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Agri-environment scheme enhancing ecosystem services: A demonstration of improved biological control in cereal crops

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ABSTRACT

The impact of two predatory guilds, epigeal and aerial natural enemies, on levels of cereal aphid control in winter wheat was examined on farms with contrasting proportions of grass margins, one of the most popular agri-environment options in England. In year 1, by 14 d after inoculation the aerial natural enemies alone had caused substantial reductions (88%) in numbers of cereal aphids compared to where no natural enemies were present. In contrast, epigeal predators achieved a 31% reduction, although this reached 88% after 28 d. In year 2, both aerial and epigeal natural enemies achieved over 87% control after 14 d. Aerial natural enemies were largely comprised of predatory Diptera and Linyphiidae (Araneae). Levels of control were positively related to the proportion of linear grass margins within 250, 500 and 750 m radii of the study arenas. There was weaker evidence that hedgerows decreased aphid control by epigeal predators. This study demonstrated that an agri-environment option can be used to improve an ecosystem service on arable farmland.

1. Introduction

Arable crop pests are typically controlled by a range of natural enemies that either reside all year within the field or migrate between the crop and uncropped land. For natural enemies, dispersal occurs as they shift between exploiting the resources within the crop and the uncropped land (Rusch et al., 2010). However, their patterns of dispersal and survival may also be disrupted by agricultural practices within the field and consequently reinvasion is sometimes necessary from outside of the field and its borders. The type and extent of uncropped land acting as a source of recolonising natural enemies can therefore have an impact on biological control at a very local scale, such as in the adjacent crop (Collins et al., 2002), but because many natural enemies are capable of widespread dispersal, also across the landscape (Tscharntke et al., 2007). Likewise some pests are able to exploit the resources of uncropped land and the subsequent level of control is a balance between pest enhancement and predation. There is evidence that biological control is higher in complex compared to simple landscapes (Tscharntke et al., 2007; Östman et al., 2001; Chaplin-Kramer et al., 2011) and there is a positive relationship with the proportion of land in agri-environment schemes, but the level of insecticide use had a negative impact (Geiger et al., 2010). More robust biological control may be expected in complex landscapes as a consequence of species complementarity and niche separation because resources are abundant across a range of scales and a greater range of species are able to exist (Loreau & Hector, 2001). However, this theory is not always supported in practice; the diversity of cereal aphid parasitoids was the same in simple and complex landscapes and it was assumed that the parasitoids could obtain all the necessary resources in simple landscapes (Vollhardt et al., 2008). Levels of biological control may also be mitigated by intraguild predation of natural enemies (Rosenheim, 1998), while pests may be better able to exploit the resources of the uncropped land and so sway the natural enemy:pest ratio in their favour (Baggen et al., 1999). In contrast, within simple landscapes there may be fewer natural enemies allowing pests to escape control more frequently and this may explain why levels of biological control improve when more resources for natural enemies were provided through an increase in uncropped land (Tscharntke et al., 2007).

Agri-environment schemes are in place across Europe and some will provide resources for invertebrates that may subsequently impact on levels of biological control at the field and farm scale, but also across the landscape (Tscharntke et al., 2005; Geiger et al., 2010). Of all the agri-environment options available in England, the establishment of grass margins and flower-rich habitats are likely to have the greatest impact on biological control. Grass margins established as buffer zones around arable fields are proving to be one of the most popular options, with 73,713 ha established by 2009 (Anon, 2009a). The majority of these were established with or

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become dominated by tussock-forming grasses that are known to support high densities of overwintering predatory beetles and spiders. They may therefore be expected to enhance levels of biological control by these generalist predators in adjacent fields (Collins et al., 2002) and across the landscape (Őstman et al., 2001).

In 2005, an interdisciplinary project was started to investigate the impediments to the adoption of biological control in UK arable crops. As part of this study the relative importance of natural enemy diversity and abundance (temporal and spatial) in pest control was examined in cereal-based systems and whether levels of biological control were affected by landscape complexity, but in particular the value of habitats created through agri-environment schemes. Cereal aphids were chosen as the model pest because they are predated and parasitized by a wide range of commonly occurring species, consequently allowing the impact of different natural enemy guilds to be investigated. Moreover, their abundance is simple to manipulate in exclusion experiments.

2. Materials and methods

In 2006, 14 independently managed arable farms located in Dorset and Hampshire, UK were selected with varying proportions of grass margins. Farms ranged from those with just a few fields to having most fields surrounded by grass margins (Figs. S1–4, 7, 8). Of the cropped area the proportion of cereal, broadleaf crops and pasture was approximately 60, 13 and 27% respectively. On each farm, a single field of winter wheat was selected that was sufficiently large to allow a 35 m long transect to be established at 80 m from the crop edge, with the ends of the transect no closer than 80 m from any other boundary. The average size of the chosen fields was 12.4 ha (range 4.5–20.2 ha). The minimum distance between fields on separate farms was 2 km. To compare the impact of different predatory guilds, two replicates of four natural enemy treatments that compared the impact of epigeal and aerial natural enemies on cereal aphids alone and in combination were randomly located along the transect 5 m apart. Each treatment plot was 1 m^2. The four treatments were: (E) epigeal predators only, through exclusion of aerial natural enemies; (F) aerial natural enemies only, through exclusion and removal of epigeal predators; (A) all natural enemies; (N) no natural enemies, through exclusion and removal of epigeal and aerial natural enemies. Epigeal predators were excluded using a plastic ring buried 10 cm deep into the ground and extended 30 cm above the soil surface (treatments F and N). Within each of these plots, two pitfall traps (6 cm diameter, half-filled with a 50% solution of ethylene glycol and detergent) were installed near the plastic ring to remove any arthropods that existed or emerged within the enclosure. Pitfall traps were emptied fortnightly and operated for the duration of the aphid monitoring period. To remove spiders that are less likely to be captured by pitfall trapping within treatments F and N, the base of the plots was sprayed with an insecticide of short persistence (tetramethrin 0.15% and permethrin 0.03%) one day prior to the aphid inoculation. For treatment E, aerial natural enemies were excluded using insect-proof netting. The netting was attached at its base to the plastic ring which was raised approximately 1–2 cm above the ground to allow access by epigeal predators. The netting extended above the crop and was sealed to a central support. Aerial natural enemies in treatment N were excluded using this method with the netting attached to the plastic ring and the ring dug into the ground to exclude epigeal predators. Treatments A and F included a roof of insect netting above the crop covering 1 m^2 to reduce aphid fall-off as a consequence of rainfall. Netting was installed a few days prior to aphid inoculation. In 2006, to test whether the level of infestation was preferentially attracting aphid natural enemies, one cage of each type was infested with either 250 or 500 *Sitobion avenae* on 12 June. In 2007, the study was repeated on 12 of the farms, but in different fields owing to crop rotations and using only one infestation rate of 500 *S. avenae* on 6 June. In each year, the number of cereal aphids and parasitized aphids on 25 tillers per cage was assessed 14 and 28 d after inoculation.

In order to gather information on the identity of the aerial natural enemies, their capture on cylindrical sticky traps was measured at 12 of the sites in 2006 (Oaten et al., 2008). Sticky traps consisting of 2 l clear plastic bottles around which was wrapped an A4-size acetate sheet covered in Tangletrap (The Tanglefoot Co., Grand Rapids, MI, USA). These were positioned above the crop, at eight equally spaced intervals along the interior perimeter of each field, 40 m from the boundary. Traps were changed at weekly intervals and data for the period 14th July until 11th July 2006. In 2007, a parallel transect of six cylindrical sticky traps was established 5 m from the cages in each field and operated during the period of aphid infestation. Epigeal predators were measured in both years using six pitfall traps located between the cages and operated for the aphid infestation period in each field.

2.1. Analysis

The total number of cereal aphids (transformed using $\log_{10}(x+1)$) and the percentage of infested tillers (transformed using arcsine square root) were first analysed for the two sample dates using a repeated measures ANOVA with type of exclusion and infestation rate (2006 only) as factors and blocked according to field. There was always a significant interaction effect ($P < 0.001$) for type of exclusion with time therefore the data were analysed using ANOVA for each date and contrasts to identify differences between the types of exclusion.

Analyses were also conducted to identify whether landscape features were affecting levels of biological control provided by epigeal and aerial natural enemies and whether there were any linear relationships between the type and amount of uncropped land and the levels of cereal aphid control achieved by the aerial and epigeal natural enemies. Because the minimum distance between independently managed experimental fields was 2 km, the habitat areas within a 750 m radius of each transect's central location were included in the analysis. These areas were digitised using a Geographical Information System (GIS) (MapInfo) and all types and areas of uncropped land identified from a combination of farm maps and ground inspections. Categories of uncropped land that were considered important for natural enemies included hedgerows, woodland, grass strips (grass margins or beetle banks), flower-rich areas (pollen and nectar mixes or floristically enhanced grassland). Length and area of these habitats was calculated using GIS. The width of linear habitats, especially grass margins differed therefore the area was used in the models as this best represented the total resource available. For each field and sampling date a General Linear Model was run using the $\log_{10}(x+1)$ transformed number of aphids as response variable and with aerial or epigeal predator presence/absence as binary factors. The regression coefficient for each field then represented the population reduction due to aerial or epigeal predators on a logarithmic scale, and termed 'aerial (epigeal) natural enemies aphid predation index'. A General Linear Model was used to test for relationships between the aerial (epigeal) natural enemies aphid predation index and year (factor), proportion of area covered by grass strips, proportion covered by hedgerows, Shannon indices of uncropped land diversity and crop diversity. Shannon indices were calculated for uncropped land using 12 categories and for crop diversity using 17 crop types (Figs. S5, 6, 9, 10). Correlations between landscape features were examined to check for colinearity. Separate analyses were run for

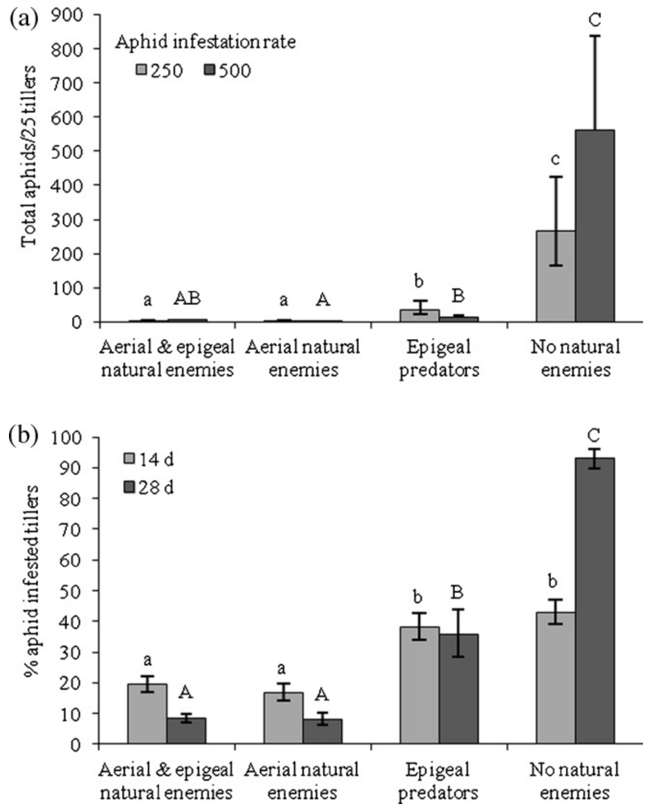

Fig. 1. (a) Mean number (±SE) of cereal aphids per ear (back-transformed), 28 d after inoculation (2006); (b) proportion of cereal aphid infested tillers (±SE) (back-transformed), 14 and 28 d after inoculation (2006). Letters denote significant differences ($P < 0.05$) between each type of exclusion cage on each sampling occasion.

buffer zones of 250, 500 and 750 m radii from the field centre and for each sampling occasion.

3. Results

In 2006, after 14 d, only type of exclusion had a significant effect on the total number of aphids ($F_{3,91} = 37$, $P < 0.001$). In comparison to total exclusion of natural enemies, there were significantly fewer aphids in cages where all enemies (91% reduction) and aerial natural enemies only (88% reduction) had access; epigeal predators alone had no effect on aphid numbers. After 28 d, there was a significant interaction between type of exclusion and level of initial level of aphid infestation ($F_{3,91} = 3$, $P = 0.03$), but a stronger effect for the former alone ($F_{3,91} = 94$, $P = 0.001$). After 28 d all enemies and only aerial natural enemies had reduced the aphids by 99% compared to where there were none, but the epigeal predators alone had also achieved a significant 86 and 98% reduction for the 250 and 500 aphid infestation levels respectively (Fig. 1a). There was a significant difference in the percentage of infested tillers between the types of exclusion at 14 d ($F_{3,91} = 25$, $P < 0.001$) and 28 d after infestation ($F_{3,91} = 95$, $P < 0.001$) and no effects of aphid infestation level or the interaction. After 14 d, there were significantly fewer infested tillers where all enemies or only aerial natural enemies were present compared to where epigeal predators alone or no natural enemies were present (Fig. 1b). Likewise after 28 d, only 8% of tillers were infested where all enemies or only aerial natural enemies were present, significantly fewer than where only epigeal predators were present (35%) or where there were no natural enemies (93% infested tillers).

In 2007, there were significant differences in the total number of aphids between the type of exclusion at 14 d ($F_{3,81} = 32$, $P < 0.001$) and 28 d after infestation ($F_{3,81} = 58$, $P < 0.001$). Compared to where there were no natural enemies, the presence of all enemies and only aerial natural enemies achieved reductions of 93 and 95% respectively, whereas epigeal predators alone achieved a reduction of 85% (Fig. 2a). By 28 d after inoculation where natural enemies were present they reduced aphids by 99% compared to where there were none. The number of infested tillers also differed with the type of exclusion at 14 d ($F_{3,81} = 18$, $P < 0.001$) and 28 d after infestation ($F_{3,81} = 62$, $P < 0.01$) with the same trends occurring as for the number of aphids (Fig. 2b).

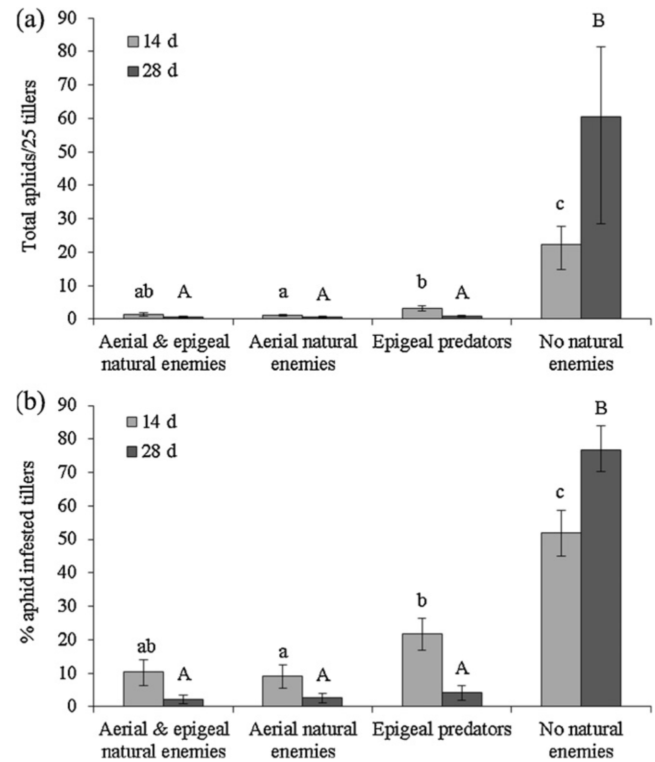

Fig. 2. (a) Mean number (±SE) of cereal aphids per ear (back-transformed) in 2007, 14 and 28 d after inoculation; (b) proportion of cereal aphid infested tillers (±SE) (back-transformed), 14 and 28 d after inoculation. Letters denote significant differences ($P < 0.05$) between each type of exclusion cage on each sampling occasion.

In the exclusion cages where the aerial natural enemies had access, a total of 1107 and 275 aphids were counted in 2006 and 2007 respectively. A further 15 and 16 mummified aphids were counted in 2006 and 2007 respectively giving parasitism levels of 1.3% and 5.8%. Overall the parasitism data was too sparse for analysis.

Significant relationships (36–38% of variance explained by the models) were found between the aerial natural enemies aphid predation index (a more negative coefficient indicates a greater the level of aphid control) and the proportion of grass strips within buffer zones of 250 m, 500 m and 750 m radii after 14 d, indicating the provision of grass strips enhanced aphid control (Table 1 and Fig. 3). The epigeal natural enemies aphid predation index showed a significant relationship (30% of variance explained by the model) with the diversity of the surrounding uncropped land within a 500 m radius, but as the proportion of hedgerows within 500 and 750 m radii increased this had a negative effect on the relationship. The proportion of each buffer zone occupied by grass strips showed a gradation between 0 and 7% in each year (Figs. S1–4, 7, 8). The Shannon indices for uncropped land and crops also showed a similar gradation across the range of values for each year (Figs. S5, 6, 9, 10). There were no significant correlations between any of the landscape variables included in the analysis.

Table 1
GLM model giving proportion of variance from regression and for significant explanatory variables (year, proportion of area covered by grass strips, hedgerows or trees, Shannon indices of uncropped land diversity and crop diversity) their *t* value and significance on aphid predation when aerial or epigeal predators present at 14 or 28 d after infestation.

Days after infestation	250 m	500 m	750 m
Aerial natural enemies			
14 d	36%: grass margins, $t=-2.7$, $P<0.05$	38%: grass margins, $t=-3.4$, $P<0.01$	37%: grass margins, $t=-3.2$, $P<0.01$
28 d	39%: year, $t=2.7$, $P<0.05$	31%: year, $t=3.3$, $P<0.01$	52%: year, $t=3.7$, $P<0.001$
Epigeal predators			
14 d			18%: crop H, $t=-2.1$, $P<0.05$
28 d	12%: year, $t=-2.2$, $P<0.05$	30%: landscape H, $t=-2.7$, $P<0.05$; hedgerows, $t=2.7$, $P<0.05$	22%: hedgerows, $t=2.5$, $P<0.05$

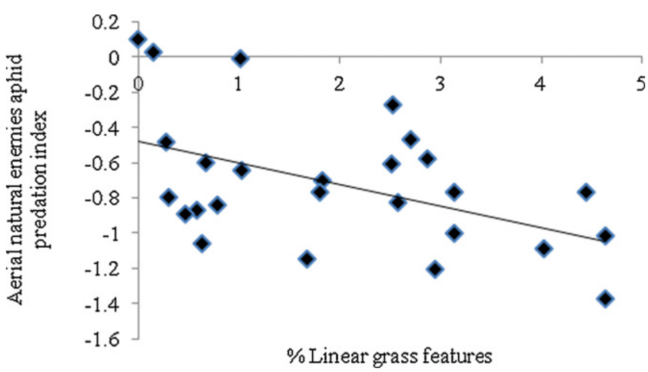

Fig. 3. Relationship between aerial natural enemies aphid predation index and proportion of linear grass margins within 500 m of the exclusion cages. A more negative index indicates fewer aphids.

Table 2
Percentage of each predator taxa captured on sticky traps (aerial natural enemies) or pitfall traps (epigeal predators).

		2006	2007
Aerial natural enemies			
Araneae	Linyphiidae	26.8	21.3
Coleoptera	Cantharidae	6.4	4.6
	Coccinellidae	1.3	0.0
	Staphylinidae	3.4	0.6
Hemiptera	Anthocoridae	0.3	5.2
Diptera	Dolichopodidae	25.4	0.0
	Empididae	14.2	16.7
	Syrphidae	5.4	41.4
	Scatophagidae	0.4	10.3
Neuroptera	Chrysopidae	16.3	0.0
Total number		760	174
Epigeal predators			
Araneae	Lycosidae	3.8	5.7
Coleoptera	Carabidae	71	66
	Staphylinidae	25	28
	Field overwintering	56	49
	Boundary overwintering	36	22
Total number		5860	6136

The aerial natural enemies captured on sticky traps largely comprised predatory Diptera including Syrphidae, Dolichopodidae, Empididae and Scatophagidae (Table 2) although Dolichopodidae were abundant in 2006 but absent in 2007, whereas Syrphidae were more abundant in 2007. Linyphiidae formed approximately a quarter of the aerial natural enemies in both years with Chrysopidae also being relatively abundant (16%) in 2007. In both years the epigeal predators were largely Carabidae, with the remainder Staphylinidae.

4. Discussion

In this study, aerial natural enemies alone were found to be capable of rapid and effective aphid control, whereas epigeal predators had a reduced and slower impact. In previous studies using the same exclusion methodology but naturally occurring aphid infestations, there were additive effects of epigeal and aerial natural enemies (Schmidt et al., 2003; Thies et al., 2011). Where both groups of natural enemies were absent there were 172 or 199% more aphids, compared to aerial ones absent (70 or 90% more aphids) or epigeal predators absent (18 or 28% more aphids). In contrast, in this study and a previous one (Holland et al., 2008) control was attributed mostly to aerial natural enemies alone and may have been a result of the higher aphid infestation levels. The aerial natural enemies, as captured on the sticky traps in this study, were largely comprised of predatory Diptera, Coleoptera and Linyphiidae. The predatory Diptera are sufficiently mobile to actively seek out aphid colonies and of these Syrphidae, being aphidophagous, considered the most effective. The value of other predatory Diptera that were abundant in this study is poorly understood; only Dolichopodidae are known to predate on aphids (Ulrich, 2004). In contrast, the initial distribution of Linyphiidae is determined by air currents although they were found to persist in sites with higher prey abundance (Harwood et al., 2003).

The epigeal predators comprised largely Carabidae and the remainder mostly Staphylinidae. Linyphiidae can also be abundant on the ground, however, pitfall traps are considered to provide an unreliable indication of their abundance (Topping and Sunderland, 1992) and they were not included in the pitfall assessments. The impact of epigeal predators alone was previously examined using vertical barriers and trapping out. Results were highly variable ranging from no impact, attributed to climatic conditions favouring a rapid aphid population increase (Holland et al., 1996), to differences in aphid numbers between exclusion and control plots of up to 2–6 times (Chiverton, 1986) or reductions of 34% (Collins et al., 2002). These latter values are similar to the 31% reduction found in this study in 2006, but in 2007 a 87% reduction was achieved by the epigeal predators after 14 d.

Overall there is ample evidence that Carabidae (Sunderland, 2002), and to a lesser extent other epigeal generalist predatory taxa, consume a wide range of crop pests including aphids. However, they are only considered effective when aphid numbers build up slowly, usually early in the season and before the peak is reached (Chambers et al., 1982). Epigeal predators are also likely to be less effective than aerial natural enemies because when aphids populations start to build up they are already distributed across fields (Holland et al., 2005, 2009) and although they can make small-scale movement to locate their prey (Winder et al., 2005), control is largely dependent on the local abundance. The economic spray threshold for cereal aphids for the growth stage of the crop in this study was 66% of tillers infested, which was exceeded in 2006 and approached in 2007 where there were no predators, otherwise both groups of predators alone or in tandem kept infestations below this level. The control achieved by the epigeal predators was lower and slower compared to the aerial natural enemies, but nevertheless adequate to prevent economic thresholds being exceeded.

Strong relationships were detected between the level of aphid control by aerial natural enemies and the proportion of grass strips in the surrounding 250–750 m. These areas were used by some aerial natural enemies for overwintering, especially Staphylinidae and Linyphiidae (Griffiths et al., 2008), and influence abundances in the adjacent crop (Holland et al., 2009). Staphylinidae were frequently captured in pitfall traps suggesting they disperse at ground level, however, results from this study and that by Oaten et al. (2007) and Oaten et al. (2008) indicated that this may also be by flight given the distances over which relationships were detected and their capture on sticky traps. Empididae were found to occur in natural ground cover (Rieux et al., 1999) but this study revealed that they were foraging more widely.

There was an indication that the presence of hedgerows was reducing the effectiveness of the epigeal predators. This may occur if these habitats provide more favourable resources than the adjacent crop. Not all predators leave their overwintering habitat and field and boundary overwintering species may seek out such features if insufficient food is present in the crop. A third of Carabidae and half the Staphylinidae measured during the winter remained within field boundaries during the summer (Thomas et al., 2000). Likewise, studies of epigeal predator spatial distributions showed higher numbers close to field boundaries (Holland et al., 2005, 2009).

Parasitic wasps are also capable of dispersing across fields, but in this study were unlikely to have been responsible for the aphid control because overall parasitism levels were very low (1.3% and 5.8%), well below the rate of 32–36% under which successful classical biological control has never been reported (Hawkins and Cornell, 1994). Counts of aphid mummies are known to underestimate parasitism but even so the levels recorded here were very low.

5. Conclusion

This study demonstrated the potential to improve an ecosystem service through the use of an agri-environment scheme option. At present agri-environment schemes across Europe are designed to reduce environmental risks, preserve nature and cultivated landscapes, although there is increasing interest in their functional biodiversity including biological control (Geiger et al., 2010). Given the considerable expenditure on agri-environment schemes, nearly 20 billion Euros during 2007–2013 (EC Europa, 2010), the drive for sustainable food security in countries such as the UK (Anon, 2009b) and desire to reduce contamination of off-crop areas with pesticides (Anon, 2007), further effort should be placed into designing and testing agri-environment options that deliver functional biodiversity and preferably multi-functionality.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2012.04.014.

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