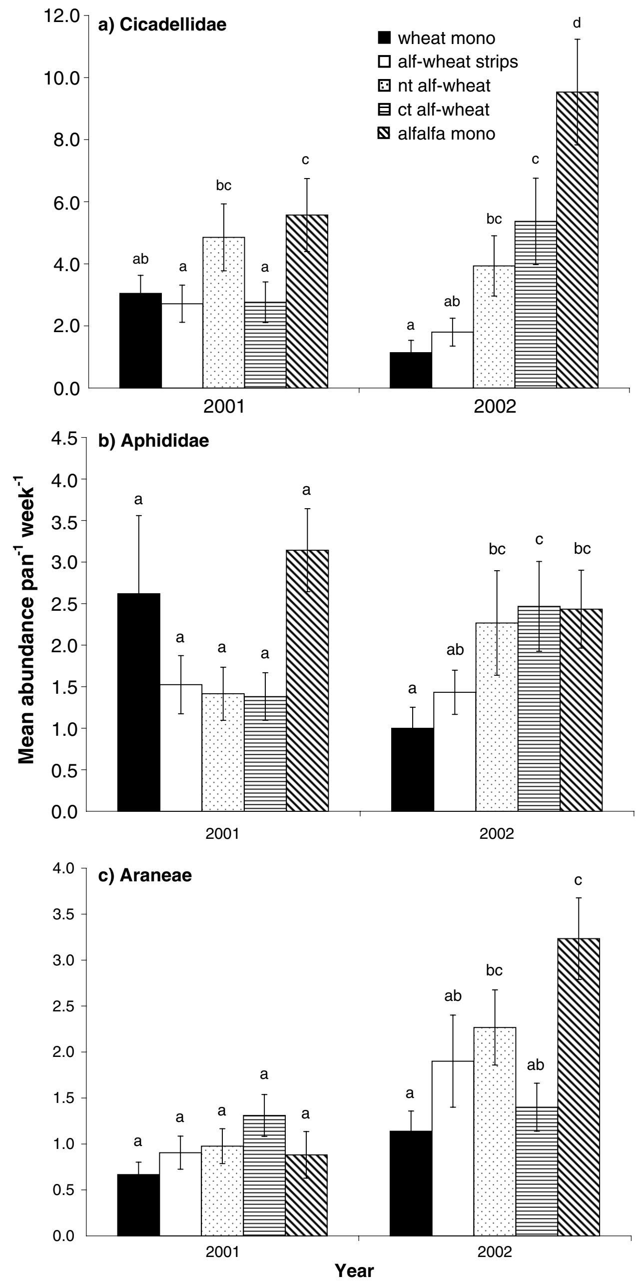

Figure 2. Mean abundances ($x \pm$ SE) for herbivorous arthropod groups: (a) leafhoppers; (b) aphids; and (c) spiders, collected in pan traps. Unless otherwise noted, different letters above treatment means indicate significant differences ($P \leq 0.05$). Note that the scales of the *y*-axes differ. Wheat monoculture is represented by black bars; alfalfa–wheat strip-crop, white bars; no-till alfalfa–wheat intercrop, by dotted bars; conservation-till alfalfa–wheat intercrop, by horizontally striped bars; and alfalfa monoculture is represented by diagonally striped bars.

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Thus, this herbivorous species appeared to function as a generalist within this diverse research design.

The final herbivorous species included in this study was the alfalfa weevil (*Hypera postica* Gyllenhal), analyzed solely from the 25 May 2002 sweep samples. Alfalfa weevil numbers are typically greatly reduced by the first cutting; thus they are only injurious early in the growing season. Weevils were rare in 2001, but were numerous in 2002. Alfalfa strips in the alfalfa–wheat strip-crop had higher densities (36 weevils per 25 sweeps) than other treatments ($P < 0.001$) with the exception of alfalfa monoculture, which also had a mean abundance (18 weevils per 25 sweeps) similar to the no-till alfalfa–wheat intercrop (7 weevils per 25 sweeps). Because alfalfa weevils prefer to feed on, and will reproduce only on, alfalfa[38], incorporation of nonhost plants, such as other forage species that could be harvested with alfalfa for hay, into alfalfa strips should decrease weevil population densities.

Ladybird beetles are a common aphid predator and are, therefore, of interest as a biological control mechanism. The most common species found was *Coccinella septempunctata* L. Differences on any sampling date were not significant because numbers caught were very low. However, repeated measures analysis for pan traps indicated that alfalfa–wheat strip-crop and conservation-till alfalfa–wheat intercrop treatments tended to have greater abundances of ladybird beetles ($P < 0.05$), than monocultures.

Total spider abundance (Fig. 2c) was calculated for all sampling regimes. Pan catches were significantly different among treatments in 2002 only; total spider numbers were highest in alfalfa monoculture (3.2 pan^{-1} week^{-1}) and no-till alfalfa–wheat intercrop (2.3 pan^{-1} week^{-1}) treatments ($P < 0.05$). Differences were also significant for the June 2002 sweep samples, when no-till (16.0 per 25 sweeps) and conservation-till (10.7 per 25 sweeps) intercrop treatments had higher spider densities than all other treatments ($P < 0.05$). Spiders are one of the main predaceous (i.e., tertiary consumers) taxa, important as a regulatory species in numerous agroecosystems[39].

Two possible reasons for high spider numbers in the no-till alfalfa–wheat intercrop are high prey densities[13] and low soil disturbance[40]. Stinner et al.[40] also suggested that predatory arthropods may inhabit no-till systems due to microhabitat conditions created by the surface litter. While no-till fields may encourage invertebrate pests, high faunal diversity in no-till systems may also foster biological control[41].

In general, arthropod population trends in no-till alfalfa–wheat intercrops were similar to those in alfalfa monocultures. The high numbers of leafhoppers in 2001 and aphids in 2002 in pan traps are attributed to the high amount of alfalfa present[42]. Due to the close alfalfa–wheat association in the no-till intercrop treatment, wheat plants were unlikely to deter alfalfa specialists from finding nearby alfalfa plants.

Our results support Root's resource concentration hypothesis. When pest numbers were significantly different among treatments, those treatments with the highest proportions of alfalfa had the highest numbers of herbivorous arthropods. However, these trends were not significant across all dates and sampling methods. Results do not support the enemies hypothesis. Natural enemy population trends were rarely significant; therefore no general statements can be made.

While no single intercropped treatment exhibited consistent advantages over monoculture treatments, significant differences among the various parameters measured were observed. Throughout both years, the no-till intercropped system produced the least above-ground biomass. Alfalfa performed much better than wheat during the drought; therefore treatments containing alfalfa yielded higher biomass during the second year of study. Higher soil N concentrations were observed in those treatments containing the greatest proportions of alfalfa. However, those treatments containing high proportions of alfalfa also attracted higher numbers of herbivorous keystone species.

Conclusions

The alternative agroecosystems discussed here add to the growing body of research focusing on intermediate steps between conventional agriculture and alternative systems of production, such as the perennial polyculture systems being developed at the Land Institute[43,44]. In general, the no-till intercrop system was not advantageous when compared to the other treatments, mostly due to low yields and relatively large populations of leafhoppers and aphids. The alfalfa–wheat strip-crop treatment demonstrated yields similar to alfalfa and wheat monoculture yields. However, benefits to soil N concentrations from strip-cropping alfalfa and wheat were not apparent. The conservation-till intercrop treatment was an intermediate intercrop design between the alfalfa–wheat strip-crop and no-till alfalfa–wheat intercrop treatments. Benefits of the conservation-till intercrop include overyielding in 2002 and high soil N. It appears that moderate tillage combined with a close association of dissimilar crop species can be quite productive, despite low subsidy inputs of fertilizers and fossil fuels.

Results may have differed if pesticides and fertilizers were applied. Fertilizer additions would likely have increased soil N concentrations in wheat monocultures and wheat strips in the alfalfa–wheat strip-crop, which may have resulted in increased grain nitrogen concentrations. Use of pesticides would have also altered our results. Applying a selective herbicide to the no-till intercrop treatment would have stunted alfalfa growth and therefore would probably have benefitted wheat growth and production. Also, lower alfalfa concentrations in the no-till intercrop, due to herbicide use, may have discouraged arthropod pests.

We expect that over time these agroecosystems would remain with less biotic diversity (genetic, species and patch) than natural grassland ecosystems. Although primary production was higher in experimental treatments than in neighboring prairie, our treatments may become less productive than natural prairie systems due to lower soil N values and higher pest pressures. Perhaps incorporating several crop species into alternative agroecosystems would encourage more complete use of resources and increase resistance to pests. This design was intended to be a step between conventional agriculture and natural systems agriculture[43]. We feel that benefits accrued merit further research regarding how to solve *problems in agriculture* (e.g., high use of subsidies, pest outbreaks in monoculture systems and soil erosion), in order to solve the *problem of agriculture* by using native perennial species, encompassing natural ecosystem processes into agroecosystem management.

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