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To what extent could edge effects and habitat fragmentation diminish the potential benefits of land sparing?

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ABSTRACT

Land sharing and land sparing are contrasting proposals for minimising the impacts of agriculture on wild species. Edge effects (biophysical gradients near habitat boundaries) might reduce population sizes on spared land, particularly in highly-fragmented landscapes, so might change conclusions about whether land sparing or land sharing is better for species' persistence. We assessed this possibility by modelling the population sizes of 120 Ghanaian bird species in the presence of a range of hypothetical edge effects under land-sparing and land-sharing strategies, and at different levels of habitat fragmentation and agricultural production. We found that edge effects can reduce population densities on spared land, and in highly-fragmented landscapes can – at modest levels of agricultural production combined with high edge penetration distances – cause the optimal strategy to switch from land sparing to land sharing. Nevertheless, land sparing maximised population sizes for more species in most cases tested. This conclusion was best supported for sensitive species with small global geographical ranges, which are likely to include those of greatest future conservation concern. The size of patches of spared land affected conservation outcomes: population sizes were maximised under a land-sparing strategy that spared large blocks of natural habitat of ~1000 or, better, ~10,000 ha. To effect land sparing in practice would require policies that promoted both increases in agricultural yield and the establishment or protection of natural habitats on spared land. Because the optimum scale of patches of spared land for edge-sensitive species is generally larger than the size of individual farms, policies that facilitate coordinated action by farmers or other land managers might be required.

1. Introduction

Agriculture represents one of the greatest threats to the future persistence of wild species. Cropland and pasture occupy around 40% of ice-free land (Foley et al., 2011), and growing demand for agricultural products drives ongoing deforestation (Geist and Lambin, 2002), threatening more terrestrial species with extinction than any other sector (IUCN, 2015). Two divergent, although not mutually exclusive, strategies have been proposed in response to this threat: land sparing and land sharing. Land sparing involves increasing agricultural yields (production per unit area) so that the area required for farmland can be reduced, compared with what would otherwise be required to produce the same quantity of products, allowing natural habitats to be retained or restored in other places (Green et al., 2005). Land sharing integrates conservation and farming in the same landscape through wildlife-friendly farming practices such as the retention of small woodlots, hedges and ponds or the adoption of agricultural practices that allow wild species to persist within the cropland or pasture itself (Fischer et al., 2014; Tscharntke et al., 2012). However, land sharing can reduce yields if it requires the presence of small unfarmed areas within the farmed landscape or reduction of inputs to crop or pasture management. It can therefore require more farmland for a given level of agricultural production, increasing pressure to convert natural habitats (Green et al., 2005).

Empirical studies to date have assessed the potential effects of land sparing and sharing on region-wide total population size of species of birds and trees in Ghana and India (Phalan et al., 2011b), birds in Uganda (Hulme et al., 2013), birds in the Eurasian steppes (Kamp et al., 2015) and birds, dung beetles and grasses in the Brazilian and Uruguayan pampas (Dotta, 2013). These studies concluded that in every region and for each taxon studied, land sparing would benefit more of the species assessed than land sharing, by allowing larger total populations in farmed and unfarmed landscapes combined (Chandler et al., 2013; Hulme et al., 2013; Phalan et al., 2011b). An analysis of 'small-scale land sparing' similarly concluded that it had greater biodiversity value than a land-sharing alternative (Chandler et al., 2013). However, none of these studies took into account the possible influence of edge effects — changes in physical and ecological parameters (population densities, species richness, community composition, vegetation structure, microclimate, light intensity, nutrient concentrations etc.) that occur near patch boundaries (Ries et al., 2004).

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It has been demonstrated that edge effects spilling onto farmland can alter conclusions about whether land sparing or land sharing is optimal (Gilroy et al., 2014a), but no study has quantified whether edge effects in natural habitats on spared land itself might similarly affect the optimal strategy.

This is an important gap for at least three reasons. First, species classified as 'losers' from agriculture that are favoured by land sparing (sensu Phalan et al. (2011b) have higher population densities in spared natural habitats than on farmland, but edge effects might reduce this difference (Laurance et al., 2011). This is especially true of many species of conservation concern, which tend to be sensitive to patch edges and reliant on intact core areas within large patches of natural habitat for long-term persistence (Banks-Leite et al., 2010; Laurance et al., 2002; Zakaria et al., 2013). Second, edge effects become increasingly important in highly-fragmented landscapes (Ewers and Didham, 2007; Laurance et al., 2002), so the effectiveness of land sparing might depend upon the scale of spared habitat patches (Phalan et al., 2011a). Finally, if the higher yields required for land sparing are accompanied by greater agro-chemical use or result in greater structural contrast with natural habitats, this could result in high-yield farming causing larger edge effects within adjacent natural habitat than low-yield farming (Barnes et al., 2014; Didham et al., 2015; Frost et al., 2014), which might compromise the conservation benefits of the land-sparing strategy.

Hence, there is a need to better understand the consequences of edge effects for land-sparing and land-sharing strategies. To address this we developed simulation models for 120 Ghanaian bird species previously assessed in a sparing–sharing context and known to be negatively affected by agriculture (Phalan et al., 2011b). We defined a range of plausible land-use and ecological scenarios that varied in the degree of habitat fragmentation, the magnitude of hypothetical edge effects and the level of agricultural production, and quantified species' region-wide population sizes under both land-sparing and land-sharing strategies. We used these models to re-assess, for this set of study species, the relative benefits of land sparing and land sharing in the presence of edge effects, and to shed light on the importance of the spatial scale of spared land.

2. Materials and methods

2.1. Study region and test landscapes

The study region comprised 9117 km^2 of cultivable land in the Western, Central and Eastern Regions of Ghana (Fig. A1) and has three main land uses: tropical forest ("forest"), extensive low- and mid-yielding mixtures of cropland, small plantations and fallow bushland ("farm mosaic"), and high-yielding plantations of oil palm and other crops ("high-yield plantation"). This region was selected because it contains a wide range of farming systems from low-yielding wildlife-friendly smallholder systems through to large-scale industrial plantations of oil palm, a globally important and rapidly expanding crop (Phalan et al., 2011b). It contains forests of global conservation importance subject to ongoing deforestation (FAO, 2010) and fragmentation (Holbech, 2005), as is also the case in much of the humid tropics.

We selected a 20 × 20 km test landscape within the study region to conduct our analysis of hypothetical edge effects (Fig. A1). Its size was chosen to be as large as possible whilst keeping the computational demands of the spatial modelling tractable. The test landscape had similar proportions of different land-covers to those of the wider study region. Using recorded land-cover in this landscape in 2007 as a starting point, we generated a series of alternative landscapes to reflect land-sparing and land-sharing strategies, varying the degree of future total agricultural production and habitat fragmentation. The mean agricultural production per unit area per year averaged over the whole area covered by the test landscape (the "production target") was varied between actual annual production per unit area in the study region in 2007 (19 GJ ha^{-1} y^{-1}; food energy basis) and estimated production in 2050 (37 GJ ha^{-1} y^{-1}) (Phalan et al., 2011b).

To develop land-sharing landscapes we assumed that the farmed areas within the test landscape were entirely covered by farm mosaic. We therefore applied the following sequential procedure, starting with 2007 observed land cover and modifying it until the production target was met: (i) areas of high-yield plantation were converted to farm mosaic; (ii) low-yielding farm mosaic was converted to mid-yielding farm mosaic; and finally (iii) forest was cleared to make way for additional mid-yielding farm mosaic (assuming that forest adjoining farmland was cleared first). The resulting land-sharing landscapes were dominated by farm mosaic with scattered remnant forest blocks (Shr1 and Shr2, Fig. 1).

Under a land-sparing approach, the objective is to minimise farmland area, so we assumed that the entire production target was met through high-yield plantation, with the remainder of the test landscape being converted to forest. We created five types of land-sparing landscapes with varying degrees of fragmentation in the restored forest. The alternatives encompassed a range in habitat fragmentation that might plausibly develop under different policy and planning regimes. At one extreme, land-use planning driven by the state or co-operative action by groups of landholders might produce non-fragmented landscapes dominated by large blocks of unfarmed land and farmland. We generated two landscapes of this type (panels Spr1 and Spr6, Fig. 1) by enlarging pre-existing areas of forest and high-yield plantation within the test landscape, resulting in forest blocks in the order of 10,000 ha in area (Table A1). At the other extreme, land-use planning at the scale of the individual land-holder might produce a highly-fragmented landscape with farm-scale spared fragments. Whether or not a strategy that resulted in such fine-scaled patches should be termed land-sparing is debatable (Fischer et al., 2014; Phalan et al., 2011a; Balmford et al., 2015). Nonetheless, we included these landscapes to make our assessment as broad as possible. We generated two such landscapes (Spr5 and Spr10), with patches as small as 1 ha (Table A1), and a series of landscapes of intermediate degrees of fragmentation (Spr2 to Spr4 and Spr7 to Spr9). We generated these landscapes by allocating 50 m × 50 m grid squares (a 0.25 ha planning unit chosen to represent a small field) to different land uses using the Modified Random Cluster algorithm (Saura and Martínez-Millán, 2000) implemented in the "secr" package (Efford, 2014) of the R programming language (R Core Team, 2014). We specified the degree of habitat fragmentation (via a fragmentation parameter p), the minimum area of individual patches (between 1 and 40 ha) and the proportion of forest in the landscape such that the production target was met (Table A1). We generated ten replicates of each randomly generated landscape and report all results as a mean over those ten replicates.

2.2. Modelling hypothetical edge effects

We developed population models for 120 bird species present in the study region and known to be negatively affected by agriculture (all those species classified as 'losers' by Phalan et al., 2011b; Table A2). We selected these species because their populations can be reduced by agricultural expansion (Phalan et al., 2011b) and because we could make reasonable assumptions about the form of edge response for such species (see below). We did not assess the 47 species recorded in the study region that benefit from agriculture (species classified as 'winners' by Phalan et al., 2011b) because farming has positive or neutral effects on their populations regardless of land sparing or land sharing (Phalan et al., 2011b), and because we had insufficient information to make reasonable assumptions about edge responses for such species. However, in principle our approach could be extended to these species also.

Population densities in forest, farm mosaic and high-yield plantation at least 800 m from fragment edges were obtained using existing regression models ("density-yield functions") that relate local (1 km^2)