INTERNATIONAL JOURNAL OF ENVIRONMENTAL SCIENCE AND ENGINEERING (IJESE)
Vol. 4: 1- 16 (2013)
http://www.pvamu.edu/texged **Prairie View A&M University, Texas, USA**

Role of cereal-legume intercropping on invertebrate community abundance

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ARTICLE INFO
Article History
Received: Dec.15, 2012
Accepted: Jan.16, 2013
Available online: July 2013

Keywords:
Intercropping regimes
Monoculture
Organic systems
Cereal-legume
Natural enemies
Predatory invertebrates
Aphid herbivores
Ground beetles.

ABSTRACT
The impacts of cereal-legume intercropping regimes upon the abundance of invertebrates in two different managed arable systems (conventional and organic) were investigated between April and September 2007. The organically managed plots were on fertile soil established following three years of clover ley. Within the two sites the experimental design was established, based on single crop treatment with four levels. These were: 1) Intercropping based on a full sowing rate of wheat (200 seeds/m^2) and faba beans (40 seeds/m^2); 2) Intercropping based on a half sowing rate (wheat 100:20 bean seeds/m^2); 3) Wheat monoculture (200 seeds/m^2); 4) Faba-bean monoculture (40 seeds/m^2). Invertebrate natural enemy and pest species were sampled using hand searching and pitfall trapping. The results revealed that intercropping positively affected the abundance of herbivores such as green peach aphids (*Myzus persicae)* and Curculionidae, as well as the predatory families, such as Araneae, Staphylinidae, Carabidae, and Chrysopidae in organic systems, but not in the conventional management system. In addition, intercropping tended to support greater species richness of ground beetles, but only in the organically managed arable systems. The data show that intercrop treatments positively affected the abundance and activity of the predatory species *Pterostichus madidus* which may have a potential role in terms of biological pest control in this system. Overall, this study suggests that intercropping regimes may provide an effective approach for boosting populations of pests' natural enemies in wheat crops. No evidence was found, however, for reducing abundance of herbivores in those treatments that had increased abundances of predators, it is suggested that the underlying mechanisms involved in pest control are complex, possibly mediated through secondary interactions between functionally diverse predatory species and their pest populations.

1. INTRODUCTION
Over the past fifty years intensive farming in Western Europe has been characterized by monocultures of crops receiving high levels of inputs of chemical fertilizers and pesticides (Hauggaard-Nielsen *et al.*, 2001). Concerning the sustainability of these systems have led UK Government Policy Commission on the Future of Farming and Food, to make a recommendation to seek alternative methods to enhance naturally occurring insect predators and parasitoids (Hole *et al.*, 2005).

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ISSN 2156-7530

Such naturally occurring predatory species have the potential to allow a reduction in inputs of chemical pesticides as they provide natural pest control (Coll and Bottrell, 1995). Both the direct impact of invertebrate predators on agricultural herbivores (Altieri *et al.*, 1985; DeBach and Rosen, 1974; Hochberg, 1996; Symondson *et al.*, 2002; Ives *et al.*, 2005; Snyder *et al.*, 2005; Tscharntke *et al.*, 2005) and the indirect effects that they have on other ecosystem processes such as primary productivity and element cycling (Downing and Leibold, 2002; Paine, 2002; Duffy, 2003; Duffy *et al.*, 2005; Fukami *et al.*, 2006; Maron *et al.*, 2006; Schmitz, 2006; Schmitz, 2007; Altieri *et al.*, 1985) represent important ecosystem services in agricultural systems (Schmitz, 2007).

Intercropping, also referred to as polycluture or diculture, is a traditional method of crop management in tropical agriculture (Altieri, 1991; Anil *et al.*, 1998), and refers to the practice of growing two or more crop species together within the same field (Dent, 1991). Intercropping has been used, for example, across Asia and Latin America in the context of small-scale sustainable agricultural systems (Altieri, 1999). Intercropping cotton with wheat is used in many areas of northern China as it allows both food and fibre (for clothes production) to be produced together in a limited land area (Guo *et al.*, 2000). The practice of sowing clover with wheat is also common in southern Australia and the Mediterranean where the nitrogen fixing legumes are used to maintain soil fertility (Vink, 1983; Fraser, 1992). In Europe intercropping was widespread before the start of the agricultural revolution (1750-1900) (Matson *et al.*, 1997; Cassman, 1999), but increased mechanization has meant that the intercropping has long been neglected. However, the potential of intercropping as a cropping system has become of increased interest to European researchers as it represents a potentially environmentally-friendly management method, particularly in the context of organic farming systems (Jensen, 2006).

The most widely cited advantages of intercropping are: 1) increased yield (Anil *et al.*, 1998; Sullivan, 1998; Altieri, 1999); 2) improved soil cover and nutrient retention (Jensen, 1996; Barbosa, 1998; Altieri, 1999; Zhang and Li, 2003); 3) increased stability of production (Barbosa, 1998; Altieri, 1999); 4) minimization of risk to the environment and cost of production (Barbosa, 1998); 5) reduced disease incidence (Barbosa, 1998, Altieri, 1999); 6) efficient use of labour (Barbosa, 1998); 7) intensification of production with limited resources (Sullivan, 1998; Altieri, 1999); and 8) maximization of returns under low levels of technology (Barbosa, 1998; Altieri, 1999; Sullivan, 1998). One potential benefit associated with intercropping that has received increased attention over recent years has been its use as a strategy for crop protection against insect pests (Andow, 1991; Altieri, 1994; Coll and Bottrell, 1995; Barbosa, 1998; Symondson *et al.*, 2002; Aquilino *et al.*, 2005; Ponti *et al.*, 2007; Fiedler *et al.*, 2008; Khan *et al.*, 2008). For example, Sekamatte *et al.* (2003) showed that plant diversity caused a significant reduction in termite attack. In addition, Letourneau *et al.* (2011) reported postive effects of plant diversification on pest management based on a meta-analysis of 522 experiments. It has been suggested that intercropping can potentially be used to enhance natural enemy abundance and diversity (the natural enemies hypothesis) or cause a reduction in the concentration of pest food, thus reducing their numbers (the resource concentration hypothesis), or indeed, both (Andow, 1991). These two hypotheses will be discussed in more details below.

Resource concentration hypothesis (Root, 1973): A number of empirical and theoretical studies have suggested that the attraction and accumulation of specialized herbivores may be increased in crop monocultures as these systems concentrate key resources required by these species (Andow, 1991). Conversely, the visual and chemical stimuli in polycultures, resulting from both host and non-host plants will result in a reduction in the rate at which herbivores are able to colonize, and will also reduce their subsequent searching behaviour for host plants within these diverse habitats (Risch *et al.*, 1983; Altieri, 1993).

Natural enemies hypothesis (Root, 1973): The preservation of resident natural enemy populations within crops combined with management to enhance their abundance and activity, represents a fundamental tenet of conservation biological control (Khan *et al.*, 2008). Intercropped systems tend to provide preferable microclimatic conditions and increased availability of food sources (including secondary invertebrates, as well as prey, pollen and nectar) for predatory invertebrates (Barbosa, 1998). As a result, colonization rates and population size of natural enemies are expected to be larger in these systems than in monocultures (Vandermeer, 1989; Andow, 1991). Note that while predatory invertebrates feed predominantly on other invertebrates, nectar and pollen are often utilized and can provide key resources for some species (Treacy *et al.*, 1987; Bugg *et al.*, 1989). For this reason, Root (1973) hypothesized that the probability of suppressing herbivore populations by generalist and specialist natural enemies would be greater in polycultures than monocultures; often called the 'natural enemies hypothesis' (Root, 1973; Russell, 1989; Andow, 1991).

In addition to the predictions of these two hypotheses, the diversity-stability hypothesis also has implications for benefits in terms of pest control associated with intercropping management practices. This hypothesis suggests that pest control in annual polycultures is more stable than in monocultures as polycultures provide increased diversity of resources, and can therefore support a higher diversity of natural enemies. These resources include: 1) alternative hosts or prey at times of host scarcity on a primary crop; 2) food resources for adult parasitoids and predators, for example nectar and pollen (Treacy *et al.*, 1987; Bugg *et al.*, 1989; Barbosa, 1998; Coll and Bottrell, 1995); 3) refuges for overwintering adults and juvenile stages (Altieri, 1991; Andow, 1991; Altieri, 1999). These allow polyculture systems to increase the number of trophically interacting species. This, therefore, should increase the collective ability of these natural enemy communities to maintain their abundances and so exert top down control on pest populations (Barbosa, 1998, Altieri, 1999). A meta-analysis of polyculture vs. monoculture comparisons confirms that in most cases polycultures do increase natural enemy species diversity (Andow, 1991).

The main objective of this study was to examine the effects of cereal-legume intercropping, with different seed sowing rates, on the abundance of herbivores and predator communities under two contrasting management systems (i.e. conventional and organic farmlands). The study expected the following two effects of intercropping upon pest and enemy abundances: 1) intercropping systems will have negative effects on the abundance of key wheat and faba bean pests; 2) there will be greater numbers of predatory insects where intercropping is used, as suggested by the natural enemies hypothesis.

2. MATERIALS AND METHODS

2.1 Experimental design:

The effect of cereal-legume intercropping on the abundance of invertebrates was studied from April 19th to September 10th 2007 in two separate experiments using organic and conventionally managed experimental plots respectively, at the Crop Research Unit, Sonning Farm, University of Reading, UK (0°54'W, 51°29'N). The effect of intercropping regimes on invertebrate and pest populations was investigated using a single replicated treatment with four levels, including the two monocultures and two different sowing rates of faba bean and wheat combination (described below).

Although the design for each experiment was identical, one experiment was undertaken under conventional farming management, i.e. received nitrogen fertilizer, herbicide and fungicide applications, while the second was managed organically and did not receive any inputs. For the conventional cropping system, nitrogen fertilizer at 200 kg/ha in the form of ammonium nitrate was applied at seedbed preparation. Also, the pre-emergent herbicide Pendimenthalin (Makhteshim Agan Ltd, UK) was incorporated into the plot soils at seedbed preparation to control weeds, while Tebuconazole and Chlorothalonil fungicides were sprayed at flag leaf emergence for disease control. The organically managed plots were sited on an adjacent field which had been managed for three years as a clover ley prior to treatment establishment. This effectively created two stand alone experiments. As each of these experiments was not replicated across multiple fields and separated spatially they were treated separately in subsequent analyses. For each separate experiment the effect of intercropping with four treatment levels was investigated. The first two levels of this treatment were intercrops defined as: 1) a conventional sowing rate of winter wheat (*Triticum aestivum* L. var. Malacca) (200 seeds/m^2) and faba bean (*Vicia faba* var. Hobbit) (40 seeds/m^2), and 2) a half sowing rate of winter wheat *T. aestivum* (100 seeds/m^2) and faba beans (20 seeds/m^2). Those two intercrop systems were compared with the remaining two levels of the treatment representing two controls, one of winter wheat sown at a standard rate of 200 seeds/m^2, and the second of faba bean sown at a standard rate of 40 seeds/m^2. These represented the more conventional monoculture approach of growing these two crops. Replication for the intercropping treatment differed between the different overall management types. The intercropping treatment was replicated within three blocks in the organic field (n=12) and six blocks in the conventional field (n=24). Within each block individual experimental plots were 16 × 2 m in size and were separated from adjacent plots by uncultivated borders of 0.6 m. Each block was separated from the next block by 2.5 m, and within each block treatment levels were allocated at random to experimental plots. The experimental design of this study can be summarized as: two systems (organic vs. conventional) × 4 crop treatments. This 2 × 4 experimental design was replicated in either 3 blocks in an organic field or 6 blocks in a conventional field. Wheat and faba bean, in monoculture or intercrop plots, were planted on 2nd November 2006 at a spacing of 25 cm within rows and 16 rows per plot of each crop, while 8 rows of each were planted in combined plots. The experimental plots were designed to reflect real field conditions however the constraint of available land meant that they were small and close together.

2.2 Invertebrate sampling protocol:

Throughout the cropping season from April until September the abundance of a suite of families and species was monitored every three weeks. Species were identified to either family or species level depending on their perceived importance as either pests or natural enemies. Firstly, the following groups of key pests of wheat and/or faba bean were identified and counted: 1) Aphid herbivores (Homoptera: Aphididae), the abundance of cereal aphids of the following species were monitored (*Metoplophium dirhodum* Walk., *Sitobion avenae* F. and *Rhopalosiphum padi* L.), black bean aphid (*Aphis fabae L.), green peach aphid (Myzus persicae* Sulzer*)*, cowpea aphid (*Aphis craccivora* Koch. and the pea aphid (*Acyrthosiphon pisum* Harris) separately; 2) the abundance of Curculionidae, Chrysomelidae and Elateridae phytophagous beetles was monitored. Secondly, a suite of natural enemies was monitored. The abundances of spiders (Araneae), ground beetles (Carabidae: Coleoptera) and rove beetles (Staphylinidae: Coleoptera) were monitored as representatives of soil surface active generalist predators. The following aphid-specialising natural enemies were also monitored: *Coccinella septempunctata* L. (Coleoptera: Coccinellidae), *Adalia bipunctata* L. (Coleoptera: Coccinellidae), larval stages of both Coccinellidae and adult Chrysopidae. The abundance of the following foliage active generalist predators was also recorded: *Geocoris spp* (Heteroptera: Lygaeidae), *Repipta* spp. (Heteroptera: Lygaeidae), Cantharidae (Coleoptera) and Nabidae (Hemiptera). These invertebrates were sampled using the following methods:

2.2.1 Hand searching:

This technique was used to investigate and count both foliage-dwelling pests (i.e. aphid herbivores and phytophagous beetles) and foliage-dwelling predators (aphid specialising natural enemies and foliage active generalist predators) in the organically managed crops only. Where both species of intercrop plant were present 30 random tillers/plants of each species were examined, although for the monoculture control plots 60 random tillers/plants of each species were selected within each experimental plot. This is because 60 random tillers were found to be the maximum that could be hand-searched in the available time for each plot. On each tiller/plant foliage-dwelling insects were visually counted and recorded. This was carried out every three weeks and the abundances of invertebrates were summed over seven multiple sampling dates. In addition to the groups listed above, spiders were also counted using this method.

2.2.2 Pitfall trapping:

Ground-dwelling predatory insects including ground beetles, rove beetles and spiders were assessed at three week intervals by the use of two pitfall traps (8.5-cm-diameter × 13-cm-deep) in each experimental plot. One of the traps was located in the central area of each plot, while the second was placed about 10 cm from the margin of the plot. Pitfalls contained water with a small quantity of unscented detergent to reduce water tension (to prevent escape from water surface) and were left open for three days. Sampling was conducted in the organic plots from April to September 2007 (totalling 7 samples), and in the conventional plots from June to September of the same year (totalling 4 samples). After three days pitfall traps were collected and returned to the laboratory for subsequent storage and sorting. The collected insect predators were counted and identified to family level. As ground beetles respond well to environmental changes, have well documented natural histories and relatively simple to identify (Woodcock *et al.*, 2003), they were identified to species level. Activity-density (Thiele, 1977 reviewed by Woodcock, 2004) is a concept which suggests that the rate of capture of invertebrates will be proportional to the interaction between their density and activity. Hereafter the number of all pitfall-collected invertebrates will be referred to as activity-density.

2.3 Statistical analysis:

Before performing analyses, count data were transformed using ln (N+1) to obtain homogeneity of variances (Gomez and Gomez, 1984). Data were analyzed using analysis of variance (ANOVA) procedures within the R project for Windows version 2.10.0 (The R Foundation for Statistical Computing, version 2.6.0, 2007). In all cases, the abundances of invertebrates of a particular collection technique were summed for a particular experimental plot and across the sampling dates. Each ANOVA contained the intercropping treatment (with 4 levels) as a fixed effect, while block was included as a covariate random effect. Organic and conventional fields were analyzed separately. To compensate for the repeated use of ANOVAs, Bonferroni corrections were applied, leading to the setting of a new significance value at P= 0.002. However, the standard significance level (P= 0.05) was also presented in this study. This is because the standard significance level was used to look for biologically realistic responses, while Bonferroni corrections were used to examine whether the responses are rigorous and valid under this very conservative statistical approach (Moran, 2003). Where significant treatment differences were detected, *post hoc* Tukey tests (R Project, 2010) were performed to identify differences in treatment means. In addition, regressions were run in R version 2.10.1 (R Project, 2010) to determine the relationship between the total predator numbers and the total pest numbers as two explanatory variables. This was also separately done to test the relationship between predator numbers and the total of aphid species.

ANOVA was also used to identify the responses of individual ground beetle species to the intercropping treatments using the same model structure described above. Only ground beetles, which represented the top 95% of the total abundance of all species, were included in this analysis. This reflected the possibility that rare species trapped within experimental plots may not have been directly using them as a habitat, but may simply have been dispersing though them (Woodcock *et al.*, 2003). As before, Tukey's tests were used to identify differences in treatment means when significant treatment differences were found.

3. RESULTS

3.1 Effect of intercropping on the abundance of both aphid herbivores and phytophagous beetles:

3.1.1 Aphid pest species:

The total cumulative abundance of *M. dirohdum, S. avenae* , *R. padi*, *A. fabae*, *A. craccivora* and *A. pisum* did not differ significantly between monoculture and polyculture plots at the standard significant level (P < 0.05) in the organically managed field (Table 1). However, the effect of the crop treatments on the mean abundance of *M. persicae* in the organically managed field was highly significant (Table 1), and this remained significant when Bonferroni corrections were applied. The mean abundance of *M. persicae was significantly lower in the bean monoculture than* the full sowing rate intercropping plots (P = 0.03) and half sowing rate intercropping plots (P = 0.02). Note, however, that both of these results were not statistically significant when Bonferroni corrections were applied. *However, there was no significant difference between* the full sowing rate intercropping plots and half sowing rate intercropping plots (P = 0.98) on the mean abundance of *M. persicae* .

3.1.2 Phytophagous beetles:

Intercropping treatments significantly affected the mean abundance of Curculionidae adults and both adult and larval stages of Chrysomelidae in the organically managed field (Table 1). However, only the abundance of *Curculionidae* adults remained significant when Bonferroni corrections were used (Table 1). The abundance of Curculionidae did not significantly differ between the full sowing rate intercropping plots and half sowing rate intercropping plots. In monoculture plots, the abundance of Curculionidae was higher in bean plots than wheat plots (P = 0.002). Similarly, Curculionidae abundance was higher in full sowing rate intercropping and half sowing rate intercropping plots than wheat monocultures (P= 0.001 and P = 0.002 respectively).

3.1.3The impacts of intercropping on the abundance of predatory invertebrates:

Specialist aphid predators:

Cereal-legume intercropping positively affected the mean abundances of Chrysopidae adults and *C. septempunctata* within the organically managed field (Table 1). However, there was no evidence that intercropping significantly affected the abundance of either Chrysopidae adults or *C. septempunctata* when Bonferroni corrections were applied (Table 1). The total cumulative abundance of *A. bipunctata* and larval stages of Coccinellidae did not significantly differ between the monoculture and intercropping plots within the organic farming system (Table 1).

3.1.4 Foliar active generalist predators:

Intercropping treatments had a positive effect on the mean abundances of *Geocoris spp.* and *Repipta spp*. within organic systems (Table 1). However, only the mean of *Geocoris spp.* remained significant when Bonferroni corrections were applied (Table 1). The mean abundance of *Geocoris spp.* was higher in the intercropping treatments compared with monoculture treatments. Multiple comparisons tests showed that *Geocoris spp.* were more abundant in the half sowing rate intercropping plots than either wheat (P = 0.003) or bean (P = 0.003) monocultures. Similarly, *Geocoris spp.* abundance was also higher in the full sowing rate intercropping plots, compared with both the wheat (P = 0.05) and bean (P = 0.05) monoculture plots. However, *Geocoris spp.* abundance did not significantly differ between the full sowing rate intercropping and the half sowing rate intercropping plot (P = 0.10). The abundance of Nabidae and Cantharidae were not significantly affected by the intercropping treatments within the organic farming system (Table 1).

Table 1: F-values of ANOVA tests of the effects of intercropping treatments on the abundances of pests and predators and their transformed means and standard errors (±SE) of means under the organic system. For F values *= significant at P < 0.05, **= significant using Bonferroni Corrections; N = non significant. Abbreviation: wheat= wheat monoculture, bean= bean monoculture, Half intercrop = 50:50 sowing rates of intercrop and Full intercrop= 100:100 sowing intercrop.

Pest and predator abundance	F values	Mean ± SE			
		Wheat	**Bean**	**Half intercrop**	**Full intercrop**
Aphid species					
M. dirhodum	$F_{3,6}$= 0.07 N	1.19 ± 0.39	0.37 ± 0.45	0.77 ± 0.57	0.96 ± 0.17
S. avenae	$F_{3,6}$= 1.34 N	3.36 ± 0.03	0.23 ± 0.28	2.61 ± 0.99	2.34 ± 0.99
R. padi	$F_{3,6}$= 0.39 N	1.87 ± 0.86	0.23 ± 0.28	1.44 ± 0.92	2.13 ± 0.33
A. fabae	$F_{3,6}$= 3.04 N	0.00 ± 0.00	2.67 ± 2.98	2.90 ± 0.73	3.13 ± 2.20
M. persicae	$F_{3,6}$= 12.81**	0.54 ± 0.66	2.76 ± 0.22	3.30 ± 0.22	3.31 ± 0.19
A. craccivora	$F_{3,6}$= 0.45 N	0.00 ± 0.00	0.00 ± 0.00	0.23 ± 0.28	0.37 ± 0.45
A. pisum	$F_{3,6}$= 5.04 N	0.00 ± 0.00	2.06 ± 0.16	1.56 ± 0.57	0.88 ± 0.70
Phtophagus beetles					
Curculionidae	$F_{3,6}$= 25.57**	2.23 ± 0.41	4.06 ± 0.12	4.19 ± 0.12	4.30 ± 0.09
Chrysomeloidae larvae	$F_{3,6}$= 5.08*	2.39 ± 0.13	1.13 ± 0.32	2.51 ± 0.29	2.82 ± 0.39
Chrysomeloidae adult	$F_{3,6}$= 5.18*	3.14 ± 0.19	3.22 ± 0.11	3.58 ± 0.25	3.67 ± 0.27
Elateroidae	$F_{3,6}$= 1.27 N	0.46 ± 0.28	0.00 ± 0.00	0.83 ± 0.17	0.60 ± 0.39
Specialist predator					
C. septempunctata	$F_{3,6}$= 5.28*	2.00 ± 0.38	1.43 ± 0.45	2.19 ± 0.36	2.41 ± 0.27
A.bipunctata	$F_{3,6}$= 1.00 N	0.00 ± 0.00	0.23 ± 0.28	0.23 ± 0.28	0.23 ± 0.28
Coccinellidae larvae	$F_{3,6}$= 0.55 N	0.00 ± 0.00	0.23 ± 0.28	0.23 ± 0.28	0.00 ± 0.00
Chrysopidae adults	$F_{3,6}$= 10.52*	0.00 ± 0.00	0.00 ± 0.00	0.23 ± 0.28	0.23 ± 0.28
Foliage-predators					
Geocoris spp.	$F_{3,6}$= 18.87**	2.16 ± 0.34	2.16 ± 0.05	2.94 ± 0.19	2.60 ± 0.33
Repipta spp.	$F_{3,6}$= 6.52*	2.02 ± 0.15	2.43 ± 0.21	2.60 ± 0.23	2.80 ± 0.05
Cantharidae	$F_{3,6}$= 1.20 N	1.36 ± 0.42	0.83 ± 0.17	1.44 ± 0.21	1.88 ± 0.17
Nabidae	$F_{3,6}$= 2.11 N	1.73 ± 0.07	1.87 ± 0.32	2.51 ± 0.65	2.67 ± 0.32
Ground- predators					
Spiders	$F_{3,6}$=119.16**	3.81 ± 0.05	4.02 ± 0.08	4.81 ± 0.04	4.67 ± 0.02
Ground beetles	$F_{3,6}$= 21.88**	2.92 ± 0.09	3.88 ± 0.28	4.10 ± 0.04	4.20 ± 0.14
Rove beetles	$F_{3,6}$= 12.26**	3.53 ± 0.23	4.34 ± 0.08	4.70 ± 0.07	4.84 ± 0.19

3. 2 The soil surface-active generalist predators:

The cereal-legume intercropping system increased activity densities of Araneae, Carabidae and Staphylinidae compared with monocultures within the organic managed plots (Table 1). In addition, all these results were significant when Bonferroni corrections were applied (Table 1). The activity densities of Araneae, Carabidae and Staphylinidae were higher in the full sowing intercropping plots, compared with wheat monoculture: (P < 0.0001), (P = 0.002) and (P = 0.006), respectively. Similarly, the mean activity density of Araneae was higher in the full sowing intercropping plots than bean monoculture (P < 0.0001), but this was not the case for either Carabidae (P= 0.49) or Staphylinidae (P = 0.31. The half sowing rate intercrop treatment had greater activity densities of Araneae (P < 0.0001), Carabidae (P= 0.002) and Staphylinidae (P = 0.01), compared with wheat monoculture. In addition, the mean activity density of Araneae was higher in the half sowing rate intercrop plots than bean monoculture plots. However, the mean activity densities of Carabidae (P = 0.50) and Staphylinidae (P = 0.62) did not significantly differ between the half sowing rate intercrop plots and bean monoculture plots. Moreover, the two different intercropping systems (full and half sowing rates) did not differ in their impact on the mean activity densities of Araneae (P = 0.26), Carabidae (P = 1.00) and Staphylinidae (P = 0.90).

The intercropping treatments did not significantly affect the total cumulative activity density of the ground-dwelling predators within the conventional farming system (i.e. Araneae ($F_{3.15}$ = 3.106, P = 0.06), Carabidae ($F_{3.15}$ =0.138, P = 0.936) and Staphylinidae ($F_{3.15}$ = 2.061, P = 0.146).

3.3 Effects of intercropping on the relationship between pests and their natural enemies:

The total predator numbers were positively correlated with total pest numbers under organic managed plots ($F_{1,10}$ = 29.24, P < 0.001) (Fig. 1 A). However, there was a positive marginally significant correlation between total predator numbers and total aphid species within the organic farming system ($F_{1,10}$ = 4.01 P = 0.07) (Fig. 1 B).

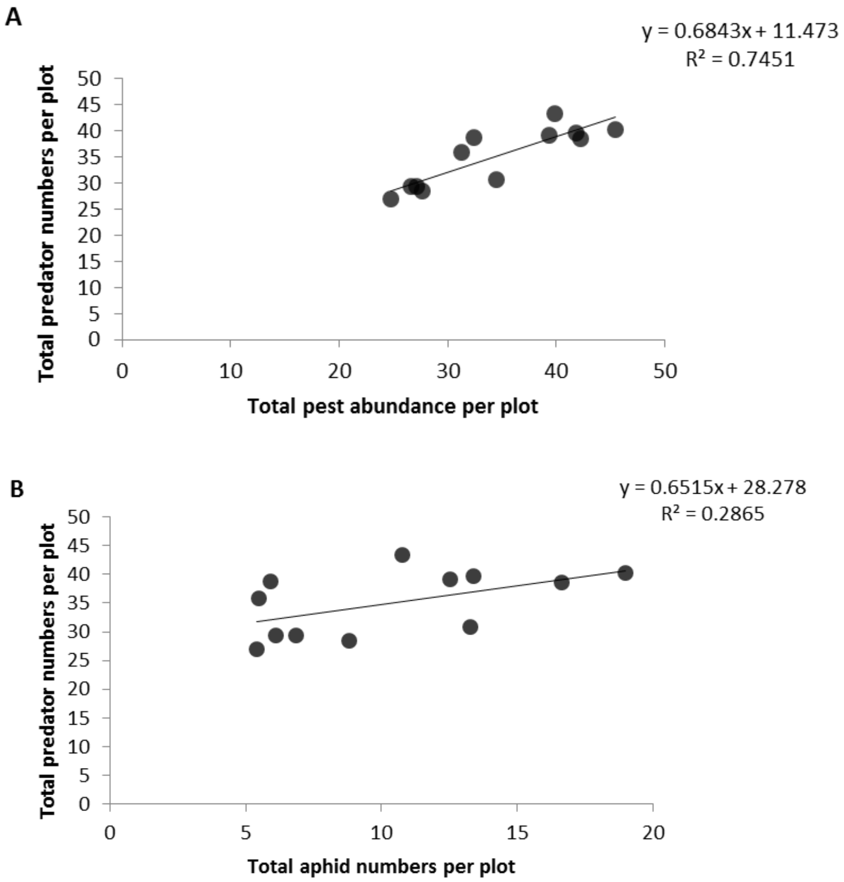

Fig. 1: The relationship between the total abundance of predators and: A) Total abundance of pests; B) Total abundance of aphids only.

3.4 Effects of intercropping on activity density and species richness of Carabidae:

A total of 2260 individual ground beetles from 40 species were collected by pitfall trapping from the two different fields. Ten species represented the top 95% abundance of all individuals across both organic and conventional managed plots (Table 2). Of these 10 species, *Pterostichus cupreu*s was the most abundant (Table 2). Intercropping treatments significantly affected the activity densities of three species, *Pterostichus madidus* ($F_{3,6}$ = 10.70, P = 0.008), *Harpalus aeneun* ($F_{3,6}$ = 5.02, P < 0.05) and *Calathus fuscipes* ($F_{3,6}$ = 6.92, P < 0.05), under organic system only . The activity density of *P. madidus* was higher in half sowing rate than full sowing rate intercropping plots (P < 0.05), but this was not the case for either *C. fuscipes* (P = 0.32) and *H. aeneun* (P = 0.84). However, *H. aeneun* was significantly higher in the wheat than bean monocultures (P < 0.05), while the activity densities of both *P.madidus* (P > 0.05) and *C. fuscipes* (P> 0.05) did not differ between wheat and bean monoculture plots. The activity density of *H. aeneun* was higher in the bean monoculture than intercropping plots (P < 0.05), whereas *P.madidus* was more abundant in intercropping plots than bean monoculture (P < 0.05) . In addition, *C. fuscipes* was likely to be more abundant in intercropping plots than wheat monocultures (P < 0.05). In contrast, the species richness of ground beetles (Carabidiae) did not differ significantly between monoculture and polyculture plots under conventional farming system (Table 2).

Table 2: Response of the activity-density (transferred mean and standard errors (±SE)) of the 10 most common ground beetles to the intercropping treatments in the two different fields (organic and conventional farming systems). Where: P represents the P values for the species with *= significant at P < 0.05 and n= not significant at P > 0.05.

	Fields										
	Organic farming system					Conventional farming system					
Species	Wheat only	Half-intercrop	Full-intercrop	Bean only	P	Wheat only	Half-intercrop	Full-intercrop	Bean only	P	Total N
Pterostichus cupreus	3.51 (0.30)	3.54 (0.17)	4.10 (0.15)	3.80 (0.10)	n	1.14 (0.26)	1.24 (0.30)	0.80 (0.31)	0.92 (0.35)	n	574
Pterostichus madidus	2.87 (0.06)	3.25 (0.16)	2.61 (0.06)	2.67 (0.18)	*	1.21 (0.14)	1.40 (0.19)	1.16 (0.28)	1.00 (0.35)	n	270
Harplus aeneun	2.86 (0.14)	2.60 (0.25)	2.31 (0.32)	1.34 (0.44)	*	1.50 (0.20)	1.27 (0.27)	1.15 (0.16)	1.50 (0.31)	n	211
Harplus rufipes	1.94 (0.10)	2.03 (0.05)	1.16 (0.28)	1.34 (0.82)	n	2.76 (0.22)	2.95 (0.38)	2.80 (0.24)	3.12 (0.23)	n	548
Amara aenea	1.69 (0.25)	1.11 (0.71)	1.25 (0.45)	0.69 (0.00)	n	0.12 (0.13)	0.12 (0.13)	0.23 (0.16)	0.00 (0.00)	n	39
Amara similata	1.39 (0.00)	1.46 (0.57)	1.57 (0.23)	1.57 (0.54)	n	0.53 (0.28)	0.69 (0.20)	0.65 (0.16)	1.06 (0.20)	n	80
Amara bifrons	1.29 (0.12)	0.46 (0.28)	0.46 (0.57)	1.10 (0.00)	n	0.91 (0.17)	0.78 (0.19)	1.31 (0.37)	0.97 (0.33)	n	73
Nebria brevicollis	1.13 (0.81)	1.36 (0.18)	2.21 (0.20)	2.23 (0.44)	*	0.12 (0.13)	0.12 (0.13)	0.23 (0.16)	0.30 (0.21)	n	81
Bembidion lampros	0.83 (0.64)	1.23 (0.34)	1.19 (0.12)	0.77 (0.57)	n	0.92 (0.35)	0.35 (0.26)	0.30 (0.21)	1.13 (0.34)	n	63
Calathus fuscipes	0.92 (0.28)	1.52 (0.17)	1.19 (0.39)	0.96 (0.17)	n	1.46 (0.29)	1.88 (0.20)	1.76 (0.23)	1.98 (0.25)	n	167

In summary, cereal-legume intercropping positively affected the abundance of four pest groups under the organic farming system (*M. persicae*, Curculionidae, Chrysomeloidae adults and Chrysomeloidae larvae) (Table 1). In addition, there was evidence of positive effects of intercropping on the abundance of several generalist predators including: *C. septempunctata*, Chrysopidae adults, *Geocoris spp.*, Araneae, Carabidae and Staphylinidae under organically managed plots (Table 1). However, the abundances of spiders, ground beetles and rove beetles were not affected by cereal-legume intercropping under conventional farming systems. As hand searching was not used in this system and the soil surface-active generalist predators showed no significant response to the intercropping treatments, data for the invertebrates in the conventional system have not been presented.

4. DISCUSSION

The study predicted that herbivore abundance would be lowest under wheat-faba bean intercropping systems. This prediction was based on the more floristically diverse intercropping regimes supporting a higher abundance of natural enemies that would prey on the herbivores (natural enemies hypothesis); and a reduction in the capacity of the herbivores to find their host plant in polycultures (resource concentration hypothesis) (Root, 1973). In the present study, there was some evidence supporting the natural enemies hypothesis but not for the resource concentration hypothesis. It was shown that intercropping systems resulted not only in an increase in natural enemy abundances, but also in the abundance of the herbivores. In addition, the results showed a positive relationship between herbivores and predators, suggesting that predators were more abundant in intercropping systems as a consequence of seeking herbivores rather than searching for beneficial factors such a suitable microclimate and supplementary food resources which are provided by intercropping as it has been suggested by natural enemies hypothesis.

Although the three common species of cereal aphid (*M. dirhodium, S. avenae* and *R. padi*) and black bean aphid (*A. fabae*) (as specialist herbivores on wheat and faba bean, respectively) were the main target herbivores of the study, their abundances were somewhat low. This was possibly the result of adverse weather conditions (heavy rain) during the experiment which may have limited their colonization and subsequent population growth (Karley *et al.*, 2004; Ostman *et al.*, 2003; Plantegenest *et al.*, 2001). This might be the major reason that their total abundance did not differ significantly between the treatments in the field sites. However, the abundances of *M. persicae* and phytophagous beetles of the family Curculionidae were positively affected by intercropping regimes under organic management systems. The finding of increased numbers of *M. persicae* and Curculionidae within intercropping was not in conflict with the resource concentration hypothesis. This hypothesis suggests that the visual and chemical stimuli in polycultures will reduce the subsequent searching behaviour of specialist pests to find their host plants within these diverse habitats (Root, 1973). Green peach aphids (*M. persicae*) (Annis *et al.*, 1981) and Curculionidae (Jones *et al.*, 2007) are generalist herbivores which use many host plants and non-host plants, including weeds. Thus, the resource concentration hypothesis is not relevant to these herbivores. In this study, increased generalist herbivores (abundance or richness) within intercrops could possibly be attributed to the occurrence of uncultivated weed species, which were more prevalent in intercropped plots in the organic field. It is likely that many of these weeds were providing alternative resources (food or refuges) for herbivores (Risch *et al.*, 1983; Capinera, 2005). The results of the study were in agreement with other studies which indicated that generalist herbivores were positively affected by crop diversification (Bukovinszky *et al.*, 2004; Schellhorn and Sork, 1997; Andow, 1991; Bukovinszky *et al.*, 2007). Two questions, thus, arose: firstly, why did other generalist aphids (such as pea aphids and cowpea aphids) not respond to the uncultivated crops (weeds) to the same extent in both monocultures and polycultures? Secondly, why did predatory species not suppress herbivores in the intercropped plots, even though the natural enemy hypothesis predicts that predators will be more effective in polyculture systems (Root, 1973; Andow, 1991; Coll and Bottrell, 1995; Symondson *et al.*, 2002; Janssen *et al.*, 2007; Miyasthita and Takada, 2007)? This could be attributed to the uncultivated crops (weeds) within agro-ecosystems supporting the development of herbivores or predators tending to feed on food resources (i.e. pollen and nectar) which are provided by weeds (Coll and Bottrell, 1995; Cortesero *et al.*, 2000; Eubanks and Denno, 2000; Robinson *et al.*, 2008). In addition, these weed species, with faba bean, made the intercropping system more complex in terms of vegetation structure, perhaps obstructing predators searching for herbivores.

The results reported here demonstrate that intercropping wheat with faba bean is associated with significant increases in the abundance of spiders and predatory insects in the organically managed plots. Indeed, higher abundances of predators in the more diverse habitats associated with the intercropping plots were consistent with most of the published literature (van Emden, 1990; Symondson *et al.*, 2002; Andow, 1991; Wratten and van Emden, 1995; Trefas and van Lenteren, 2008). According to the natural enemies hypothesis, this higher abundance of predaceous invertebrates could be due to the intercropping, which increased the abundance of natural enemies by supplying alternative prey, plant resources (pollen and nectar) and suitable microhabitats, hence increasing herbivore suppression (Root, 1973). For example, the generalist herbivores (green peach aphids and Curculionidae) were highly abundant in the intercrop plots, and as such they represented alternative prey for the predaceous invertebrates. This may in part explain the higher abundance of polyphagous predators in intercropped treatments. In addition, extra-floral nectar and floral resources from faba bean (Treacy *et al.*, 1987; Kremen *et al.*, 2004) and weeds (Capinera, 2005) may have made intercropping plots more attractive to predaceous invertebrates, many of which are known to use secondary food resources. Furthermore, plant architecture (Coll and Bottrell, 1996) and different microclimatic habitats, which are created by habitat diversification (Barbosa, 1998), may also have contributed to supporting a higher abundance of predators in the intercropped treatments than the monocultures. The higher abundance of predators within intercropped treatments did not lead to higher herbivore suppression than in the monocultures, because the generalist herbivores (green peach aphids and Curculionidae) were more abundant within intercropped treatments. This could be attributed to the following: 1) the predators supported by intercropped treatments are generalist predators which do not specifically feed on the key pests, but feed generally on all herbivore species present (Coll and Bottrell, 1995); 2) increasing predator diversity may increase opportunities for intra-guild predation between the predators due to discrepancies in their body sizes (Rosenheim *et al.*, 1995); 3) increased vegetation complexity may interrupt the searching activity of predators for herbivores (Coll and Bottrell, 1995).

The study also showed generally higher abundances of ground beetles at the organic site, possibly due to the effect of weed cover (Barbosa, 1998; Sutherland *et al.*, 2006), where weeds may provide a richly structured vegetation, associated favourable microclimates for reproduction and prey abundance, all suitable conditions for ground beetles (Armstrong and McKinlay, 1997a; Barbosa, 1998; Trefas and van Lenteren, 2008). Again, the abundances of the predaceous species *P. madidus* and *C. fuscipes* were positively affected by intercrop regimes which may play a key role in terms of pest regulation (Kromp, 1999). The responses presented are, however, consistent with other studies (Wiech and Wnuk, 1991; Kromp, 1999; Armstrong and McKinlay, 1997b; Armstrong and McKinlay, 1997a; Hummel *et al.*, 2002; Eyre *et al.*, 2009). However, increasing vegetation density may interrupt the mobility of predaceous ground beetle species (Armstrong and McKinlay, 1997b). Therefore, this may explain, in part, why the abundance of *P. madidus* was likely to be greater in half density sowing intercropped treatment than full sowing intercropped plots. This finding was consistent with some studies which found that the foraging behaviour of natural enemies was inhibited in more diverse plant assemblages (Weisser, 1995; Gingras and Boivin, 2002; Gols *et al.*, 2005; Hoddle, 2003; Aquilino *et al.*, 2005; Gingras *et al.*, 2008).

In conclusion, the results showed that cereal-legume intercropping regimes tend to have a greater abundance of both generalist herbivores and predaceous invertebrates in organically managed farmland. However, before any solid advice could be given, this study would need to be repeated on a larger scale with greater separation between individual treatment plots. Results from this experiment did not show any evidence for intercropping reducing the herbivores under organic farming systems, even though predaceous invertebrates were more abundant in this system. However, intercropping systems did not show any effects on either herbivores or predators under conventionally managed plots. This preliminary finding has potential ramifications for the recent UK Government Policy Commission on the Future of Farming and Food which has made recommendations to support the organic sector by offering payments to organic farmers (Hole *et al.*, 2005). However, if the UK Government Policy Commission is going to attempt to rely upon intercropping to promote pest control within organic farming systems, the current study would suggest that intercropping may not work for this type of farming system. Alternatively, the conventional farming system may benefit from intercropping for pest and weed management, although harvesting may still remain a major problem associated with intercropping, especially in grain production (Anil *et al.*, 1998). However, the development of intercropping regimes as a pest management strategy requires knowledge of predator-prey interactions within this system. In addition, the studies in this area have had varying conclusions; some positive, some negative, with others suggesting there to be no effect of multiple predators on pest control (Sih *et al.*, 1998; Polis and Strong, 1996; Duffy, 2003; Ives *et al.*, 2005; Wilby *et al.*, 2005; Casula *et al.*, 2006; Straub *et al.*, 2008; Letourneau *et al.*, 2009). As yet no generalizations have been made in terms of how herbivores and their natural enemies respond to intercropping regimes (Andow, 1991).

5. ACKNOWLEDGEMENTS

Author thanks Dr. Andrew Wilby and Dr. Ben Woodcock for their supervision, objective criticisms and support throughout the duration of this study. Also, I would like to thank Mr. Richard Casebow , Mrs. Rebecca Kiff and Mrs. Stephanie Harris for accessing facilities in the field at the Crops Research Unit, Sonning Farm at University of Reading.

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