Title:

Land use alters the abundance of herbivore and predatory insects on crops: the case of alfalfa

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Key message

- Intensively managed orchards in the landscape decrease alfalfa predators.
- Alfalfa predators and herbivores are more abundant in landscapes with more proportion of alfalfa
- Proportion of forest cover decreases some predatory taxa in alfalfa
- Noncrop habitats, winter cereals, and the landscape Shannon index have minor effects.
- Insect abundance in alfalfa varies with the plant growth stage

Abstract

We assess the effects of changing land use and crop management on alfalfa insect abundance by comparing it in 50 alfalfa fields when they were inserted in landscapes with different proportions of arable crops and orchards. Land use in a buffer of 500m. was assessed and alfalfa insect abundance was estimated with sticky yellow traps. Numbers of catches of several herbivores and predators were related to the proportion of landscape components and several field variables. Results indicated that the proportion of orchards in the buffer negatively affected the abundance of predators on alfalfa; likely because orchards treated with pesticides are a sink for predators moving in the landscape, among other possible causes. Other landscape variables such as noncrop habitats, winter cereals, and landscape diversity analyzed by the Shannon index had a minor influence. Among field variables, field size influenced positively the abundance of insects on alfalfa whereas alfalfa growth stage and age affected positively or negatively the different herbivores and predators. Of course, abundance of predators and prey was affected by the abundance of prey and predators, respectively. These findings suggest that a high proportion of intensively managed crops (orchards) in the landscape interferes with the role of alfalfa as a reservoir of predatory insects for adjacent crops and that the responses to local and landscape structures are temporal and species-specific as previously concluded for maize. Consequently, landscape and field management strategies to improve pest control must consider both types of variables as well as their changing influence when we modify them.

Keywords: Agricultural landscape structure, Local variables, Alfalfa herbivores and predators, orchards, noncrop habitats.

1. Introduction

In recent decades, agriculture has intensified at local and regional scales worldwide, increasing the proportion of monocultures, field sizes, and the degrees of fragmentation of natural and seminatural habitats, causing fundamental changes in agricultural landscapes (Tscharntke et al. 2005; Baessler and Klotz 2006). These landscape changes are considered to be important factors modifying the abundances of both insect pest and natural enemy populations in agroecosystems (Ali et al. 2020). However, a meta-analysis showed that crop pests and predators can also exhibit inconsistent responses to the composition of landscapes and that these responses might result from variations in how habitat and biocontrol are measured (Karp et al. 2018). Many studies investigating the impacts of natural enemies on pest suppression have focused on short-term effects and have rarely considered the effects of spatial and temporal changes in the use of land (Jonsson et al. 2018). Different natural enemies can respond to landscape variables at distinct scales (Chaplin-Kramer et al. 2011), and a lack of stability due to factors such as high levels of pesticide application in some crops (e.g., orchards) can affect their continuous recolonisation from the surrounding landscape (Happe et al. 2019). In many cases, naturally occurring natural enemies could largely replace chemical inputs to control pests (Karp et al. 2018; Jactel et al. 2019). Most landscape and biocontrol studies mainly focus on the importance of natural and seminatural habitats as providers of arthropods and services, but few studies look at the importance of other crops. A deep understanding of landscape effects on insect pests and/or natural enemies could help to modify the environment at the within-crop, within-farm or even landscape levels and the existing pesticide application practices. Such an understanding could then be used by farmers, pest control advisers and researchers to adjust the spatiotemporal structure of crops and to design successful pest management programmes that could help to mitigate pests and minimise risks associated with insecticide spraying (Meisner et al. 2017; Ali et al. 2020).

In the Ebro Basin, alfalfa is one of the most common crops in the landscape. The alfalfa produced in this region represents more than 40% of Spain's total alfalfa production (MAPA 2020). During the last two decades, several studies have described the composition, abundance and ecological role of insects that live in alfalfa, concluding that alfalfa is an important reservoir of natural enemies in the Ebro Basin (Núñez 2002; Pons et al. 2005) and a source of predators that colonise neighbouring maize fields (di Lascio et al. 2016; Madeira et al. 2014, 2018; Madeira and Pons 2016). This role of alfalfa has been studied at both the field and farm scales, but it may also be modulated by the characteristics of the landscape (Rusch et al. 2010). In the study region, the proportions of alfalfa crops in the landscape surrounding maize fields have been found to influence the abundances of herbivores and predatory insects in maize (Clemente-Orta et al. 2020), but less is known about the inverse effect: how landscape composition affects herbivore and predator abundance on alfalfa.

In recent years, the transformation of dryland areas to irrigated land, along with changes in market demands, have led to modifications of agricultural land use in our region. The most significant modifications occurred at the relative proportions of cultivated surface devoted to alfalfa and stone fruits; alfalfa has decreased in favour of orchards (IEC 2020). A relevant consequence of the expansion of fruit tree cultivation is the increase in the amount of chemical pesticides sprayed in the area. These changes may have modified the abundances of pests and their natural enemies in alfalfa and other crops as in the case of maize (Clemente-Orta et al. 2020). An increase in pesticide use has been signalled as a main cause of landscape-wide natural enemy reduction, affecting both their behaviour and habitat recolonisation (Rusch et al. 2010). In addition, landscapes dominated by stone fruit orchards have been reported to negatively affect the richness of beneficial arthropod species in adjacent fields (Samnegård et al. 2018; Clemente et al. 2020).

In a previous study, the authors examined the effects of landscape composition on the abundances of pests and predators in maize fields (Clemente et al. 2020). To enhance the understanding of landscape effects on conservation biological control in the whole agroecosystem, we further evaluated whether changes in landscape composition or crop management practices could contribute to the design of more sustainable pest management programs for alfalfa. Surveys were performed in alfalfa fields over three consecutive years in spring and summer to test whether the increase in orchard surface together with their associated intensive management has negative consequences for the abundance of natural enemies and biological control functions in neighbouring alfalfa fields; we also tested whether those negative impacts change during the spring *vs*. the summer season.

2. Material and methods

2.1. Study area

This present study was conducted in three consecutive years in commercial alfalfa fields located in an area of the Ebro basin in which altitude was between 120 and 346 m, annual rainfall between 200 and 400 mm, T_{min} between 8 and 24 °C and T_{max} between 18 and 38 °C (Fig. 1A and Appendix A1 Table S1). In this study, we were interested in crop-dominated landscapes (approximately 80% of crops). For this reason, the study area where alfalfa fields were selected comprised 700 km^2, formed mainly by a mosaic of irrigated crop land with non cultivated patches (older fallows, natural habitats, margins, irrigation Canals and roads) and forest repopulated by *Pinus halepensis* (Mill). The prevalent arable crops are alfalfa and a crop rotation that mostly includes winter and summer cereals. Land use in the area has changed significantly in the recent 30 years with more surface devoted to orchards to the detriment of arable crops (IEC 2020), leading to a mixed landscape mosaic with fields of different shapes and sizes. The survey was conducted in 50 alfalfa fields. Some of the fields were the same over the three years, but others, due to crop rotations, remained in the study for only one or two years (Fig. 1A). Alfalfa fields were selected in a gradient of landscape composition ranging from landscapes with predominance of arable crops to others with a high percentage of orchards (Fig. 1B, Table S2). The size of selected fields varied between 1.3 and 28.5 ha, a common range in the area (Appendix A1 Table S1). To avoid potential spatial autocorrelation, the minimum distance between alfalfa fields was ≥ 2 km.

Alfalfa is a perennial crop that remains in the field for 4 to 5 years and normally undergoes 5 to 6 cuttings during the growing season (March–October). When needed, a single insecticide treatment in April against the main pest, the alfalfa weevil (*Hypera postica* Gyllenhall), is applied (Madeira et al. 2014). However, in orchards, pesticide applications are more frequent and may include 7 to 14 chemical sprays (insecticides, fungicides and bioregulators), mowing of the herbaceous cover in the inter-rows (approximately once per month), herbicide applications and tree fertilisation (Cantero-Martínez 2013; Bosch 2018; Teulon et al. 2018). Such intensive management practices in orchards are also common in other European countries (Happe et al. 2019). In both winter cereals and maize, pre- and postemergence herbicides are applied and seeds are treated with fungicides and/or insecticides.

2.2. Landscape structure variables

Landscape structure was quantified using ArcGIS software 10.3.1 (ESRI 2015). Every year, we characterised the landscape surrounding each sampled alfalfa field in a circular buffer area (0.5-km radius). The landscape composition was described by direct field inspection, orthophotos of the Plan Nacional de Ortografía Aérea (PNOA, https://pnoa.ign.es/), and geographical information maps of the Instituto Geográfico Nacional of Spain (https://www.ign.es). To incorporate seasonal variations in the landscape, two characterisations were performed every year, first in spring and then in summer. The elements initially identified in the landscape with the field inspection were grouped into eight categories: alfalfa, winter cereals, maize, orchards, forest, noncrop habitats and margins (Table 1 and Appendix A1 Table S2).

Landscape diversity was characterised with the Shannon index (hereafter SHDI-L) where the different landscape elements were expressed as a function of the proportional abundance (roads and buildings not included), *Li*, and was calculated with FRAGSTAT (McGarigal et al. 2012) as follows*:*

$$SHDI - L = -\sum_{i=1}^{32} L_i \times \ln L_i$$

2.3. Field variables

These included alfalfa age, alfalfa growth stage, perimeter/area ratio of the field, and abundances of predatory (for the study of the herbivores) or of prey taxa (for the study of predators) (Table 1 and Appendix A1 Table S3). Alfalfa age was provided by the respective farmer, and the alfalfa growth stage was recorded at each sampling date using a measuring tape. The perimeter/area ratio of the alfalfa fields was calculated using ArcGIS software.

2.4. Insect sampling and processing

The insects (herbivores and predators) in alfalfa fields were sampled with yellow sticky traps (30×25 cm, Serbios, Badia Polesine, Italy). Three sticky traps were left for 1 week in each field; each trap was mounted on a metal bar and placed inside alfalfa fields starting at 30 m from the field border, with a distance of 15 m between traps along a line transect approximately parallel to the field border. Traps were positioned just above the crop canopy and were raised as alfalfa plants grew. Sampling was carried out about once a month, in the first year, 1 sample in spring and 3 samples in summer in the second year, 2 samples in spring and 3 samples in summer and in the third year, 2 samples in spring and 2 samples in summer. Therefore, the number of samples was 6, 23, and 21 in the first, second, and third year (Appendix A1 Table S1). Once the traps were collected, they were kept at 6-8 °C until catch identification at the family, genus or species level depending on their state of conservation. The abundance of trapped insects in the field was then averaged over the three yellow sticky traps.

2.5. Statistical analyses

We used Spearman rank correlations (Dormann et al. 2013) to test the degrees of correlation between landscape structure and field variables (Appendix A1 Table S4). Despite a few variables were moderately correlated (Spearman's rho 0.4-0.59) (Campbell and Swinscow 2009), they were not excluded to build the models, as done by Schmidt et al. (2019).

To analyse the effects of the landscape structure and local variables on alfalfa herbivore and predator abundances in spring and summer, we used a linear mixed-effects model where year was a random factor using the 'nlme' package (Pinheiro et al. 2018) in R software (R Development Core Team, 2018). Mean insect catches per trap in each field and sampling date were log transformed [log10(x+1)] to achieve as normal a distribution of the model residuals as possible. Spatial autocorrelation among fields of mean catches in spring and summer was tested using Moran's I statistic (Paradis 2019) (Appendix A1 Table S5). Landscape metrics for each model was standardised (mean centred and scaled) using the 'caret' package (Max et al. 2018). We applied a multimodel inference approach to obtain a robust parameter estimate using the 'MuMIn' package (Bartoń 2018). The dredge function of the models was used to describe the effects of independent variables on each dependent variable. Models were selected by comparing the Akaike information criterion corrected for small sample sizes (AICc) with the values of the full model. Model averaging was performed on the model set with ΔAiCc < 2 (Burnham and Anderson 2004). The model residuals were graphically inspected with Q-Q plots and histogram graphics to ensure there were no violations of normality and homoscedasticity assumptions (Zuur et al. 2010). Finally, we used the 'effects' package (Fox et al. 2016) to represent the effects in partial residual plots.

3. Results

3.1. Herbivore and predator abundances

A total of 54,934 predators (17,102 in spring and 37,832 in summer) and 1,513,673 herbivorous insects (456,547 in spring and 1,057,126 in summer) were collected in the 50 sampled alfalfa fields in the three years. Although the species of predators and herbivores trapped on traps in spring and summer were the same, their abundance varied from one season to the other (Fig. 2 and Fig. 3). The predators were collected and identified as *Aeolothrips* spp. (Thysanoptera: Aeolothripidae) (predators of small arthropods mainly thrips but facultatively also feeding on pollen), *Orius* spp.

(Hemiptera: Anthocoridae), Staphylinidae, Miridae, Nabidae (generalist predators), Cantharidae (rather generalist predators of small arthropods), *Stethorus* spp. (predators of red spider mites), and several predators of aphids namely Chrysopidae, Syrphidae and the coccinellids *Propylea quatuordecimpunctata* L., *Hippodamia variegata* Goeze, *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) (Fig. 2). *Aeolothrips* spp. was the most abundant predator in both seasons, representing 61 and 57% of predators collected in spring and summer, respectively. In the case of herbivores, the following taxa were collected and identified: *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) and other Thripidae, *Empoasca vitis* Göthe (Hemiptera: Cicadellidae), Aphididae, *Zyginidia scutellaris* Herrich-Schäffer (Hemiptera: Cicadellidae), *Laodelphax striatellus* Fallén (Hemiptera: Delphacidae) and other planthoppers (Fig. 3). *Frankliniella occidentalis* was the most abundant herbivore, representing 80 and 88% of the total herbivores in spring and summer, respectively.

3.2 **Abundance of alfalfa insects in relation to landscape variables**

The most parsimonious models for predators and herbivores are shown in Appendix A2 (Tables S6 and S7, respectively), and the significant landscape variables are presented in Tables 2 and 3 for predators and herbivores, respectively. Although models of Nabidae and Miridae were represented, they were not considered in the results and conclusions, in the case of Nabidae due to their low abundance and in the case of Miridae due to the common omnivory of the family.

The landscape structure surrounding alfalfa fields affected the abundances of both predators and herbivores found on this crop. However, the effect of landscape variables varied with the season (Tables 2 and 3).

The landscape variables that most affected predator and prey abundances were the proportions of orchards, forests, alfalfa, maize and margins. The most significant results are summarized in the following paragraphs. Abundances of predators significantly related to the surrounding landscape are shown in Figures 4-8. Only in a few cases, the proportion of alfalfa was positively related to Chrysopidae in spring and to Syrphidae and Staphylinidae in summer. On the contrary, the abundance of predators was negatively related mainly to the proportion of orchards and forest for several predatory species in spring, as well the proportion of margins in summer for *Orius* spp., *Aeolothrips* spp. and *Stethorus* spp. Maize in spring was negatively related to Cantharidae and in summer, but positively related to *P. quatuordecimpunctata* and *Aeolothrips* spp.

In the case of herbivores (Figs. 4-8), orchards were positively related to almost all herbivores (*E. vitis* and Aphididae in spring and summer, *F. occidentalis* and *Z. scutellaris* in spring and *L. striatellus* in summer, except the other species of Thripidae, which were negatively related in spring. The abundances of *F. occidentalis* and other Thripidae in spring was positively and negatively related to the proportion of forest, respectively. Alfalfa was positively related with other Thripidae in spring and with Aphididae in summer. Margins were positively related to the herbivores Aphididae (spring) and other Thripidae (summer). Maize in spring was negatively related to *E. vitis* and positively related to Aphididae in summer.

3.3. Abundance of alfalfa insects in relation to field variables

The effects of alfalfa field variables on predators and herbivores recorded on alfalfa are shown in Appendix A2 (Tables S6 and S7, respectively). Tables 2 and 3 show only the significant variables. The variables prey and predators in the field and the alfalfa growth stage were the field variables that most affected insect abundances (Fig. 9-11). Abundances of predators and herbivores (prey) were mostly positively related as expected in most of predator-prey relationships particularly for generalist predators. The alfalfa growth stage was positively related to the herbivore *E. vitis* and other planthoppers in spring and to the predator *Orius spp*. (spring and summer), *H. variegata*, Chrysopidae and *Stethorus* spp. in summer. The opposite effect was observed for the herbivores Aphididae (spring), other Thripidae and other planthoppers (summer) and for the predators *Aeolothrips* spp. (spring and summer) and Staphylinidae (summer).

4. Discussion

In the northeastern Iberian Peninsula, natural enemies are a crucial component of integrated pest management (IPM) approaches for pest control in alfalfa (Pons et al. 2005). These natural enemies are important biological control agents of alfalfa pests, not only because they reduce the damage caused by pests but also because alfalfa is a source of the most abundant predators for other crops such as maize (Clemente-Orta et al. 2020; Madeira et al. 2014, 2018; di Lascio et al. 2016) and orchards (Batuecas et al. 2021). Our results demonstrate that the proportions of orchards, forest, margins, maize, and alfalfa in the surrounding landscapes were the landscape variables that most influenced predator and herbivore abundances in alfalfa.

The proportion of orchards in the landscape had negative effects on some alfalfa predators in spring, such as *Orius* spp. (the most abundant generalist predators recorded in alfalfa), Chrysopidae, Syrphidae, Cantharidae and Staphylinidae. Similar negative effects were reported in maize in our previous study in the area (Clemente-Orta et al.

2020). Negative impacts of orchards in the landscape on the abundance of predators within other crops were also observed by Samnegård et al. (2018) and by Yang et al. (2018, 2019). In addition, the impact of orchards on the abundance and source-sink dynamics of predators can be related to orchard management (Lefebvre et al. 2016) since crop management practices (mainly intensity of pesticide use) have been shown to counteract the positive effects of landscape on higher predator abundances (Ricci et al. 2019, Saqib et al. 2020). Natural enemy abundance and diversity in orchards depend on orchard management, and in general, they were higher in organically managed orchards than in nonorganically managed orchards (Happe et al. 2019). In contrast, a higher abundance of intensively managed orchards in the surrounding landscape reduced the colonisation of vegetable crops by predatory mirid bugs (Yang et al. 2018, 2019; Samnegård et al. 2018; Aviron et al. 2016). Although the negative effects of pesticides on predators in orchards may be masked by continuous orchard recolonisation from surrounding arable crops (Markó et al. 2017; Batuecas et al. 2021), this does not seem to be the case in orchards close to our alfalfa fields, as alfalfa fields within landscapes with a high proportion of orchards had low abundances of the abovementioned predators. However, although orchards in this area are sprayed, a rich community of spiders can still be captured in pitfall traps (Barrientos et al. 2019). Conversely, except for other Thripidae, the abundances of herbivores were higher in landscapes with high proportions of orchards. This higher herbivore abundance could be due to both the lower abundance of predators in alfalfa fields close to orchards and because some alfalfa herbivores are shared with fruit trees and orchard ground covers. This is the case for the western flower thrips *F. occidentalis*, an important pest of peach orchards under our conditions (Teulon et al. 2018); therefore, alfalfa and peach orchards could exchange thrips populations that would look for the best environment to feed and reproduce. Overall, the development of more sustainable orchard management practices (Aparicio et al. 2021; Denis et al. 2021) may enhance the populations of beneficial arthropods, which can later be a source for recolonization of arable fields after disturbances (Jeanneret et al. 2016).

Forest was the second most influential landscape variable, showing five negative relationships (four predators and one herbivore). A positive relationship was shown only for the herbivore *F. occidentalis*. In the study area, forest habitats are small patches mainly formed by *Pinus halepensis* and a low diversity herbaceous plant cover. This low diversity of forest cover is likely to be the reason for the negative effect on predators, in contrast to the key positive role of forest cover recorded in tropical agricultural landscapes, where it increases natural enemy diversity and associated biological control services (Medeiros et al. 2019).

Alfalfa cover in the landscape only showed positive effects. Three predatory groups (Chrysopidae in spring and Syrphidae and Staphylinidae in summer) and two herbivorous groups (other Thripidae in spring and Aphididae in summer) were more abundant in landscapes with high proportions of alfalfa. Alfalfa has been described in our area as a great reservoir for many generalist and specialist parasitoids and predators during all seasons, including the predators described above (Núñez, 2002; Pons et al. 2005; Pons et al. 2013), which can move from different alfalfa fields to colonise other adjacent crops (di Lascio et al. 2016; Madeira et al. 2016; Madeira et al. 2018; Batuecas et al. 2021). Herbivores such as aphids and other Thripidae were favoured by a high proportion of alfalfa in the landscape. Aphids are one of the most important pests of alfalfa (Meissle et al. 2010; Pons et al. 2005). Since they are crop-specific (Blackman and Eastop 2000), they do not switch between the main arable crops in spring and summer (winter cereals and maize, respectively) in the study area. The positive relationship between alfalfa and these herbivores, mainly for aphids, could be a consequence of a resource concentration effect that occurs when high resource density patches attract and support the most specialist insects, which are more likely to find, remain on and reproduce on their hosts when these plants grow in such stands (Otway et al. 2005).

Few effects of the proportion of maize in the landscape on the abundance of alfalfa insects were found. Cantharidae and the herbivore *E. vitis* were negatively correlated with maize in spring, and the predators *P. quatuordecimpunctata* and *Aeolothrips* spp. and Aphididae were positively correlated in summer. The significant relationship observed for *P. quatuordecimpunctata* confirms the results of previous studies that concluded that maize plays a major role as a source of *P. quatuordecimpunctata* and *H. variegata* for alfalfa after alfalfa cutting, some alfalfa individuals could move to maize after cutting and recolonize alfalfa once this crop has regrown (di Lascio et al. 2016). A more specific investigation would be necessary to explain the positive relationship found between aphid abundance on alfalfa and the proportion of maize in the landscape since these two crops do not share aphid species (Asín and Pons 1998; Pons et al. 2005; Madeira et al. 2014). Contrary to expectations, the number of *Z. scutellaris* in alfalfa was not related to maize, although it is one of the most abundant herbivores in maize.

Field margins and noncrop vegetation in agricultural landscapes are potential ecosystem service providers because they offer seminatural habitats for arthropods (Mkenda et al. 2019), especially when they suffer less disturbance and can act as refuges of natural enemies by providing them with important resources (Landis et al. 2000; Alomar et al. 2002; Hatt et al. 2018). Although these habitats have often been shown to increase the abundance and diversity of natural enemies contributing to pest biological control in adjacent crops (Alignier et al. 2014; Tscharntke et al. 2016), their positive role depends on how margins are managed by growers. However, in our study, we only observed negative effects of margins for predators. *Aeolothrips* spp., *Orius* spp. and *Stethorus* spp. decreased in abundance with an increase in margins in the landscape. In addition, field margins enhanced the abundance of the herbivores Aphididae in spring and other Thripidae in summer. The opposite result was recorded in the area by Clemente-Orta et al. (2020) for maize and *Orius* spp.

The noncrop habitats were only related to the abundances of two predators. *Orius* spp. increased their abundance (spring and summer) when the proportion of noncrop habitat increased whereas, in parallel, Syrphidae decreased in spring. Veres et al. (2012) attributed this role of noncrop habitats as refuges for *Orius* overwintering. However, the opposite has been found in some publications that report a positive effect of seminatural habitats on the abundance of hoverflies (e.g., Haenke et al. 2014; Schirmel et al. 2018). The benefit of noncrop habitats in terms of pest biocontrol enhancement remains inconclusive, as remarked by the meta-analysis of Karp et al. (2018). The different nature and composition of noncrop or seminatural habitats are likely to explain at least partially the different results found in the literature for their role in natural enemy abundance.

Commonly, landscape diversity is expressed by the Shannon diversity index. In our study, Shannon index of landscape cover types was not a variable that significantly influenced predator abundance on alfalfa. However, significant negative relationships found between the landscape Shannon index and the abundance of relevant alfalfa pests (*F. occidentalis* and *L. striatellus*) could be explained by undetected increases in the abundance or preying activity of predators. There are several studies that have remarked that landscape diversity itself is not a meaningful characteristic that affects biological control services and pest suppression (Martin et al. 2016; Rusch et al. 2016; Tscharntke et al. 2016; Landis 2017; Karp et al. 2018), while others have reported a positive relationship between landscape diversity and natural enemy abundance (Rusch et al. 2016; Aguilera et al. 2020).

Winter cereals was the landscape variable that affected the abundances of the fewest alfalfa insects. Only two insects were affected: the predatory Staphylinidae were negatively affected, and the leafhopper *E. vitis* was positively affected, both in spring. It was expected that effects only occurred in spring because alfalfa and winter cereals only overlap at that time, although the sowing and harvesting dates of winter cereals have been more variable in recent years. In summer, winter cereals are already harvested. Since it has been reported that both crops share many predatory species in our area (Pons and Eizaguirre 2009), we expected more alfalfa-winter cereal mutual influences in spring.

Landscape variables may explain part of the insect abundances in a crop, but local (field and immediate surroundings) conditions may also contribute to determine insect abundances. In our study, the predator-prey relationship in alfalfa was the most influential local variable; all herbivore abundances and almost all predator abundances were positively related to their predators or prey, respectively. This was to be expected, as more predators would concentrate in fields with more pest abundances. Exceptions were the planthopper *L. striatellus* and predatory Syrphidae, which were both shown to be negatively related to predators or prey, respectively, in summer. The positive effects of natural enemy abundance and prey abundance in alfalfa and other crops are commonly found in the literature (Elliott et al. 2002; Pons et al. 2005; Albajes et al. 2011; Ardanuy et al. 2018; Clemente-Orta et al. 2020; Ali et al. 2020). Alfalfa growth stage was the second most significant local variable. In the study area, alfalfa undergoes five cuttings during spring and summer, causing disturbances to aerial insects that have to find temporary refuge in adjacent habitats and later move back to alfalfa. In the process of alfalfa recolonisation, insect movement dynamics are species-specific; some species return earlier than others, as observed in some predators (Madeira et al. 2014, 2016, 2018; di Lascio et al. 2016). This could explain both the positive and the negative relationships between insect abundances and alfalfa growth stage. In fact, recent studies show that landscape effects could be present but masked or conditioned by the effects of local farm management (Begg et al. 2017; Petit et al. 2017; Karp et al. 2018). Other local variables, such as the field's area-perimeter relationship and the alfalfa field age, play less important roles in determining the effects of local variables on alfalfa insect abundances and are only noticeable in summer.

Conclusions

- Orchard, forest, margins, maize, and alfalfa are the most influential landscape variables determining herbivore and predator abundances in alfalfa crops.
- A high proportion of orchards in the landscape has a negative impact on the abundance of predators in alfalfa due to the intensive management of orchards.
- The occurrence of forest patches negatively impacts the abundance of some predators.
- Alfalfa cover has only positive effects on the abundances of a few predators and herbivores on alfalfa.
- Contrary to expectations, noncrop habitats, other arable crops (winter cereals), and landscape measured by the Shannon index only play minor roles in determining the abundance of predators in alfalfa.

- The abundance of alfalfa insects is mainly influenced by the amount of potential prey or potential predators on the crop and by alfalfa growth stage.

This study provides evidence for the negative effects on alfalfa predators caused by the increase in intensively managed orchards within areas previously dominated by arable crops in the northeastern Iberian Peninsula. It also points out the importance of the temporality of local and landscape effects on the abundance of insects in different crops. In addition, the responses to local and landscape structure are highly species-specific. For these reasons, management strategies to maximise natural biocontrol should be designed at multiple spatial scales, including both local and landscape scales, also considering temporality, all of which are factors that may contribute to maintaining and increasing communities of natural enemies that can regulate crop pests in the study area.

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Author contribution

RA, OA and FM conceived and designed research. FM, GCO, SS, IB, OA and RA collected the data. FM and RA analysed data. FM wrote the paper. RA, GCO and OA revised the final version. All authors read and approved the manuscript.

Compliance with ethical standards

Conflicts of interest: The authors declare that they have no conflict of interest.

Ethics approval: This article does not contain any studies with human participants or vertebrates performed by any of the authors.

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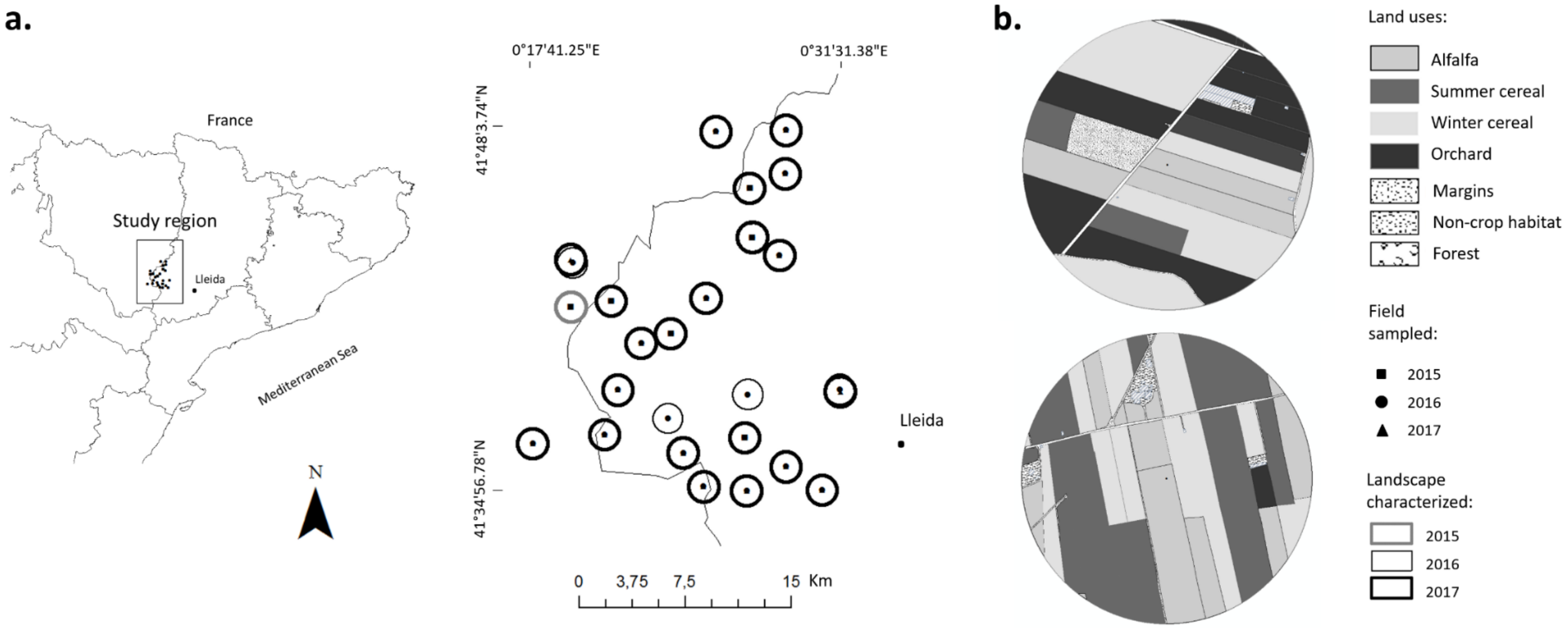

Fig. 1. a. Location of alfalfa fields sampled in 1st. 2nd and 3rd years (2015, 2016 and 2017) in the Ebro Basin in the north-eastern Iberian Peninsula and **b.** Example of buffer description. Different shades indicate different crops in the landscape. The central point in the buffer indicates the middle sticky trap in the alfalfa field.

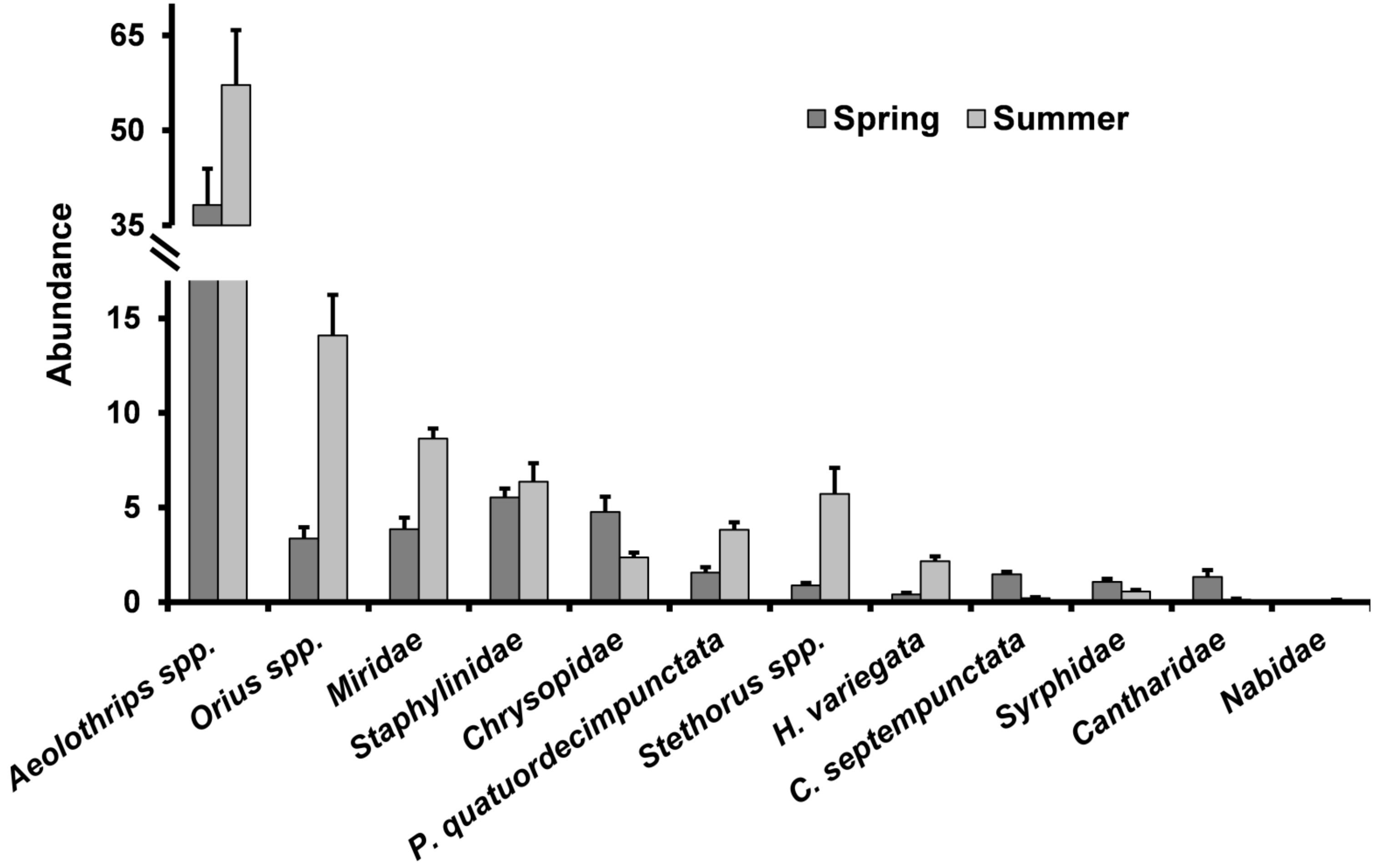

Fig. 2. Abundance of predators (mean number of insects/trap ± SE) in alfalfa collected with yellow sticky traps in all samplings in spring and summer.

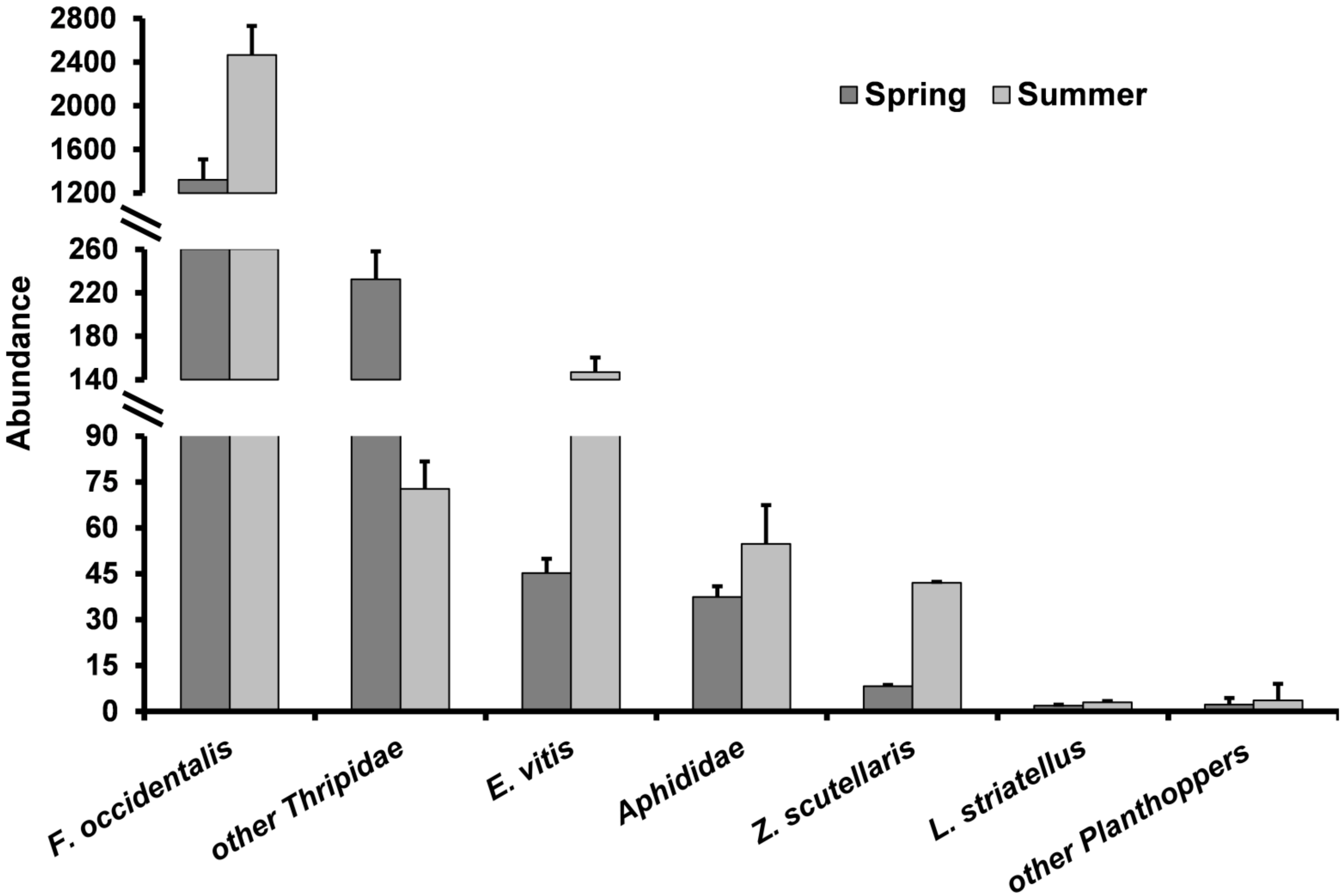

Fig. 3. Abundance of herbivores (mean number insects/trap ± SE) in alfalfa collected with yellow sticky traps in all samplings in spring and summer.

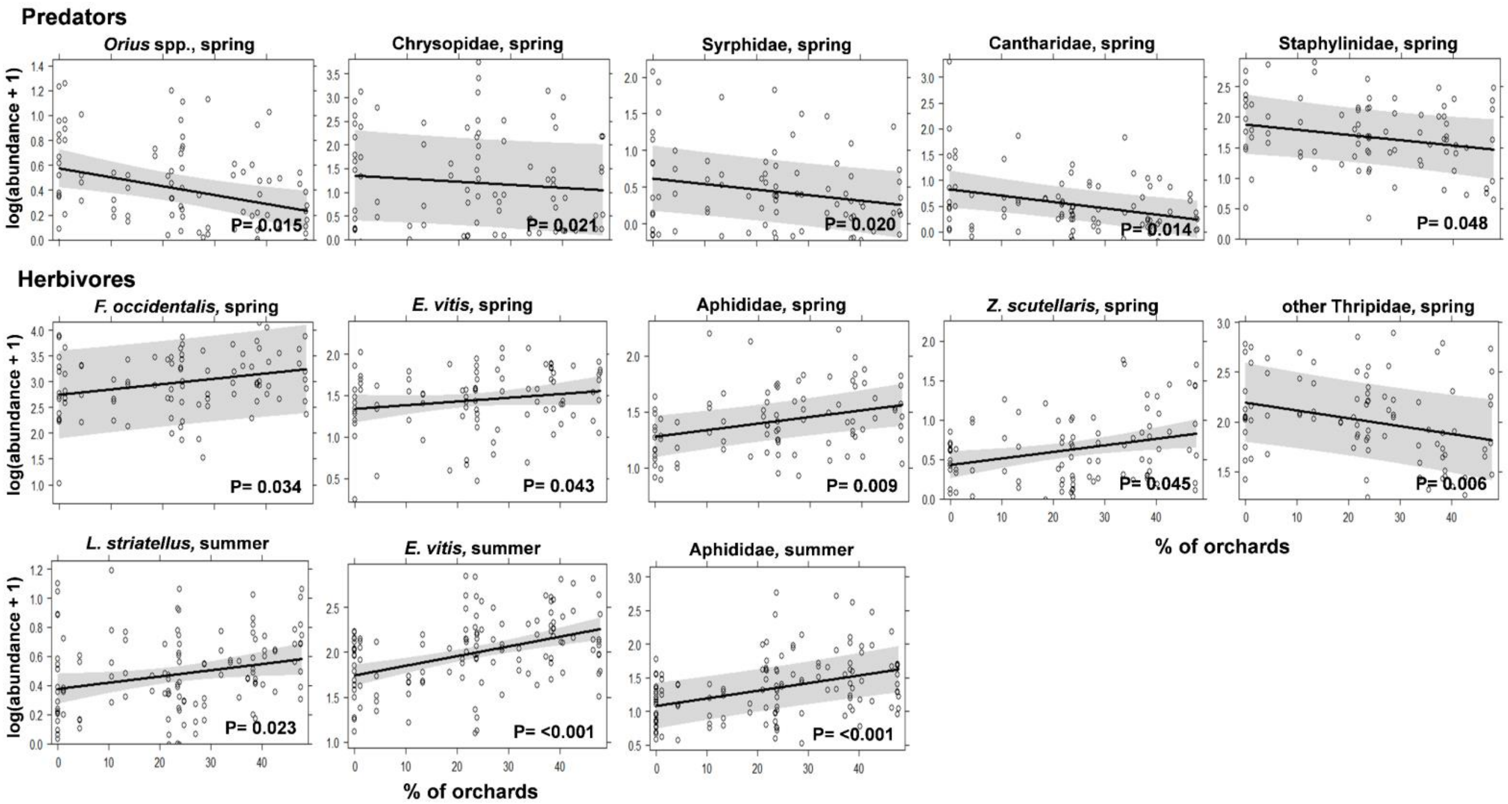

Fig. 4. Effects of the proportion of orchards (spring and summer) in the landscape on the abundances of predators and herbivores.

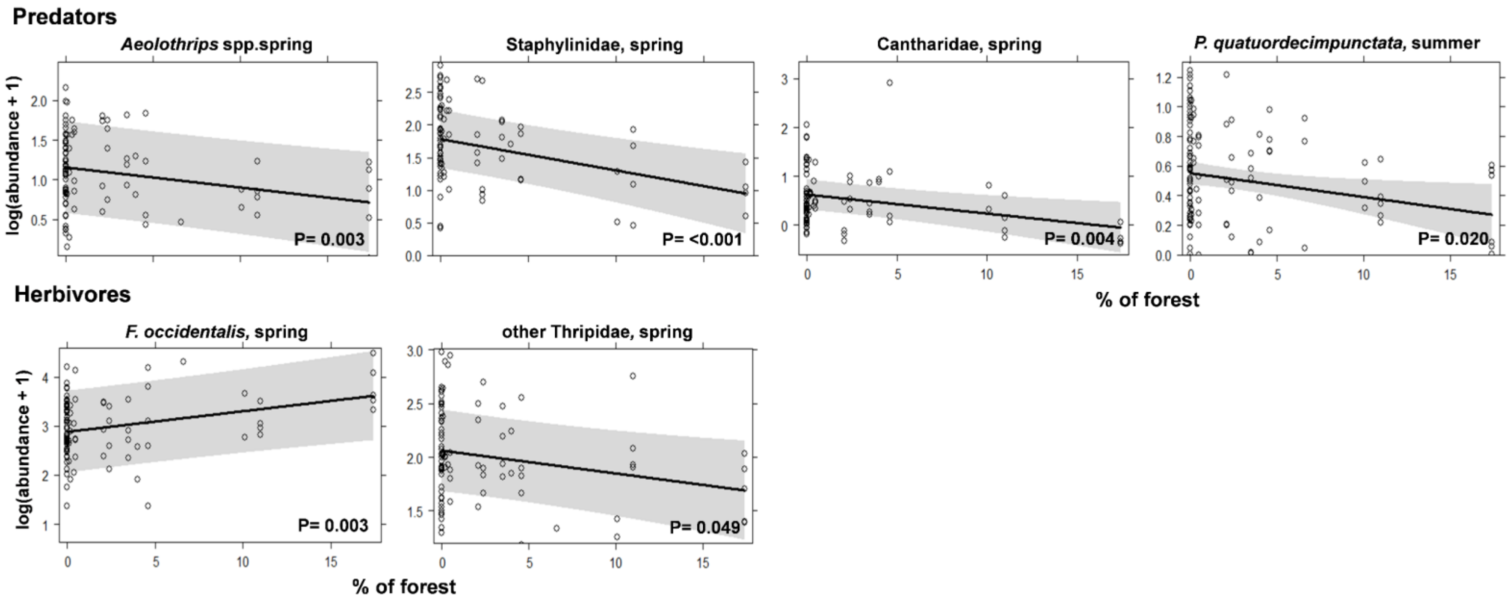

Fig. 5. Effects of the proportion of forest (spring and summer) in the landscape on the abundances of predators and herbivores.

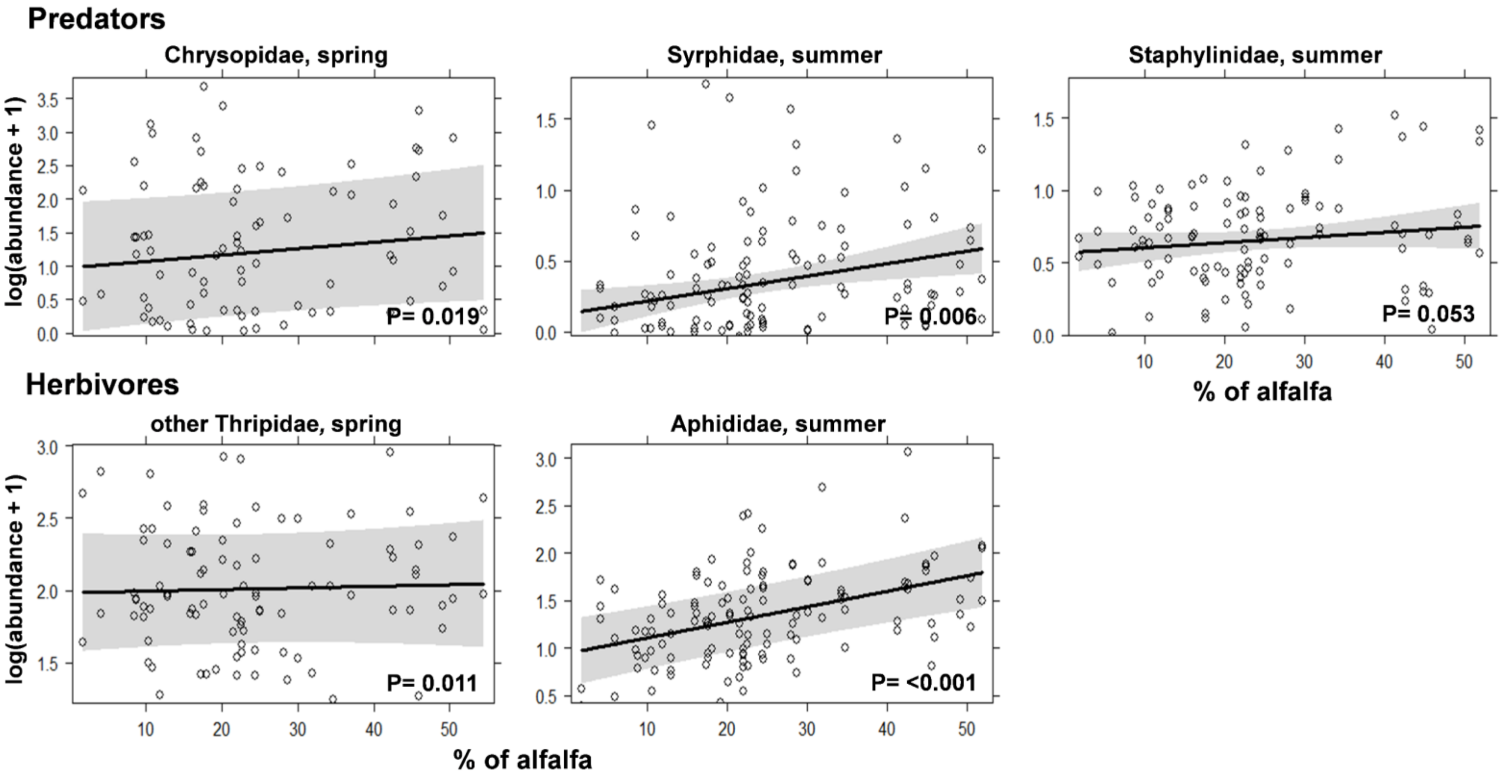

Fig. 6. Effects of the proportion of alfalfa (spring and summer) in the landscape on the abundances of predators and herbivores.

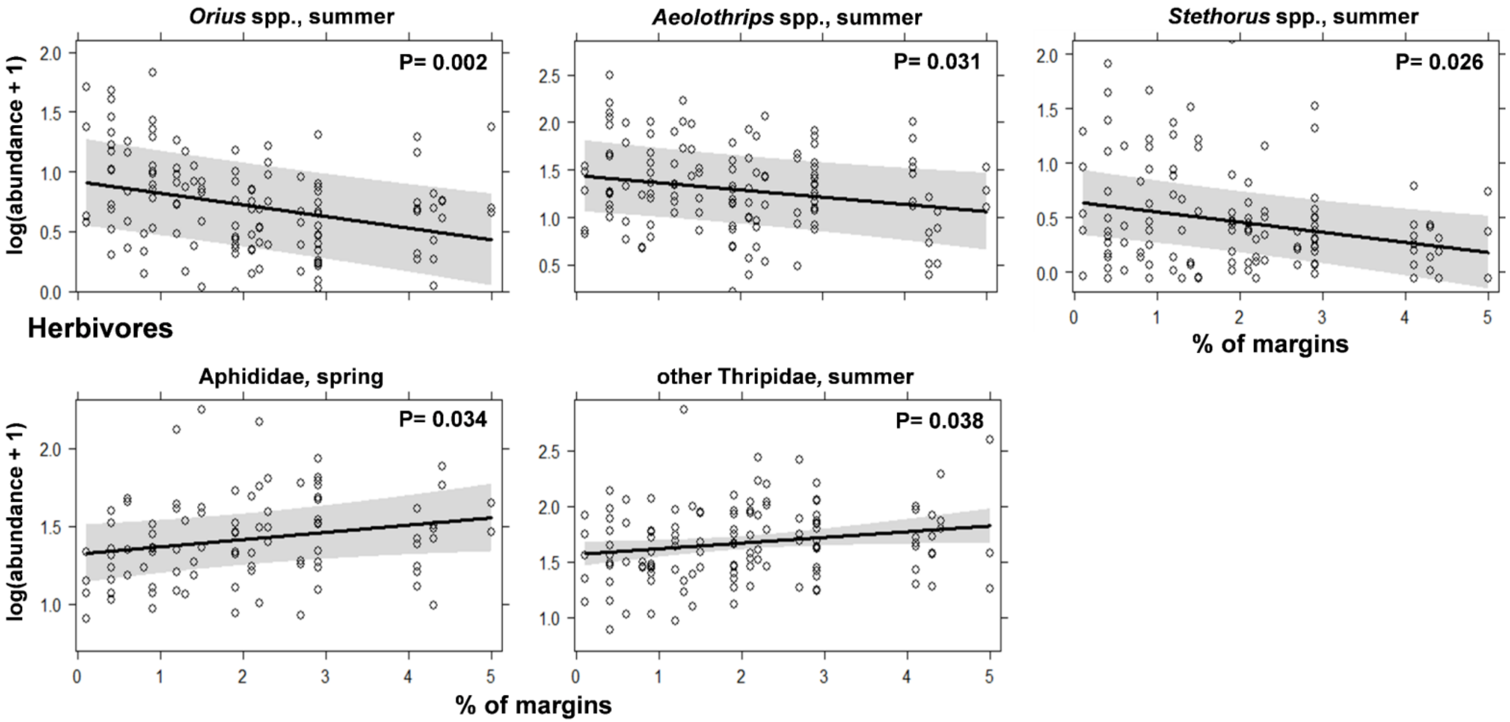

Fig. 7. Effects of the proportion of margins (spring and summer) in the landscape on the abundances of predators and herbivores.

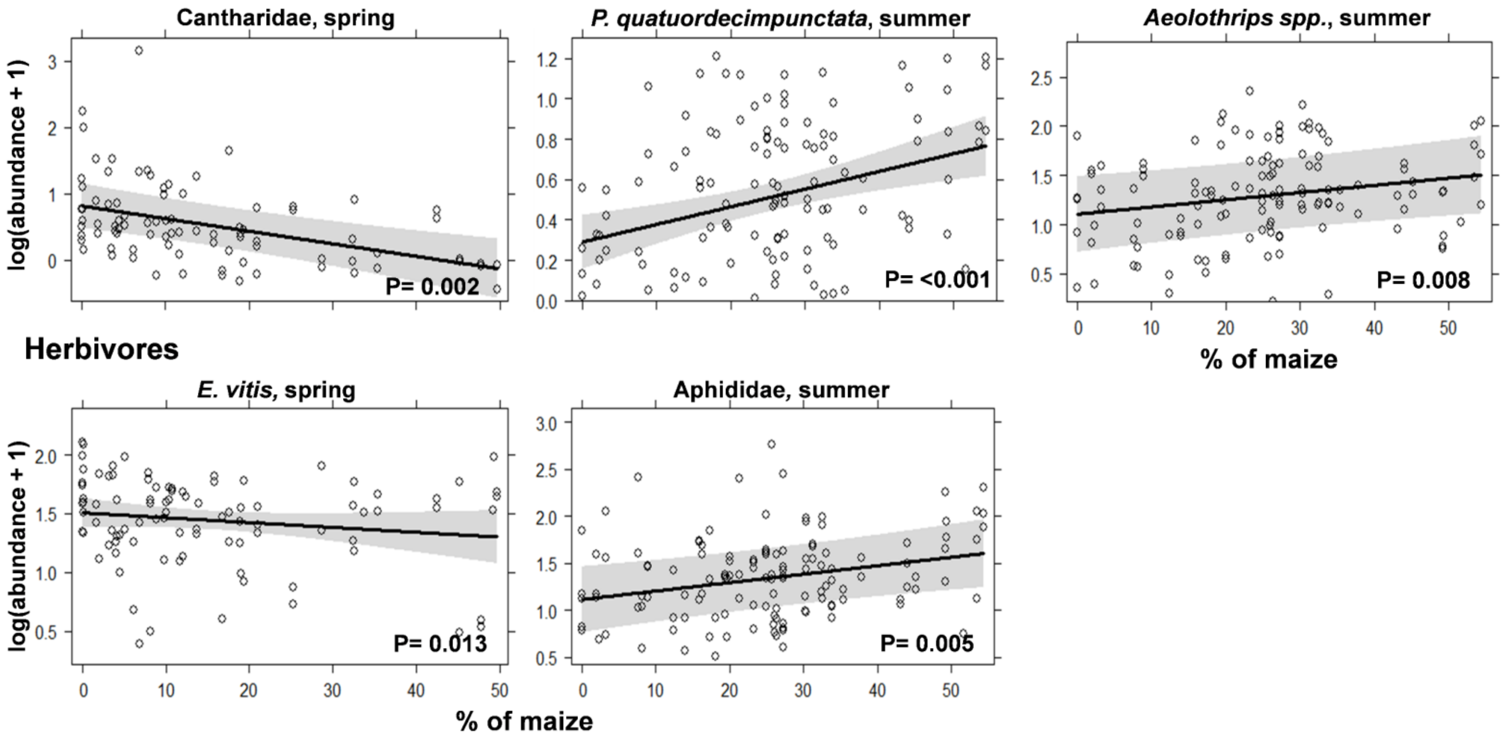

Fig. 8. Effects of the proportion of maize (spring and summer) in the landscape on the abundances of predators and herbivores.

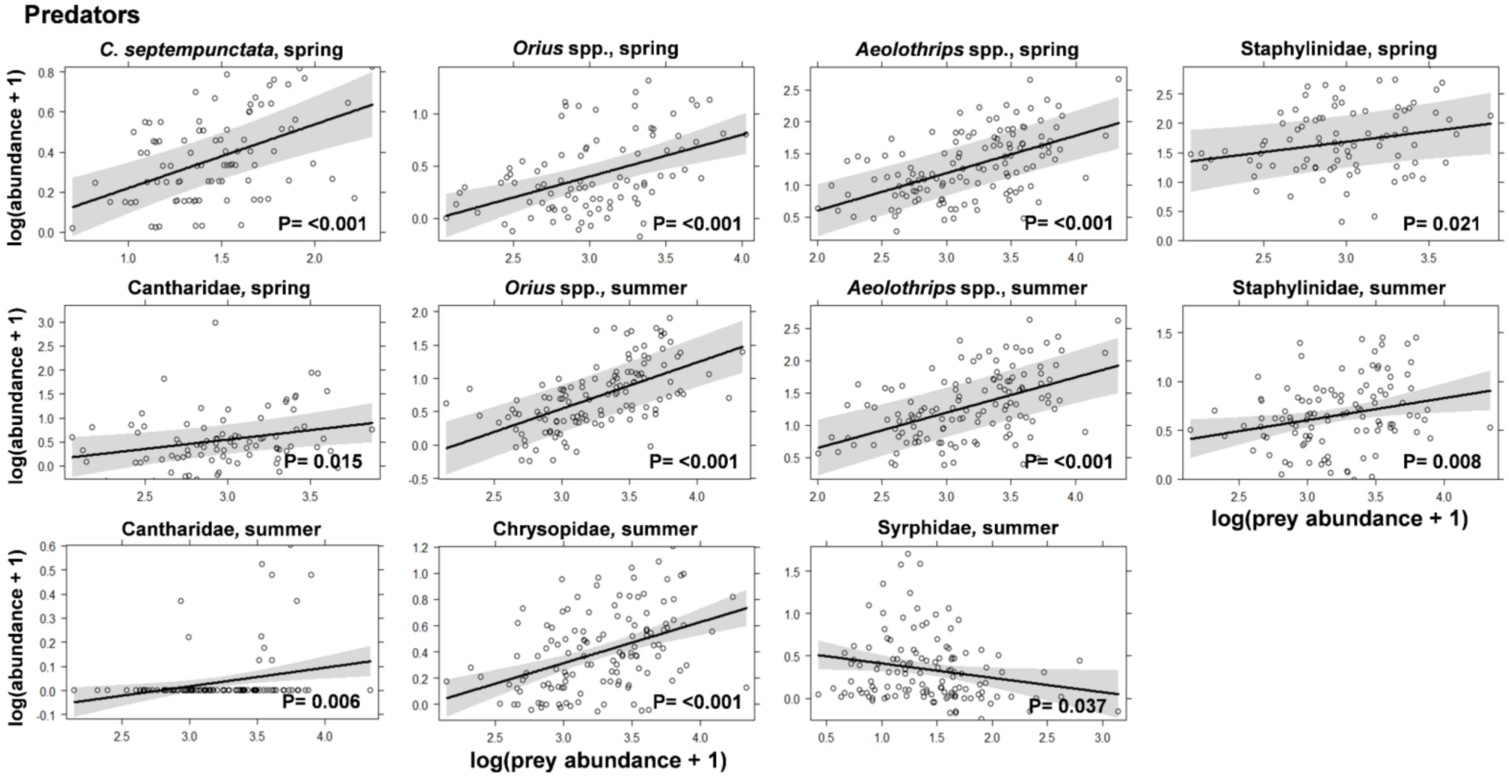

Fig. 9**.** Effects of the abundance of prey on the alfalfa field (spring and summer) on the abundance of predators.

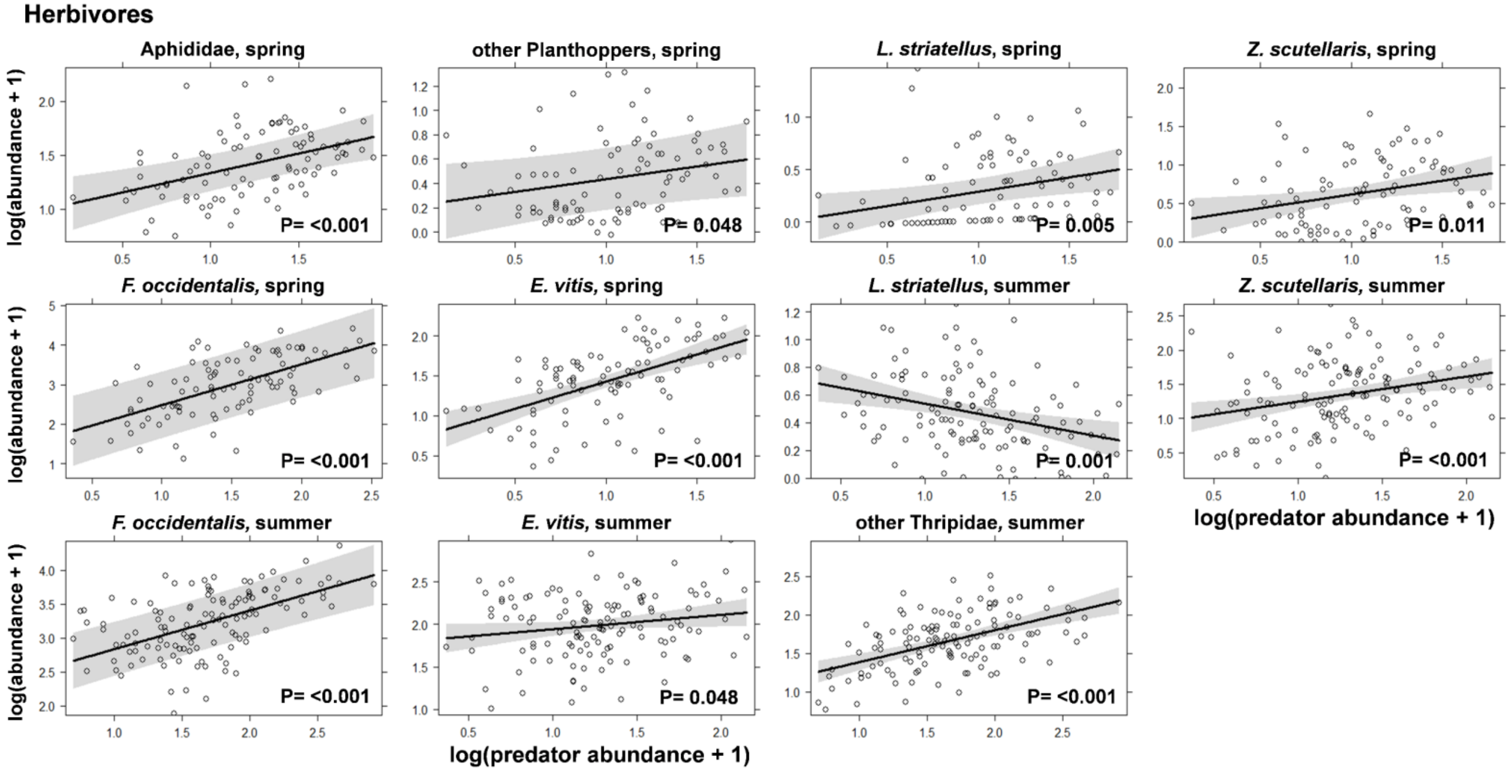

Fig. 10. Effects of the abundance of predators on the alfalfa field (spring and summer) on the abundance of herbivores.

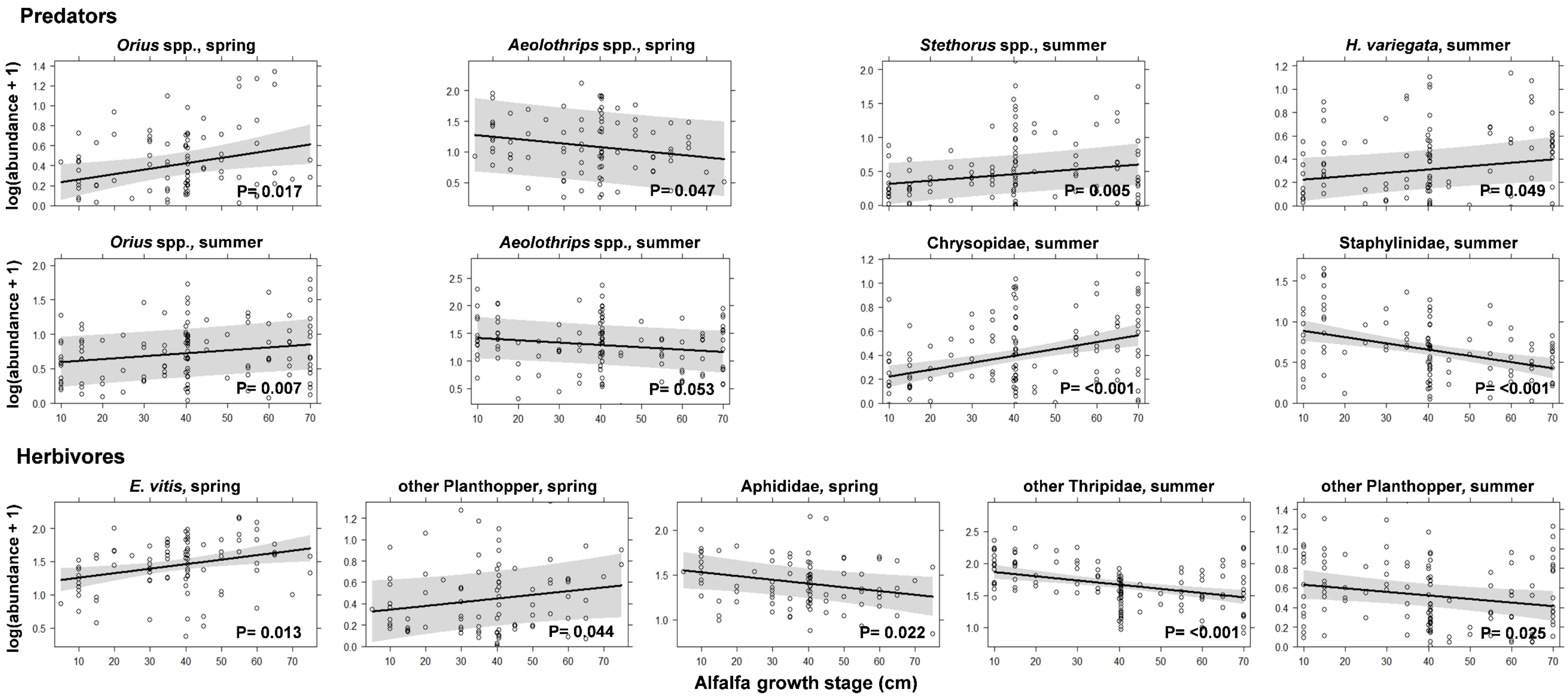

Fig. 11. Effects of the alfalfa growth stage (spring and summer) on the abundances of predators and herbivores.

Table 1. Landscape structure and local variables around sampled alfalfa fields within 0.5-km radii in the north-eastern Iberian Peninsula used in this study.

Categories	**Variables**	**Description**
Landscape structure	Alfalfa	Proportion of alfalfa
	Winter Cereals	Proportion of winter cereals (mainly wheat and barley)
	Maize	Proportion of maize
	Orchards	Proportion of fruit orchards (mainly peach)
	Forest	Proportion of forest repopulated by *Pinus halepensis*
	Noncrop	Proportion of unproductive areas, older fallows, natural habitats and wetlands
	Margins	Proportion of margin strips (Marshall and Moonen, 2002)
	Shannon index	Shannon diversity index calculated as landscape diversity in the buffers
Local environment	Perimeter/Area	Perimeter to area ratio of the sampled alfalfa field (m^{-1})
	Alfalfa growth	Stage of alfalfa development (cm)
	Alfalfa age	Number of years of alfalfa in the field
	Prey/Predator	Abundance of main prey and predators by each insect group

Table 2. Significant variables (p values ≤ 0.05) in the best models (ΔAIC<2) relating predator abundance with landscape and field variables. Variables were standardised (mean-centred and scaled). Relative importance is the sum of Akaike's weight associated with the variables in the best models. Marginal R² values indicate the amount of variation explained by fixed factors only, while Conditional R² values represent the variance explained by both fixed and random factors in the model.

	Spring									Summer								
								R²									R²	
Species/Group	**Variables best Model**	**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	**Relative importance**	**Marg.**	**Cond.**	**Variables best Model**	**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	**Relative importance**	**Marg.**	**Cond.**
C. septempunctata	(Intercept)	-0.27	0.25	0.25	1.06	0.29090		0.24	0.37	(Intercept)	0.05	0.10	0.10	0.46	0.64600		0.23	0.37
	Prey	0.33	0.07	0.07	4.93	0.00000	1			Perimeter/Area	-0.05	0.03	0.03	1.99	0.04620	0.79		
H. variegata	n.a.									(Intercept)	0.75	0.23	0.23	3.19	0.00143		0.09	0.26
										Alfalfa growth	0.13	0.07	0.07	1.96	0.04990	1		
										Perimeter/Area	-0.14	0.07	0.07	2.08	0.03746	1		
P. quatuordecimpunctata	n.a.									(Intercept)	1.16	0.12	0.12	9.63	< 2e-16		0.07	0.38
										Alfalfa age	-0.17	0.07	0.07	2.36	0.01829	1		
										Forest	-0.17	0.07	0.07	2.32	0.02029	1		
										Maize	0.27	0.08	0.08	3.44	0.00058	1		
Chrysopidae	(Intercept)	1.03	0.56	0.57	1.81	0.07010		0.09	0.57	(Intercept)	-1.33	0.46	0.47	2.84	0.00450		0.07	0.54
	Alfalfa	0.21	0.09	0.09	2.35	0.01900	0.64			Alfalfa growth	0.25	0.06	0.06	4.33	0.00002	1		
	Orchards	-0.21	0.09	0.09	2.30	0.02130	0.39			Prey	0.30	0.06	0.06	4.82	0.00000	1		
Syrphidae	(Intercept)	0.24	0.32	0.32	0.73	0.46510		0.15	0.46	(Intercept)	0.58	0.12	0.12	4.84	0.00000		0.12	0.12
	Noncrops	-0.12	0.05	0.05	2.39	0.01700	1			Alfalfa	0.11	0.04	0.04	2.73	0.00637	1		
	Orchards	-0.12	0.05	0.05	2.32	0.02060	0.96			Prey	-0.07	0.04	0.04	2.09	0.03703	1		
Aeolothrips spp.	(Intercept)	-2.08	0.97	0.98	2.12	0.03367		0.22	0.69	(Intercept)	-1.31	0.75	0.76	1.72	0.08525		0.30	0.54
	Alfalfa growth	-0.20	0.10	0.10	1.99	0.04711	0.87			Alfalfa age	0.21	0.09	0.09	2.19	0.02874	1		
	Forest	-0.29	0.10	0.10	2.95	0.00317	1			Alfalfa growth	-0.17	0.09	0.09	1.94	0.05297	0.89		
	Prey	0.68	0.10	0.10	6.77	< 2e-16	1			Prey	0.59	0.09	0.09	6.74	< 2e-16	1		
										Maize	0.28	0.10	0.10	2.67	0.00766	1		
										Margins	-0.21	0.10	0.10	2.15	0.03136	0.89		
Orius spp.	(Intercept)	-2.04	0.64	0.65	3.15	0.00163		0.35	0.36	(Intercept)	-3.61	0.77	0.78	4.63	0.00000		0.36	0.65
	Alfalfa growth	0.21	0.09	0.09	2.38	0.01732	1			Alfalfa growth	0.21	0.08	0.08	2.68	0.00738	1		
	Prey	0.43	0.09	0.09	4.76	0.00000	1			Prey	0.70	0.09	0.09	8.08	< 2e-16	1		
	Noncrops	0.25	0.09	0.09	2.69	0.00714	1			Margins	-0.25	0.08	0.08	3.07	0.00212	1		
	Orchards	-0.25	0.10	0.10	2.41	0.01594	0.94			Noncrops	0.22	0.08	0.08	2.71	0.00673	1		
Staphylinidae	(Intercept)	0.58	0.52	0.53	1.10	0.27238		0.19	0.43	(Intercept)	-0.28	0.67	0.67	0.41	0.68262		0.28	0.28
	Forest	-0.21	0.06	0.06	3.34	0.00085	1			Alfalfa growth	-0.34	0.08	0.08	4.19	0.00003	1		
	Prey	0.16	0.07	0.07	2.30	0.02143	1			Prey	0.24	0.09	0.09	2.66	0.00778	1		
	Orchards	-0.15	0.07	0.07	1.97	0.04840	0.8			Alfalfa	0.18	0.09	0.09	1.93	0.05308	0.39		
	Winter Cereal	-0.16	0.07	0.07	2.09	0.03647	0.9											
Nabidae	n.a.									(Intercept)	0.07	0.07	0.07	1.08	0.28220		0.07	0.25
										Alfalfa growth	-0.04	0.02	0.02	2.08	0.03710	1		
Miridae	(Intercept)	-2.59	0.72	0.73	3.55	0.00039		0.21	0.70	n.a.								
	Prey	0.49	0.07	0.07	6.71	< 2e-16	1											
	Shannon	0.20	0.08	0.08	2.58	0.00983	1											
Cantharidae	(Intercept)	-0.58	0.48	0.49	1.19	0.23396		0.28	0.37	(Intercept)	-0.48	0.20	0.20	2.33	0.01990		0.12	0.12
	Forest	-0.18	0.06	0.06	2.87	0.00416	1			Prey	0.08	0.03	0.03	2.74	0.00620	1		
	Prey	0.16	0.07	0.07	2.42	0.01533	1											
	Maize	-0.25	0.08	0.08	3.15	0.00161	1											
	Orchards	-0.18	0.07	0.08	2.45	0.01440	1											
Stethorus spp.	n.a.									(Intercept)	1.06	0.33	0.33	3.21	0.00135		0.13	0.34
										Alfalfa growth	0.25	0.09	0.09	2.77	0.00569	1		
										Margins	-0.21	0.09	0.10	2.22	0.02643	0.95		

Table 3. Significant variables (p values ≤ 0.05) in the best models (ΔAIC<2) relating herbivore abundance with landscape and field variables. Variables were standardised (mean-centred and scaled). Relative importance is the sum of Akaike's weight associated with the variables in the best models. Marginal R^2 values indicate the amount of variation explained by fixed factors only, while Conditional R^2 values represent the variance explained by both fixed and random factors in the model.

	Spring									Summer								
								R^2									R^2	
Species/Group	**Variables best Model**	**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	**Relative importance**	**Marg.**	**Cond.**	**Variables best Model**	**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	**Relative importance**	**Marg.**	**Cond.**
F. occidentalis	(Intercept)	3.57	1.05	1.06	3.35	0.000798		0.24	0.73	(Intercept)	4.99	0.55	0.55	9.07	< 2e-16		0.28	0.59
	Forest	0.43	0.14	0.15	2.96	0.003112	1			Alfalfa age	-0.25	0.08	0.08	2.92	0.003510	1		
	Predators	0.98	0.13	0.14	7.20	< 2e-16	1			Predators	0.62	0.09	0.09	7.06	< 2e-16	0.55		
	Orchards	0.35	0.16	0.17	2.12	0.034354	0.89											
	Shannon	-0.40	0.17	0.17	2.29	0.022037	0.77											
other Thripidae	(Intercept)	4.57	0.50	0.51	8.99	<2e-16		0.13	0.55	(Intercept)	2.20	0.28	0.28	7.87	< 2e-16		0.33	0.33
	Forest	-0.21	0.10	0.11	1.97	0.049200	0.84			Alfalfa growth	-0.29	0.07	0.07	4.17	0.000031	1		
	Orchards	-0.37	0.13	0.13	2.72	0.006600	0.61			Predators	0.42	0.07	0.07	6.09	< 2e-16	1		
	Alfalfa	0.33	0.13	0.13	2.53	0.011600	0.43			Margins	0.15	0.07	0.07	2.07	0.038100	1		
E. vitis	(Intercept)	1.79	0.30	0.30	5.93	<2e-16		0.43	0.43	(Intercept)	4.08	0.32	0.33	12.52	< 2e-16		0.23	0.23
	Alfalfa growth	0.24	0.10	0.10	2.48	0.013300	1			Predators	0.19	0.09	0.09	1.98	0.047700	0.9		
	Predators	0.65	0.12	0.12	5.42	0.000000	1			Orchards	0.41	0.09	0.10	4.30	0.000017	1		
	Maize	-0.31	0.12	0.12	2.48	0.013300	0.59			Perimeter/Area	-0.18	0.09	0.09	2.10	0.036000	1		
	Orchards	0.29	0.14	0.14	2.02	0.043600	0.57											
	Winter Cereal	0.28	0.12	0.12	2.38	0.017100	0.46											
L. striatellus	(Intercept)	-0.01	0.29	0.29	0.05	0.958990		0.1408	0.2338	(Intercept)	1.75	0.21	0.21	8.24	<2e-16		0.15	0.15
	Predators	0.30	0.11	0.11	2.81	0.005030	1			Predators	-0.24	0.07	0.07	3.24	0.001200	1		
										Orchards	0.17	0.07	0.07	2.27	0.023300	0.83		
										Shannon	-0.16	0.08	0.08	2.04	0.041600	0.83		
Aphididae	(Intercept)	2.14	0.36	0.37	5.79	0.000000		0.25	0.46	(Intercept)	3.10	0.39	0.40	7.82	< 2e-16		0.13	0.47
	Alfalfa growth	-0.17	0.07	0.07	2.28	0.022348	1			Alfalfa	0.42	0.12	0.12	3.58	0.000341	1		
	Predators	0.38	0.10	0.10	3.71	0.000205	1			Maize	0.29	0.10	0.10	2.81	0.005003	1		
	Margins	0.17	0.08	0.08	2.12	0.033691	0.93			Orchards	0.42	0.10	0.11	3.96	0.000076	1		
	Orchards	0.26	0.10	0.10	2.59	0.009708	1											
other Planthoppers	(Intercept)	0.59	0.40	0.41	1.46	0.145300		0.12	0.42	(Intercept)	1.15	0.22	0.22	5.27	0.000000		0.09	0.23
	Alfalfa growth	0.17	0.09	0.09	2.01	0.044200	0.9			Alfalfa growth	-0.16	0.07	0.07	2.23	0.025900	1		
	Predators	0.21	0.10	0.10	1.98	0.047900	0.88			Shannon	0.16	0.08	0.08	2.08	0.037800	0.89		
Z. scutellaris	(Intercept)	0.60	0.34	0.34	1.74	0.081100		0.16	0.16	(Intercept)	1.82	0.38	0.38	4.75	0.000002		0.11	0.11
	Predators	0.35	0.14	0.14	2.56	0.010500	1			Predators	0.42	0.12	0.12	3.45	0.000567	1		
	Orchards	0.27	0.14	0.14	2.00	0.045200	0.84											