The benefits of land sparing are limited by invasions of alien species

Magdalena Lenda[1], Piotr Skórka[2], Johannes Knops[3], Dorota Kotowska[4], Dawid Moroń[5], and Hugh Possingham[6]

[1]The University of Queensland - Saint Lucia Campus
[2]Affiliation not available
[3]Xi'an Jiaotong-Liverpool University
[4]Institute of Nature Conservation Polish Academy of Sciences
[5]Polish Academy of Sciences
[6]University of Queensland

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Abstract

Globally, agriculture intensification is a dominant driver of biodiversity loss. The concepts of land sparing and land sharing are alternatives to seek a balance between maintaining and restoring biodiversity while producing adequate food. To date, land sparing has been suggested as the best strategy to maintain biodiversity, but very few intact lands remain on Earth for sparing. Recently, international policies for nature conservation have proposed removing land from agricultural management to meet the need for more land sparing. However, the idea of land sparing has not considered the risk of biological invasions in abandoned land. Many abandoned agricultural lands are colonized by invasive species, creating monospecific patches with low biodiversity. Such invasions have cascading effects on other trophic levels and decrease ecosystem services in nearby agricultural fields, which negatively impacts yield. Moreover, invaded abandoned fields have lower biodiversity than extensively managed agricultural land. Thus, the risk of inducing plant invasions and triggering detrimental impacts on biodiversity, ecosystem services, and agricultural yields limits land sparing from abandonment as a conservation strategy. Our simulations also suggest that land sharing may be the best solution for sustaining biodiversity when the risk of invasion is high.

The benefits of land sparing are limited by invasions of alien species

Magdalena Lenda[1,2*], Piotr Skórka[2], Dorota Kotowska[2], Dawid Moroń[3], Hugh P. Possingham[1], Johannes M.H. Knops[4]

[1] School of Biological Sciences, The University of Queensland, Brisbane, Queensland, Australia, email: Magdalena.lenda1@gmail.com, h.possingham@uq.edu.au

[2] Institute of Nature Conservation, Polish Academy of Sciences, Mickiewicza 33, 31-120 Kraków, Poland, Skorasp@gmail.com, kotowska@iop.krakow.pl

[3] Institute of Systematics and Evolution of Animals, Polish Academy of Sciences

Sławkowska 17, 31-016 Kraków, Poland, dawidmoron1@gmail.com

[4] Department of Health and Environmental Sciences at Xi'an Jiaotong Liverpool University in Suzhou, Jiangsu, China, Johannes.Knops@xjtlu.edu.cn

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***corresponding author:** Magdalena.lenda1@gmail.com, tel. +48 530 344 595, fax: -

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Abstract

Agriculture intensification is a dominant driver of biodiversity loss. Land sparing has been suggested as the best strategy to maintain biodiversity, but very few intact lands remain on Earth for sparing. Recently, international policies for nature conservation have proposed removing land from agricultural management to meet the need for more land sparing. However, the idea of land sparing has not considered the risk of biological invasions in abandoned land. Many abandoned agricultural lands are colonized by invasive species, creating monospecific patches. Such invasions decrease biodiversity and have cascading effects on other trophic levels and decrease ecosystem services in nearby agricultural fields, which may negatively impacts yield. Thus, the risk of inducing plant invasions and triggering detrimental impacts on biodiversity, ecosystem services, and agricultural yields limits land sparing from abandonment as a conservation strategy. Our simulations suggest that land sharing may be the best nature conservation strategy in invaded landscapes.

Main text

Agricultural intensification and further conversion of natural ecosystems into agricultural lands are global threats to biodiversity, causing extinctions of native fauna and flora. By 2050, the human population may reach 9.6 billion (Gerland et al. 2014)—feeding more and more people will increasingly demand more agricultural production and land—leading to continuous agricultural intensification. This is expected to add to further land clearing, pesticide and herbicide use, soil pollution, water shortages, and greenhouse gas emissions contributing to climate change.

Two concepts from classic landscape ecology have been proposed to address this looming biodiversity crisis**:** 1) *land sparing* and 2) *land sharing* (Green et al. 2005). Land sparing refers to 'sparing' of nature; coupling the intensive use of agricultural land on one hand and saving intact areas where wildlife and biodiversity thrive. Land sparing assumes that primary habitats are the most biodiverse; that agricultural lands have very little biodiversity value and that preserving natural lands, while intensifying management of agricultural areas can maintain biodiversity while achieving sufficient yields to feed humans (Gibson et al. 2011, Laurance et al. 2014). In contrast, land sharing is an integrative approach, defined as accepting lower yields in agricultural lands combined with biodiversity conservation and extensive land management (Lindenmayer and Cunningham 2013). Land sharing/sparing concepts have been developed and tested mostly in pristine areas, such as intact tropical forests, where agricultural land clearing creates a drastic land change into row crop agriculture or rangelands. Studies conducted in tropical forests suggest that land sparing is a better strategy for maintaining regional species diversity while achieving agricultural yield goals (Phalan et al. 2011,

Kamp et al. 2015). However, this situation is not relevant to regions invaded by alien species, which may complicate land sharing and land sparing models.

Most of the world is not pristine and has been in human use for hundreds, if not thousands of years, which includes virtually all of Europe. In the European Plain, the only temperate, terrestrial pristine nature remaining is the Białowieża Forest in Central Europe. Outside of Antarctica, thousands of years of agricultural management have shaped cultural landscapes often with unique flora and fauna, which has adapted and coevolved with land management. Over 8000 years ago, prior to Neolithic agriculture, Europe was mostly a wooded continent. Starting 6000 years ago, forests have been progressively cleared for agriculture and transformed into managed grasslands and tilled crop fields (Roberts et al. 2018). The management of these agricultural landscapes created by humans has shaped complex ecosystems and regions with high biodiversity values, that depend on continuous agriculture (Rosin et al. 2016). Nature conservation programs such as "Natura 2000", which is the oldest and largest in the European Union, promote extensive land management to maintain local biodiversity. For example, in Central Europe, many protected insects, birds, and plant species depend on extensive land management, such as mowing or cattle grazing. Low-intensity management of grasslands, heathlands, and peatlands supports threatened and declining species, such as large blue butterflies, *Phengaris teleius* and *P . nausithous* , both flagship species in European biodiversity conservation. Many protected bird species occur only in managed landscapes, such as ortolan bunting (*Emberiza hortulana*) or corncrake (*Crex crex*), a grassland-specialized bird vulnerable to extinction (IUCN). Mown or grazed meadows are also important for plants such as threatened orchids, Siberian iris (*Iris sibirica*), globeflower (*Trollius europaeus),* chess flower (*Fritillaria meleagris*), and crocus (*Crocus scepusiensis*). However, currently, these agriculture-associated habitats have the worst conservation status among all ecosystems (Pe'er et al. 2014). The increasing demand for food continues to drive agricultural intensification in Europe. Aided by subsidies, the scale and intensity of agricultural operations is increasing throughout the EU with an increase in agrochemical inputs, such as fertilizers. These processes have led to a continuing decline in farmland biodiversity (Tryjanowski et al. 2011).

Although managed agricultural landscapes can harbor high levels of biodiversity, in theoretical nature conservation, one may suggest abandoning this land to create new spared areas designated for nature conservation. Such theoretical considerations and the establishment of new spared areas from already managed land due to agricultural management cessation have already been applied in Europe. An international nature conservation idea, "Rewilding", described recently in the journal Science proposed to abandon agricultural land or repurpose previously abandoned post-agricultural land into new nature conservation areas (Navarro and Pereira 2012, Sylvén and Windstrand 2015, Perino et al. 2019). Similarly, since 2013, the European Union (EU) "Greening policy" has advocated abandoning at least 5% of arable land to create permanent set-aside land (i.e., ecological focus areas) such as fallow lands, afforested areas, field margins, hedges, buffer strips, etc. (Van Zeijts et al. 2011, Hauck et al. 2014). Both the "Rewilding" and "Greening policy" resemble the land sparing concept, as both rely on reestablishing natural lands within landscapes that are currently entirely, actively managed. In these policies, agricultural land abandonment and natural secondary succession are usually combined with further agricultural intensification (Van Zeijts et al. 2011, Hauck et al. 2014, Sylvén and Windstrand 2015, Perino et al. 2019). The Rewilding idea emphasized the positive effect of land abandonment on nature conservation, as has happened in Chernobyl after the nuclear catastrophe (Perino et al. 2019). However, none of these sparing concepts propose a specific strategy for landscapes threatened by alien species invasions. When invaded, such areas also become propagule sources that further threaten other areas designated for nature conservation. In a parallel to the Chernobyl vegetation succession, abandoned paddy fields at Fukushima have become dominated by alien invasive goldenrod *Solidago altissima* within one year after the nuclear catastrophe, which resulted in agricultural land abandonment in the area (Fig. S1, Yamashita et al. 2014).

The theoretical concept of land sparing and land sharing together with the applied nature conservation policies as "Rewilding" and "Greening" omit scientific, published data which show that abandoned agricultural land is frequently threatened by invasive, alien plant species (Figs. 1 & 2, Cramer et al. 2008, Lenda et al. 2021). This plant invasion risk has not been addressed in the land sharing/land sparing conceptual framework

and in practical solutions. Invasive species need to be considered because they can disturb natural succession (Gusev 2015), affect fire regimes (Otero et al. 2015), decrease native biodiversity of plants, pollinators, ants, and birds (Fig. 2, Moroń et al. 2009, Skórka et al. 2010, Lenda et al. 2013), and homogenize ecosystems (Lenda et al. 2019). For example, in Central Europe, up to 90% of abandoned agricultural land is dominated by alien goldenrods *Solidago* sp. (*S. canadensis* and *S. gigantea*) (Szymura et al. 2016, Lenda et al. 2019, 2021). Goldenrods create homogenous habitat patches with up to 100% dominance within just a few years, (Fig. 1, Moroń et al. 2009, Lenda et al. 2019) that negatively affect ecosystem service providers (Fig. 2) and decrease their functional diversity (Patchey and Gaston 2006). Invasive species can cause up to 70% decline in wild pollinator abundance (Fig. 2, Moroń et al. 2009, 2019), and a 50% decline in farmland bird abundance and ant diversity (Fig. 2, Skórka et al. 2010, Lenda et al. 2013). Thus, if invasive species establish dominance in spared "natural" land, the biodiversity of such areas would be much lower than that of extensively managed agricultural habitats (Fig. 1; Moroń et al. 2009, Skórka et al. 2010). In addition, creating such "natural areas" using agricultural land abandonment and land sparing in the presence of invasive plant species will lower native species richness and abundance by increasing invasion on new, post-agricultural land. We also demonstrated this effect on birds recorded from managed fields, non-invaded abandoned fields, and invaded abandoned fields (Fig. 2). Using simulations, we created virtual landscapes varying in cover of abandoned fields in two scenarios: with and without invasions (see description of Methods in Supplementary material). It was clear that non-invaded land sparing (land abandonment) increases bird species richness (up to about 40% cover in a landscape) and abundance in an agricultural landscape, however, there was no gain in bird diversity if the abandoned land was invaded (Fig. 2, details in Supplementary material).

The problem of alien plant species invading abandoned lands is a global problem. For example, dense stands of the invasive grass *Saccharum spontaneum* prevent forest regeneration in abandoned pastures in Panama (Joo Kim et al. 2006). The grass invasion of *Ampelodesmos mauritanica* on abandoned farmland in Catalan, Spain increases fire frequency and intensity (Grigulis et al. 2005), which increases soil erosion (Otero et al. 2015).

In this study, based on our new and earlier results, we suggest that land sharing may be the best solution for sustaining biodiversity when the risk of invasion is high. This is because land management practices such as plowing, cutting, and grazing, even if they are undertaken extensively, usually prevent the successful establishment and spread of invasive alien species (Fig. 1). A clear example of this are the recent Persian Walnut and goldenrod invasions in Central Europe. Seed catching birds each year carry Persian walnut seeds over distances up to 1 km from a seed source, and bury them in arable fields, creating a seedbank. These walnut seeds germinate and grow; however, each year's land management, such as plowing and cutting, prevents establishment and thereby invasion (Fig. 1, Lenda et al. 2012, 2018). The mechanism of goldenrod invasion is similar, with the difference being that goldenrod seeds are wind-dispersed (Fig. 1). In this case, with land abandonment and management cessation, goldenrod seedlings can establish and become dominant in agricultural lands.

Vast land abandonment and/or management cessation allows the establishment of invasive plants in agricultural lands. Seeds of many invasive species are already present in the soil; hence, after germination, fast-growing, highly competitive, and often allelopathic seedlings can achieve dominance. Furthermore, these invaded abandoned agricultural lands can become hotspots of invasive species dominance that can spread further into other natural landscape elements. Thus, a land sparing strategy in such an environment promotes further progression of plant invasions.

If the land sparing concept is intended to improve food production and biodiversity conservation, intensively managed cropland alongside invaded spared land could be a catastrophe for both agriculture and biodiversity. This is because biodiversity in agricultural ecosystems provides biodiversity and ecosystem services. We believe that land sharing mitigates many of the dangerous consequences of large-scale invasions.

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Figures

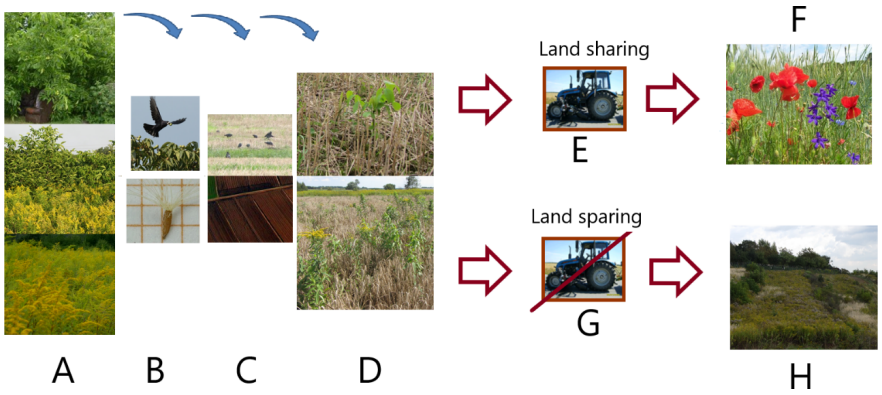

Fig. 1. Conceptual framework of invasive plant species spread into abandoned agricultural lands, showing the ecological mechanism driving the invasion. This model is applicable when invasive plant species are present in the landscape and agricultural land is abandoned for nature conservation. The model is based on walnut *Juglans regia* and goldenrod *Solidago sp.* invasions but can also be applied to other taxa. A) Landscape elements, such as backyards and already abandoned fields contain walnut and goldenrod plants that are seed sources. B) Birds collect and disperse seeds (walnut) or seeds are dispersed by wind (goldenrod). C) Birds cache seeds into managed arable fields, pastures, and meadows (Lenda et al. 2012); here rooks (*Corvus frugilegus*) cache walnut seeds. Wind dispersed seeds are carried and deposited randomly, including in sites such as managed agricultural land (goldenrod). In both cases, dispersed seeds form a soil seedbank. D) Seeds germinate and grow. E) Invasive plant seedlings are eliminated by agricultural management in a land sharing strategy. F) Although the plant invasion risk is high because seed sources and dispersers are present, the invasion does not progress. The invasion is stopped by agricultural land use (here plowing), which damages seeds and seedlings, thus the native biodiversity remains. G) In a land sparing strategy, seedlings are no longer damaged by agricultural management after land abandonment. H) Land use change and land abandonment including management cessation allow seeds of invasive species to germinate, grow into mature plants, and create monocultures. Here, goldenrod invasion can be seen after 2 years of agricultural field abandonment. The monospecific goldenrod patches drastically reduce biodiversity of native plants, pollinators, ants and birds, while increasing soil N (see Fig. 2). Scenario for the walnut invasion is similar. This mechanism clearly shows that land sparing is an unfavorable strategy in the presence of invasive species. In such sites, land sharing is the best strategy, because it prevents local biodiversity from extinctions caused by invasive species.

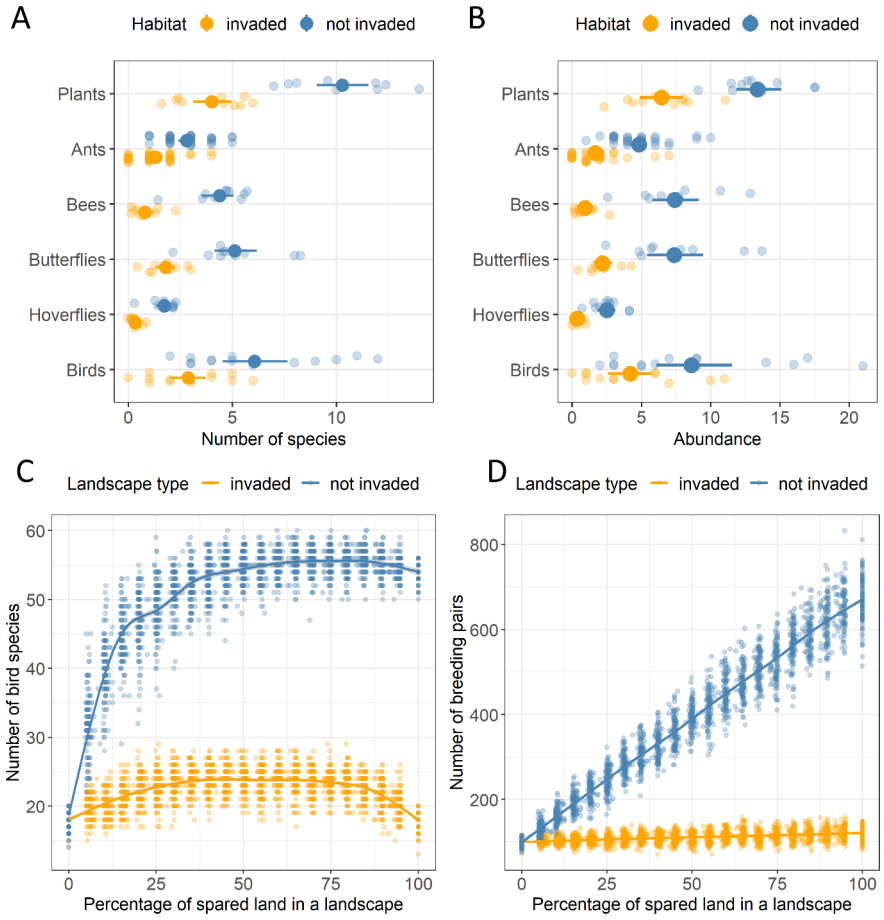

Fig. 2. Species richness (A) and abundance (B) of the ecosystem service providers in invaded (orange) and not invaded (blue) agricultural land. Means with 95% confidence intervals are shown. Abundance of plants represents the mean cover of native plants per plot, for insect pollinators it is the mean number of individuals per 200 m transect, for ants it is the number of their nests in a 100 m^2 plot and for birds it is the number of breeding pairs in a habitat patch. Data for vascular plants, bees, butterflies, and hoverflies recalculated from Moroń et al. (2009), data for ants taken from Lenda et al. (2013) and data on birds are from Skórka et al. (2010). Unpublished data from bird mapping in abandoned fields (both invaded and not invaded by goldenrods) and managed fields were used to demonstrate how different proportions of spared land may affect bird species richness (C) and number of breeding pairs (D) in landscapes with no invasion of goldenrods (blue) and under the invasion (orange). Virtual landscapes of about 1 km^2 were created from managed fields and abandoned fields (spared land) by a random selection of the real data. The proportion of spared land varied from 0 (only managed fields) to 100% (only abandoned fields) for two scenarios (i.e., invaded and not invaded landscape). For each cover of spared land, 100 landscapes were simulated. Curves are general additive models fitted to the data (details in Supplementary material 1).