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LETTER

Comparing organic farming and land sparing: optimizing yield and butterfly populations at a landscape scale

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Abstract

Organic farming aims to be wildlife-friendly, but it may not benefit wildlife overall if much greater areas are needed to produce a given quantity of food. We measured the density and species richness of butterflies on organic farms, conventional farms and grassland nature reserves in 16 landscapes. Organic farms supported a higher density of butterflies than conventional farms, but a lower density than reserves. Using our data, we predict the optimal land-use strategy to maintain yield whilst maximizing butterfly abundance under different scenarios. Farming conventionally and sparing land as nature reserves is better for butterflies when the organic yield per hectare falls below 87% of conventional yield. However, if the spared land is simply extra field margins, organic farming is optimal whenever organic yields are over 35% of conventional yields. The optimal balance of land sparing and wildlife-friendly farming to maintain production and biodiversity will differ between landscapes.

Keywords

Biodiversity, conservation, easement, land use, protected area, restoration, sustainable agriculture, trade-off, wildlife-friendly farming, yield.

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INTRODUCTION

The last 60 years have seen an unprecedented rise in global agricultural productivity, but future demand for food may outstrip our ability to supply it (Tilman *et al.* 2001; Evans 2005; Kiers *et al.* 2008). There is likely to be increasing pressure to convert useable land to agriculture to meet global demands (Tilman *et al.* 2001; Green *et al.* 2005; Ewers *et al.* 2009). At the same time, the interacting threats of habitat fragmentation and climate change (Thomas *et al.* 2004a; Laurance & Useche 2009) will leave many wild species facing population decline or extinction. To minimize extinctions, we urgently need to maintain and create more space where wildlife can thrive (McInerny *et al.* 2007; Heller & Zavaleta 2009; Hodgson *et al.* 2009).

One approach to balance the needs of humans and wildlife is to make farms more hospitable to wildlife. In Europe there has been increasing emphasis – and expenditure – on farming in an environmentally sensitive way, including organic farming. In the UK alone, £435 m was spent on agri-environment schemes in 2008, as compared to a budget for all other nature conservation of *c.* £80 m (Natural England, Scottish Natural Heritage & Countryside Council for Wales information services, personal communication). To date, the effectiveness of agri-environment schemes in protecting wildlife has been mixed (e.g. Kleijn & Sutherland 2003; Bengtsson *et al.* 2005; Hole *et al.* 2005; Kleijn *et al.* 2006; Merckx *et al.* 2009; Vickery *et al.* 2009).

Biodiversity is often higher on organic farms, but the benefit of organic farming also depends on the surrounding landscape (Feber *et al.* 1997, 2007; Weibull *et al.* 2000; Rundlof & Smith 2006; Ekroos *et al.* 2008; Rundlof *et al.* 2008; Gabriel *et al.* 2010). This landscape dependence makes assessing the benefit of any biodiversity-focussed agri-environment scheme complicated. A high abundance of a taxon on a farm with a particular management intervention could be because that farm sits in a more biodiverse landscape [and the landscape itself predisposes the farmer to adopt the scheme (Gabriel *et al.* 2009)], or because the intervention attracts individuals from the nearby landscape without changing total population size. On the other hand, a successful intervention may lead to spill-over of wildlife into the surrounding landscape, meaning that the total effect of the intervention is greater than the effect observed at the site. Additionally, there could be a threshold amount of resources needed across an entire landscape to support populations of some species (Whittingham 2007): under such circumstances, a single intervention could have little effect, but several interventions close together could have a large effect.

Despite the large number of studies exploring the differences between wildlife-friendly and conventional farming, a crucial question remains unanswered. That is: what is the net effect on wildlife when the land being converted to wildlife-friendly farming has a lower yield, and so more land, somewhere, must be farmed to provide the same harvest? To assess the net consequences of farming, it is necessary to sum the benefits for wildlife and total food production over the farmed and unfarmed land (Green *et al.* 2005). In some cases, it could be best for wildlife to adopt a 'land sparing' strategy: that is, farm as intensively as possible on a portion of the land, and leave the rest devoted to wildlife conservation, e.g. nature reserves (Green *et al.* 2005). Green *et al.* (2005) suggested that land sparing would tend to be the best strategy in parts of the world where primary vegetation remained, and where most wildlife is badly affected by even low-intensity agriculture. In contrast, wildlife in western Europe has co-existed with low-intensity agriculture for many centuries, such that wildlife-friendly farming (land-sharing) could be the best strategy here (Fischer *et al.* 2008). However, this assertion has not been tested.

This study provides the first quantitative assessment of the land sharing/land sparing trade-off for one exemplar taxon: butterflies. Butterflies are used as an example of wildlife for its own sake, which people are interested in conserving, and which are sensitive to small-scale habitat change (Asher *et al.* 2001; Thomas *et al.* 2004b). A recent multi-taxon study furthermore indicates that they are representative of taxa that respond most positively to organic farming (Gabriel *et al.* 2010). We consider organic farming as a mechanism of land sharing because it specifically attempts to make the cultivated area more hospitable to wildlife by restricting pesticide and herbicide use.

The conceptual land sparing/sharing models of Green *et al.* (2005) only considered the proportion of land under each land use. However, as landscape effects can be important, we need to consider the spatial arrangement of different land uses as well as their quantities. This study uses a hierarchical nested sampling design to quantify the effects of management (conventional farming, organic farming or nature reserve) and landscape context (landscapes with low or high fractions of organic land) on the density and diversity of butterflies. We use observed butterfly responses to predict the average density of butterflies in an entire landscape depending on the fractions of organic farming, conventional farming, and reserves. From these predictions, we calculate the critical organic:conventional yield ratio that determines whether land sparing (conventional farming plus spared land) or land sharing (organic farming) is the optimal solution to maximizing butterfly abundance whilst maintaining yield. We then compare the critical yield ratios to actual yield ratios measured in the same fields as the butterflies.

METHODS

Field surveys

Sixteen 10 × 10 km landscapes in the Central South West and North Midlands of England were selected (Gabriel *et al.* 2009, 2010; Figure S1), and within each landscape we surveyed one organic farm, one conventional farm, and one grassland SSSI (Site of Special Scientific Interest: a UK conservation designation, henceforth termed 'reserves'). SSSI designation denotes grassland of high nature conservation value generally – not necessarily exceptional for butterflies in particular. We intended them to represent the potential wildlife value of land that is 'spared' from farming and managed for biodiversity. The 16 landscapes consisted of eight matched pairs (clusters) with similar environmental conditions (Gabriel *et al.* 2009, 2010) but with either a high or low amount of organic farming at the landscape scale (on average 17.2% organic farming in 10 × 10 km in the eight organic 'hotspots' vs. 1.4% in the eight 'coldspots'). Thus, the design differentiated between effects from local farm management and management in the neighbourhood.

Butterflies (Lepidoptera) were recorded along the centre and margins of six fields on each farm with standardized transect walks of 15 min. Three fields were arable (predominantly winter wheat and barley) and three were permanent pastures (henceforth 'grass', Figure S1). SSSIs were surveyed using the same transect technique but for 90 min (totalling the same as for three fields) and using a zig-zag path to attempt to gain an unbiased sample of the entire area of the SSSI (there was no margin/centre distinction, Figure S1). Individuals within 2.5 m either side of the transect were identified and counted. Surveying was done when weather conditions were suitable for butterfly activity (Pollard 1977: temperature > 15, or > 17 °C if cloudy, wind speed < 5 Beaufort Scale, between 10:00 AM and 5:00 PM). A team of field assistants conducted one survey of every site and a second survey of ¾ of sites between June and August 2008. We also include data from a pilot study of the arable fields in June and July 2007.

Yield (grain dry weight) of all cereal fields was estimated by taking three 50 × 50 cm samples from the field centres shortly before harvest. Additional farm management data were collected by a farm business analyst in face-to-face interviews.

Data analysis

Butterfly density

The number of butterflies counted on each transect per 15 min (equivalent to *c.* 0.18 ha as surveyors were trained to walk at the same speed) was taken to be proportional to the population density of butterflies (Pollard 1977). We used ln(butterfly count + 1) as the response variable in a linear mixed model [using the nlme package in *R* (Pinheiro *et al.* 2009; R Development Core Team 2009)]. We included random effects of site (the individual field or reserve) nested within landscape (10 km square) and cluster (pair of matched landscapes with high or low organic coverage) on the model intercept.

Model selection was done by backwards elimination of the fixed effects using likelihood ratio tests (an equivalent to the *F* test that can be used with mixed-effects models fitted using maximum likelihood; Pinheiro & Bates 2000). The starting model included the following variables: management (conventional, organic or reserve), crop type (grass or arable), location (margin, centre or reserve), four landscape variables derived from principal components analyses (PCA) (see below), day of year (second-degree polynomial), climate [each 10 km square's 10-year average growing degree-days above 5 °C (GDD5)], recorder identity, and the interactions between management, crop type and location (in combination termed 'habitat' variables) and the PCA variables.

To characterize the neighbourhood around each transect, the proportion of land farmed organically (data from Defra) and the proportion of land in SSSIs (data from Natural England) were measured in eight 'buffers' (circles of different radii between 250 and 3000 m centred on the transect) using ArcGIS (ESRI, Redlands, CA, USA). Across transects, these eight measures (arising from the eight buffer sizes) were highly correlated. To reduce the eight correlated measures to a smaller number of uncorrelated measures, we used PCA. One PCA was applied to the proportions of organic farming and another to the proportions of SSSI. In the PCAs, variables were centred but not re-scaled, because, as proportions, they were already on the same scale. For each analysis, two principal components accounted for over 95% of the original variance (Table 1). These four PCA axes (Table 1) were used as explanatory variables for butterfly density. The PCA axes can be interpreted in terms of the amount and pattern of organic or SSSI landcover: the first axis broadly measures 'amount' and the second axis 'aggregation' (Table 1).

Butterfly species richness

To have sufficient individuals per sample to analyse species richness, the data from the three replicate fields of each type on each farm were pooled (as were any separate transect sections within each SSSI). Then only observations with > 1 individual (75% of observations) were used. Species richness was modelled as a function of the number of individuals in a sample, plus the habitat variables used for models of density (see above), day of year, visit number (1–3 visits were made to each site), GDD5 and the organic PCA axes 1 and 2.

Table 1 Summary of the principal component analyses of data on percentage cover of either organic farming or grassland SSSIs (reserves) within eight buffers of different radii around the butterfly transects

	Organic PCA		SSSI PCA	
	PC1 'amount'*	PC2 'aggregation'*	PC1 'amount'*	PC2 'aggregation'*
Cumulative proportion of variance explained	0.87	0.97	0.84	0.96
Rotations of original variables				
% cover within 250 m	0.60	0.49	0.66	0.54
% cover within 500 m	0.51	0.17	0.51	−0.01
% cover within 750 m	0.41	−0.10	0.39	−0.22
% cover within 1000 m	0.34	−0.27	0.29	−0.29
% cover within 1500 m	0.24	−0.42	0.18	−0.40
% cover within 2000 m	0.17	−0.43	0.13	−0.44
% cover within 2500 m	0.12	−0.40	0.10	−0.47
% cover within 3000 m	0.09	−0.36	0.84	0.96

SSSI, Site of Special Scientific Interest; PCA, principal components analyses.

*The first axis is positively correlated to the proportion of organic farming (or SSSIs) in all buffers, but most strongly with the smaller buffers (most positive rotations), therefore we term this the 'amount' axis. The second axis is high when the distribution is clustered at short distances, and low when it is more evenly spread across the landscape so we term this the 'aggregation' axis (see also Figure S2).

The shape of the relationship between the number of individuals (N) and number of species (S) is different in different communities (Magurran 2004), so we considered three possible functional forms: $S \propto \log(N)$; $\log(S) \propto \log(N)$ and $S \propto N/(c + N)$ (Michaelis-Menten). The first of these gave the best fit (the lowest residual sum of squares, comparing fits using the 'nls' function in *R*, before other variables were added). Theoretically, we expect explanatory variables to affect the slope of the species–individual relationship (whilst the intercept remains at one individual, one species), so we report results from a linear model where $S = c + \log(N) \times (b_1 \times X_1 + b_2 \times X_2 + \cdots + b_k \times X_k)$. However, the results are quantitatively similar, if the model included effects on the intercept instead.

Predictions

To show the potential effects of different land-use strategies (the balance of organic farming or land sparing) we used our fitted model of butterfly density to predict densities for different hypothetical landscapes. The model of butterfly density was re-fitted with restricted maximum likelihood estimation before generating predictions (Pinheiro & Bates 2000). In hypothetical landscapes, we varied the proportions of organic farming and of spared land (either reserves or extra conventional non-cropped margin habitat) whilst keeping all other factors constant (day of year, climate and recorder, the ratios of grass to arable, and the spatial aggregation of organic fields).

Based on 2008 data for England (Defra 2008), we assumed for these predictions that 25% of the landscape is in land uses not considered in this study and thus the sum of conventional farming, organic farming and reserves in our hypothetical landscapes was always 75%. We varied organic farming between 0 and 25% (approximately the range in our study landscapes) and the area of reserves between 0 and 5% (currently grassland SSSIs cover 2% of England). Within hypothetical farms, we assumed that 55% of fields were arable and 45% grass (again based on averages from Defra 2008). Based on the individual field sizes and margin widths in our study we assumed that 11% of each grass field and 9% of each arable field would have the higher butterfly densities associated with the margin. In our study, there was no significant difference in margin:centre area ratios of organic and conventional fields. For grass fields, transect was taken 2.5 m from the boundary so the margin is the strip within 5 m of the boundary. For arable fields, transect was taken at the edge of the cultivated area, so margin is the uncultivated strip plus 2.5 m.

Because significant landscape effects were detected (see Results), we had to specify the spatial arrangement of organic fields in hypothetical landscapes, as well as the proportion of the landscape they cover. To make the landscapes reasonably realistic, but also make calculations simple, we assumed that fields are squares of 250 × 250 m and that organic fields always occur in square blocks of 3 × 3 fields (based on the average field size and distance of spatial autocorrelation in our data). We assumed that these blocks were regularly spaced in an arbitrarily large landscape. The spacing (in x and y directions) of organic blocks thus increased as the proportion of organic farming decreased. With these assumptions, we could enumerate all unique landscape situations a field could be in, and calculate the appropriate PCA axes for each one (using the predict.prcomp function in *R*). We predicted butterfly density from the model for every 'habitat' (see Fig. 1) in every possible landscape situation (possible situations depend on whether the site is organic or not; the SSSI PCA axes were not found to affect butterfly density; see Results). Then we calculated the average butterfly density of the entire landscape by multiplying these densities by the proportion of each habitat.

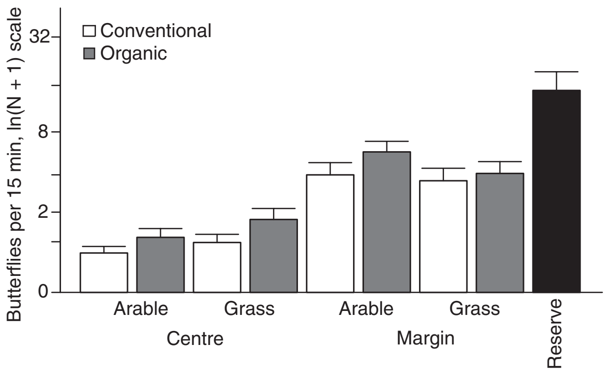

Figure 1 Effects of local habitat (combination of management, field type and within-field location) on butterfly density: the number of butterflies seen per 15 min of transect. Bars show mean + SEM (to be conservative, the SEM (SD/$\sqrt{n}$) is calculated with n being the number of sites, rather than the number of observations – there were usually 2–3 visits to each site, see Methods).

RESULTS

Butterfly density

Butterfly density is mostly explained by the combination of management, field type and location ('habitat', Fig. 1, Table 2). Density is higher on organic than on conventional farms, and highest on reserves, and within farms density is higher at field margins than in field centres and higher in grass fields than arable fields (Fig. 1, Table 2). The potential confounding effects are also important (Table 2). There are significant effects of the amount/pattern of organic farms in the surrounding landscape (organic PC 1 and 2, Table 2), but these are much smaller in magnitude than the effects of

Table 2 Relative contribution of different explanatory variables in the model of butterfly density, obtained by dropping each variable in turn from the full model. All models include nested random effects of site, landscape and cluster (see Methods) and are fitted with the *R* function lme with the maximum likelihood option. Altogether there are 917 observations (transect walks) and 207 sites

Variable dropped	AIC increase*	Likelihood ratio	*P*-value	Difference in likelihood-based R^2† (%)
Organic in landscape PC1	4.3	6.3	0.0123	0.3
Organic in landscape PC2	9.6	11.6	0.0007	0.6
Field type (grass or arable)	13.9	21.9	0.0002	1.1
Management (conventional, organic or reserve‡)	15.0	23.0	0.0001	1.1
Location (centre, margin or reserve‡)	321	328.6	< 0.0001	19.3
Habitat (the combination of field type, management and location)	436	451.9	< 0.0001	28.6
Habitat dropped but reserve vs. farm added‡	394	353.7	< 0.0001	21.1
Other co-variates (day of year, GDD5 and recorder)	389	410.7	< 0.0001	25.4

*AIC is a metric to compare and select models (Burnham & Anderson 2002), calculated as $-2\log(\text{lik}) + 2k$, where k is the number of parameters fit to the data.

†Likelihood-based R^2 is $1 - [\text{lik(null model)}/\text{lik(model)}]^{2/n}$ (Nagelkerke 1991).

‡When either Management or Location is dropped from the model, the difference due to reserves will still be captured by the other factor which remains in the model, so neither of these tests the effect of reserves. We cannot directly test the effect of reserves alone, but its effect can be seen by comparing the effect of dropping habitat completely with the effect of dropping habitat and adding a factor which is reserve vs. farm: the difference in AIC between these two options (rows 6 and 7 of the table) is 42.

habitat. Butterfly densities are relatively high when either of the two organic PCA axes are low: there is a weak negative effect of 'amount' and a stronger negative effect of 'aggregation' (Figures S2 and S3). The overall impact of this in terms of the original variables is that organic farming situated within *c.* 750 m of a transect has a negative effect on butterfly density, whereas any organic farming situated between *c.* 750 m and 3 km away has a positive effect (Figure S3). Given the areas of the different buffers, we can show that the net effect of any organic land on the landscape is marginally positive (the positive effect acting over a large area outweighs the negative effect acting over a smaller area, Figure S3). There are no significant effects of the PCA variables describing SSSIs in the landscape, or the interactions between PCA variables and habitat.

The random effects part of the mixed model indicates that there is a variance due to site of 0.09, as compared to a residual variance of 0.5. Only a negligible amount of variance is attributed to the 16 landscapes and 8 clusters. This means that repeated visits to the same site were somewhat correlated to each other, but there was no additional spatial autocorrelation at the scale of the landscape or cluster.

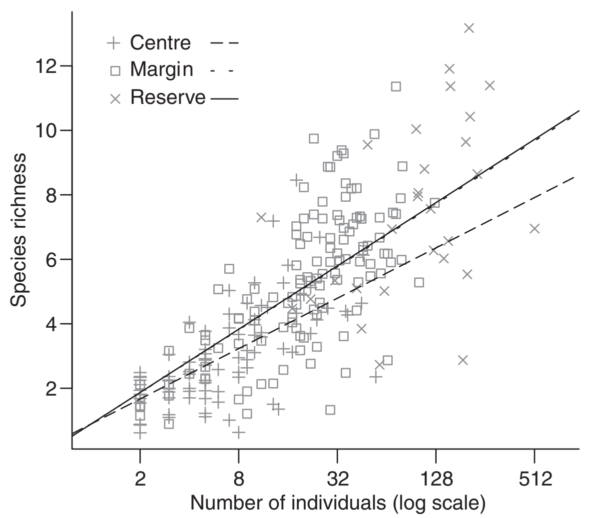

Figure 2 Relationship between species richness and number of individuals in sample, and fitted lines for reserves, field margins and field centres (see key). A random jitter (between −0.5 and 0.5) has been added to the species richness so that overlapping points can be seen. In total there are 237 observations (81 had to be excluded because ≤ 1 individual was recorded).

Butterfly species richness

The number of butterflies seen is the single most important determinant of species richness (explaining 59% of the variation by itself; Fig. 2). However, the slope of the line between log abundance and species richness is affected by several variables: reserves and field margins have more species (controlling for number of individuals) than field centres ($P < 0.0001$ and $P = 0.001$ for reserves and margins respectively, compared to centres, see Fig. 2). Grass fields have fewer species (controlling for number of individuals) than arable fields ($P = 0.004$), although they have higher

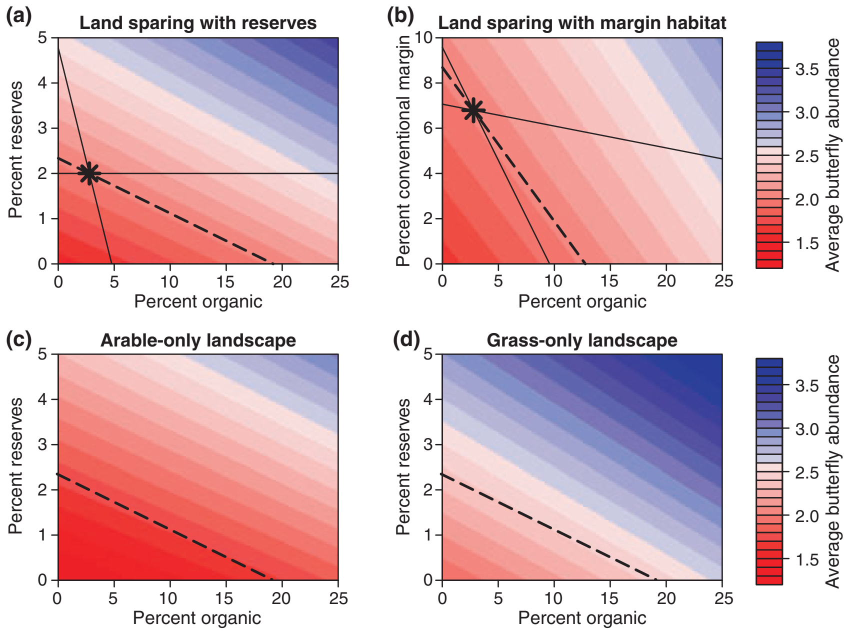

Figure 3 Whole landscape average butterfly abundance (red to blue shading, units of individuals per 15 min) as a function of the allocation of land use. (a) Altering percentage organic farming and percentage reserves in the landscape, assuming percentage conventional = 75-organic-reserve, and all other factors remain constant (see Methods – predictions). Star shows current average percentages for England. Black lines show possible yield constraint lines for different values of the organic:conventional yield ratio ($Y_{org}/Y_{con} - 1$ = slope of constraint line, see Appendix S1). Solid constraint lines are the extremes when organic yield = conventional yield (horizontal) or organic yield = 0 (gradient = −1). Dashed constraint line is the critical line where the optimal strategy switches from land sparing to organic farming, i.e. the line of equal butterfly density. Lines of equal butterfly density were calculated by interpolation over a grid of points using the function 'contourLines' in *R*. The slope of this line +1 gives the critical value of yield ratio (Y_{org}/Y_{con}): 87.5% in this example. (b) Altering percentage organic farming and percentage conventional margin habitat, to examine the situation where spared land could only be converted to habitat resembling conventional field margins. In this scenario the slope of constraint line = $(1 - m)Y_{org}/Y_{con} + 1$, where m is the proportion margin in organic fields, which remains fixed (see Appendix S1), and we find that the critical value of organic yield ratio (dashed line) is 35%. NB the different *y*-axis scales. (c, d) Same as (a) but assuming all fields are either arable or grass. The critical constraint line from panel (a) is copied onto (c) and (d) to show that in (c) the lines of equal butterfly density are shallower, and in (d) they are steeper.

densities of individuals (see butterfly density section, above). Species richness is also affected by day of year (positive, $P = 0.004$) and year of survey (2007 being higher, $P = 0.0002$). There are no significant effects of organic farming or the organic PCA axes on species richness, once butterfly density is taken into account.

Predictions

The average butterfly density of an entire landscape is expected to increase both with the proportion of organic farming and with the proportion of reserves (Fig. 3a). Reserves have a greater impact, relative to their area, than organic farms: a landscape with 2.5% reserves and no organic farms has roughly the same density of butterflies as one with no reserves and 20% organic farms (Fig. 3a).

This information could inform land-use decision making. If the yield from an agricultural landscape needs to be maintained and at the same time the landscape can be managed to maximize biodiversity, the optimal land use can be estimated as a classic constrained optimization problem. We assume that there is no constraint to a farm converting to or from organic farming. However, it may not be possible to convert farmland to the equivalent of grassland reserves. Therefore, we show two scenarios – either a choice between organic farming and reserves (Fig. 3a) or a choice between organic farming and extra conventional margin habitat (Fig. 3b). The margins in the latter scenario are assumed to contribute nothing to yield.

To illustrate the scenarios, we assume that the landscape starts with England's current average land use (the stars in Fig. 3a,b). The constraint of maintaining current yield can be translated into a 'constraint line': there must be a line of equal yield that passes through the starting point. The optimal strategy, given the constraint, is found at the point on the constraint line where the maximum butterfly density occurs. Without knowing what the yields actually are, we know that the slope of the constraint line will equal

$Y_{org}/Y_{con} - 1$ for land sparing with reserves (proof in Appendix S1). To appreciate this, consider the constraint lines for two extreme cases (solid black lines, Fig. 3a). If organic yield was equal to conventional yield organic farming can be increased without any impact on total yield, so the constraint line is horizontal (slope = 0, Fig. 3a). If this were the constraint, notice that butterfly density would increase as organic farming increases (moving right along the line), so the optimal strategy would be as much organic farming as possible. At the other extreme if organic yield was zero any increase in organic area has to be exactly offset by a decrease in reserve area to maintain yield, leading to the steepest constraint line with a slope of −1 (Fig. 3a). If this were the constraint, notice that butterfly density would decrease as organic farming increases (moving right along the line), so the optimal strategy is at 0% organic.

Because the butterfly surface is fairly smooth and planar, the optimal strategy will usually be at one extreme end of the constraint line (totally organic or totally land sparing); there therefore exists a 'critical value' of organic yield ratio where the optimal strategy switches. The 'critical value' of Y_{org}/Y_{con} will be when the constraint line coincides with a line of equal butterfly density (dashed lines in Fig. 3a,b). When it is assumed that spared land could be converted to reserves the critical value is *c.* 0.875 (Fig. 3a dashed line – the slope of the constraint line is $Y_{org}/Y_{con} - 1$, so the critical value is the slope of the butterfly contours +1). When it is assumed that spared land would be converted to conventional margin habitat, the slope of constraint line is $(1 - m)Y_{org}/Y_{con} + 1$, where m is the proportion margin in organic fields, which remains fixed at 0.1 (see Appendix S1). In this case, we find that the critical value of organic yield ratio is *c.* 0.35 (Fig. 3b dashed line – the slope of the butterfly contours +1 divided by 0.9).

The predicted butterfly densities depend on the proportions of arable and grass fields, and the margin:centre ratios. To illustrate this, we have replicated Fig. 3a for a landscape with only arable fields (Fig. 3c) and a landscape with only grass fields (Fig. 3d). This makes a substantial difference to the total numbers of butterflies (grass fields always have higher density), but it also makes a slight difference to the slopes of the lines of equal butterfly density, as can be seen by comparing the shaded strips in panels c and d with the dashed line, which is copied from panel a. This suggests that the critical value of organic yield ratio changes from *c.* 86% in grass-only landscapes to *c.* 89% in arable-only landscapes.

Yields were measured in our study arable fields (Fig. 4a) but to compare the grass fields we only have data on livestock units (LSU) per hectare of grazing land on the farm (Fig. 4b), which does not have a direct relationship with yield. Organic farms had on average 45% of the winter cereals yield and 85% of the LSU per hectare of conventional farms (Fig. 4). We also noted that winter cereal yield ratios varied with the landscape context. Landscapes with more than 60% arable land within 3 km had low average yield ratios of 30% ± 4.2%, varying between 18 and 38%. Mosaic landscapes with 40–60% arable land had average yield ratios of 52% ± 4.2% and a maximum of 89%.

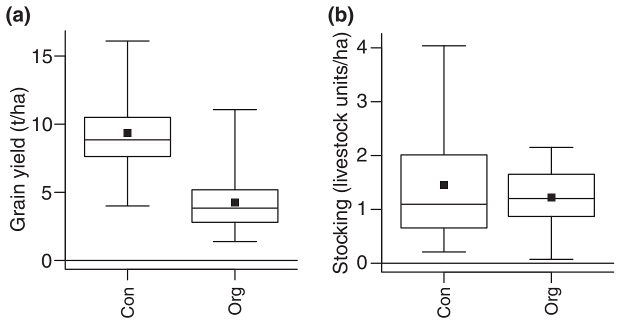

Figure 4 Differences between conventional and organic farms in winter cereal yield (a) and stocking density (b). Black squares are means, boxplots show minimum, quartiles, median and maximum across all 32 farms and 2 years of study (2007–2008).

DISCUSSION

This study has shown that, for the type of fields and farms investigated, organic farms support a higher density of butterflies than conventional farms, but a lower density than grassland reserves. We have also shown that organic farms boost butterfly numbers in the surrounding landscape, but that these effects are small relative to the effects of local habitat. This generally confirms results observed elsewhere for butterflies and also for other flower-visiting insects (e.g. Holzschuh *et al.* 2008; Rundlof *et al.* 2008).

We have also used our data to demonstrate a calculation of the optimum land use to deliver wildlife benefits under the constraint of maintaining yields. Organic farms support more butterflies than conventional farms, so if there were no difference in yield it would always be better to farm organically. However, the lower the organic:conventional yield ratio, the more advantageous an alternative land sparing strategy would be. We calculated the critical yield ratio for four example situations based on landscape and butterfly data. Our observed yield ratio of 45% for winter cereals is in between the critical value for sparing with conventional field margin habitat (35%) and that for sparing with reserves (87.5%). Hence, if spared land had the biodiversity value of reserves observed in this study, a mixture of spared land and conventional farming would provide greater butterfly value for a given crop production than organic farming everywhere. However, if new spared land only had a conservation value similar to existing conventional field margins, then organic farming would be a better option for butterflies. Yield ratios for the pasture fields were not measured directly, but based on the LSU/ha ratio (85%), and other data in the literature (Nieberg & Offermann 2000; Badgley *et al.* 2007), we think they are likely to be higher than the cereal yield ratios. This seems to imply that organic farming would probably be a better option than land sparing for grassland, but note that when the real yield ratio is close to the critical yield ratio, any combination of land sparing and wildlife-friendly farming is equally good for butterflies, and a mixed strategy might offer insurance against uncertainty in the yield ratios.

One strength of our study is that with closely paired farms, we controlled for environmental differences such as soil conditions and landscape context and matched farms for size and enterprise structure. Hence, we can be confident that the biodiversity and yield effects that we observe are due to management. A limitation with this design is that we only compared two common field types (cereal and pasture) on only mixed farms rather than a range of specialist crops and farms. Organic farms tend to grow a wider range of crops per farm than conventional farms (Norton *et al.* 2009), and this might cause increased biodiversity at the farm scale, but it would be difficult to make a controlled comparison between this and the same food grown on several specialized conventional farms. However, although we cannot generalize across all crops and all landscapes our data pertain to crops that have been and are likely to remain staples in the European environment (e.g. wheat is Europe's most common crop, and meeting projected global food demand will necessitate an increase in cereal production across Europe (FAO 2006; House of Commons 2009).

Our conclusions must come with caveats. We only studied butterflies and the literature on organic and conventional farming shows that different taxa respond differently (Bengtsson *et al.* 2005; Fuller *et al.* 2005; Hole *et al.* 2005; Gabriel *et al.* 2010). Furthermore, organic farming is not the only method of wildlife-friendly farming (Hole *et al.* 2005), and it has broader aims than simply supporting wildlife (EU 2007). Also, our critical yield ratio arises as a consequence of the hypothetical landscape that we have specified. We do not underestimate the difficulty of translating a hypothetical landscape into a real one. Absolute and relative yields, and biodiversity responses, are likely to vary from region to region. Nonetheless, there is considerable utility in thinking about production and conservation at a scale greater than the farm, and trying to develop policy levers that encourage neighbouring farmers to cooperate (Gabriel *et al.* 2010).

A range of agri-environment schemes are well established and have received intensive scrutiny (e.g. Fuller *et al.* 2005; Tscharntke *et al.* 2005; Kleijn *et al.* 2006; Whittingham 2007; Concepcion *et al.* 2008). In contrast, no policy mechanism currently exists to deliver land sparing in the sense used in this paper, i.e. offsetting intensification with increased areas of dedicated wildlife reserve. Without policy intervention, achieving high yields does not lead to lower demand for land (Ewers *et al.* 2009; Rudel *et al.* 2009); indeed, it creates economic incentives for more land to be farmed rather than less (Matson & Vitousek 2006). Developing a 'land sparing' option, alongside the current options for qualifying for agri-environment subsidies, deserves serious consideration (e.g. several farmers cooperating to invest in a large habitat restoration project). If such a policy option were developed, it would be most effective if carefully targeted to specific farm-wildlife contexts. Such targeting obviously requires much more data and many more analyses of the kind we have presented here.

More interdisciplinary research is urgently needed on how the net benefits of different farming methods compare, so that agricultural policy can be as environmentally sustainable as possible. Agriculture affects, and is affected by, many environmental processes at a range of spatial scales. As our results indicate, increasing biodiversity on a farm occurs at a potential cost in terms of extra land required to maintain overall productivity. And this extra cost may arise anywhere in the globe if lower local production leads to more imports. Our simple model considers yield and one measure of wildlife, but neglects costs other than land area. Future work should ideally examine a wide range of taxa, and a representative range of crops and landscapes, and could also separate the different effects that wildlife can have on agricultural productivity (benefits in terms of 'ecosystem services' and costs if some species are competitors or pests). It is possible to undertake sophisticated life cycle analyses of farming [incorporating the costs of time, fuel, agrichemicals, etc. (e.g. Gelfand *et al.* 2010) or wider environmental costs such as pollution (Wood *et al.* 2006)] and the next step may be to incorporate such costs into a model such as ours. However, the costs and benefits will take different weights depending on whose point of view is considered, e.g. maintaining yield may be a sensible constraint for a government or the 'common good', but farmers may care more about maintaining profitability, which depends on a multitude of market forces.

Our conclusion is that the optimal strategy for managing biodiversity whilst maintaining yield is context-dependent. The optimal strategy depends on the ratio of yields between farming types, the ratio of biodiversity between farming types, and the change in biodiversity for the land spared or taken into agriculture. All of these factors will vary with different farming systems, crops, taxa and landscapes. In some situations (e.g. in highly productive landscapes), land sparing may be optimal as long as the spared land would have high wildlife value. In other situations (e.g. in low productivity landscapes), land sharing may be optimal, especially when farmland already supports high biodiversity.

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SUPPORTING INFORMATION

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

Figure S1 Diagram of study design.
Figure S2 Illustration of organic landcover principal components analysis.
Figure S3 Effect of organic landcover on butterfly density.
Table S1 Butterfly species recorded in this study.
Appendix S1 Derivation of the slope of the yield constraint line.

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