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Novel management to enhance spider biodiversity in existing buffer strips

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Running title: Enhancing spiders in existing buffer strips

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Abstract

1. Grass dominated buffer strips have been widely sown to mitigate against intensive agricultural management practices that have negatively impacted on invertebrate and plant biodiversity in arable farming systems. Such strips are typically floristically species poor and dominated by grasses. Here we develop management practices to enhance the floristic diversity of these existing strips to benefit spiders, a key provider of natural pest control in crops.
2. Across three UK arable farms we investigated the benefits of: i) scarification to create germination niches, into which wildflower seeds were sown; ii)the effect of graminicide applications to suppress the dominance of grasses. Spiders were sampled twice per year (July and September) during 2008 and 2009.
3. The treatments which received either scarification with wildflower seeds, or graminicide application, resulted in the greatest wildflower cover and lowest grass cover, with a general trend of increased abundance of adult and juvenile spiders. Abundance of *Pachygnatha degeeri*, *Bathyphantes gracilis* and juvenile wolf spiders of the genus *Pardosa* were positively correlated with wildflower cover, likely reflecting increased prey availability. Sward structure was negatively correlated with *E. atra*, *O. fuscus* and juvenile *Pardosa* abundance.
4. Management that utilises existing commonly adopted agri-environment options, such as grass buffer strips, represent a potentially important conservation tool for increasing the quantity and quality of invertebrate habitats, thereby maximising opportunities for provision of multiple ecosystem services including pest regulation by predators such as spiders. These management practices have the potential to be incorporated into existing UK and European agri-environment schemes.

Keywords: Agri-environment scheme, Araneae, graminicide, wildflowers.

Introduction

Invertebrates are key ecosystem services providers in agro-ecosystems (Power, 2010), supporting pollination (Klein *et al.*, 2007), maintaining soil fertility (Smith *et al.*, 2008) and providing natural pest control (Sunderland, 1999; Denys and Tscharntke, 2002). Many invertebrates also represent an essential dietary component for higher trophic levels, including birds (Vickery *et al.*, 2002). Despite their importance, population declines of invertebrates have been observed in the UK and NW Europe during the latter part of the twentieth century (e.g. Aebischer, 1991). These declines have been widely attributed to the modern intensive arable management practices that have been developed to maximise crop yield (O'Connor and Shrubb, 1986; Meek *et al.*, 2002; Robinson and Sutherland, 2002). For example, increased use of herbicides and fertilisers have caused detrimental effects on many plant species with negative consequences for both predatory and phytophagous invertebrates which rely on plants for food and shelter (Marshall *et al.*, 2003). These management practices have resulted in the creation of arable habitats of low conservation value for invertebrates, plants and birds (Vickery *et al.*, 2002).

Agri-Environment Schemes (AES) are one of the policy instruments developed in response to biodiversity loss in agricultural landscapes and provide financial incentives for environmentally sensitive farming (Ovenden *et al.*, 1998). In the UK the establishment of perennial grass buffer strips as part of AES has achieved wide-scale uptake, with approximately 29,000 ha currently in existence (Natural England, 2009). These strips are typically established by sowing a mixture of grass species such as *Festuca rubra* Linnaeus and *Dactylis glomerata* L. (Defra, 2010). For this reason the strips tend to lack a wildflower component, and are botanically species-poor (Vickery *et al.*, 2002). Introducing wildflowers has the potential to increase their biodiversity value through the provision of foraging resources for pollinating and phytophagous invertebrates (Potts *et al.*, 2007), as well as increasing the architectural structure of the sward for the benefit of predatory invertebrates, such as spiders (Morris, 2000). The competitive strategies of many grasses used in the creation of these areas has meant that attempts to establish wildflowers into existing grass-dominated buffer strips have proved problematic (Blake *et al.*, 2011). Without the creation of germination niches the establishment of wildflowers from seed is unlikely to achieve success (Grubb, 1977). While scarification has been used to create germination niches for plants (Woodcock *et al.*, 2008), many grasses will rapidly colonise scarified ground limiting the effectiveness of this approach. The use of graminicides has the potential to suppress, rather than eliminate, susceptible grasses in existing buffer strips thus providing opportunities for seedling establishment (Westbury and Dunnett, 2008).

Here, we investigate how enhancement of existing grass buffer strips on arable farmland can be used to promote spider abundance and species richness. Spiders are an integral component of arable farmland and have considerable functional importance (Wise, 1993) both as predators of crop pests and as food for higher trophic levels (Denys and Tscharntke, 2002). Spiders also exhibit diverse foraging strategies and are thus capable of utilising different components of the sward (Wise, 1993). For example, web-building spiders exploit tall plants emerging from the sward on which to anchor their webs, whilst families such as the Lycosidae actively hunt on the ground (Dennis *et al.*, 2001). In this study we investigate the impact on spider assemblages of diversifying the floristic composition and structure of existing buffer strips. This will be conducted using two management treatments: (a) scarification to create germination niches into which a perennial wildflower seed mixture can be sown; and (b) the application of a graminicide at different rates and timings to reduce the competitive dominance of the existing grasses. We tested the following predictions: 1) The greatest wildflower cover, and lowest grass cover, will be observed in the treatments receiving scarification with wildflower seeds, and graminicide, and that the presence of both these management treatments will provide the most optimal outcome; 2) Spider abundance and species richness will be greatest when both scarification and graminicide have treatments are present.

Materials and Methods

Study Sites

The study was performed on three arable farms in the UK, two in Berkshire (Aborfield, N51º23'39":W0º55'08"; North Sydmonton, N51º21'31":W1º17'21") and one in Hampshire (Ramsdell, N51º17'29":W1º08'16"). The soil type was gravel over London clay (Aborfield), freely-draining line-rich loam (North Sydmonton), and shallow lime-rich soil over chalk or limestone (Ramsdell). The grass buffer strips were established in the autumn of 2004 (Aborfield and North Sydmonton) and spring of 2005 (Ramsdell) in accordance with the UK's agri-environment scheme regulatory bodysguidelines (Defra, 2010). Typically these margins are established with X species of fine and tussocky grass species, such as *F. rubra* and *D. glomerata*, at a rate of 20 kg ha^{-1}. The strips were situated adjacent to fields cropped in rotation with winter wheat, winter barley, oilseed rape and winter beans (Aborfield), and winter wheat and winter barley (North Symonton and Ramsdell) since 2007. Prior to the start of experimental manipulations, buffer strips at all sites were managed by cutting once per year in the autumn. All farms were managed conventionally utilising inorganic fertilisers and pesticides.

Experimental Design

The study was initiated in spring 2008 at all sites, when ten management treatments were established on the outer 4 m (i.e. adjacent to the crop) of the existing 6 m grass buffer strips (Table 1). Treatment 1 was the control and represented the existing buffer strip (established in 2004/2005 and receiving no subsequent experimental management or seed addition). The remaining nine treatments received two different management practices, applied either alone or in combination. These management practices were: a) wildflower seeds (treatments 2-8); b) graminicide application differing in rate and timing (treatments 3-10).

Treatments 2-8 were scarified to a depth of approximately 5 cm using a power harrow. This was undertaken in March 2008 and created approximately 60 % bare ground. A wildflower seed mixture was then sown at a rate of 2.4 kg ha^{-1}, using a battery-operated WE-B Universal Hand Power Spreader (Wolf-Garten, Betzdorf, Germany). The wildflower species were *Achillea millefolium* L. (sowing rate 0.04 kg ha^{-1}), *Centaurea nigra* L. (0.50 kg ha^{-1}), *Galium verum* L. (0.10 kg ha^{-1}), *Leucanthemum vulgare* Lamarck (0.10 kg ha^{-1}), *Lotus corniculatus* L. (0.40 kg ha^{-1}), *Plantago lanceolata* L. (0.33 kg ha^{-1}), *Rumex acetosa* L. (0.10 kg ha^{-1}), *Silene dioica* L. (0.25 kg ha^{-1}) and *Trifolium pratense* L. (0.57 kg ha^{-1}). These sowing rates were chosen based on seed weight such that each species was represented at 20 seeds m^{-2}. This seed mixture was sown into all treatments with the exception of treatment 1 (control), and treatments 9 and 10 which received only graminicide application (see below).

Treatments 3-10 were sprayed with the selective graminicide fluazifop-P-butyl (Fusilade Max 125 g L^{-1} EC, Syngenta Crop Protection Ltd.) at different application rates and timings to investigate the effects of temporal variation on grass suppression. Fluazifop-P-butyl is a selective, non-residual post-emergence phenoxy herbicide used to control grasses in broadleaved crops and other situations including non-cropped buffer strips (Syngenta Crop Protection Ltd., 2003). Treatments 3-5 received graminicide at 187.5 g a.i. ha^{-1}, with either two applications in April 2008 and 2009 (treatment 3), a single application in April 2008 (treatment 4), or two applications in April and September 2008 (treatment 5). Treatments 6-8 received graminicide at 93.75 g a.i. ha^{-1}, with either two applications in April 2008 and 2009 (treatment 6), a single application in April 2008 (treatment 7), or two applications in April and September 2008 (treatment 8). Graminicide was also applied in treatments 9 and 10 to observe if applications at the higher rate of 187.5 g a.i. ha^{-1} in either April 2008 (treatment 9) or April 2008 and 2009 (treatment 10) could suppress the high biomass of grasses present, open up the sward, and provide maximum opportunities for the species in the seed bank. The application rates of 93.75 g a.i. ha^{-1} and 187.5 g a.i. ha^{-1} were chosen as they represented the half and full label rate respectively permitted for use in non-cropped buffer strips (Syngenta Crop Protection Ltd., 2003). All graminicide applications were performed with a 2 m plot sprayer, operating at a pressure of 2.4 bars, and a water volume of 200 L ha^{-1}.

Each of the ten management treatments was randomly assigned to one of ten plots. The plots were arranged in three separate replicate blocks with each plot represented once in each block, thus 30 plots at each study site. Plots within a block shared the same aspect. Each plot measured 25 m x 4 m, with a 5 m untreated area between plots. The inner 2 m of the buffer strip was not used in the study and was managed in accordance with Defra guidelines (Defra, 2010). During the autumn of 2008 and 2009, the outer 4 m of all plots were cut with a tractor-mounted flail mower to a height of approximately 15 cm. Cuttings wereleft *in situ* reflecting standard practice as most arable farmers lack baling machinery.

Vegetation Sampling

The vegetation was assessed once in June 2008 and June 2009 using 0.5 × 0.5 m quadrats. Ten replicate quadrats were randomly positioned within each plot, leaving a buffer of approximately one metre to account for edge effects. All species were identified and assigned a percentage cover value based on an eight point scale (1 = <1 %, 2 = 1-5 %, 3 = 6-10 %, 4 = 11-20 %, 5 = 21-40 %, 6 = 41-60 %, 7 = 61-80 %, 8 = 81-100 %). Plant nomenclature followed Stace (1997). Coarse grain vegetation structure was measured during June 2008 and 2009 using the 'drop-disc method' which provides an indication of leaf and stem density within the sward (Stewart *et al.*, 2001). A disc of standard weight (200g) and diameter (30 cm) with a central slot was dropped from a height of one metre down a vertically held ruler. Height readings were taken as the distance from the ground where the disc came to rest. Eighteen measurements were taken from each plot, located in a diagonal line across the plot at one metre intervals.

Spider Sampling

Spiders were sampled twice a year (July and September) to coincide with peak insect activity, using a Vortis suction sampler (Burkard Co. Ltd, Rickmansworth, UK) during 2008 and 2009. Suction sampling is an established method for the collection of quantitative data on above-ground grassland invertebrates (Woodcock *et al.*, 2007; Brook *et al.*, 2008). In each plot, 55 × 10 second suctions (1.05 % of the plot area), were made by moving the Vortis vertically down onto the vegetation. This number of suctions is sufficient to ensure a collection of 90 % of all spider species (Brook *et al.*, 2008). Sampling was conducted between 10:00 and 17:00 h when the weather was dry. Samples were evenly spaced out along the experimental plot. Juvenile spiders were identified to family, and adults to species according to Roberts (1993).

Data analysis

Spider abundance and species richness, summed percentage cover of all wildflowers present, summed percentage cover of all grasses present, and sward structure were averaged across the three blocks of each treatment within a site, giving for each response and explanatory variable three replicates of each treatment (one for each farm). This was intended to reduce the impacts of within site variation associated with the fact that individual blocks were often split across multiple fields within a farm. Summed percentage cover values could be greater than 100 % to take into account the three dimensional structure of the sward, and overlap of species in the quadrat. Repeated-measures analysis using general linear mixed models in SAS 9.2 (SAS, 2008), were used to analyse the responses of plants, and spider abundance and species richness, to treatment effects and continuous and categorical environmental variables. Response variables were the abundance ($\log_e n + 1$) and species richness ($\log_e n + 1$) of spiders, summed percentage cover of wildflowers ($\log_e n + 1$), and grasses ($\log_e n + 1$), and the mean sward structure value ($\log_e n + 1$). The analysis was divided into four separate models.

Model 1 tested for the vegetation responses of percentage cover of wildflowers, and grasses, and sward structure to the management treatments, and their interactions with year.

Model 2 tested for the responses of the vegetation to the categorical environmental variables of (i) presence or absence of sown wildflower seed mixture (Seed); (ii) rate of graminicide (0, 93.75 or 187.5 g a.i. ha^{-1}) (Rate); (iii) timing of graminicide application (no application, April only or April and September) (Timing); number of graminicide applications (0, 1 or 2 applications across both years of the study) (No. Apps); and their interactions with year.

Model 3 tested for the responses of the abundance and species richness of total adult spiders, total juvenile spiders, and individual spider species (*Pachygnatha degeeri* Sundevall, *Tenuiphantes tenuis* Blackwall, *Bathyphantes gracilis* Blackwall, *Oedothorax fuscus* Blackwall, *Erigone atra* Blackwall, and juvenile *Pardosa* species) to the management treatments, and their interactions with year.

Model 4 tested for the responses of the abundance and species richness of total adult spiders, total juvenile spiders, and individual spider species, to the wildflower cover (WF), grass cover (Grass) and sward structure value (Sward), and their interactions with year.

All models used an autoregressive covariance structure to account for increased similarity between repeated measures in subsequent sampling years. Site (i.e. farm) was used as a random effect. Solutions for both fixed explanatory and random effects were estimated using the residual maximum likelihood approach, with denominator degrees of freedom calculated using Kenward Rogers approximation. For all models, simplification was by stepwise elimination of non-significant terms until the most parsimonious model was achieved. Significance values were derived from F-ratios of fixed effects, calculated using adjusted sums of squares where the final minimum adequate model contained only those parameters that had significant F-values, or were part of significant interactions terms. Between-treatment differences in response variables were tested using *post hoc* Tukey's multiple comparison test ($P = 0.05$).

Results

Over the two experimental years, a total of 12,810 spiders belonging to 61 species were sampled, comprising 7,803 juveniles and 5,007 adults (Supporting Information, Appendix S1). Juveniles were identified to family, with the exception of *Pardosa* which was identified to genus. The five most common adult species, comprising approximately 88 % of the total adults sampled, were *P. degeeri* (2637 individuals), *T. tenuis* (842), *B. gracilis* (421), *O. fuscus* (273) and *E. atra* (233). Sixteen adult spiders were represented by only a single individual. Juvenile *Pardosa* accounted for approximately 47 % of the total juveniles sampled (3681 individuals).

Response of vegetation to management treatments

Summed percentage cover of wildflowers, and grasses, and mean sward structure values all responded to the management treatments, and categorical variables of seed, and rate, timing and number of graminicide applications (Supporting Information, Appendix S2). Wildflower cover was significantly greater in the management treatments which received both wildflower seeds and graminicide (i.e. treatments 3-8) ($F_{9,18} = 12.57$, $P < 0.001$), compared to the control (treatment 1) and those treatments which only received either wildflower seeds (treatment 2), or graminicide (treatments 9 and 10) (Fig. 1a). Furthermore, significant effects of wildflower seed ($F_{1,24} = 33.84$, $P < 0.001$) and number of graminicide applications ($F_{2,24} = 34.23$, $P < 0.001$) were observed for wildflower cover. Tukey's test revealed a greater wildflower cover following both the addition of wildflower seed, and also one or two graminicide applications ($P < 0.05$).

As expected there was a significantly lower cover of grasses in the treatments which received graminicide (i.e. treatments 3-10) ($F_{9,18} = 15.06$, $P < 0.001$) (Fig. 1b), and a significant interaction between treatment and year which resulted in a general trend of greater grass cover in 2009 compared to 2008 ($F_{9,20} = 5.81$, $P < 0.001$) (Fig. 1b). There were also significant interactions between seed and year ($F_{1,26} = 22.10$, $P < 0.001$), and number of graminicide applications and year ($F_{2,26} = 13.82$, $P < 0.001$), for the grass cover response.

Tukey's test revealed a lower grass cover in 2008 in those treatments which received wildflower seeds, and a greater grass cover in 2009 in those treatments which received one graminicide application, compared to two ($P < 0.05$). In addition, significant effects of wildflower seed ($F_{1,23} = 19.86$, $P < 0.001$) and year ($F_{1,26} = 10.72$, $P < 0.01$) were observed, with a lower grass cover following the addition of wildflower seed, but a greater grass cover in 2009 compared to 2008 ($P < 0.05$). As expected, grass cover also responded to graminicide rate ($F_{1,23} = 8.94$, $P < 0.01$) and number of applications ($F_{1,23} = 13.74$, $P < 0.01$). Tukey's test revealed a trend of decreasing grass cover with increasing rate (0 > 93.75 > 187.5 g a.i. ha^{-1}) and number of graminicide applications (0 > 1 > 2 applications) ($P < 0.05$).

Mean sward structure was significantly lower in the treatments receiving graminicide ($F_{9,18} = 11.73$, $P < 0.001$) (Fig. 1c). Whilst there were greater mean sward structure values in 2009 compared to 2008 ($F_{1,29} = 64.25$, $P < 0.001$), the interaction between treatment and year was not significant. Significant effects of the number of graminicide applications ($F_{2,24} = 46.83$, $P < 0.001$) and year ($F_{1,26} = 52.81$, $P < 0.01$) were observed, with lower sward structure values in treatments receiving one or two applications, but greater sward structure values in 2009 compared to 2008 ($P < 0.05$). There were also significant interactions between seed and year ($F_{1,26} = 8.21$, $P < 0.01$), and number of graminicide applications and year ($F_{2,26} = 4.18$, $P < 0.05$), for the sward structure response. Tukey's test revealed greater sward structure values in treatments receiving wildflower seeds in 2009 compared to 2008, and greater sward structure values in those treatments where no graminicide was applied, compared to those which received one or two applications ($P < 0.05$). No other significant effects of interaction terms were determined for any of the response variables.

Response of spiders to management treatments

There was a general trend of increased abundance for both total adult ($F_{9,18} = 3.58$, $P < 0.05$) and total juvenile ($F_{9,18} = 3.20$, $P < 0.05$) spiders in the management treatments receiving wildflowers and / or graminicide (treatments two to ten), compared to treatment one (Figs. 2a and 2b) (Supporting Information, Appendix S3). Year was also significant for both adult ($F_{1,29} = 210.79$, $P < 0.001$) and juvenile abundance ($F_{1,29} = 21.08$, $P < 0.001$), and whilst Tukey's test revealed lower abundances in 2009 compared to 2008 ($P < 0.05$), there were no significant treatment interactions. Neither total adult species richness nor juvenile family richness responded to treatment; however there was a significant year effect for adult species richness ($F_{1,29} = 7.48$, $P < 0.001$), with higher values in 2008 ($P < 0.05$).

Significant treatment effects were observed for *Pachygnatha degeeri* ($F_{1,29} = 91.21$, $P < 0.001$) and juvenile *Pardosa* species ($F_{9,18} = 5.70$, $P < 0.001$), with significantly higher abundances in the majority of the treatments that received both wildflowers and graminicide ($P < 0.05$). Significant year effects were also observed for *P. degeeri* ($F_{9,18} = 5.29$, $P < 0.01$) and the juvenile *Pardosa* species ($F_{1,29} = 48.57$, $P < 0.001$). Whilst higher abundances of *P. degeeri* were observed in 2009 compared to 2008, the opposite effect was observed for juvenile *Pardosa* species ($P < 0.05$). No significant treatment effects were observed for *B. gracilis*, *O. fuscus*, or *E. atra*; however all did respond to year with significantly higher abundances in 2009 ($P < 0.05$). In addition, there was a weak interaction between treatment and year for *E. atra* ($F_{9,20} = 2.53$, $P < 0.05$) with significant differences between treatment one, and treatments five and six in 2008. No other significant effects of interaction terms were determined for any of the response variables.

Response of spiders to vegetation

Significant positive effects of wildflower cover were observed for the abundance of *P. degeeri* ($F_{1,47.4}$ = 30.76, $P < 0.001$, R^2: 0.24) and *B. gracilis* ($F_{1,10.1}$ = 5.83, $P < 0.05$, R^2: 0.025), and despite positive responses across both years, there were no significant interactions between cover and year (Supporting Information, Appendix S4). Whilst significant interactions were observed for *O. fuscus* ($F_{1,30.1}$ = 9.81, $P < 0.01$), adult *Pardosa* ($F_{1,29.1}$ = 10.51, $P < 0.01$) and juvenile *Pardosa* ($F_{1,27.8}$ = 11.38, $P < 0.01$), the direction of these correlations showed a high degree of variability, changing from positive to negative between the two sampling years. Abundance of *T. tenuis* was negatively correlated with wildflower cover ($F_{1,31.6}$ = 6.09, $P < 0.05$, R^2: 0.12).

There was a significant interaction between grass cover and year for the abundance of juvenile *Pardosa* ($F_{1,47.3}$ = 5.34, $P < 0.05$) with negative responses observed in both years (2008 R^2: 0.29; 2009 R^2: 0.23). The abundance of *B. gracilis* showed a weak positive correlation for grass cover ($F_{1,9.3}$ = 7.10, $P < 0.05$, R^2: 0.0001), although there was no interaction of year.

Sward structure was negatively correlated with the abundance of *O. fuscus* ($F_{1,47.6}$ = 5.79, $P < 0.05$, R^2: 0.32), *E. atra* ($F_{1,46.8}$ = 28.20, $P < 0.001$, R^2: 0.52), and *Pardosa* juveniles ($F_{1,49.2}$ = 6.65, $P < 0.05$, R^2: 0.61). No other significant effects of interaction terms were determined for any of the response variables.

Discussion

The greatest wildflower cover and lowest grass cover was observed in the management treatments which received scarification with wildflower seeds, and graminicide application. Sowing wildflower seeds, following scarification, can be an effective method of introducing desirable species into grasslands (Edwards *et al.*, 2007). Pywell *et al*. (2007), however, suggested that successful establishment is likely to be difficult without additional management to reduce the cover of competitive plant species, particularly of grasses. In our study, those treatments which received scarification with wildflower seeds, and graminicide application, produced a greater cover of wildflowers than was observed for the control or where only scarification was used to promote wildflower seed establishment. This indicates that scarification alone was not sufficient to promote wildflower establishment as as the recovery of the grasses following scarification occured rapidly where the grasses were not further suppressed by graminicide application (Grubb, 1977; Blake *et al.*, 2011).

A possible limitation of the test design was that the addition of wildflower seeds was always conducted in conjunction with scarification, i.e. the scarification was used as a method of incorporating the seeds into the existing sward. Thus, it was not possible to determine if scarification alone could stimulate the species within the seed bank without the need for wildflower seed. However, given the competitive nature of existing grasses (Pywell *et al.*, 2007), and the need to create opportunities for the wildflower species as sowing into a closed sward is unlikely to be successful (Grubb, 1977; Edwards *et al.*, 2007), it was considered appropriate to sow the wildflower seed in conjunction with scarification.

The importance of applying graminicide following the management of scarification with wildflowers was demonstrated through an increase in wildflower cover, and decrease in grass cover. This supports previous work which has shown that graminicide applications can reduce levels of competitive grasses in buffer strips (Blake *et al.*, 2011) and promote the development of wildflowers (Westbury and Dunnett, 2008). As expected, increasing both the rate and frequency of graminicide applications resulted in a lower grass cover, and reduced sward structure. There was a general trend of increasing grass cover in 2009 compared to 2008. As the grasses do provide biodiversity benefits, particularly for predatory beetles and ground-nesting birds (Thomas *et al.*, 2002; Vickery *et al.*, 2002), it is important that they are not eliminated completely. For this reason, and instead allowed to grow back when the wildflowers have successfully established themselves, as occurred in 2009. While grass cover was reduced in treatments nine and ten which received graminicide at a rate of 187.5 g a.i. ha^{-1}, the wildflower cover was similar to the control and treatment two. Given the lack of desirable species present in the seed bank of agriculturally-improved habitats (Edwards *et al.*, 2007), this suggests that the use of graminicide alone is insufficient in allowing unsown wildflowers to successfully colonise and establish in existing swards, and that the addition of wildflower seed should be considered.

In support of prediction two there was a general trend of increased abundance of adult and juvenile spiders in the management treatments receiving both scarification with wildflower seeds and graminicide. These effects were likely driven by the strong responses of *P. degeeri* and juvenile *Pardosa* which were positively correlated with wildflower cover during both years of the study. The inflorescences associated with the enhanced wildflower cover likely attracted potential prey for these spiders such as aphids, flies, bees and butterflies (Bell *et al.*, 2001). Furthermore, aphids were found in high numbers in the buffer strips (RJ Blake, *personal observation*) and have been demonstrated to be an important food source for *P. degeeri* (Harwood *et al.*, 2005). *Bathyphantes gracilis* abundance was also positively correlated with wildflower cover and this could be due to the flowering plant structures providing greater web-building opportunities (Gibson *et al.*, 1992). The increased wildflower cover may have also reduced potential predation by other spiders and higher trophic groups such as birds by providing more areas to hide (Wise, 1993; Morris, 2000). In contrast, *T. tenuis* abundance was negatively correlated with wildflower cover, whilst the direction of correlation for *O. fuscus* abundance varied between sampling years, and *E. atra* did not respond to wildflower cover.

Whilst plant community assemblage has been shown to be a key determinant for predatory taxa including spiders (Woodcock *et al.*, 2007), our responses suggest that other factors, besides wildflower cover, may be important for some species, such as members of the Linyphiidae. For example, previous studies have demonstrated the importance of sward structure and composition for spider abundance and species richness (Gibson *et al.*, 1992; Morris, 2000). In our study, sward structure was negatively correlated with the abundance of *E. atra*, *O. fuscus* and juvenile *Pardosa* species. These observations support Woodcock et al. (2007) who found a higher species richness of sward active spiders in architecturally simple swards, possibly due to increased efficiency of prey capture, and increased opportunities for ballooning (Bell *et al.*, 2001).

The species richness of adult spiders, and abundance of all spiders, was lower in 2009, and probably due to the autumn cut in 2008. Buffer strips are important refuges and overwintering habitats for invertebrates in agricultural fields (Thomas and Marshall, 1999; Meek *et al.*, 2002). For example, the spiders *E. atra* and *T. tenuis*, both common in our study, tend to colonise crops in the spring, before moving into buffer strips and other non-crop habitats in late summer for subsequent breeding and overwintering (Schmidt and Tscharntke, 2005; Bonte *et al.*, 2008). The timing of the cutting, i.e. after the spiders had moved back into the buffer strips, likely led to a negative impact on the spider populations through detrimental changes in prey availability, microclimate, habitat structure and overwintering site potential (Thomas and Jepson, 1997; Bell *et al.*, 2001). Whilst current agri-environment scheme guidelines recommend that buffer strips are cut regularly to prevent woody growth (Defra, 2010), rotational management of the strips could allow some areas to be cut less often for the benefit of spiders and other overwintering invertebrates (Gibson *et al.*, 1992; Bell *et al.*, 2002).

A total of 61 spider species were identified, of which *Pachygnatha degeeri* and *T. tenuis* accounted for nearly 70 % of the total. Whilst these two species have been shown to be among the most dominant species in agricultural habitats in Central and North-west Europe (Samu and Szinetar, 2002), the sampling method is likely to have influenced the species composition (Thomas and Jepson, 1997; Dennis *et al.*, 2001). Our chosen method of suction sampling was effective in collecting those species distributed throughout the sward canopy, including *T. tenuis* (Topping and Sunderland, 1992) and *P. degeeri* (Harwood *et al.*, 2005). Whilst the abundance of juvenile *Pardosa* was high, representing nearly half of all juveniles, adult *Pardosa* abundance was very low. *Pardosa* are epigeal spiders and whilst a suction sampling of ten seconds has been demonstrated to be effective at collecting over 90 % of spider species (Brook *et al.*, 2008), the greater body mass of adult *Pardosa* compared to juvenile *Pardosa* and members of the Linyphiidae or Tetragnathidae, could help explain the low numbers. Pitfall trapping would provide a more effective method of sampling adult *Pardosa* and other epigeal species (Topping and Sunderland, 1992).

Conclusions

Despite the introduction of agri-environment schemes, arable biodiversity continues to decline (Robinson and Sutherland, 2002). Buffer strips represent a potentially key non-cropped habitat within arable landscapes to help meet the revised EU target of halting and reversing biodiversity loss in Europe by 2020. This study has demonstrated that the management practices of scarification with wildflower seeds, and graminicide, can be utilised to enhance wildflower cover in existing grass buffer strips for the benefit of spiders. Furthermore, promoting spiders through the enhancement of non-crop habitats in farmland may also benefit agriculture, because abundant and species-rich communities of predators are more likely to control pests (Tscharntke *et al.*, 2005). However, there is a need to maintain a balance if conservation strategies are to be successful. Buffer strips require management to prevent woody growth, and whilst a single annual cut is a good way of achieving this (Defra, 2010), this can have detrimental impacts on overwintering spiders and other invertebrates. Differential management of the buffer strips would allow a range of taxa to be supported, underpinning the provision of multiple ecosystem services (Power, 2010). For example, managing the outer portion with a combination of scarification with wildflower seeds and graminicide, as in our study, could enhance spider abundance and species richness, and benefit pollinating insects and butterflies. Leaving the inner portion unmanaged, or cut less often, would allow an architecturally simple sward to develop for the benefit of beetles, sward active spiders and ground-nesting birds, and also provide overwintering habitat.

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Table 1 Management treatments

Treatment	Management			Timing of graminicide application
	Scarification	Wildflower Addition	Graminicide (g a.i. ha^{-1})	
1	**-**	**-**	n/a	n/a
2	+	+	n/a	n/a
3	+	+	187.5	Apr 2008 & 2009
4	+	+	187.5	Apr 2008
5	+	+	187.5	Apr & Sep 2008
6	+	+	93.75	Apr 2008 & 2009
7	+	+	93.75	Apr 2008
8	+	+	93.75	Apr & Sep 2008
9	**-**	**-**	187.5	Apr 2008
10	**-**	**-**	187.5	Apr 2008 & 2009

Appendix S2 Summary of vegetation model outputs. Model 1 tests the response of summed percentage wildflower cover, summed percentage grass cover, and mean sward height to management treatments (treat) and their interaction with year (year). Model 2 tests the response of vegetation to the categorical environmental variables, and their interaction with year.

Model	Wildflower cover ($\log_e$ n + 1)	Grass cover ($\log_e$ n + 1)	Mean sward height ($\log_e$ n + 1)
1	Treat: $F_{9,18}$ = 12.57***	Treat: $F_{9,18}$ = 15.06***	Treat: $F_{9,18}$ = 11.73***
	Year: NS	Year: $F_{1,20}$ = 31.83***	Year: $F_{1,29}$ = 64.25***
	Treat × year: NS	Treat × year: $F_{9,20}$ = 5.81***	Treat × year: NS
2	Seed: $F_{1,24}$ = 33.84***	Seed: $F_{1,23}$ = 19.86***	Seed: NS
	Rate: NS	Rate: $F_{1,23}$ = 8.94**	Rate: NS
	Timing: NS	Timing: NS	Timing: NS
	No. Apps: $F_{2,24}$ = 34.23***	No. Apps: $F_{1,23}$ = 13.74**	No. Apps: $F_{2,24}$ = 46.83***
	Year: NS	Year: $F_{1,26}$ = 10.72**	Year: $F_{1,26}$ = 52.81***
	Seed × year: NS	Seed × year: $F_{1,26}$ = 22.10***	Seed × year: $F_{1,26}$ = 8.21**
	Rate × year: NS	Rate × year: NS	Rate × year: NS
	Timing × year: NS	Timing × year: NS	Timing × year: NS
	No. Apps × year: NS	No. Apps × year: $F_{2,26}$ = 13.82***	No. Apps × year: $F_{2,26}$ = 4.18*

NS, $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Coding for environmental variable is given in the Methods. Non-significant terms removed from models by stepwise deletion.

Appendix S3 Summary of spider model outputs. Model 3 tests the response of the abundance and species richness of the spiders to management treatments (treat) and their interaction with year (year).

	Abundance ($\log_e n + 1$)	Richness ($\log_e n + 1$)
Total adults	Treat: $F_{9,18} = 3.58$* Year: $F_{1,29} = 210.79$*** Treat × Year: NS	Treat: NS Year: $F_{1,29} = 7.48$*** Treat × Year: NS
Total juveniles	Treat: $F_{9,18} = 3.20$* Year: $F_{1,29} = 21.08$*** Treat × Year: NS	Treat: NS Year: NS Treat × Year: NS
Pachygnatha degeeri	Treat: $F_{1,29} = 91.21$*** Year: $F_{9,18} = 5.29$** Treat × Year: NS	n/a
Tenuiphantes tenuis	Treat: NS Year: NS Treat × Year: NS	n/a
Bathyphantes gracilis	Treat: NS Year: $F_{1,29} = 58.63$*** Treat × Year: NS	n/a
Oedothorax fuscus	Treat: NS Year: $F_{1,29} = 72.27$*** Treat × Year: NS	n/a
Erigone atra	Treat: NS Year: $F_{1,20} = 162.55$*** Treat × Year: $F_{9,20} = 2.53$*	n/a
Pardosa spp. (juveniles)	Treat: $F_{9,18} = 5.70$*** Year: $F_{1,29} = 48.57$*** Treat × Year: NS	n/a

NS, $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Coding for environmental variables is given in the Methods. Non-significant terms removed from models by stepwise deletion.

Appendix S4 Summary of spider model outputs. Model 4 tests the response of the abundance and species richness of the spiders to the wildflower cover (WF), grass cover (grass), sward height (sward) and their interaction with year (year).

	Abundance ($\log_e n + 1$)
Pachygnatha degeeri	WF: $F_{1,47.4} = 30.76$*** Grass: NS Sward: NS Year: $F_{1,29.6} = 141.79$*** WF × year: NS Grass × year: NS Sward × year: NS
Tenuiphantes tenuis	WF: $F_{1,31.6} = 6.09$* Grass: NS Sward: NS Year: NS WF × year: NS Grass × year: NS Sward × year: NS
Bathyphantes gracilis	WF: $F_{1,10.1} = 5.83$* Grass: $F_{1,9.3} = 7.10$* Sward: NS Year: $F_{1,32.6} = 71.86$*** WF × year: NS Grass × year: NS Sward × year: NS
Oedothorax fuscus	WF: NS Grass: NS Sward: $F_{1,47.6} = 5.79$* Year: $F_{1,28.1} = 22.76$*** WF × year: $F_{1,30.1} = 9.81$** Grass × year: NS Sward × year: NS
Erigone atra	WF: NS Grass: NS Sward: $F_{1,46.8} = 28.20$*** Year: $F_{1,47.5} = 38.17$*** WF × year: NS Grass × year: NS Sward × year: NS
Pardosa spp. (juveniles)	WF: $F_{1,38.5} = 11.78$** Grass: NS Sward: $F_{1,49.2} = 6.65$* Year: $F_{1,46.5} = 5.93$* WF × year: $F_{1,27.8} = 11.38$** Grass × year: $F_{1,47.3} = 5.34$* Sward × year: NS

NS, $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Coding for environmental variables is given in the Methods. Non-significant terms removed from models by stepwise deletion.

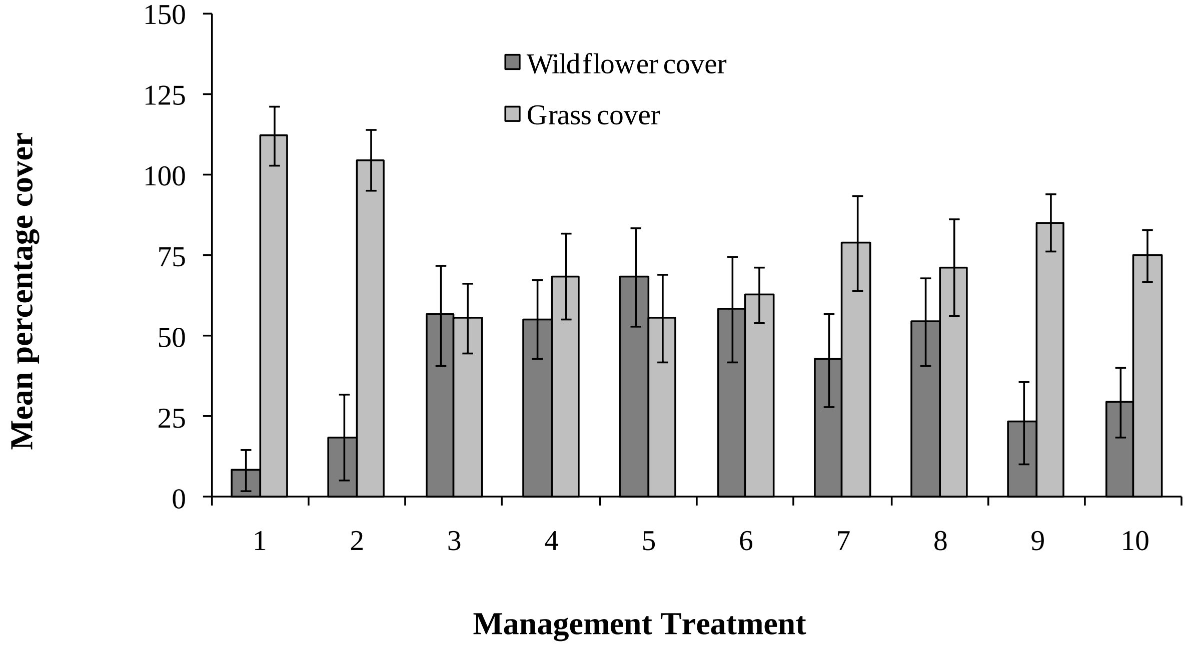
Figure captions

Fig. 1. Responses of vegetation to management treatments from 2008 – 2009 (a) Mean percentage total wildflower and grass cover (± SE) across all sites and years; (b) Interaction between mean percentage total grass cover and year (± SE) across all sites; (c) Mean sward height (± SE) across all sites and years. Graphs show untransformed data. Full description of the management treatments 1-10 is given in the text.

Fig. 2. Responses of spider abundance to management treatments from 2008 – 2009 (a) Mean adult abundance (± SE) across all sites and years; (b) Mean juvenile abundance (± SE) across all sites and years. Graph shows untransformed data. Full description of the management treatments 1-10 is given in the text.

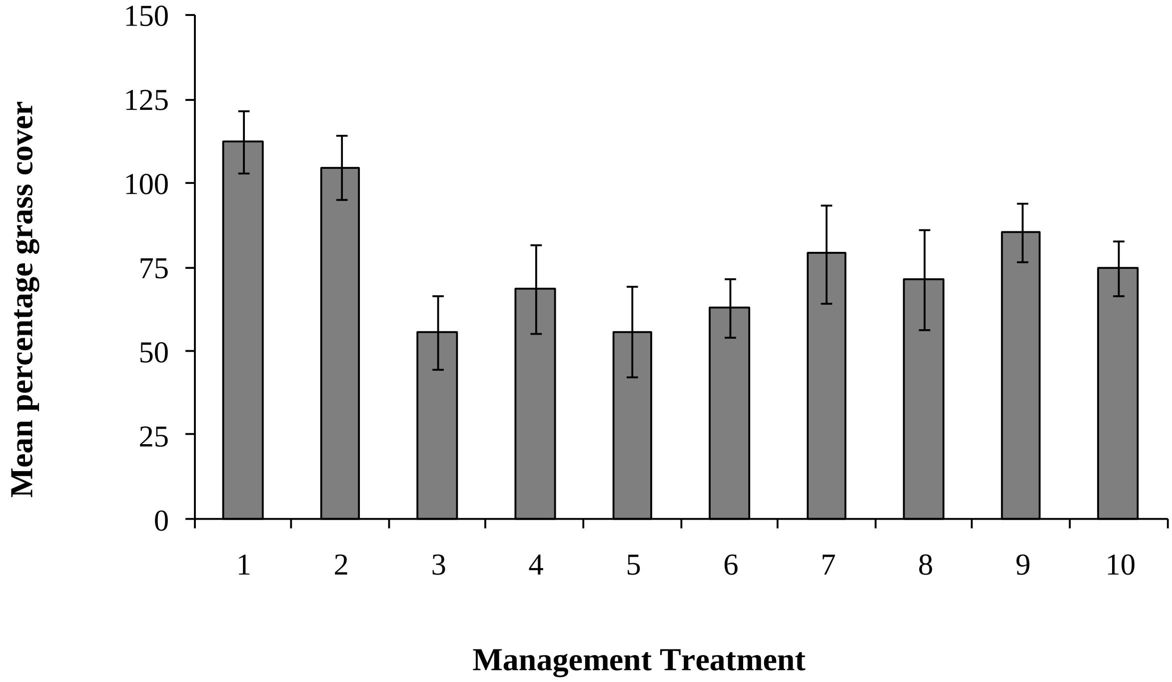
Fig. 1.

(a)



150
125
100
75
50
25
0
Mean percentage cover
Wildflower cover
Grass cover
1
2
3
4
5
6
7
8
9
10
Management Treatment

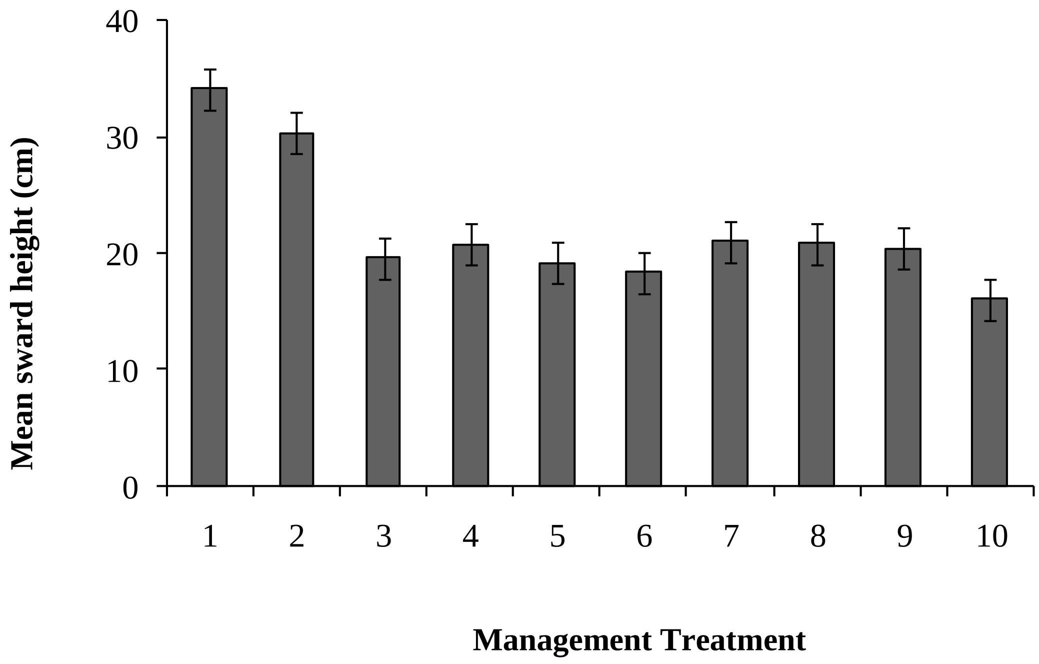
(b)



150
125
100
75
50
25
0
Mean percentage grass cover
1
2
3
4
5
6
7
8
9
10
Management Treatment

Fig. 1.

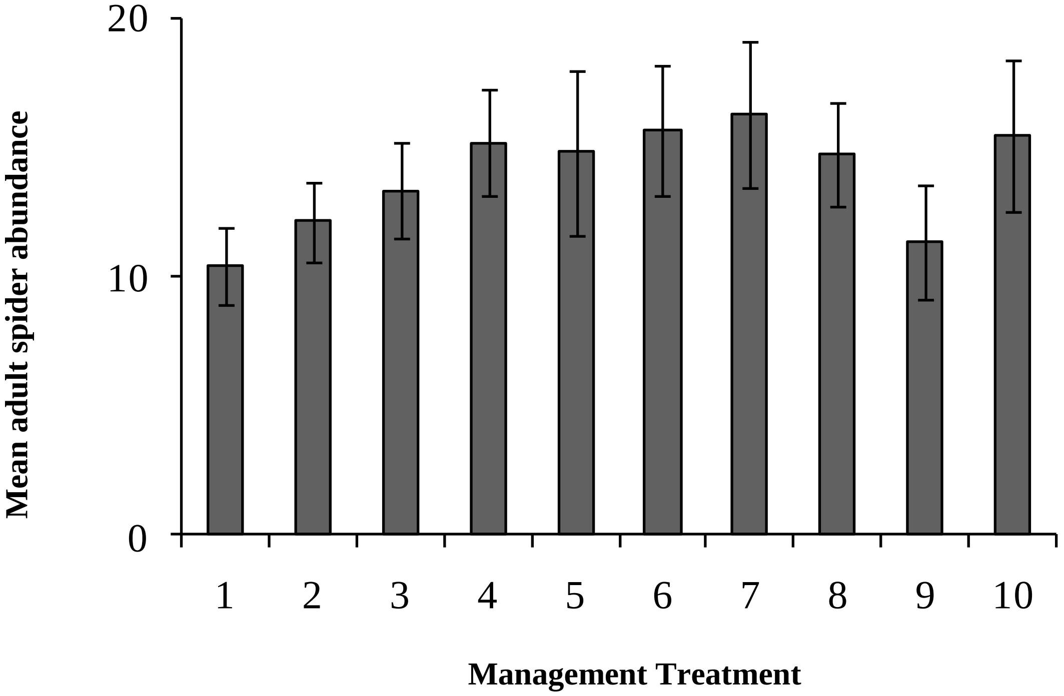
(c)



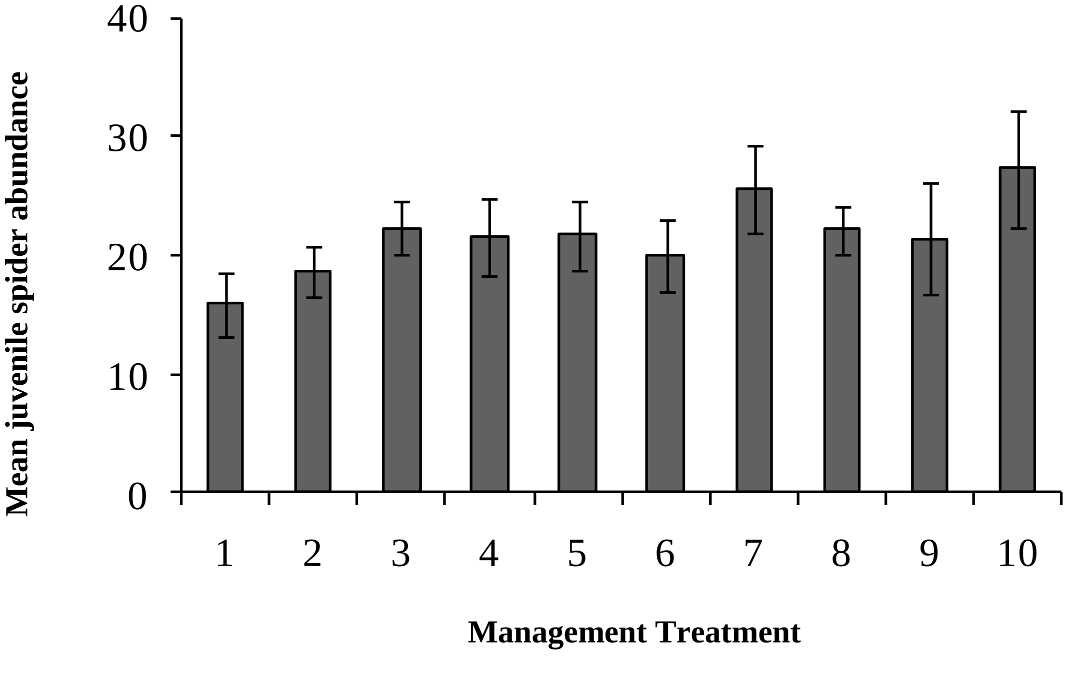
Mean sward height (cm)
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
Management Treatment

Fig. 2.

(a)


0
10
20
Mean adult spider abundance
1
2
3
4
5
6
7
8
9
10
Management Treatment

(b)


0
10
20
30
40
Mean juvenile spider abundance
1
2
3
4
5
6
7
8
9
10
Management Treatment