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PERSPECTIVE

Biological invasions limit the effectiveness of land abandonment as a conservation strategy

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Abstract
Context Agricultural intensification has led to widespread biodiversity loss. The concepts of rewilding and land sparing suggest that agricultural land abandonment may reverse biodiversity decline in intensively managed agricultural areas. For example, the Green Deal policy in the European Union mandates the abandonment of 4% of agricultural land for nature conservation.
Objectives We examined if scientific literature describes connections between land abandonment and concepts related to land abandonment such as rewilding, land sparing with biological invasions. Then, we studied if invasion of alien plant species may undermine potential benefits for local native biodiversity from land abandonment.
Methods and results Our literature review suggests that land abandonment is often linked to alien plant invasions (314 articles) however current conservation strategies implementing land abandonment such as land sparing and rewilding often do not consider the risk posed by the invasion and colonization of the abandoned land by alien plant species. Using a case study of alien goldenrods *Solidago* spp. we showed via meta-analysis that abandoned agricultural land is often dominated by these invasive plants in Central Europe. Our results show that goldenrod invasion on abandoned land leads to higher biodiversity declines than extensive agricultural management on uninvaded

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land. Moreover, our simulation study showed that biodiversity did not increase with the share of abandoned fields in a landscape if they are invaded by alien goldenrods.

Conclusions The negative effects of alien species invasion on biodiversity, ecosystem services, and in consequences agricultural yield may limit the effectiveness of land abandonment as a conservation strategy. Hence, we argue that strategies such as agricultural rewilding that include extensive land management rather than abandonment alone, may be a better to safeguard biodiversity in agricultural landscapes in the presence of invasive alien plant species.

Keywords Biodiversity · Cultural landscapes · Ecosystem services · Land sharing · Land sparing · Rewilding

Introduction

The biodiversity crisis during the Anthropocene, aggravated by the rampant disappearance of pristine areas, has prompted the consideration of land abandonment as a means of acquiring land for conservation purposes (Daskalova and Kamp 2023). There is a global trend in the migration of people from the countryside to cities combined with land management intensification (Potapov et al. 2022) on the one hand, and agricultural land abandonment in some regions on the other hand (Crawford et al. 2022; Daskalova and Kamp 2023). Two main international nature conservation concepts have been recently used to refer to land abandonment: rewilding and land sparing (Perino et al. 2019; Bateman and Balmford 2023; Daskalova and Kamp 2023). Rewilding pertains to the reestablishment of natural lands for conservation purposes within landscapes that are currently under active management (Soule and Noss 1998; Navarro and Pereira 2012; Perino et al. 2019). In the rewilding framework, it is assumed that agricultural land abandonment will be followed by natural secondary succession, often referred to as passive management or passive restoration (Donlan et al. 2006; Sylvén and Widstrand 2015; Bateman and Balmford 2023). Rewilding is, however, a multifaceted concept (van Meerbeek et al. 2019). Corson et al. (2022) listed the following rewilding types: trophic (species introductions to restore top-down trophic interactions), ecological (allowing ecological processes to regain dominance), Pleistocene rewilding (restoration of a Pleistocene baseline), agricultural (low-intensity management), and passive rewilding (little or no management). In this article, we define rewilding more narrowly as "methods for returning wild lands, and wildness, to landscapes we have altered," as defined by Perino et al. (2019). Specifically, we describe the situations in which rewilding has been proposed as a practical method for restoring abandoned agricultural land into more natural landscapes.

Land sparing is another strategy associated with land abandonment (Kamp et al. 2015; Bateman and Balmford 2023). Land sparing involves coupling the intensive use of agricultural land with the conservation of intact areas where wildlife and biodiversity thrive (Green et al. 2005; Phalan et al. 2011). This is based on the assumption that primary habitats are the most biodiverse, whereas agricultural land has minimal original biodiversity. Thus, biodiversity can be maintained and food security can be ensured by preserving land spared from agricultural use while intensifying the management of agricultural areas (Gibson et al. 2011; Laurance et al. 2014). In contrast to land sparing, land sharing is a conservation strategy aimed at maintaining low yield and profit from croplands and pastures through extensive farming (Kamp et al. 2015; Bateman and Balmford 2023). In land sparing, an abandoned land is spared from any agricultural activities to protect biodiversity (Kamp et al. 2015; Fayet et al. 2022a; Fayet et al. 2022b). Bateman and Balmford (2023) recently suggested replacing extensive farming or agricultural rewilding with a land-sparing strategy by deallocating a part of an extensively managed land from cultivation and intensifying crop production on the remaining land. The implementation of such a strategy may lead to substantial land-use changes: land abandonment in some areas and land management intensification in others. The concepts of rewilding and land sparing have also been incorporated in government policies. For example, Nature Restoration Law and the European Green Deal which adopt several strategies to achieve climate neutrality, mandate the abandonment of 4% of agricultural land for conservation purposes (Fayet et al. 2022a; Fayet et al. 2022b). However, the introduction of this policy has raised serious concerns and led to massive protests among farmers across Europe (Lu 2024).

Although both rewilding and land-sparing may contribute substantially to nature conservation, conservation biologists often do not include published studies indicating that abandoned agricultural land is frequently threatened by invasive alien plant species (de Groot et al. 2007; Moroń et al. 2009; Lenda et al. 2012; Szymura et al. 2016) (Fig. 1). Invasive plants such as goldenrods (*Solidago* spp.) or walnuts (*Juglans* spp.) rapidly colonize abandoned land; within a few years, they form monotypic patches that may disrupt natural succession patterns (Gusev 2015), affect fire regimes (Otero et al. 2015), and decrease native biodiversity. Although an abandoned land may not be permanent, it may serve as a source of propagules and act as an invasion pool, further harming other areas designated for nature conservation (Fig. 1). For instance, passive rewilding after the nuclear catastrophe in Chernobyl (Perino et al. 2019) was considered successful because vast areas that have not undergone land management created opportunities for nature to reestablish crucial ecological processes (Hostert et al. 2011; Didukh et al. 2023). These authors suggest that land abandonment without management is beneficial and leads to natural succession (passive restoration). However, a recent botanical study revealed the appearance of 'artificial forests' in Chernobyl, created by invasive species such as *Robinia pseudoacacia* and *Acer negundo* (Deryabina et al. 2015). Moreover,

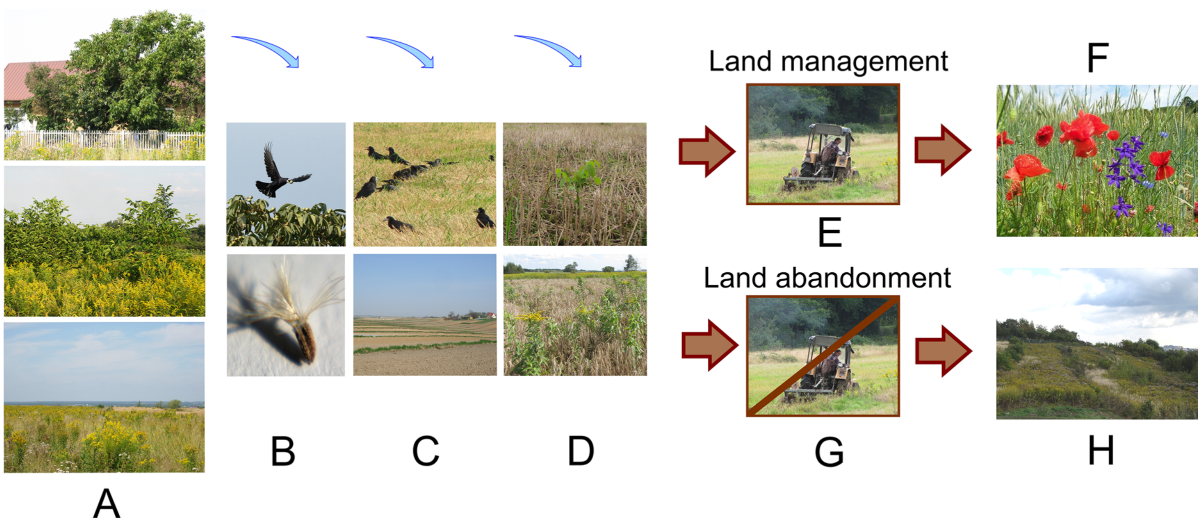


Fig. 1 A graph representing the spread of exemplary invasive plant species into abandoned agricultural lands, showing the ecological mechanism driving the invasion. This model is applicable when invasive plant species are present in the landscape and agricultural land is abandoned for nature conservation. The model is based on walnut (*Juglans regia*) and goldenrod (*Solidago* spp.) invasions; however, it is also applicable to other plant taxa. A Landscape elements, such as backyards and abandoned fields that contain walnut and goldenrod plants, are seed sources. B Seeds (walnut) are collected and dispersed by birds or by wind (goldenrod). C Birds cache walnuts 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 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 (e.g., land-sharing strategy). F Although the risk of plant invasion is high because seed sources and dispersers are present, the invasion does not progress. The invasion is thwarted by agricultural land use (here plowing), which damages the seeds and seedlings of invasive plant species; thus, native biodiversity is maintained. G In land abandonment–related conservation strategies, seedlings are no longer damaged by agricultural management after land abandonment. H Land-use change and land abandonment, including management cessation, allow the seeds of invasive species and other plant species to germinate, grow into mature plants, and create monocultures. Here, goldenrod invasion may immediately occur within 2 years after agricultural field abandonment. The monospecific goldenrod patches drastically reduce the biodiversity of native plants, pollinators, ants and birds while increasing soil nitrogen (see Fig. 3). The scenario for walnut invasion is similar. This mechanism clearly shows that land abandonment–related conservation strategies are unfavorable in the presence of invasive species. In such sites, land sharing or agricultural rewilding may be the best strategies to be implemented because they prevent local biodiversity from extinction caused by invasive species

in a similar case of vast land abandonment following a nuclear catastrophe, the vegetation succession observed in the abandoned paddy fields in Fukushima became dominated by the invasive goldenrod species *Solidago altissima* within a year of the nuclear disaster (Yamashita et al. 2014) (Fig. S1). This example highlights the ability of invasive plant species to rapidly colonize abandoned land and underscores the need to consider their impact on conservation efforts. Several examples of alien species invading abandoned land can be found worldwide, indicating the global significance of this phenomenon (Fig. 2).

The objectives of this study were to combine evidence on the consequences of invasive alien plants (focusing on *Solidago* spp.) for abandoned agricultural land using different approaches. First, we analyzed whether the topic of invasive species is represented in the scientific studies on land abandonment, land sparing, and rewilding. Next we tested the impact of the invasive goldenrod species on various organisms providing ecosystem services in abandoned land. Finally, using original field data, we simulated how the increasing share of abandoned land with and without goldenrods affects bird species richness in agricultural landscapes.

We specifically asked the following questions:

(1) How many scientific publications link land abandonment with invasive species?
(2) How many scientific publications on land abandonment mention rewilding and land sparing?
(3) How many scientific publications on rewilding and land sparing consider the risk of invasive species?
(4) Basing on the meta-analytic approach, what is the effect size of invasive alien goldenrod *Solidago* spp., on native organisms inhabiting abandoned land.

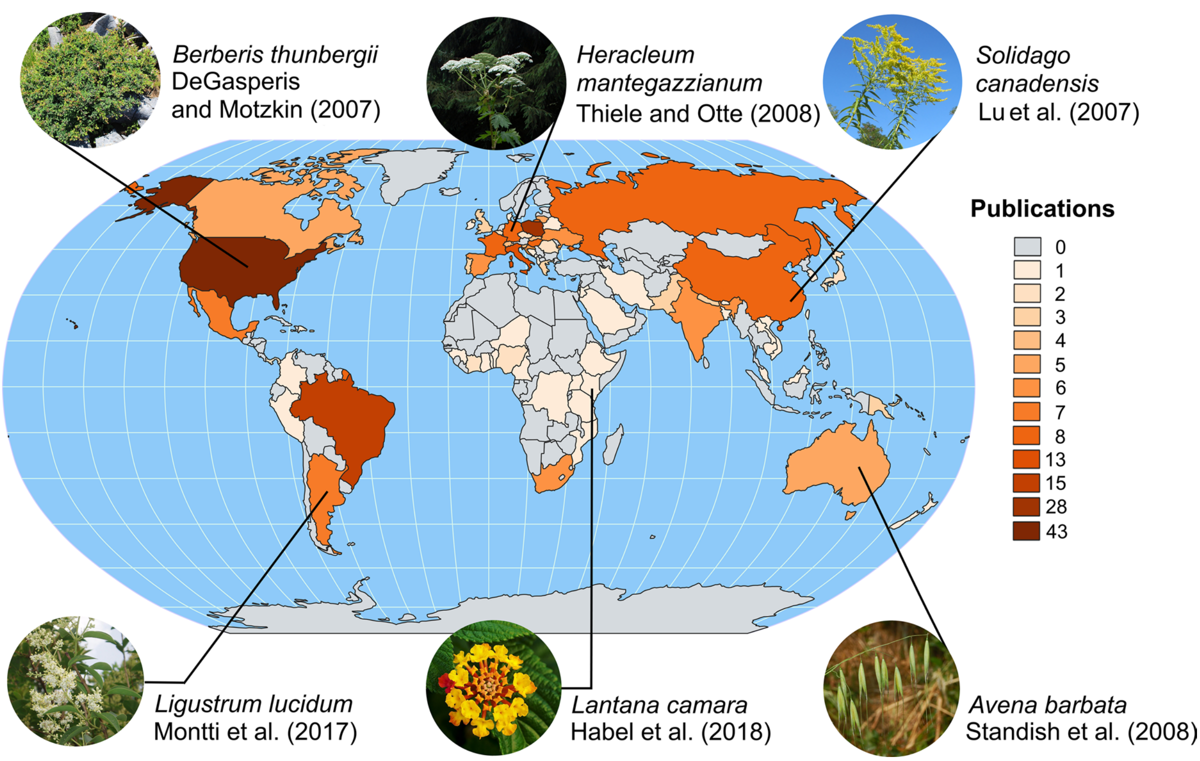


Fig. 2 Distribution of research (n = 314) linking land abandonment with invasion of alien species based on search performed in Web of Science. Examples are provided for every continent: North America—DeGasperis and Motzkin (2007), Europe—Thiele and Otte (2008), Asia—Lu et al (2007), South America—Montti et al (2017), Africa—Habel et al (2018), Australia—Standish et al (2008). The pictures of plant species were obtained from Wikipedia.com (distributed by CC BY 0, 2.5 and 3.0 Deed: https://creativecommons.org/licenses/)

(5) Via simulations how increasing share of abandoned land in the agricultural landscape affect biodiversity of birds in two scenarios: with invasion of alien goldenrods and without this plant.

These analyses allowed us to identify knowledge gaps, direct future research and inform decision makers which conservation strategy associated with land abandonment is preferred if the risk of invasion of alien plant species is high.

Methods

Searching in scientific literature for links between land abandonment, rewilding, land sparing, and invasive species

In order to get baseline estimates of number of papers on specific topics we conducted a literature search in the Web of Science for all articles on: land abandonment, invasive species rewilding, land sparing to invasive species (see Table 1 for keywords and syntax). Then we combined keywords to check for any studies considering simultaneously land abandonment and invasive species, land abandonment and rewilding, land abandonment and land sparing (Table 1). We further combined keywords and checked if scientific publications on land abandonment and rewilding, and land abandonment and land sparing consider risk of plant invasions (Table 1). In this review we also used "fallow" as a synonym of abandoned land, because some authors in publications use it interchangeably and technically fallow land (land purposely abandoned for certain period of time) is similar to land abandonment (Skórka et al. 2007). Moreover, in the case of rewilding, we referred to publications available on the official website of Rewilding Europe (https://rewildingeurope.com/publications/). Rewilding Europe is a pan-European organization gathering scientists and practitioners describing the main ideas, conservation goals, and problems of rewilding. When reviewing the brochures, we checked whether land abandonment was mentioned in any of their publications as a cause of biological invasions and whether land abandonment was considered positive or negative for nature conservation.

Meta-analysis on the effects of alien goldenrods on biodiversity of the main ecosystem services providers

To illustrate the negative impact of invasive alien species on biodiversity we conducted a meta-analysis of research that sampled native organisms e.g. plants, ants, butterflies, hoverflies, bees, birds, nematodes) on abandoned post-agricultural land (i.e., abandoned

Table 1 Literature search in Web of Science (performed on March 10, 2023). The topics searched were land abandonment, invasive species, rewilding and land sparing. We determined the number of scientific publications about (a) rewilding refers to land abandonment and invasive species; (b) land sparing refers to land abandonment and invasive species; and (c) land abandonment refers to invasive species. N results correspond to the number of scientific articles retrieved from the Web of Science

Literature search topic	Keywords	N results
Land abandonment and invasive species	ALL = (Fallow OR abandon*)	15,290
	ALL = (Invasive species)	25,396
	ALL = [(Fallow OR abandon*) AND invasive species]	314
Rewilding, land abandonment, and invasive species	ALL = (Rewild*)	781
	ALL = [(Fallow OR abandon*) AND rewild*]	104
	ALL = {[(Fallow OR abandon*) AND rewild*] AND invasive species*}	2
Land sparing, land abandonment, and invasive species	ALL = (Land sparing)	557
	ALL = [(Fallow OR abandon*) AND land sparing]	44
	ALL = {[(Fallow OR abandon*) AND land sparing] AND invasive species}	1
Land abandonment, land sparing, rewilding and invasive species	ALL = (Fallow OR abandon*) AND ALL = (Land sparing) AND ALL = (rewilding) AND ALL = (Invasive species)	0

grasslands and abandoned agricultural fields) covered with native (non-invaded) vegetation or invaded by alien goldenrods (*Solidago canadensis* and *Solidago gigantea*). These organisms are known as the main ecosystem services providers such as pollination, pest and carcass control, nutrient cycling. We choose goldenrods because they are the most common invasive species in abandoned land and may have significant effect on biodiversity and agricultural ecosystems. First, we conducted a comprehensive systematic search in the Web of Science literature database using the search strategy via syntax: ("invasive Solidago" OR "alien Solidago" OR "non-native Solidago" OR "exotic Solidago" OR "introduced Solidago" OR "invasive goldenrod*" OR "alien goldenrod*" OR "non-native goldenrod*" OR "exotic goldenrod*" OR "introduced goldenrod*" OR "Canadian goldenrod*" OR "giant goldenrod*" OR "Solidago canadensis" OR "Solidago gigantea" OR "Solidago altissima" OR "Canadian goldenrod" OR "giant goldenrod" OR "tall goldenrod"). No limitations were imposed on the publication dates of the retrieved articles to ensure a comprehensive coverage of relevant literature. This process yielded a total of 3123 articles (Fig. S2). After removing duplicates, articles underwent screening. Non-original research papers were excluded. Full-text articles were then screened using the following exclusion criteria: (1) lack of treatments that could be assigned to invaded and non-invaded; (2) lack of species richness or abundance estimates impeding the quantitative analysis; (3) studies that were unable to provide the necessary effect sizes or sample sizes were excluded from the meta-analysis, regardless of their relevance; (4) lastly, studies not based on real research case sites were also excluded. Ultimately 20 articles were included in the meta-analysis (Fig. S2). We extracted following information from the papers: author names, publication year, geographic location, diversity type (species richness and/or abundance), sample size, abandoned habitat type (grassland, former cropland). Data were recorded in Excel spreadsheets for subsequent analysis. We compared diversity indices between invaded versus non-invaded sites. Species richness and abundance are readily comprehensible and uncontroversial indicators for describing biodiversity (Fjellstad et al. 2001).

We conducted the random effects meta-analysis model that assumes that the estimated effects in the studies originate from different populations, and the heterogeneity among studies includes not only sampling errors but also genuine effect differences (Borenstein et al. 2009). The data collection for this study encompasses studies with varying with experimental designs, rendering the random effects model more appropriate. Employing this model, we obtained a 95% confidence interval (CI) and visualized the results with a forest plot using `forest()` function from the "metafor" R package (Viechtbauer 2010). A 95% CI not overlapping with zeros indicated a statistically significant combined effect size (Song et al. 2019) of goldenrod invasion on species richness and abundance. As we detected heterogeneity in the meta-analysis results, meta-regression was employed to explore the sources of heterogeneity (Hedges et al. 2010). Therefore, we did meta-regression with two moderators: invaded habitat type (grassland and cropland) and publication year. However, the effect of both moderators was statistically non-significant thus finally we removed them from meta-analysis. Both for species richness and abundance we included study identity as a random factor via using 'rma.mv()' function. Moreover, organism type was assigned as the second random factor. We did so because we were more interested in overall effect of goldenrods on diversity measures rather than group-specific estimates.

Modelling the effect of increasing cover of invaded and non-invaded abandoned land on birds in agricultural landscapes

In the third part of this study, we used data about farmland bird diversity (indicators of ecosystem health and service providers [e.g. Whelan et al. 2008; Fraixedas et al. 2020]) in continuously intensively managed land (arable fields), two types of abandoned land which were (a) uninvaded post-agricultural abandoned fields (formerly intensively managed land) and (b) invaded post-agricultural abandoned fields (also intensively managed in the past) to simulate effects of different cover of abandoned land of the two types on species richness and abundance. The intensively managed fields were cropland where pesticides were used against pests (Decis, Bi 5X, Raxil) and weeds (Roundap, Huzar, Funaben), and chemical fertilizers, mostly nitrate of ammonia, phosphorus and potassium were applied.

Birds were mapped in 80 abandoned fields invaded by goldenrods (mean field size ± SD = 1.20 ± 0.95 ha, range: 0.16—4.75 ha), 80 abandoned fields not invaded by goldenrods (mean field size ± SD = 1.04 ± 0.71 ha, range: 0.18—4.45 ha), and 80 managed arable fields (mean field size ± SD = 1.24 ± 0.78 ha, range: 0.36—4.7 ha). The study was performed between 2005 and 2020. Each year 1 (in 2006) to 48 (in 2015) fields were surveyed via the combined mapping method (Tomiałojć, 1980). Each field was visited six times with controls beginning at dawn and conducted until 11 a.m. Also, one evening control was performed (7–11 p.m.) in the second half of May. A network of natural elements (shrubs, trees, paths, etc.) was used to map the breeding territories. A breeding territory was assumed to be a place where at least three observations were made of an individual bird or singing males (Skórka et al. 2010).

The above described data on birds from managed and abandoned fields were used for the ecological modelling and simulating the effect of increasing cover of abandoned land in agricultural landscape with and without goldenrod invasion (invaded abandoned land and not invaded abandoned land) on species richness and abundance. We considered following scenarios in agricultural landscape with:

(1) A combination of intensively managed land with unmanaged and not invaded abandoned fields and its effect on biodiversity of birds.
(2) A combination of intensively managed land with unmanaged and invaded abandoned fields and its effect on biodiversity of birds.

These scenarios represent two extremes of a continuous gradient between intensification of agricultural production, land abandonment and invasion risk, because almost no landscape is ideally intensified or ideally abandoned, invaded or extensively managed (McGowan et al. 2018).

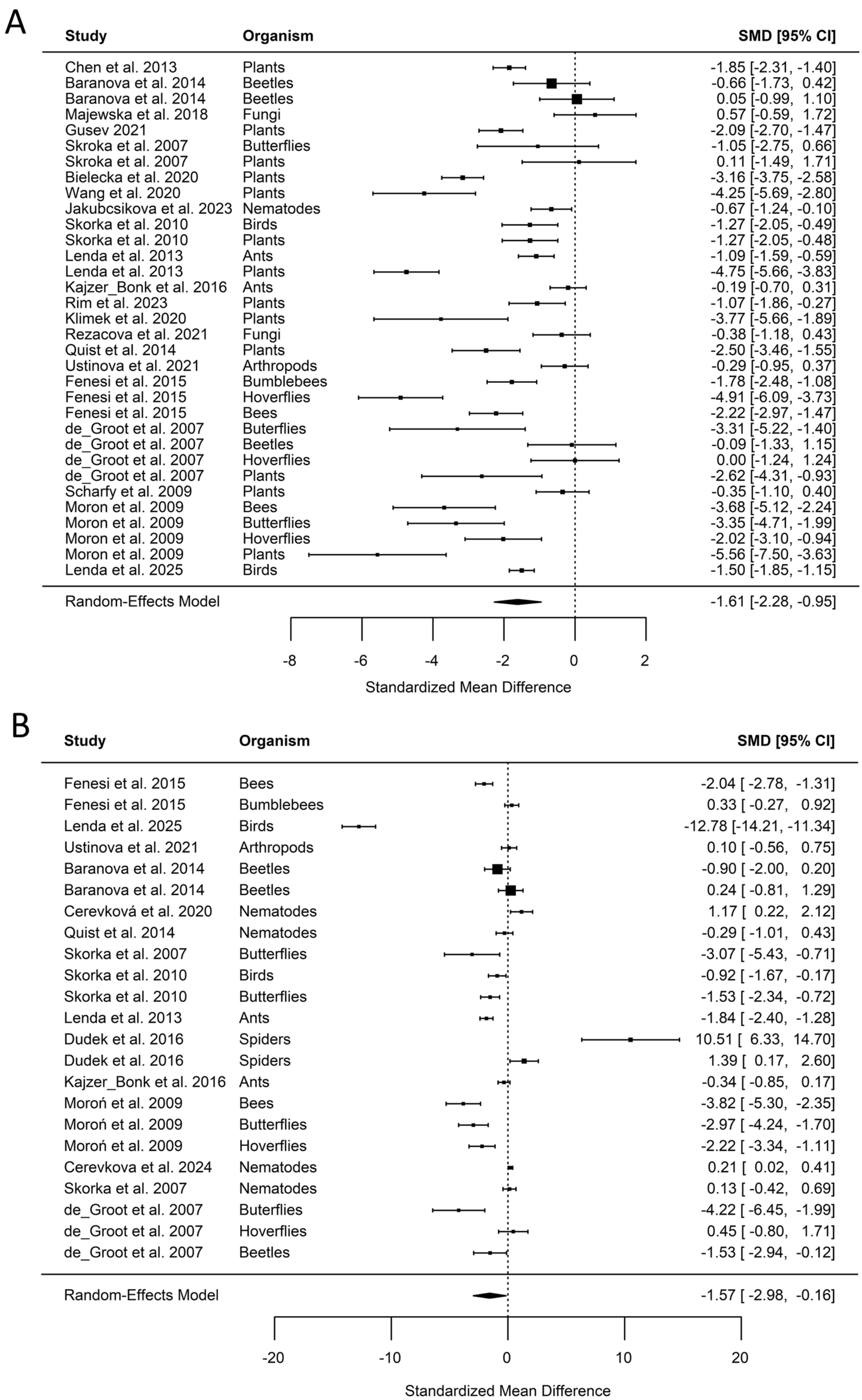
Simulations were based on statistical resampling techniques (Monte Carlo simulations with replacement). To simulate the effect of the invasion on the diversity of birds in different covers of abandoned land (abandoned fields) we created virtual landscapes (~ 100 ha in area) by random sampling fields and bird data from the database of managed and abandoned fields. For example, to simulate 10% cover of not invaded abandoned land in a landscape, we sampled (with replacement) bird data from not invaded abandoned fields so that the total area of randomly chosen fields was about 10 hectares (fields differed in size, see above). Then, the remaining 90% of a landscape area (i.e., 90 ha) was sampled from crops. The same procedure was applied when constructing landscapes with 10% of invaded abandoned (abandoned fields covered by the invasive species). We simulated a cover of abandoned land equalling 0, 5, 10…, 90, 95 and 100% in two scenarios described above (with invasion of goldenrods and without). For each cover of abandoned land (both invaded and not invaded) 100 virtual landscapes were created. Then general additive models [using 'mgcv' R package (Wood 2006)] were fitted to the sampled data to see how cover of abandoned land in the two scenarios related to the bird species richness and abundance (number of breeding pairs).

All analyses were done in R statistical environment.

Results

Searching in scientific literature for links between land abandonment, rewilding, land sparing and invasive species

We obtained from Web of Science 15,290 articles on land abandonment, 25,396 articles on invasive species, and 314 articles on land abandonment and invasive species combined, suggesting that land abandonment may be sometimes related to invasions of alien plant species (Table 1). The association between land abandonment and plant invasions was noted in all continents (Fig. 2). Further, using Web of Science we retrieved 781 articles on rewilding strategies and 104 articles on rewilding and land abandonment, which suggest that rewilding is associated with the land abandonment. However, we found only two articles discussing rewilding, land abandonment, and invasive species altogether (Table 1). Moreover, not even one of the official brochures issued by Rewilding Europe (https://rewildingeurope.com/publications/) mentioned this problem in its 39 issues, containing 389 publications. Meanwhile, we retrieved 557 articles in Web of Science on land sparing, 44 articles on land sparing and land abandonment, and only one article


A
Study
Organism
SMD [95% CI]
Chen et al. 2013
Plants
-1.85 [-2.31, -1.40]
Baranova et al. 2014
Beetles
-0.66 [-1.73, 0.42]
Baranova et al. 2014
Beetles
0.05 [-0.99, 1.10]
Majewska et al. 2018
Fungi
0.57 [-0.59, 1.72]
Gusev 2021
Plants
-2.09 [-2.70, -1.47]
Skroka et al. 2007
Butterflies
-1.05 [-2.75, 0.66]
Skroka et al. 2007
Plants
0.11 [-1.49, 1.71]
Bielecka et al. 2020
Plants
-3.16 [-3.75, -2.58]
Wang et al. 2020
Plants
-4.25 [-5.69, -2.80]
Jakubcsikova et al. 2023
Nematodes
-0.67 [-1.24, -0.10]
Skorka et al. 2010
Birds
-1.27 [-2.05, -0.49]
Skorka et al. 2010
Plants
-1.27 [-2.05, -0.48]
Lenda et al. 2013
Ants
-1.09 [-1.59, -0.59]
Lenda et al. 2013
Plants
-4.75 [-5.66, -3.83]
Kajzer_Bonk et al. 2016
Ants
-0.19 [-0.70, 0.31]
Rim et al. 2023
Plants
-1.07 [-1.86, -0.27]
Klimek et al. 2020
Plants
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Rezacova et al. 2021
Fungi
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Quist et al. 2014
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Ustinova et al. 2021
Arthropods
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Fenesi et al. 2015
Bumblebees
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Bees
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de_Groot et al. 2007
Buterflies
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de_Groot et al. 2007
Beetles
-0.09 [-1.33, 1.15]
de_Groot et al. 2007
Hoverflies
0.00 [-1.24, 1.24]
de_Groot et al. 2007
Plants
-2.62 [-4.31, -0.93]
Scharfy et al. 2009
Plants
-0.35 [-1.10, 0.40]
Moron et al. 2009
Bees
-3.68 [-5.12, -2.24]
Moron et al. 2009
Butterflies
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Moron et al. 2009
Hoverflies
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Moron et al. 2009
Plants
-5.56 [-7.50, -3.63]
Lenda et al. 2025
Birds
-1.50 [-1.85, -1.15]
Random-Effects Model
-1.61 [-2.28, -0.95]
-8
-6
-4
-2
0
2
Standardized Mean Difference
B
Study
Organism
SMD [95% CI]
Fenesi et al. 2015
Bees
-2.04 [-2.78, -1.31]
Fenesi et al. 2015
Bumblebees
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Lenda et al. 2025
Birds
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Ustinova et al. 2021
Arthropods
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Baranova et al. 2014
Beetles
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Cerevková et al. 2020
Nematodes
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Skorka et al. 2010
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Ants
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Dudek et al. 2016
Spiders
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Spiders
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Kajzer_Bonk et al. 2016
Ants
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Moroń et al. 2009
Bees
-3.82 [-5.30, -2.35]
Moroń et al. 2009
Butterflies
-2.97 [-4.24, -1.70]
Moroń et al. 2009
Hoverflies
-2.22 [-3.34, -1.11]
Cerevkova et al. 2024
Nematodes
0.21 [0.02, 0.41]
Skorka et al. 2007
Nematodes
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de_Groot et al. 2007
Buterflies
-4.22 [-6.45, -1.99]
de_Groot et al. 2007
Hoverflies
0.45 [-0.80, 1.71]
de_Groot et al. 2007
Beetles
-1.53 [-2.94, -0.12]
Random-Effects Model
-1.57 [-2.98, -0.16]
-20
-10
0
10
20
Standardized Mean Difference

◂**Fig. 3** Meta-analysis showing effect sizes of goldenrods on species richness (A) and abundance (B) of the ecosystem service providers in invaded and non-invaded abandoned land. The 95% confidence intervals of the effect size are shown for individual studies. The size of the mean effect (a square) corresponds positively with sample size

on land sparing, land abandonment, and invasive species altogether (Table 1). Therefore, land sparing is related to land abandonment in scientific literature but hardly ever consider risk imposed by invasive species. None article considered jointly land abandonment, rewilding, land sparing, and invasive species (Table 1).

Meta-analysis on the effects of alien goldenrods on biodiversity of the main ecosystem services providers

The meta-analysis revealed that there was variation in the effect of goldenrods on species richness and abundance of different organisms (Fig. 3A, B). However, overall goldenrods negatively affected the species richness and abundance of ecosystem services providers in the abandoned land (Fig. 3A, B).

Modelling the effect of increasing cover of invaded and non-invaded abandoned land on birds in agricultural landscape

Bird species richness and abundance (number of breeding pairs) in the invaded abandoned fields (species richness: mean $\pm$ SE = 1.36 $\pm$ 0.15; abundance: mean $\pm$ SE = 1.39 $\pm$ 0.16; n = 80 fields) were comparable to those in the managed fields (species richness: mean $\pm$ SE = 1.21 $\pm$ 0.11; abundance: mean $\pm$ SE = 1.24 $\pm$ 0.12; n = 80 fields); however, these values were lower than those in the non-invaded abandoned fields (species richness: mean $\pm$ SE = 6.33 $\pm$ 0.50; abundance: mean $\pm$ SE = 6.94 $\pm$ 0.59; n = 80 fields). Simulations performed on this data showed that bird species richness and abundance did not improve by increasing the coverage of the abandoned land invaded by goldenrods (Fig. 4A, B). Conversely, increasing the coverage of the non-invaded abandoned land (up to approximately 40%) increased bird species richness and abundance (linearly) in the simulated agricultural landscapes (Fig. 4A, B). This suggests that there is no gain for biodiversity from the increase of invaded abandoned land in agricultural landscapes for biodiversity.

Discussion

Our analysis of literature showed that studies on rewilding and land sparing usually do not take into account the well documented relationship between land abandonment and plant invasions, and, thus, do not provide effective solutions for landscapes threatened by invasive species that cause substantial decline in biodiversity (Lenda et al. 2023). This is surprising because many previous studies on abandoned meadows and agricultural fields (cropland) show that the abandoned land is colonized by invasive plant species that usually results in biodiversity loss, including ecosystem services provided by pollinators and pest controllers (Moroń et al. 2009; Skórka et al. 2010; Lenda et al. 2013; Lenda et al. 2019). For example, in Central Europe, up to 90% of abandoned agricultural land is dominated by alien goldenrods (Szymura et al. 2016; Lenda et al. 2019; Lenda et al. 2021), which can create homogenous habitat patches with up to 100% dominance within a few years (Lenda et al. 2019; Lenda et al. 2023; Świerszcz et al. 2024). Our case study carried on invasion of goldenrods in Central Europe suggests that if an invasive plant species has established dominance on abandoned land, the biodiversity of these areas will be significantly lower than that of extensively managed agricultural habitats. Our meta-analysis confirmed the negative impact of this plant on native biodiversity. There are, of course, many other invasive alien species colonizing abandoned land, thus the cumulative effect of invasion of alien plant species may be even stronger (but see: Lenda et al. 2019). Thus, the creation of "natural" spared or rewilded areas through agricultural land abandonment in the presence of invasive plant propagules may later reduce native species richness and abundance by increasing the invasion and colonization rates of alien plant species on newly abandoned, post-agricultural land. Although our study was based on the data from goldenrod invasions, non-native plant species invading abandoned lands are a global problem (Fig. 2). For example, dense stands of the invasive grass *Saccharum spontaneum* prevent forest regeneration in abandoned pastures in Panama

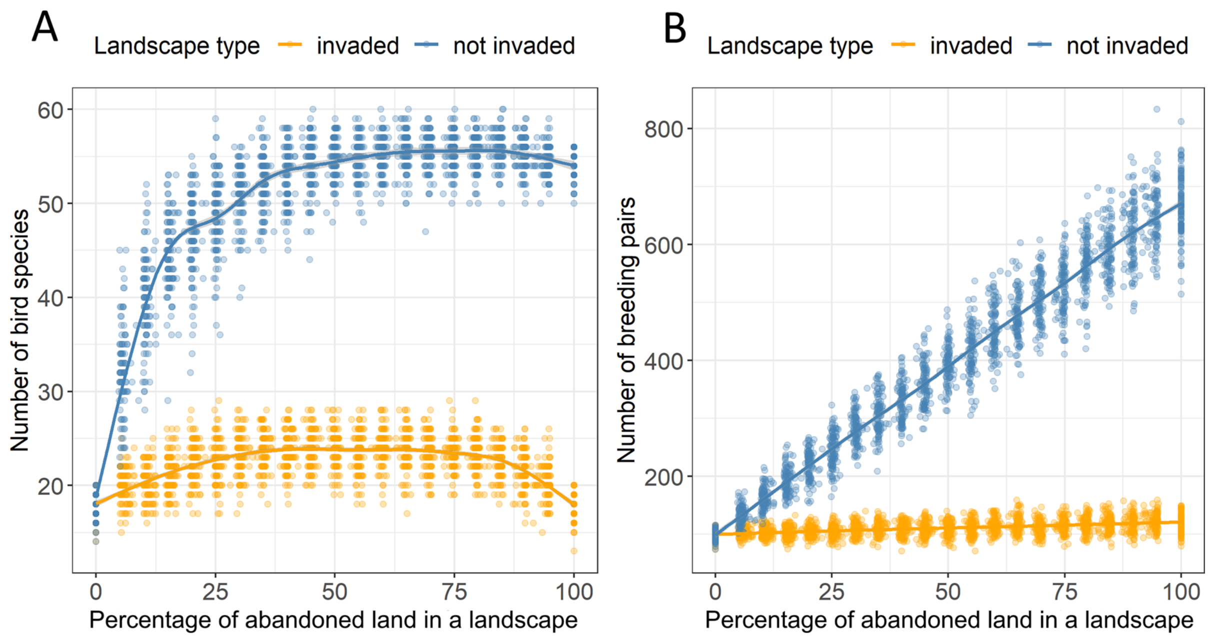

Fig. 4 Simulations based on bird data showing how different proportions of abandoned land may affect bird species richness (A) and number of breeding pairs (B) in goldenrod-invaded (orange) and non-invaded (blue) landscapes. Virtual landscapes of approximately 1 km^2 were created from managed fields and abandoned fields by randomly selecting data. The proportion of abandoned land varied from 0 (only managed fields) to 100% (only abandoned fields) for two scenarios (i.e., invaded and non-invaded landscape). For each cover of abandoned land, 100 landscapes were simulated. Curves are general additive models fitted to the data

(Hooper et al. 2005), whereas the invasion of alien grasses on abandoned plantations in Maui and Hawaii Island increases wildfire frequency and intensity (Faccenda and Daehler 2022). Abandoned farms with small fruit plantations are the invasion pools of *Prunus cerasus* and *Malus domestica*, which invade protected Patagonian forests in Argentina (Bravo et al. 2019). In Nepal, the invasion of *Ageratina* sp. into abandoned fields has led to the alteration of arbuscular mycorrhizal fungi in the soil (Balami et al. 2021). Abandoned croplands in South Africa have increased the invasion of woody plants, such as *Acacia mearnsii* (Moyo and Ravhuhali 2022). Interestingly, the invasion of the shrub *Prosopis juliflora* into the pastoral landscape of Ethiopia may lead to the abandonment of the invaded land (Mehari 2015).

In addition to land abandonment, agricultural intensification is major direction of global land-use changes (Potapov et al. 2022). Agricultural intensification and the further conversion of natural ecosystems into modern agricultural land pose global threats to biodiversity, resulting in the extinction of native fauna and flora. Human population is expected to reach 9.7 billion by 2050 (United Nations Department of Economic and Social Affairs, Population Division 2022). To feed this growing population, there would be an increasing demand for fair food distribution and greater agricultural production, leading to further agricultural intensification. Even with the adoption of existing agricultural technologies, flexitarian diets, and food waste reduction, still ensuring food security is a challenge if the aim is to maintain environmental well-being (Wollenberg et al. 2016; Gao and Bryan 2017). According to Alexandratos and Bruinsma (2012), global agricultural production is projected to increase by about 60% by 2050 compared with the 2005/2007 baseline, driven by rising demand for meat, sugar crops, oil crops, and cereals. Such intensification of agricultural practices (rather than expansion of agricultural land) may lead to increased pesticide and herbicide use, greater greenhouse gas emissions, soil pollution, and water scarcity.

This bifurcating trend in agricultural land management contradicts the history of agriculture.

Agriculture changed simultaneously with the development of human civilization. For example, in Europe, 6000 years ago, forests were 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", the oldest and largest in the European Union, promote extensive land management to maintain local biodiversity. For example, in Central Europe, several 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 the large blue butterflies *Phengaris teleius* and *Phengaris nausithous*, which are both flagship species in European biodiversity conservation (Nowicki et al. 2007). Several protected bird species, such as ortolan bunting *Emberiza hortulana* and corncrake *Crex crex*, which is a rare grassland-specialized bird, only inhabit managed landscapes. Mown or grazed meadows are also important for threatened plant species such as orchids, Siberian iris *Iris sibirica*, globeflower *Trollius europaeus,* chess flower *Fritillaria meleagris*, and crocus *Crocus scepusiensis*. However, currently, these agriculture-associated habitats have a low conservation status among European ecosystems because they are primarily devoted to agricultural production, and land management is changing through either intensification or abandonment (Pe'er et al. 2014), which have led to a continuous decline in farmland biodiversity (Tryjanowski et al. 2011).

Currently, one-sixth of all land worldwide is highly vulnerable to invasive plants (Early et al. 2016). In such landscapes, land abandonment intended for nature conservation may unintentionally promote plant invasions, leading to declines in biodiversity and ecosystem services. The relationship between land abandonment, invasion risk, and management is not binary, though. When invasive alien plant species are still rare in the landscape or in a time-lag phase before rapid expansion (Crooks 2005), the risk of invasion can be significantly reduced through strategic management during the first few years after abandonment. This early period is critical—management interventions at this stage can successfully prevent invasions (Shan & Hou 2024; Świerszcz et al. 2024). Moreover, once plant assemblages on abandoned land develop and stabilize, management may become less necessary, as invasion impacts can diminish due to the dominance of certain native species (Flory et al. 2017).

However, land abandonment can also serve as a trigger for invasive species to break the lag phase. Newly created suitable habitats provide opportunities for colonization, especially for species with high propagule pressure that can disperse over long distances via wind, animals, or vegetative means (e.g. roots in goldenrod). Because dispersal pressure is continuous, abandoned land often becomes a key entry point for invasive species. As more fields are abandoned, the abundance of invasive species in the landscape tends to increase, amplifying the overall problem (Lenda et al. 2012).

Practical recommendations

To maintain biodiversity and prevent habitat loss due to invasive species that are already widespread, we propose the implementation of nature conservation strategies based on wildlife-friendly farming and sustainable land reuse and management, such as land sharing (Phalan et al. 2011) or agricultural rewilding (Corson et al. 2022). In areas at a high risk for alien plant invasion the extensive and rotational land management practices, such as plowing, cutting, and grazing, can effectively prevent the successful establishment, spread, and impact of invasive alien species (Lenda et al. 2012; Lenda et al. 2018; Świerszcz et al. 2017, 2024). Even in rewilding concept interventions are allowable (Van Meerbeek et al. 2019) and the agricultural rewilding (Corson et al. 2022), although did not consider invasive species directly, may actually prevent invasions and increase biodiversity. Policy changes are thus needed to better support landowners in reusing resources and managing their land to mitigate the risk of alien plant invasion; integrated landscape planning and effective assessment tools are essential for this purpose. Thus, any renewed strategy aimed at nature conservation in agricultural land implemented via policy should be based on a biodiversity impact assessment of invasive alien species present in the environment. This information has been largely omitted to date. For example, the

European Restoration Law and European Green Deal, which are new large conservation policies, do not take adequately into account the risk of invasive species spreading across several regions in the European Union. The policy should include various incentives for farmers to prevent the establishment of invasive species and enhance or maintain the ecological and biodiversity services that already exist. Also, further research is needed that directly test impact of invasion risk on the potential profits from incorporating land sparing or land rewilding in different landscapes.

Study limitations

Our study contains certain limitations that should be taken into account when interpreting data and conclusions. First, we did not consider in our study the temporal dimension in invasion processes. This problem is rarely considered in studies on invasive species (Strayer et al. 2006). Early management after land abandonment can greatly reduce risks when species are rare or in a lag phase (Crooks 2005; Świerszcz et al. 2024). Also land abandonment is not usually permanent. It is abandoned for 14.2 years on average, then is recultivated, and over 50% of the abandoned land is recultivated before 30 years (Crawford et al. 2022). However, land abandonment may be the trigger for alien species to break the lag-phase and become invasive also in other habitats, eliciting cascading effects (David et al. 2015; Lenda et al. 2018).

Secondly, although we recognize that relevant knowledge exists in multiple languages (Amano et al. 2023), our literature search was conducted in English to ensure the inclusion of peer-reviewed studies. This choice, along with the use of a relatively narrow set of keywords, may have restricted the breadth of topics and contexts represented. Concepts such as organic farming, multifunctional farming, and high nature value farmland—important in agricultural landscape conservation—were not fully integrated. Future research should explore the intersections among existing conservation concepts to better inform policy and practice.

Lastly, our meta-analysis and field sampling were limited in spatial and taxonomic scope. We focused on an illustrative example of a single invasive plant species—goldenrod—which, while highly problematic in Europe, does not represent all invasion scenarios. Similarly, statistical simulations were restricted to birds due to available field data. Applying our approach to other invasive species, taxonomic groups, and landscapes would strengthen the generality of the conclusions.

Conclusion

Rewilding and land-sparing strategies have been successful in promoting secondary natural succession in abandoned land, especially those damaged by natural disasters or man-made catastrophes. However, when invasive alien plant species are present within or nearby an abandoned land, it seems best to apply land sharing or rewilding with interventions (agricultural rewilding) because agricultural activities such as mowing and plowing destroys the dispersed seeds and seedlings of invasive alien species.

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Author Contribution ML, PS, JMHK, HP, DK, and KC conceptualized the study and wrote the original draft; DK, PS, KC, XG and ML conducted formal analysis and visualization; ML, PS, and HP provided resources, acquired funding, and administered the project; and ML, JMHK, PS, HP, DK, KC and XG reviewed and edited the manuscript.

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Data availability All data and codes will be made publicly available in Dryad after the manuscript is accepted for publication.

Declarations

Conflict of interest Authors have no conflict of interest to declare.

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