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Identifying effective actions to guide volunteer-based and nationwide conservation efforts for a ground-nesting farmland bird

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Summary

1. Modern farming practices threaten wildlife in different ways, and failure to identify the complexity of multiple threats acting in synergy may result in ineffective management. To protect ground-nesting birds in farmland, monitoring and mitigating impacts of mechanical harvesting is crucial.

2. Here, we use 6 years of data from a nationwide volunteer-based monitoring scheme of the Montagu's harrier, a ground-nesting raptor, in French farmlands. We assess the effectiveness of alternative nest protection measures and map their potential benefit to the species.

3. We show that unprotected nests in cultivated land are strongly negatively affected by harvesting and thus require active management. Further, we show that protection from harvesting alone (e.g. by leaving a small unharvested buffer around the nest) is impaired by post-harvest predation at nests that become highly conspicuous after harvest. Measures that simultaneously protect from harvesting and predation (by adding a fence around the nest) significantly enhance nest productivity.

4. The map of expected gain from nest protection in relation to available volunteers' workforce pinpoints large areas of high expected gain from nest protection that are not matched by equally high workforce availability. This mismatch suggests that the impact of nest protection can be further improved by increasing volunteer efforts in key areas where they are low relative to the expected gain they could have.

5. *Synthesis and applications*. This study shows that synergistic interplay of multiple factors (e.g. mechanical harvesting and predation) may completely undermine the success of well-intentioned conservation efforts. However, identifying areas where the greatest expected gains can be achieved relative to effort expended can minimize the risk of wasted volunteer actions. Overall, this study underscores the importance of citizen science for collecting large-scale data useful for producing science and ultimately informs large-scale evidence-based conservation actions within an adaptive management framework.

Key-words: active management, agricultural intensification, *Circus pygargus*, citizen science, evidence-based conservation, nest predation, raptors

Introduction

In an attempt to tackle large-scale biodiversity losses, conservation efforts have globally increased, targeting many species and ecosystems (Hoffmann, Hilton-Taylor *et al.* 2010). These efforts have not always been based on available scientific evidence, or this evidence has been too scanty, thereby potentially impairing ultimate success (Pullin *et al.* 2004; Sutherland *et al.* 2004). Evaluating the effectiveness of current efforts is a crucial step in conservation, as it allows making evidence-based decisions

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for present and future actions which yield the desired outcomes (Salafsky *et al.* 2002; Sutherland *et al.* 2004). This is particularly relevant given that, as more evaluations are carried out, it becomes clear that well-intentioned conservation actions may ultimately result in no net benefit to the target species, and sometimes even be detrimental (Ferraro & Pattanayak 2006; Walsh *et al.* 2012; Santangeli, Högmander & Laaksonen 2013; Santangeli *et al.* 2013).

Farmland is dominant in Europe and supports invaluable biodiversity (Pain & Pienkowski 1997). However, farmland-associated taxa are facing a massive collapse largely attributed to intensification of agricultural practices (Pain & Pienkowski 1997; Tscharntke *et al.* 2005). Under intensive production regimes, farmland species are affected by increased use of chemicals as well as mechanization and simplification of the landscape (Pain & Pienkowski 1997; Robinson & Sutherland 2002). These factors often act in synergy (Whittingham & Evans 2004). Much literature has been produced on the multiple processes by which agricultural intensification has reduced bird populations in particular (see e.g. the review by Newton 2004). Many farmland birds are ground nesters, and mechanical destruction of clutches, broods or even adults of ground-nesting birds has been repeatedly suggested to impact their populations (e.g. Pain & Pienkowski 1997), but the extent of this impact is rarely quantified (but see Grüebler *et al.* 2008; Schekkerman, Teunissen & Oosterveld 2009). The impact of mechanized harvest on birds obviously depends on the lag between laying and harvesting dates. This impact has increased in recent decades, as a consequence of increased production of silage on grassland, increased speed and efficiency of harvesting machines and use of earlier crop varieties (see e.g. Robinson & Sutherland 2002). Moreover, climate change is likely to make this impact even stronger with crops reaching maturity earlier as temperatures increase (Newton 2004).

Effects of crop harvesting on ground-nesting birds, in addition to direct losses, may also be indirect through increased exposure of surviving nests to predators (Whittingham & Evans 2004; Grüebler *et al.* 2012), as harvest modifies the landscape and reduces nest concealment. Therefore, protecting nests from destruction due to harvesting may not necessarily result in increased bird productivity, if nest predation increases after harvest (Kragten, Nagel & De Snoo 2008; Schekkerman, Teunissen & Oosterveld 2009; Rickenbach *et al.* 2011; but see Grüebler *et al.* 2012).

A ground-nesting species for which mechanical harvesting was found to threaten population persistence is the Montagu's harrier (*Circus pygargus*; Arroyo, García & Bretagnolle 2002). In western Europe, this raptor of open land breeds in a wide range of habitats, from semi-natural such as grasslands and even clear-cut forests, to highly anthropogenic, such as cereal crops. In the latter, a varying, often large proportion of nestlings are not fledged at harvest time; this puts them at high risk of mortality from harvesting in the absence of protection (Arroyo, García & Bretagnolle 2002; Millon *et al.* 2002). Conservation programmes to protect nests from harvesting activities have been implemented for many years across different countries in western Europe, mainly by networks of volunteers using a variety of protection measures (Arroyo, Bretagnolle & García 2003). Protection measures are often expensive in terms of human or economic resources. Therefore, assessing (i) their effectiveness, (ii) whether protection from harvesting operation may be hindered by factors like predation or (iii) whether there is a mismatch between areas of high expected gain from protection and availability of resources for conservation (including workforce) are crucial issues to address in order to improve the effectiveness and efficiency in which conservation resources are used. Robust evaluation studies, however, often require large amounts of data to allow taking into account multiple ecological factors affecting the species under study, and these are often not available.

Under current pervasive underfunding of conservation budgets, the recent explosion of citizen science represents a very powerful mean for collecting low-cost large-scale ecological data that prove fundamental in addressing a variety of applied ecological questions (Tulloch *et al.* 2013a). For example, such large amounts of data can be used to evaluate the effectiveness of different conservation interventions and pinpoint the most effective actions. On the other hand, volunteers may not be always available where they are most needed. It is therefore important to also explore whether the availability of volunteers in space mirrors the conservation and monitoring needs (Tulloch *et al.* 2013b).

Here, we use data collected on over 6000 nests of Montagu's harrier monitored throughout France over six years, with the aim to identify the most effective protection measures and highlight areas where an increase in volunteers' effort could result in highest benefits to the species across the country. More specifically, we compare breeding performance at nests under different protection measures in relation to unprotected nests, accounting for nesting habitat types representing different pressures (e.g. harvest damage). Among the different protection measures, we pay particular attention to those protecting from harvesting alone, and those that also allow protecting from predation. Finally, we derive a nationwide map showing areas of mismatch between expected gain from nest protection and availability of volunteers' workforce. This would ultimately identify the gaps in human resources which, if filled, would yield high benefits to the species.

Materials and methods

STUDY LANDSCAPE AND STUDY POPULATION

The study was conducted across the whole of France during the years 2007–2012, linked to a national-scale wing-tagging

programme (www.busards.com) aimed at evaluating harrier dispersal. Throughout the country, agricultural areas are dominant (about 55% of the total area), especially in the western and northern regions. In recent decades, farmland practices have intensified across France, as in most of Europe (Pain & Pienkowski 1997). In France, the total breeding population of Montagu's harriers, though varying between years because of variability in abundance of its main prey (common vole *Microtus arvalis*), was estimated at 3900–5100 pairs in the early 2000s (Thiollay & Bretagnolle 2004).

FIELD PROTOCOL AND NESTING HABITAT DATA

Every year, around 300–400 trained local volunteers searched for Montagu's harrier nests across its breeding range in the country, following a standardized protocol. Over the six study years, 6091 nests were surveyed (annual mean ± 1SD: 1015 ± 161). Detected nests were visited to monitor content and evaluate protection needed by comparing bird phenology with expected harvest date. About half of monitored nests (46%; annual range: 40–52%) were first visited during the incubation period, allowing the record of clutch size. A final visit to all nests was made when chicks were near fledging: nest productivity was measured as the number of fully grown chicks recorded at this stage.

The habitat in which nests were located was carefully recorded (15 categories) and then subsequently assigned to one of the following three classes (hereafter called 'land uses') representing different pressures in relation to harvest: annual crops (wheat, winter barley or other annual crops), which are harvested in summer; pluriannual crops (mostly grass and legumes for fodder production), which are first mowed in spring; and perennial habitats (long-term fallow fields or land dominated by bushes, scrubs, heath or tree saplings), which are not normally harvested. Of the overall sample of nests, 73% were in annual crops, 9% in pluriannual crops and 17% in perennial habitats. Of the nests in annual crops, most (68%) were in wheat and 28% in winter barley.

PROTECTION MEASURES FOR MONTAGU'S HARRIER NESTS

Several types of protection measures were implemented through the years. The most common measures in annual or pluriannual crops were as follows (for sample size, see Fig. 2): retaining a small (5 m^2 in annual and 10–25 m^2 in pluriannual crops) buffer of standing crop (hereafter 'buffer'); buffer retention but delimited by a fence protecting the sides and often the bottom of the nest that was placed before harvest time (hereafter 'fenced buffer'); relocation of the chicks to a nearby safe field or field edge ('relocation'); relocation with placement of a protective fence ('fenced relocation'; 5% of nests); signalling the nest location with a stick holding a flag to the farmer, who would then be responsible for avoiding the nest at harvesting ('flag'); and finally removal of the chicks and subsequent captive rearing and release. The latter category was not considered further in the analyses as productivity per nest could not be calculated. Nests in perennial land uses were occasionally exposed to some levels of anthropogenic land management activities, and some measures to delay those activities were carried out. However, these were not clearly defined and detailed and have been excluded from analyses.

Furthermore, in order to explore the possible impact of predation on nest productivity, we make a reasonable assumption that the longer a nest is protected against predation (i.e. with a fence), the lower its probability of being predated. Because the exact exposure length (duration of period with no fence surrounding the nest) was not available in most cases, we defined four exposure classes by lumping the six protection measures in annual or pluriannual crops as follows: long exposure (i.e. nests protected from harvesting machinery but without a fence at any time: buffer, relocation and flag protection types), medium exposure (nests protected by a fence from the time of harvest onwards: fenced relocation), short exposure (nests under the fenced buffer protection type, where the fence was placed 2–20 days before harvest). A fourth category was that of unprotected nests: this also had a long exposure to predators, and no protection from harvesting.

Protection measures in perennial land uses were directed to reduce nest predation: placing a protective fence before land management activities ('fence') or applying a predator repellent (i.e. naphthalene balls) around the nest ('repellent').

In terms of cost (including monetary as well as investment in fieldwork time), the baseline common to all protection measures is the time required for finding a nest (between three and 12 h, depending on volunteers experience) and to find and deal with farmer (about four hours). Fencing a nest takes about 30 min (costs of material: ca. 10 € per fence). Harriers do not reuse the same nest twice, and the same fence is retrieved and reused year after year for protecting new nests, so the direct cost of the fence is in a one-off. Costing relocation is complicated as it strongly depends on the nest position within a field. Relocation should be made at short-distance steps to minimize nest abandonment risks. Thus, nests close to a field edge may be relocated in one go, with lower associated fieldwork time than if the process would have required moving the nest at different steps. However, as for the buffer, the difference in costs between relocation alone, and relocation with a fence, is very small. Conversely, placing a flag entails negligible added costs in addition to baseline costs.

ANALYTICAL FRAMEWORK

We modelled the variation of three breeding performance parameters: clutch size; brood reduction, here defined as the difference between clutch size and number of fledglings for nests that produced at least one fledgling; and productivity, that is number of nestlings fledged. We used generalized linear mixed models (GLMMs). All models were based on a Poisson distribution with log link function, and year was always included as a random effect to account for possible among-year variation in breeding performance due to unquantified variables such as food availability. The dispersion parameter was below 1·3 for all models, suggesting no over dispersion.

We first tested for the effect of three land-use classes (annual, pluriannual, perennial) on three different response variables (clutch size, brood reduction and productivity) separately in the absence of nest protection. In these three models, we used data from unprotected nests with known clutch size, and land use was included as a categorical predictor (with three classes). Clutch size or brood reduction may vary between land uses because of either differences in food abundance, quality variation among harriers breeding in different land uses, or both. A difference in productivity between land uses may be caused by varying predation levels, food availability or harvest destruction (in nests in annual

and pluriannual land uses). We hypothesized that if clutch size and brood reduction, but not fledgling production, were similar between the three land uses, this would indicate that differences between habitats were mainly due to harvesting or predation rather than to food availability or individual quality.

A fourth and fifth model considered protected and unprotected nests on annual and pluriannual land uses only and included also nests with unknown clutch size. Both models had productivity as the response variable and land use (with two classes: annual vs. pluriannual) as one of the predictors. In addition, the fourth model also included protection type (categorical variable with six levels, see above) as a predictor. Further, nests were, or were not, protected against predation, and the timing of protection against predation differed between different protection types. We exploited this variability to test the effect of different levels of exposure to predation on nest productivity in a fifth model which included exposure (categorical variable with four levels, see above) as a predictor in addition to land use. In the fourth and fifth models, we also tested for the interaction of land use with protection type and land use with exposure, respectively. These interactions aimed to verify whether the effect of protection type or exposure differed between the two land uses considered: as pluriannual land-uses are harvested much earlier than annual land uses, this may affect the relative effectiveness of different protection types.

Finally, we built a sixth model considering only nests in perennial land uses, therefore not exposed to harvest destruction but potentially affected by predation. In this model, productivity was the response, while protection type (with three classes: fence, repellent and unprotected) was the only predictor.

We checked the robustness of all results against possible differences in clutch size among the categories under study by repeating the three latter models including clutch size as a continuous covariate (thus with reduced sample size, see above). Analyses were carried out with SAS 9.2 (SAS Institute, Cary, NC, USA). Statistical differences between classes of categorical variables were tested by *post hoc* comparisons of least-square means and corresponding *P*-values adjusted for multiple comparisons using the Tukey–Kramer correction method. We checked for spatial autocorrelation by visual investigation of spline correlograms based on models residuals, but none of them showed any clear spatial pattern.

MAPPING CONSERVATION EFFORT AND EXPECTED GAIN

Harrier nest protection in France involves 300–400 volunteers each year. It is therefore important to investigate whether the availability of such large workforce matches the expected gain from nest protection, that is whether areas with high potential for increasing nest productivity with protection lack volunteers. The expected gain from protection will ultimately depend on harrier density and the difference in productivity between protected and unprotected nests: if the difference in productivity and/or density is low, expected gain of increasing protection there will also be low. Thus, we first calculated the difference between average productivity of protected nests (considering only nests protected with a fence, e.g. fenced buffer, fenced relocation or fence alone on perennial land) minus that of all unprotected nests at a resolution of 100-km^2 squares (see Fig. S1a,b, Supporting information). Because not all 100-km^2 squares across France had available nest data, we interpolated the values from the squares with available data across the whole country using ordinary kriging with an exponential shape derived from an empirical variogram investigation (see Fig. S2, Supporting information) from observed data. Next, we multiplied the interpolated expected gain (average extra chicks produced per nest following protection) by the density of breeding pairs per square to derive an overall expected gain of chicks per square assuming protection of all nests. Data on breeding harrier density were derived from predictive density models that accounted for land-use and climatic conditions using survey data from the years 2000–2002 (see Thiollay & Bretagnolle 2004 for methodology of the French raptor breeding survey, and Le Rest, Pinaud & Bretagnolle 2013 for details on the density modelling methodology). We derived a measure of volunteers' workforce (i.e. available effort), expressed as average number of man-days of fieldwork per year for each region of France. We then run a linear regression, at the 100-km^2 square level, between the expected gain from nest protection and volunteers' workforce. From the latter analysis, we excluded squares with very low density (<0·1 pairs per 100 km^2) as they are irrelevant for nest protection. We ultimately mapped the residuals of the regression, which thus depict areas where the available effort is higher or lower than the expected gain resulting from effective nest protection. We ran the spatial analyses and correlograms in R (R Core Development Team 2012) and used ARCGIS 10.1 (ESRI®, New York, NY, USA) for producing the maps.

Results

BREEDING PERFORMANCE IN THE ABSENCE OF NEST PROTECTION

Clutch size at unprotected nests varied only weakly among the different land uses ($F_{2,\ 949} = 2{\cdot}84$; $P = 0{\cdot}059$). Clutch size was slightly higher (0·5 eggs per clutch on average) in perennial than pluriannual land uses (adjusted $P = 0{\cdot}047$), while no difference was apparent from the other pairwise comparisons (Fig. 1a). Brood reduction was similar between the three land uses considered (overall test statistics for land-use variable: $F_{2,\ 352} = 0{\cdot}63$, $P = 0{\cdot}535$; Fig. 1b). Conversely, productivity markedly differed among land uses ($F_{2,\ 862} = 58{\cdot}32$ and $P < 0{\cdot}001$), being less than half for nests in annual and pluriannual compared to nests in perennial land uses (adjusted *P*-values <0·001 for both pairwise comparisons; Fig. 1c). Lower productivity at nests in annual and pluriannual land uses was thus mainly attributable to higher nest destruction rather than lower breeding investment and food availability in those land uses compared to perennial crops.

EFFECTIVENESS OF NEST PROTECTION

Protection implemented for Montagu's harrier nests in annual or pluriannual crops increased productivity, but effectiveness varied among protection types and land uses (Table 1; Fig. 2a). Productivity was highest at nests protected from predation and harvest (i.e. fenced buffer or fenced relocation), particularly in annual crops (Fig. 2a). Among the measures protecting from harvest alone, but not from predation, only relocation yielded higher

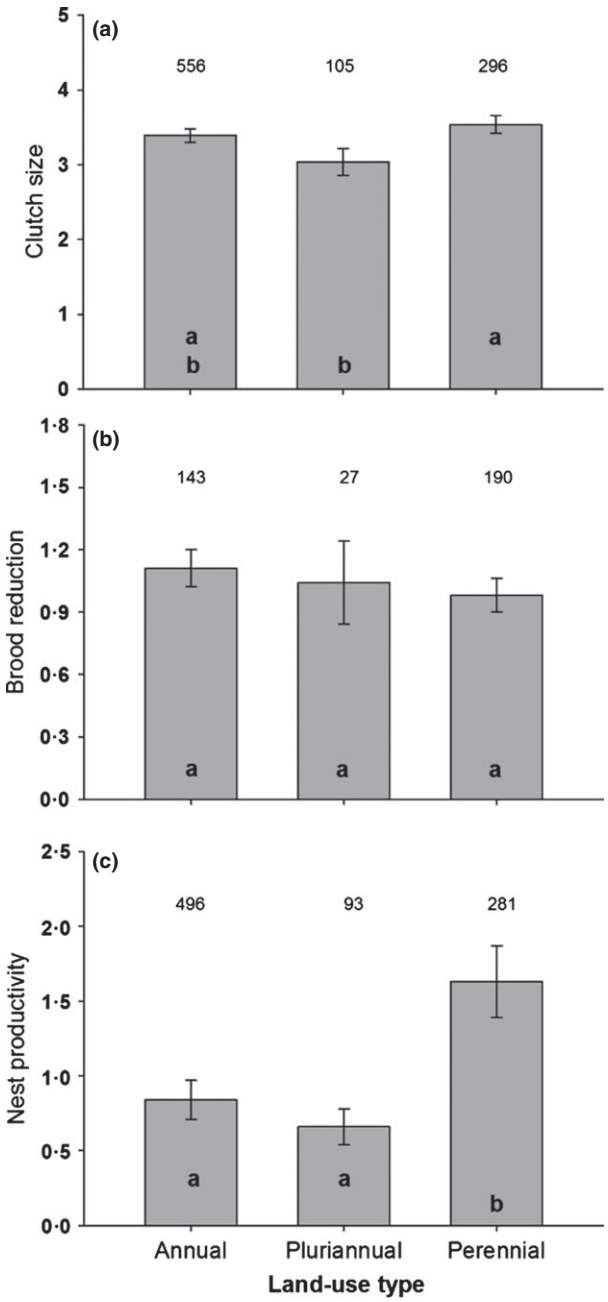

Fig. 1. Variation in (a) clutch size, (b) brood reduction and (c) productivity of unprotected nests with known clutch size of the Montagu's harrier located on three main land-use types. Values depict least-square means (±SE) derived from GLMMs with Poisson distribution and log link function, and year was included as a random factor. Numbers above the bars depict the sample of nests for each category. Results of the multiple comparisons between classes are indicated by the letters within the bars. Classes sharing the same letter are not significantly different ($\alpha = 0{\cdot}05$ after Tukey–Kramer correction method for multiple testing).

productivity than no protection, but only for nests in annual crops. All other measures that did not include a fence yielded a productivity similar, or even lower, than that of unprotected nests, especially in pluriannual land uses, suggesting their effectiveness was rather poor (Fig. 2a; see also Table S1, Supporting information, for results of all the pairwise comparison combinations and relative adjusted *P*-values).

Table 1. Difference in productivity between two different land uses (annual and pluriannual) in interaction with (a) six protection types (including unprotected nests, $n = 4363$, see Materials and methods) and (b) four levels of exposure (long, medium, short and permanent exposure in unprotected nests, $n = 4363$) of Montagu's harrier nests. Exposure depicts the period a nest was left without a surrounding fence (hence exposed to predation). In both models, a Poisson distribution with log link function was used, and the year was included as a random factor. A detailed breakdown of values for each class of the variables is shown in Fig. 2, while results of multiple pairwise comparisons between classes are provided in Table S1

Variable	d.f.	*F*	*P*
(a)			
Protection (6 classes)	5	53·19	<0·001
Land use (2 classes)	1	37·12	<0·001
Protection*Land use	5	2·62	0·023
(b)			
Exposure (4 classes)	3	85·79	<0·001
Land use (2 classes)	1	81·55	<0·001
Exposure*Land use	3	6·48	<0·001

When protection types were pooled into classes representing different exposure to predation, some interesting patterns emerged (Table 1 and Fig. 2b). When nests had a long exposure to predation, whether they were protected from harvest or not, productivity was always below two fledglings per nest and was strongly affected by land-use type, being much lower in pluriannual than annual crops. This suggests that an increase in predation at nests not protected by a fence completely obliterates any benefit derived from harvest protection efforts (Fig. 2b; see Table S2, Supporting information, for pairwise comparisons). Differences in productivity between nests with short or medium exposure (i.e. with a fence placed either before harvest or at harvest time) were much smaller (Fig. 2b).

All above results were confirmed when analyses were repeated using a subset of the data with known clutch size (see Fig. S3, Supporting information).

In perennial land uses (e.g. fallow land, heathland, scrubland), productivity significantly differed according to the protection measure implemented ($F_{2,\ 858} = 5{\cdot}82$, $P = 0{\cdot}003$; Fig. 3). Specifically, protection from predation with a fence around a nest yielded a significant 46% increase in productivity compared to non-protection (adjusted $P = 0{\cdot}007$). In contrast, using a repellent yielded only a marginal 18% increase (Fig. 3).

DISTRIBUTION OF CONSERVATION EFFORTS RELATIVE TO POTENTIAL BENEFITS

The Montagu's harrier is unevenly distributed throughout the country, with four main strongholds of breeding density (Fig. 4a). Further, we show that areas with highest overall expected gain (i.e. number of extra fledglings per unit area) from implementing effective nest

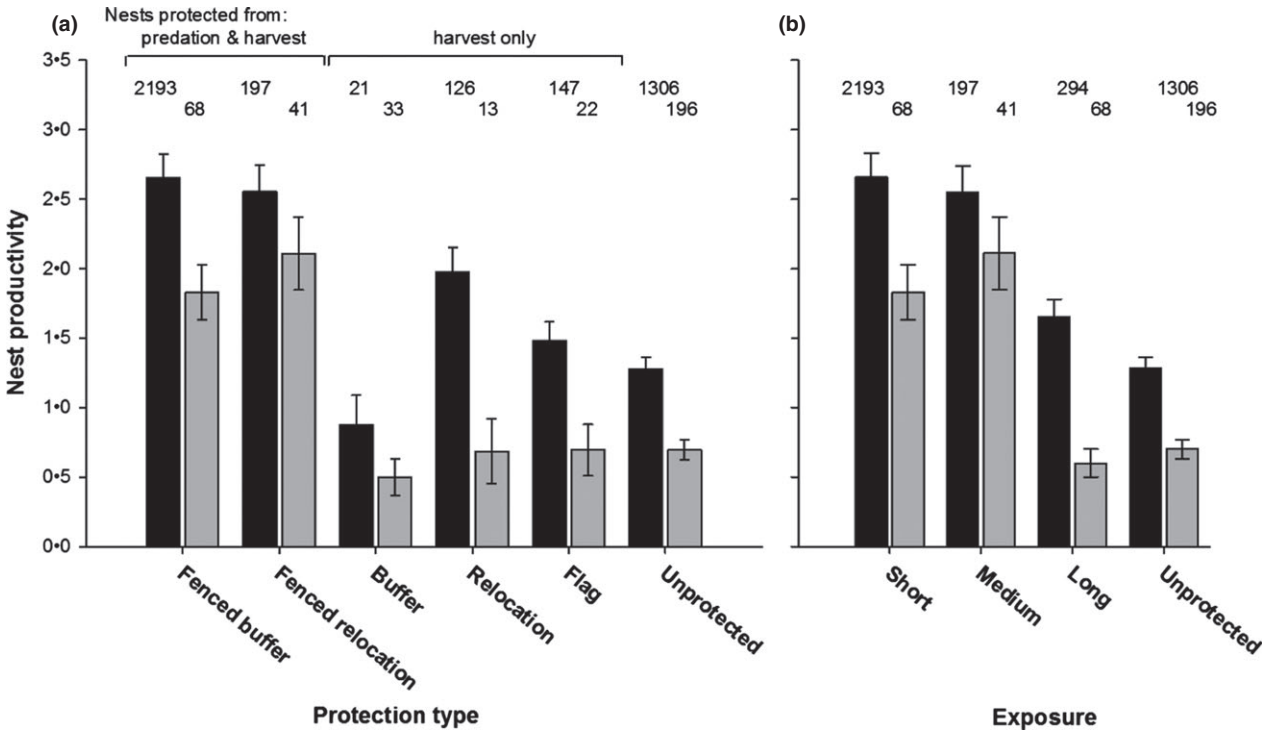

Fig. 2. Productivity of Montagu's harrier nests located on two cultivated land uses (annual and pluriannual; black and grey bars, respectively) in interaction with (a) protection type (including unprotected nests) and (b) exposure level (including unprotected nests) during 2007–2012 in France. Exposure depicts the period a nest was left without a surrounding fence (hence exposed to predation for a short, medium, long or permanently exposed as represented by unprotected nests). Values depict least-square means (±SE) derived from the models shown in Table 1. Numbers above the bars depict the sample of nests for each category in annual (upper row) and pluriannual (lower row). Results of multiple pairwise comparisons between classes are provided in Tables S1 and S2 for results shown in panel a and b, respectively.

protection measures to all unprotected nests are spatially aggregated (Fig. 4b), closely matching high-density areas. In some areas, expected gain can be very high, up to 60 fledglings per 100 km^2 due to high breeding density and high difference in productivity between unprotected and protected nests. Volunteers' workforce per nest is also uneven through the country (Fig. 4c). The combination of expected gain from nest protection and volunteers' workforce (Fig. 4d) clearly highlights large areas where high expected gain from protection are not corresponded by equally high workforce availability. This suggests that there is large potential for effectively protecting the species by increasing volunteers' workforce in the key areas we identified (red squares in Fig. 4d).

Discussion

PROTECTING AGAINST NEST DESTRUCTION IN FARMLAND

Our results confirm that the productivity of Montagu's harriers breeding in French farmland is strongly sustained by active management through volunteer-based nest protection. In the absence of such protection, nest productivity is reduced by *c.* 50% in cultivated land. Simulation work (Arroyo, García & Bretagnolle 2002) suggested that below two fledglings per female, the viability of Montagu's harrier populations is impaired. Our empirical data show that, in the absence of protection, such critical levels are only realized in perennial land uses (i.e. semi-natural vegetation), which are used by only 15% of the French harrier population (Millon, Bretagnolle & Leroux 2004). Similar results have been found for Spain, another stronghold of western European Montagu's harrier populations (Santangeli, di Minin & Arroyo 2014).

The extent of the problem may be even larger than observed here, because the sample of unprotected nests considered in this study may not be random. It is likely that a fraction of nests that were left unprotected were so because they were considered to be at low risk of destruction; for example, they were early nests with high chances of fledging before harvest. Because early nests may often be found when eggs have already hatched, their clutch size was not recorded. This most likely explains the difference in productivity of unprotected nests in annual crops shown in Fig. 1c, where only nests of known clutch size are considered, and Fig. 2a where all nests, including those of unknown clutch size, possibly early nests, were included. Therefore, our sample of unprotected nests may show higher productivity than what may result if unprotected nests were selected in a strictly random manner.

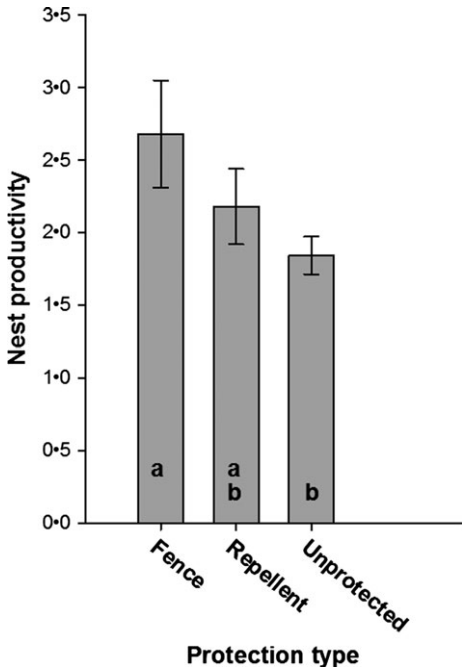

Fig. 3. Productivity of Montagu's harrier nests located in perennial (semi-natural) land uses under two different protection types (as well as unprotected; sample size: 28, 41 and 874 for fence, repellent and unprotected, respectively) during 2007–2012 in France. Values depict least-square means (±SE) derived from a GLMM with Poisson distribution and log link function, and year was included as a random factor (see Materials and methods). Results of the multiple comparisons between classes are indicated by the letters within the bars. Classes sharing the same letter are not significantly different ($\alpha = 0{\cdot}05$ after Tukey–Kramer correction method for multiple testing).

Additionally, nest monitoring for protection purposes could be more concentrated on areas where harvesting impacts are possibly highest, which may amplify the extent of the problem. We consider the latter bias to be probably small, given the very large spatial and temporal extent covered by our data set, and the fact that the initial aim of the detailed monitoring was a countrywide dispersal study (www.busards.com) rather than solely for conservation purposes.

Protection measures in cultivated land significantly increased productivity, although effectiveness varied between protection and land-use types. Productivity was always lower for nests in pluriannual than annual crops, regardless of the protection measure applied. This may be related to various factors, among others the earlier harvest date in pluriannual crops (thus extended exposure after protection and until fledging), and higher vole abundance in these types of habitat (Jareno *et al.* 2014) which may attract more predators. Montagu's harriers choose their nest sites according to vegetation height and density (Arroyo, García & Bretagnolle 2004), and fodder crops are selected over cereal crops because they are taller than cereal when harriers settle. This suggests that if availability of fodder crops were to increase over time, the efficacy of overall conservation efforts may decrease.

The fact that buffer and relocation provide equally high productivity (at least when coupled with a fence) is of great advantage for local conservation practitioners, because it allows choices of alternative actions that can depend on local landscape and social context. In areas where farmers do not accept a buffer, relocation may be applied. It is in fact well known that the attitude of landowners can play a crucial role in determining ultimate implementation of conservation measures in private land (Knight *et al.* 2011). However, relocation may be also constrained by availability of a safe uncultivated field or field margin at a short distance to the nest. This may often be the case in areas of intensive agriculture where fields are large (Robinson & Sutherland 2002), and the distance to the nearest field edge may be prohibitively high for relocation.

PREDATION HINDERS EFFECTIVENESS OF PROTECTION FROM HARVEST

All measures to protect against harvesting destruction which did not employ a protective fence yielded no or little improvement in productivity compared to non-protection (with the exception of chick relocation applied in annual crops). This suggests that post-harvest predation becomes a very strong limiting factor, probably due to increased detectability of the nest after harvesting. Productivity was similar for nests protected from harvesting with a short or medium exposure period to predation (fence placed just after or before harvest, respectively), suggesting that the negative predation effect in farmland occurs mainly after harvest. Post-harvest predation may render protection efforts completely useless (Fig. 2). Similar outcomes were reported from a protection programme for lapwing *Vanellus vanellus* nests in Dutch farmlands (Kragten, Nagel & De Snoo 2008). Indeed, predation rates of Montagu's harrier nests have been found to be associated with nest concealment (Gillis *et al.* 2012). Moreover, the fact that nest relocation without a fence, but not buffer, was highly effective in annual crops is likely due to better concealment of relocated nestlings as compared to nests protected by a buffer alone in the middle of a bare field.

In perennial land uses, where destruction by harvest is not an issue, protection through a fence, but not repellent, significantly increased nest productivity. These results are in line with available evidence suggesting that nest exclosures seem to generally provide high benefits to breeding birds in many circumstances, while the effectiveness of using a predator repellent is questionable (Williams *et al.* 2012).

Nest predation is a main cause of nestling mortality in many species (Martin 1995), and for several ground-nesting birds, it may be considerably high (e.g. for Lapwing, Black-tailed godwit *Limosa limosa*; Rickenbach *et al.*

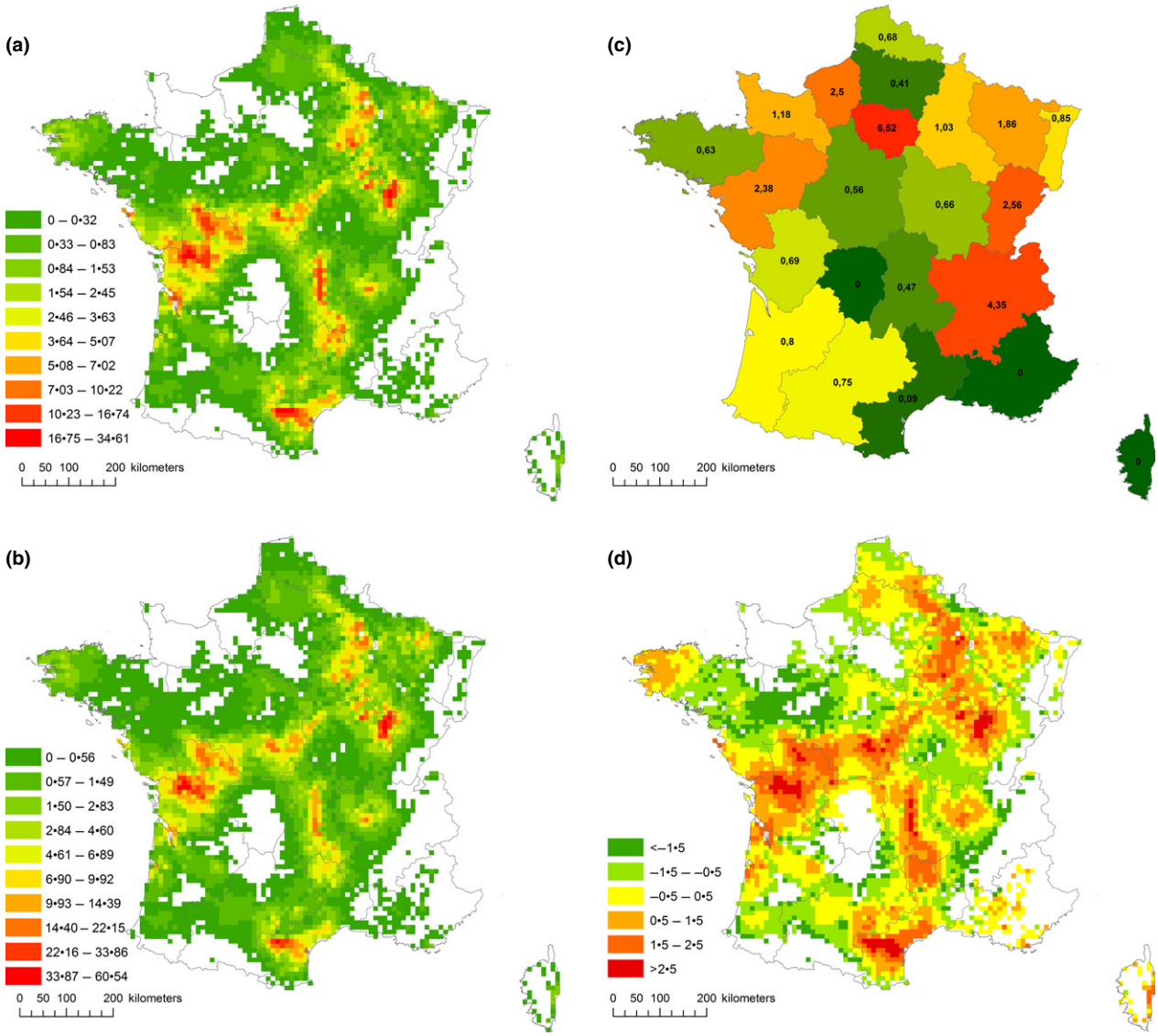

Fig. 4. Spatial distribution of (a) predicted density (breeding pairs per 100 km^2) of Montagu's harriers in France; (b) overall extra chick production (expected gain) per square if all the unprotected nests were protected with most effective measures (i.e. using an additional fence; see Materials and methods for further details); (c) distribution of volunteers workforce available (average number of fieldwork man-days per nest per year) in each region of France; d) spatial mismatch between expected gain from protection (as in b) and volunteers' availability (average number of fieldwork man-days per year per region); areas with high potential benefit but low available effort are in red (values depict residuals of a regression between benefits and effort, see Materials and methods for further details). Grey lines represent national and regional boundaries, while white areas in panels a, b and d have very low density (<0·1 pairs per 100 km^2) and thus irrelevant for nest protection.

2011; Smith *et al.* 2011). Modern agriculture was previously found to increase predation impacts on chicks of wader species breeding in farmland (Schekkerman, Teunissen & Oosterveld 2009), though a recent study on Marsh harrier *C. aeruginosus* concluded that predation rates are actually lower in agricultural habitats compared to natural habitats (Sternalski *et al.* 2013). Our results suggest that, at least for the Montagu's harrier, the problem of predation is not so much agricultural land per se, but the increased post-harvest nest exposure and resulting predation. This may also be the case for other species breeding in farmland (e.g. grey partridge *Perdix perdix*, corncrake *Crex crex*).

DISTRIBUTION OF CONSERVATION EFFORTS RELATIVE TO EXPECTED GAINS

During the last decade, there has been an explosion of citizen science programmes, whereby non-scientist amateurs contribute to data collection useful for scientific research (Tulloch *et al.* 2013a). Citizens also have potential to implement conservation actions that can benefit biodiversity (Cooper *et al.* 2007). Given that the volunteer workforce, although large, is often limited and unevenly distributed across the landscape, it is important that efforts are directed so that the most effective actions are applied in the areas where they can yield the greatest expected gain.

Any management that necessitates finding and protecting individual nests of a particular species is likely to be very costly in terms of direct human resources. In our study case, the cost (both economic and in terms of extra-time) for setting up fences is only marginally larger than that of setting unfenced buffers or relocating nestlings, and this additional cost is largely overturned by the expected gain in terms of increased nest productivity. An additional half an hour for placing a fence for buffer or relocation (note that we neglect the direct cost of the fence here, but this is marginal, see Materials and methods) to the baseline cost (7–16 h for nest search and dealing with farmer) would yield an increase in overall cost of <8% from the baseline costs. Conversely, the additional fence would yield an increase in nest productivity of 100% or more (see Fig. 2). This suggests that it is most cost-effective to protect from both harvest and predators than from harvest alone.

For the future, it would be relevant if volunteers are asked to also collect information regarding the costs (economic as well as time) for implementing each intervention. Often the costs of specific actions vary according to local context, such as the degree of nest aggregation in the case of Montagu's harrier nest protection (Santangeli, di Minin & Arroyo 2014). Gathering detailed cost information would allow performing a spatially explicit cost-effectiveness analysis. This was not done in the present study due to a lack of detailed cost information, but would represent a valuable complement to the present findings.

Our mapping exercise suggests that areas holding highest potential for effective protection of harrier nests in France fall within or nearby the main strongholds of breeding Montagu's harrier populations in the country (Fig. 4a,b). Further, we highlight areas where high expected gains from nest protection are not paralleled by high availability of volunteer's workforce (Fig. 4d). Increasing workforce in those areas will have a disproportionately positive impact on the species. This could be achieved by increasing efforts to recruit more volunteers in areas of high expected gain (e.g. by motivating them based on the scientific evidence that their actions will have a demonstrated positive impact), or by redirecting volunteers from other projects in the same area, if conditions allow. Given that citizen science projects have only recently come to the attention of scientists, the potential they can offer in terms of data collection is still to be fully realized. Recently, Tulloch *et al.* (2013a,b) highlighted the need to utilize citizen science data to under-utilized objectives. Here, we provide a rare example where citizens not only contributed data, but also applied management interventions. This allowed not only to protect the species at a large scale, but also to evaluate the effectiveness of different interventions whereby factors like predation and farming operations have a clear impact on the species.

CONCLUSIONS

Food demand is predicted to double by 2050 (Tilman *et al.* 2011), and with it, increased mechanization of agricultural practices and brood losses of ground-nesting farmland birds. Such losses are already considerable (Arroyo, García & Bretagnolle 2002; Grüebler *et al.* 2012). Protection measures have been implemented to reduce such losses in several species (Schekkerman, Teunissen & Oosterveld 2009; Smith *et al.* 2011; Santangeli, di Minin & Arroyo 2014), but their effectiveness may be impaired if multiple factors interact in synergy, for example increased predation in modified landscapes after harvesting. Our findings are thus instrumental for conservation management, as we show that measures aimed at reducing nest loss from harvesting can be completely offset by post-harvest predation. Furthermore, not only do we provide the evidence base for effective actions, but we also pinpoint areas where nest protection can be highly effective but where volunteers' effort is scarce, and should thus be increased. We thus encourage more studies like ours that will have a disproportionate impact in terms of applied conservation because they address real-world issues and provide clear solutions to aid best conservation practice while reducing waste of already scarce conservation resources.

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Data accessibility

Nest level original data and pixel level values for producing Fig. 4 are available for download in Figshare, DOI: http://dx.doi.org/10.6084/m9.figshare.1379877 (Santangeli *et al.* 2015).

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Fig. S1. Maps of nest productivity at protected and unprotected nests.

Fig. S2. Variogram for the difference between productivity of protected and unprotected nests.

Fig. S3. Productivity of nests under different protection and exposure level.

Table S1. Results of multiple *post-hoc* tests for class combinations in Fig. 2a.

Table S2. Results of multiple *post-hoc* tests for class combinations in Fig. 2b.