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Evaluating the trade-off between machinery efficiency and loss of biodiversity-friendly habitats in arable landscapes: The role of field size

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ABSTRACT

Agricultural intensification has occurred in much of Europe since the middle of the 20th century implying profound changes in arable landscapes, and being the main cause of biodiversity erosion in farmed ecosystems. Because current public demands also include non-market goods such as biodiversity, landscape, historic environment, and natural resources, it is necessary to evaluate the trade-off between agriculture production and biodiversity conservation associated to agricultural practices. In this paper we examine one of the most important structural changes in arable landscapes: field enlargement. We evaluate its contribution to increase machinery efficiency, but also the associated erosion of biodiversity-friendly habitats such as field margins. We found a threshold in field size around 1–2 ha above which machinery efficiency increases very little, indicating that there is no need for bigger fields from the production point of view. We suggest to use this threshold as criterion for sowing in-field strips and restoring field margins, which are measures thought to enhance biodiversity in arable landscapes.

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1. Introduction

The increasing intensification of agriculture during the last decades has led to dramatic losses in farmland biodiversity (Ormerod et al., 2003). One of the best studied groups, farmland birds, has experienced more severe population declines than any other group of birds in Europe (Birdlife International, 2004). Because there is compelling and extensive evidence to show that severe decline of farmland biodiversity has been driven by agriculture intensification (e.g. Gregory et al., 2004; Mattison and Norris, 2005), modern agriculture is currently considered a major anthropogenic threat to biodiversity, comparable to climate change in its ability to affect vast areas (Sala et al., 2000; Donald et al., 2002).

Among other consequences, agricultural intensification produced structural changes in the farmed landscape. Mean size of fields increased with the concomitant decrease of their number (e.g. Fernández et al., 1992; Baessler and Klotz, 2006). The variety of crop types or land uses also diminished and many remaining patches of semi-natural habitat were removed from the landscape (Donázar et al., 1993; Petit and Firbank, 2006). Although these changes were mainly adopted to increase machinery efficiency in times of little concern about biodiversity in farmlands, many European countries are now moving into the so-called third generation of agricultural practices, where farmsteads are expected not only to produce food but also to promote biodiverse and cultural landscapes (Buckwell and Armstrong-Brown, 2004; Henle et al., 2008). In this scenario, methods for increasing machinery efficiency should be evaluated against its detrimental effects on biodiversity.

In this paper, we focused on this trade-off between machinery efficiency and biodiversity depending on field size. Large fields impact biodiversity by directly lowering cover of both margins and small patches of semi-natural habitat, which have been demonstrated to be reservoirs of biodiversity in farmed landscapes (Marshall and Moonen, 2002; Wilson et al., 1999). Indirectly, the larger the field, the smaller the amount of different crop types that could coexist in a given landscape. Thus, both direct and indirect effects of increasing field size lead into decreasing landscape heterogeneity, which play a key role in maintaining biodiversity in farmed landscapes (Benton et al., 2003).

As case study, we focused on cereal fields and their harvesting procedure in Andalusia (Southern Spain). As flag species of this habitat, we used the lesser kestrel *Falco naumanni*, a small insectivorous falcon that inhabits open and cultivated landscapes. The species is positively associated with cereal-dominated, extensively cultivated landscapes, which also provide fallows, and patches of semi-natural habitats (Bustamante, 1997; Franco

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et al., 2004; García et al., 2006). These marginal habitats and field margins are preferred foraging places (Donázar et al., 1993; Franco et al., 2004; García et al., 2006; Tella et al., 1998) because of their higher prey density (Rodríguez and Bustamante, 2008). Their reduction due to agriculture intensification (i.e. increasing field sizes) is thought to be one of the main causes of the species' decline (Peet and Gallo-Orsi, 2000). Thus, increasing field sizes is in part responsible of the endangered situation of the species, currently included in the category 1 of species of conservation concern (Birdlife International, 2004).

To address the topic, we built a spatially explicit simulation model where the efficiency of the harvesting procedure was evaluated in landscapes differing in the size of fields and their spatial aggregation. Variability of field size, working load per harvesting machine and machine capabilities were set according to current state of art in the study area to approach real scenarios.

2. Methods

2.1. The model

Our model system consists of a landscape generator, and a simulation model. The landscape generator creates arable landscapes differing in the size of fields and in the aggregation of crop types. The simulation model quantifies the time necessary to harvest all cereal plots in the landscape accounting for the harvesting procedure and the displacement between fields.

Simulated landscapes are similar to those found in many European countries, with three major different crop types (in western Andalusia olive groves *Olea europaea*, sunflowers *Helianthus annuus* and wheat *Triticum* spp.), fields of rectangular shape (5:4) and grassy margins between them. Fields of these crop types were distributed in a square lattice of 2362 × 2362 cells of 1 m^2, thus representing 558 ha, which is a realistic working area per harvesting machine (Junta de Andalucía, 2004). Field length ranged from 30 m to 390 m in steps of 30 m accounting for real variability found in agricultural landscapes both in Southern Spain and many European countries (Herzog et al., 2006; Junta de Andalucía, 2004). This range also accounts for the variability of field sizes found in 136 localities holding colonies of the case study species (*Falco naumanni*) in Andalusia (see inset of Fig. 1).

Each cell in the lattice could belong to any of the three different crop types or to the category "field margin". The first row and column of the lattice were considered margins. Margins of 1 m-width were also created to separate individual fields. Landscapes were created starting from the bottom left corner of the lattice, thus fields at the upper and right borders of the lattice could be smaller than the others because the end of the lattice could be reached before the final length or width of the field was attained. Due to the relatively big size of the simulated landscape, however, the number of fields involved is minimal. Nonetheless, this may create landscapes with cereal proportion different from 33%. In these cases, a correction factor was applied to avoid any influence on harvesting time (see Section 2.3). Once a cereal cell was harvested, it was set as "stubble".

We considered a series of landscapes that differed in the degree of cereal aggregation defined as the average proportion of cereal fields in the neighbourhood of each cereal field (Fig. 2). Different aggregations were created by varying the frequency of crop type assignment. In the least aggregated landscape, the first field got the crop type 1, the second field the crop type 2, the third field the crop type 3, and this series is repeated until the landscape is completed (step = 1; Fig. 2, right). In the most aggregated landscape, the crop type 1 was assigned from field 1 to field $n/3$, the crop type 2 from field $n/3 + 1$ to field $2n/3$, and the crop type 3 from field $2n/3 + 1$ to field n (step = $n/3$, being n the total number of fields). Each crop type is then located in a single clump within the landscape (Fig. 2, left). In between of these extremes, 98 additional steps of crop type assignment were selected at random to create landscapes of different field aggregation.

2.2. The harvesting procedure

Once the landscape was created, the harvesting machine was introduced in the bottom left corner of the lattice and a cereal cell was searched among the eight neighbouring cells (Moore neighbourhood) with the following priority N, S, E, W, NE, NW, SW and SE. If found, the machine moved to that cell and started

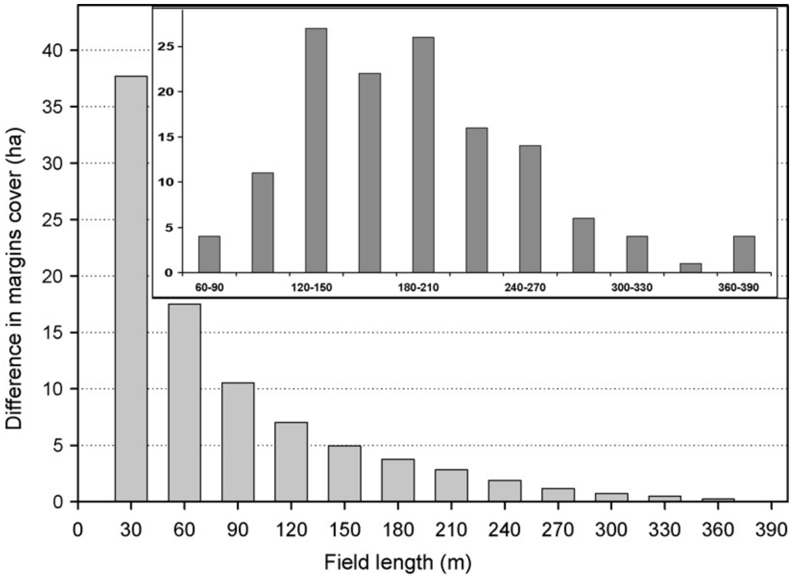

Fig. 1. Cover of field margins calculated by the model in landscapes of 558 ha with different field sizes. Values represent the difference of cover with respect to the minimum cover in the range (390 m of field length). By using the same *X*-axis, the inset indicates the frequency distribution of mean field sizes found in the 136 localities holding lesser kestrel colonies in Andalusia, Spain.

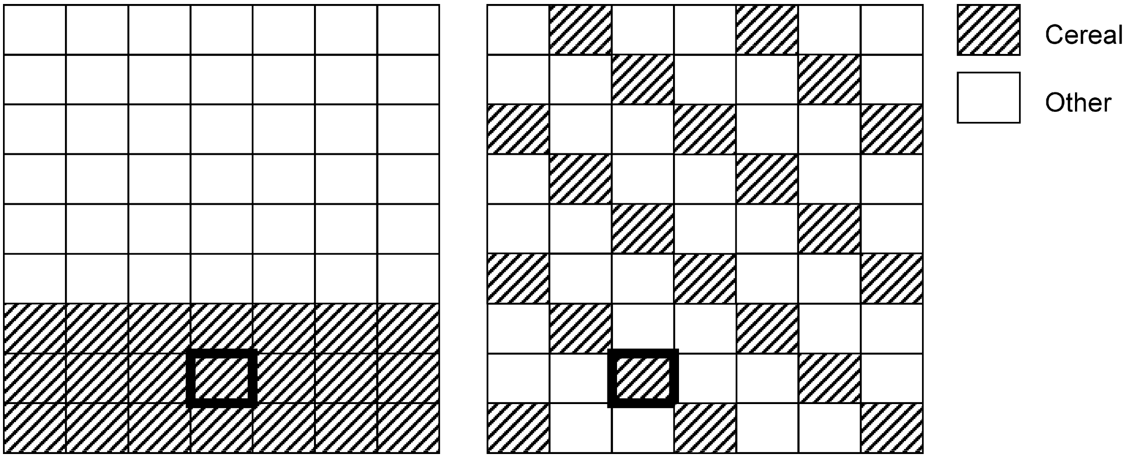

Fig. 2. Examples of highest (left) and lowest (right) cereal aggregation in a landscape with field length of 390 m (landscapes with smaller fields would produce similar patterns). Aggregation values for the selected fields (in bold) were 8/8 = 1, and 2/8 = 0.25, respectively. Width of margins (lines between fields) is not scaled.

harvesting. The harvesting procedure was parameterized according to field evaluations made by the Universidad Politecnica de Madrid in southern and central Spain on a regular harvesting machine (Marquez, 2003). We thus used a harvesting head of 5 m (five cells) and a working capability of 1.9 ha/h. When harvesting close to field margins, only cells belonging to current field were harvested. If no cereal cell was found in the neighbourhood, the harvesting machine moved to the next cell and look again for cereal cells in the neighbourhood. When displacing along field margins, a speed of 20 km/h was used. The harvesting machine was allowed to move only along cereal fields (while harvesting) or margins. Three different types of movements within the landscape were used: SIMPLE, FOREIGN, and LOCAL.

(1) In simulations using the SIMPLE movement, the harvesting machine searched for cereal cells in the Moore neighbourhood (as previously described). If a cereal cell was found, the machine entered the cell and started harvesting. If not, the machine looked for field margin cells in all directions of the compass within the Moore neighbourhood with the following priority: NE, N, E, S, W, NW, SW and SE. As regular way of dealing with boundaries in spatially explicit models, the borders of the lattice were modelled as periodic so that when the harvesting machine crossed the border, it re-entered from the other side of the lattice.

    In contrast to the simple heuristic rules of the SIMPLE movement, the FOREIGN and LOCAL movements are more realistic scenarios in which harvesting machines were confined to a certain area. Given that real landscapes have a finite size, we applied reflecting boundaries. For this purpose, we added one more column and row to the lattice in the right and upper limit, respectively, which were set as margins.

(2) The FOREIGN harvesting procedure tried to mimic a FOREIGN harvesting driver without knowledge of the area, thus relying on the closest fields to proceed. Because not all farmers own a harvesting machine, this rule was thought for areas where renting (normally with driver) is frequent. Under the FOREIGN movement, the harvesting machine also entered cereal cells as soon as they were found within the Moore neighbourhood. If no cereal cells were found, it moved along margins, turning (but never going back) in case of reaching the landscape limit. As main difference with respect to the other movement rules, in crossroads without neighbouring cereal fields, a random pattern was followed (excluding the arrival direction), and in case of being in the outmost margin, turning inside the landscape was selected whenever possible. In case of two contiguous cereal fields, the harvesting machine was forced to finish a field before going to the neighbouring one.

(3) The LOCAL movement was similar to the FOREIGN, but the harvester always proceeded to the closest cereal field by using field margins (i.e. Manhattan distance). This movement tried to imitate local harvesters that know perfectly were the closest field is located.

2.3. Model output

The model was written in C++ and 100 simulations with different field aggregations were run for each field size and scenario (see Table S1 in supplementary material).

To avoid dealing with real numbers during simulations, harvesting times were calculated in s^{-2} and afterwards they were transformed into days of 15 h (daylight time) for a better interpretation of data. Because harvesting times increased with increased cereal proportion in the landscape following a linear relationship, we corrected these harvesting time values to the reference point of 33% cereal cover, using the slopes of the linear relationship (Pearson correlation) between harvesting time and cereal cover. This relationship was always significant ($p < 0.01$).

2.4. Statistical analyses

We used Spearman correlations to describe the relationship between harvesting time and field aggregation. Wald–Wolfowitz runs tests were used to compare harvesting time between landscapes of different field size. We used this test because, in contrast to the more common Mann–Whitney *U*-test, it is also sensitive to differences in the general shapes of the distributions in the two samples (i.e. differences in dispersion, skewness, etc.; StatSoft Inc., 1984–2001).

3. Results

Harvesting time decreased with increasing field length in the three different movements (Fig. 3). This relationship was allometric ($y = a + bx^c$, where y is harvesting time and x is field length), with marked differences among movements in the *b*-value: very high in the FOREIGN movement ($b = 874$), low in the LOCAL movement ($b = 9.1$), and intermediate in the SIMPLE ($b = 206$), which determined different patterns of decay (Fig. 3). Decreasing harvesting times in the three movements showed

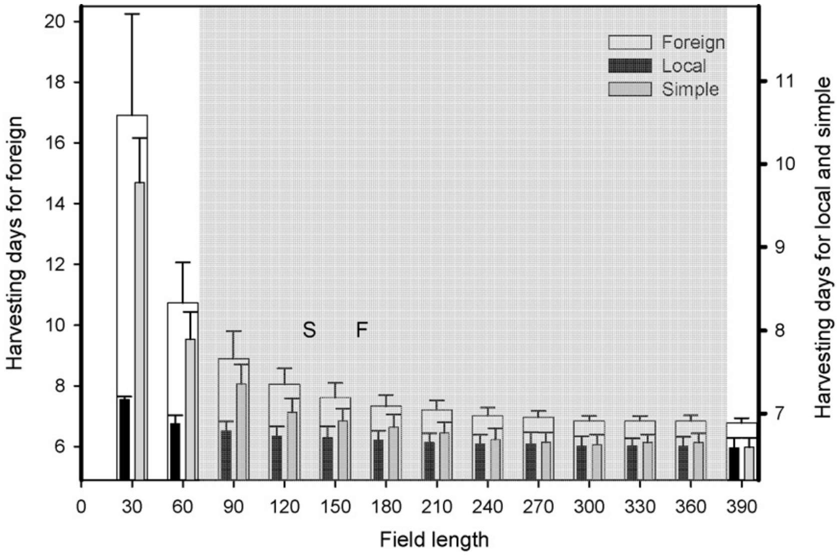

Fig. 3. Mean harvesting time (+S.D.) depending on field length (in meters) under three different movement rules. For the FOREIGN movement, harvesting time (*Y*-axis) is located on the left. For the others, harvesting time is located on the right. The shaded area indicates the range of field sizes found in localities holding lesser kestrel colonies in Andalusia. ''S'', and ''F'' indicate the point where differences in harvesting time between increasing field sizes become non significant for the SIMPLE and FOREIGN movements, respectively.

thresholds between 120 m and 180 m of field length (1–2 ha) above which machinery efficiency is increasing at a very low rate (at least 90% of maximum efficiency in the simulated range was already achieved). However, at this threshold, the model showed margins reductions of around 5 ha (Fig. 1). Accordingly, differences in harvesting time between landscapes of increasing field size remain significant until field lengths of 120–150 m in the SIMPLE movement, and 150–180 m in the FOREIGN (Fig. 1). Due to the tiny standard deviation of the LOCAL movement simulations, and despite the similarity among bars, differences were significant in all pair comparisons of the LOCAL movement (Fig. 1).

Mean cereal aggregation ranged from 0.14 (less than two neighbouring cereal fields) to 0.98 (the majority of cereal cells were completely surrounded by cereal). Harvesting time showed a negative relationship with the aggregation of cereal fields (Fig. 4). This relationship was stronger in the SIMPLE than in the LOCAL movement, although both showed significant Spearman correlation ($p < 0.01$) in almost the entire range of simulated field sizes. Slopes of this relationship decreased with increasing field size (Fig. 4). On the contrary, in the FOREIGN movement, this relationship was not significant in almost the entire simulated range, with some exceptions in landscapes with field sizes of 90 m (Spearman $R = -0.28$), 150 m ($R = -0.29$), and 240 m ($R = -0.21$).

4. Discussion

Agricultural intensification has occurred in much of Europe since the middle of the 20th century (Pain and Pienkowski, 1997). This implied profound changes in agricultural practices, and it has been proven to be the main cause of biodiversity erosion in farmed ecosystems (Donald et al., 2001, 2002; Mattison and Norris, 2005; Wilson et al., 1999).

Although these changes were made under incentives for overproduction, current public demands have also included non-market goods such as biodiversity, landscape, historic environment, and natural resources (Buckwell and Armstrong-Brown, 2004). This requires revisiting some of these changes made to increase agricultural production, which were not evaluated against their impact on biodiversity. That is the case of increasing field sizes, a measure that was mainly taken to improve machinery efficiency, but it was found to be one of the best correlates (among 17 indices) of biodiversity loss (Baessler and Klotz, 2006).

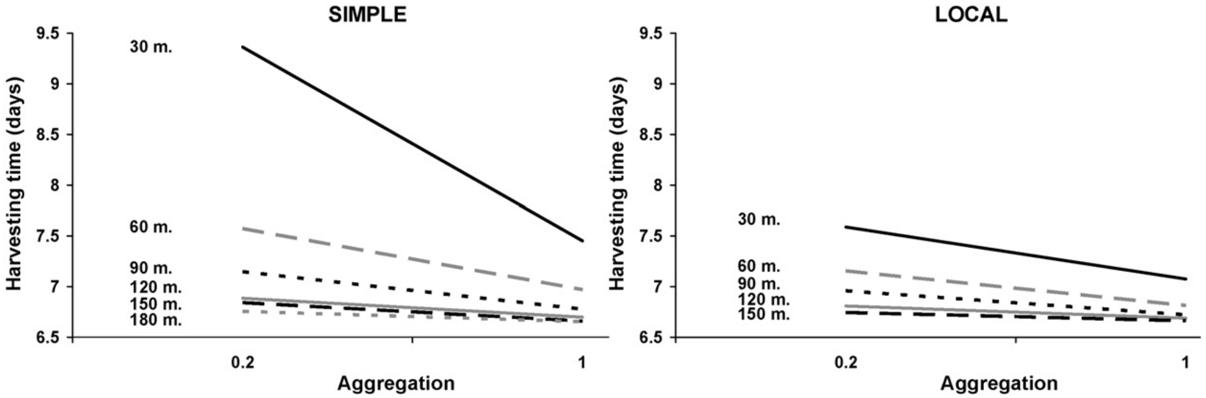

Fig. 4. Linear relationship between field aggregation and harvesting time depending on field size. For more clarity, relationships for field lengths above 150 m and 180 m were omitted in the LOCAL and SIMPLE movements, respectively.

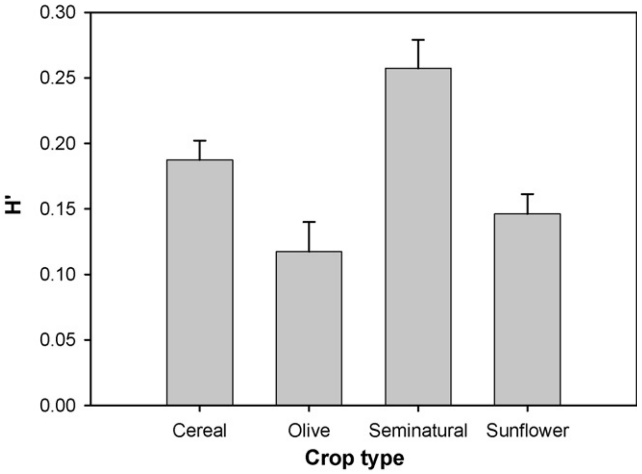

Fig. 5. Mean value (+S.E.) of Orthoptera diversity (Shannon H') sampled in the main crop types of six localities of Southern Spain during a three-year study (see Rodríguez and Bustamante, 2008 for details).

Regarding the case study species, diversity of its main prey, Orthoptera, demonstrated to be higher in semi-natural habitats such as small patches of fallow, grasslands, and margins than in any of the main crop types of the area (Fig. 5; see Rodríguez and Bustamante, 2008 for details).

By using a simulation model, we evaluated the gain in machinery efficiency derived from increasing field size against the potential loss in biodiversity derived from decreasing field margins. The relationship between machinery efficiency and field size was allometric, the former increasing markedly with increasing field size up to a certain threshold above which this trend virtually disappears. On the other hand, the availability of field margins could still show reductions of around 5 ha (Fig. 3). Although this was true for all three movement rules, the pattern was very clear under the FOREIGN, but very weak under the LOCAL movement. Both could be seen as theoretical extremes defining the range of harvesting efficiency. On the one hand, LOCAL defines the potential maximum harvesting efficiency. However, this model assumes the access to the closest field to be possible in all cases, and very often, this is limited by topography and property (see Fig. 6). Likewise, it assumes that the closest field is always ready for harvesting, while normally cereal fields dry up with certain spatial heterogeneity (personal observation). On the other hand, the FOREIGN model defines the minimum harvesting efficiency because it assumes to lack any information on the location of cereal fields. However, a foreign driver is expected to get some advice from local farmers to move from one field to the next. Even though these theoretical maximum and minimum extremes are probably never reached in the field, quantifying this range was useful to identify those field sizes above which machinery efficiency stabilized, and could be used as criterion for sowing in-field strips or restoring margins, which are measures commonly used in agri-environmental schemes to enhance biodiversity in farmlands.

Field aggregation showed a negative relationship with harvesting time that was especially important at small field sizes, where it contributes to increase machinery efficiency. In addition, crop aggregation is frequently the consequence of the clumping of soil types required for certain crop types, and/or location of infrastructures (e.g. irrigation systems). For these reasons, and although less aggregated crop types would enhance biodiversity in farmed landscapes, this kind of management would require more local evaluations.

Fig. 6. Schematic representation of a harvesting day in La Palma del Condado, Huelva (Spain) using a Landsat 7 satellite image and a catastrian layer. Numbers represent the observed harvesting sequence. Harvested cereal fields at that time are denoted with "H", unharvested fields with "U" and other crops with "O". Because field work was made on 2nd July, 2008 and the image was taken on 26th June, 2008 some of the colours may not match the real state of the field (harvested/unharvested) when the harvesting procedure was observed. Thick lines represent unpaved roads, which were partially used by the machine to move from one field to the next.

According to current state of the art of machinery and field sizes in Andalusia, farmland biodiversity may benefit from restoring margins or sowing in-field strips in fields above 2 ha. This measure has been suggested previously to prevent further losses in endangered populations of birds (Brickle et al., 2000), and these linear habitats demonstrated to be reservoirs of farmland biodiversity (Marshall and Moonen, 2002; Wilson et al., 1999), also improving connectivity among patches in the landscape (Diekötter et al., 2008), and providing pest-predators, thus reducing insecticide inputs (Hossain et al., 2002). In addition, our model showed that machinery efficiency would not decrease significantly with this measure and the loss of arable area and potential increase of weeds could be easily compensated by means of subsidies for environmentally-friendly practices (Kleijn et al., 2006). For the case study species, whose population decline was associated to reductions in both the extent and quality of foraging habitats (Peet and Gallo-Orsi, 2000), any gain of foraging habitats constitutes an improvement of feeding conditions. In fact, a previous study evaluating the impact of prey availability and quality on the breeding success of the species found that four out of six study colonies would require improvements of feeding conditions to allow colony persistence in the long-term (Rodríguez et al., 2006). Likewise, mean size of fields (which could be considered a proxy of margins abundance) have demonstrated to be a good predictor of lesser kestrel prey (Rodríguez and Bustamante, 2008), which supports restoring margins or sowing in-field strips in fields above 2 ha as a promising management option. Because many localities holding lesser kestrel colonies are above this threshold (see Fig. 1), a great proportion of them may benefit from this measure.

Despite this paper focused on a particular farming work (cereal harvesting) and on a particular area (Southern Spain), it is also applicable to other countries as long as range of field sizes and machinery are similar (see Herzog et al., 2006 for a comparison between countries). It should be noted that the model assumes 15 h a day as harvesting time, but daytime and working periods of drivers should be used to correct the results for their use in different circumstances. This study highlights the importance of revisiting the utility of structural changes that came along with agriculture intensification. Further efforts should be done to quantify other trade-offs between agricultural practices and biodiversity, thus selecting the targets where future management should be done in order to revert the process of biodiversity loss experienced in farmed landscapes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2008.10.010.

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