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Cost-effective biodiversity conservation with organic farming - spatial allocation is key

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ABSTRACT

To make the best use of the limited funding for biodiversity conservation, resources should be used cost-effectively. Support to organic farming is a widely implemented strategy to enhance farmland biodiversity, yet its cost-effectiveness for biodiversity conservation remains largely unexplored. Using an ecological-economic model calibrated with data from southern Sweden, we evaluated the cost-effectiveness of organic farming for enhancing biodiversity in landscapes of varying agricultural productivity (low and high). We focused on flowering plant diversity, which further has an essential role in supporting pollinators and natural enemies of crop pests.

Our findings reveal that organic farming generally proves more cost-effective for enhancing biodiversity in high-productive compared to low-productive agricultural landscapes. We also found that depending on landscape characteristics, conversion of 10–20 % of arable land to organic management could substantially increase species richness at a relatively low cost (<6 % reduction in farmers' profits). However, with further increases in conversion rates, costs escalated exponentially while the benefits to biodiversity diminished. Across larger spatial scales (1000 to 2000 ha), biodiversity peaked when land was approximately evenly divided between conventionally and organically managed farms, owing to species turnover dynamics.

Our study underscores the importance of tailoring policies to incentivize organic farming where it has the greatest impact on biodiversity. Importantly, it suggests that policies aimed at incentivizing organic farming in high-productive regions could be more cost-effective for biodiversity conservation than current policies that favour conversion in low-productive regions.

1. Introduction

Insufficient funding remains a major barrier to achieving regional and global goals for biodiversity conservation (Commission, 2020; UNEP, 2022). Therefore, it is imperative that conservation strategies are implemented cost-effectively, ensuring maximal outcomes given the limited available resources. This is particularly important in addressing impacts from major drivers of biodiversity declines (Deutz et al., 2020), where agricultural intensification is often identified as a main contributor (Kehoe et al., 2017; Raven and Wagner, 2021; Tscharntke et al., 2012a). However, research in this crucial area remains scarce (Ansell et al., 2016).

Organic farming is widely recognized as an environmentally friendly alternative to conventional farming (Eyhorn et al., 2019; Reganold and Wachter, 2016). By avoiding using synthetic pesticides and fertilizers, organic farming promotes a wide range of species and associated ecosystem services (Reganold and Wachter, 2016; Tuck et al., 2014). However, compared to conventional farming, yields of crops grown organically are often substantially lower (e.g. Alvarez, 2022), ultimately affecting profitability and adoption rates. To facilitate the transition to organic farming, policies compensating farmers for opportunity costs are often necessary. For instance, in the European Union (EU), payment schemes supported organic farming with €1.3 billion annually between 2014 and 2022 (European Commission, 2022), significantly supporting its expansion. Currently, organic farming covers 9 % of all utilized agricultural land in the EU (Eurostat, 2023), with a target of reaching 25 % by 2030 (European Commission, 2020).

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However, current incentive structures might not be optimized for cost-effective biodiversity conservation. While payments to organic farming aim to reflect average opportunity costs relative to conventional farming, they are uniform across regions (Regulation 1305/2013/EU, 2013). This favours adoption of organic farming in less productive regions, where the yield gaps, and thus opportunity costs, between organic and conventional practices are lower (De Ponti et al., 2012; Gabriel et al., 2009). Consequently, low-productive regions often exhibit higher adoption rates of organic farming (Eurostat, 2019; Gabriel et al., 2009; Rundlöf and Smith, 2006). Conversely, the potential of organic farming to enhance biodiversity is generally greatest in high-productive regions (Tuck et al., 2014; Winqvist et al., 2012). This is attributed to that low-productive regions generally have more remaining natural habitats, which boost biodiversity while limiting the additional biodiversity benefits attainable through organic practices (Rundlöf and Smith, 2006; Tscharntke et al., 2005).

Hence, organic farming tends to be adopted in regions where both opportunity costs and biodiversity benefits are comparatively low. However, it remains unclear whether this is the most cost-effective spatial allocation for organic farming to promote farmland biodiversity. Our study addresses this knowledge gap by investigating how landscape contexts (in terms of agricultural productivity and the amount of natural habitats) affect the contribution of organic farming to biodiversity relative to opportunity costs. Gaining such knowledge is essential for developing policy instruments that incentivize organic farming while promoting cost-effective biodiversity conservation (Sidemo-Holm, 2022).

We assess farmland biodiversity at the landscape scale, reflecting the ecological value of organic farming for a wider range of species compared to the more commonly applied field-scale approach (Tscharntke et al., 2005; Tuck et al., 2014). Specifically, we focus on flowering plant diversity, which is typically substantially higher in organic than conventional fields (Tuck et al., 2014). A diverse flora in crop fields and the surrounding landscape further supports a wide range of beneficial organisms that rely on flowers for nourishment and shelter, including pollinators and natural enemies of crop pests (Balfour and Ratnieks, 2022; Lu et al., 2014; Sidemo-Holm et al., 2021).

To conduct the study, we developed a theoretical ecological-economic model that determines the cost-effectiveness of organic farming in enhancing species richness in landscapes with varying levels of productivity and landscape complexity, in terms of the proportional extent of non-arable habitats suitable for flowering plants (for which we used semi-natural grasslands as a proxy). With the theoretical model as a conceptual foundation, we integrate a biodiversity function and an empirical economic optimization model, to create a novel empirical ecological-economic model (e.g. Wätzold et al., 2016). The ecological information was derived from a study on organic and conventional farms in southern Sweden (Carrié et al., 2018), while the economic model was parameterized using an automated procedure based on published statistics for the same region (see Mérel and Howitt, 2014). In this way, we were uniquely able to predict the optimal distribution of arable land between conventional and organic farming to reach biodiversity targets while minimizing opportunity costs within different types of agricultural landscapes. This insight into the cost-effectiveness of organic farming for enhancing farmland biodiversity in contrasting landscapes offers valuable guidance for decision-makers aiming to identify cost-effective biodiversity conservation schemes.

2. Theoretical ecological-economic model

To evaluate the optimal usage of arable land to maximize profit from agricultural production while reaching biodiversity targets, we begin by developing a theoretical ecological-economic model. The model predicts the effects of agricultural land use on gross farm profits (revenues minus variable production costs) and species richness (predicted by a biodiversity function). In the model, we assume that agricultural land X_j (hectares) can be allocated between three different agricultural land uses j: conventional farming (CON), organic farming (ORG) and semi-natural grassland used for livestock production (SNG). The model accounts for the effect of the three possible agricultural land uses $\mathbf{X} = (X_{\mathrm{CON}}, X_{\mathrm{ORG}}, X_{\mathrm{SNG}})$ on gross profit and species richness in an agricultural landscape.

We first develop the objective function for maximizing gross profit without any biodiversity target following principles from agricultural economics (Debertin, 1986). Since there is a natural limit on how much land can be used for farming, the objective function is subject to the land constraint $\sum_{j=1}^{3} X_j \leq \overline{X}$, where $\overline{X}$ is the total available agricultural land in the landscape. Thus, the objective function is:

$$MAX\pi(\mathbf{X}) = \sum_{j=1}^{3} \left(p_j - c_j\right) Y_j X_j - h_j(X_j) - \mu\left(\sum_{j=1}^{3} X_j - \overline{X}\right) \tag{1}$$

where p_j is the price per unit output from land use j, c_j is the variable cost per unit output from land use j, Y_j is the quantity of output from one hectare of j, h_j is a non-linear per hectare cost function for land use j, and μ is a Lagrange multiplier representing the shadow price of the land constraint implied by $\overline{X}$, i.e. the marginal value of one extra hectare of land to the farmer.

The non-linear cost function h_j accounts for potentially increasing marginal costs of increasing the area of a particular land use. The marginal cost typically increases because the most profitable land, e.g. with high productivity and/or close to the farm, is farmed first after which less profitable land is added. Thus, we assume that $\partial h_j / \partial X_j \geq 0$ and $\partial^2 h_j / \partial X_j^2 \geq 0$, which also ensures that Eq. (1) is an increasing concave optimization problem, i.e. $\partial \pi_j / \partial X_j \geq 0$ and $\partial^2 \pi_j / \partial X_j^2 \leq 0$, and thus the first order conditions for profit maximization are both necessary and sufficient to define the optimal solution (Klein, 2014).

Given these assumptions, the derivation of the objective function Eq. (1) with respect to the land-use choice variables X_j, returns the land use solution that maximizes gross profit given the land constraint:

$$\frac{\partial \pi}{\partial X_j} = \left(p_j - c_j\right) Y_j - \frac{\partial h_j}{\partial X_j} = \mu \forall j. \tag{2}$$

Thus, the optimum combination of the land uses CON, ORG and SNG is where the gross profit from one hectare of land use is equalized among all j and equals μ, i.e. the shadow price of agricultural land. Thus μ can be interpreted as the maximum amount they would be willing to pay to increase land beyond $\overline{X}$, e.g. by renting another hectare of land (if that was possible). If not all land is profitable to use, then $\mu = 0$.

Second, we develop an objective function for maximizing gross profit with the addition of a biodiversity constraint $S(\boldsymbol{X}) \geq \overline{S}$ to model a biodiversity target/policy goal. Here, $S(\boldsymbol{X})$ is the biodiversity function that simultaneously considers the effect of all land uses CON, ORG and SNG on species richness, and $\overline{S}$ denotes the biodiversity target for species richness. Thus, combinations of land uses are constrained by the requirement that $\overline{S}$ species need to be preserved in the agricultural landscape. We assume that the conservation function is increasing concave, i.e. $\partial S / \partial \boldsymbol{X} \geq 0$ and $\partial^2 S / \partial \boldsymbol{X}^2 \leq 0$. This assumption follows theoretical and empirical understanding of the relationship between species richness and area (Rosenzweig, 1995). We use Lagrange's theorem to set up and solve the problem with both the land use and biodiversity constraints:

$$MAX\pi\,(\mathbf{X}) = \sum_{j=1}^{3} \left(p_j - c_j\right) Y_j X_j - h_j(X_j) - \mu\left(\sum_{j=1}^{3} X_j - \overline{X}\right) - \lambda(S(\mathbf{X}) - \overline{S}\,) \tag{3}$$

where λ represents a Lagrange multiplier that, in the optimum, equals the marginal cost of species conservation, i.e. the opportunity cost of preserving an additional species. Through derivation, the land use that maximizes profit given the biodiversity target is defined by:

$$\frac{\partial \pi}{\partial X_j} = \left(p_j - c_j\right) Y_j - \frac{\partial h_j}{\partial X_j} - \mu = \lambda \frac{\partial S(\boldsymbol{X})}{\partial X_j} \forall j. \tag{4}$$

The optimum combination of the land uses CON, ORG and SNG is thus where the marginal profit from changing one hectare of land use *j* to another land use minus the marginal value of land (μ) equals the marginal opportunity cost of increasing species richness through land use *j* (marginal conservation cost), and hence is equalized for all *j,* which defines the equi-marginal cost principle for cost-effective conservation.

3. Empirical analysis

Following from the theoretical model Eq. (3), we integrated a biodiversity function with an (empirical) economic model. The resulting (empirical) ecological-economic model was then used to predict optimal land-use combinations to maximize gross profit while reaching biodiversity targets in particular landscape contexts. We established biodiversity targets as a rise in the absolute count of flowering plant species richness from the baseline land-use combination where gross profit was maximized. Below, we first describe the studied landscape contexts, then the biodiversity function and the economic model, and ultimately the ecological-economic model which was applied to predict marginal conservation costs for increasing flowering plant species richness depending on landscape scale, productivity, and complexity (i.e. the area of semi-natural grassland).

3.1. Landscape contexts

We studied two natural agricultural regions in southern Sweden with similar temperate climate (average annual temperature 7.6 °C and precipitation 650 mm), but distinct productivity. In the region identified by the Swedish Board of Agriculture as Götalands södra slättbygder (hereafter referred to as the high-productive region) the average yield of winter wheat is 8.5 t/ha for conventional farms and 5 t/ha for organic farms (Jordbruksverket, 2023). In the other region, Götalands mellanbygder (referred to as the low-productive region) the average yield of winter wheat is 7 t/ha for conventional farms and 4 t/ha for organic farms (Jordbruksverket, 2023). The regions also differ in terms of the proportion of agricultural land occupied by semi-natural grasslands (permanent unfertilized grasslands), our proxy for landscape complexity (see Carrié et al., 2018). In the high-productive region, semi-natural grasslands accounted for 5 % of all agricultural land, while in the low-productive region, they constituted 25 % (Statistics Sweden, 2020a). The two regions serve as representative examples of less and more productive regions across Europe (Gabriel et al., 2009; Statistics Sweden, 2020a).

We calibrated our models using biodiversity and agricultural data from the two regions, and modelled the cost-effectiveness of organic farming for biodiversity conservation depending on region and landscape scale (100, 1000 and 2000 ha).

3.2. Biodiversity function

The biodiversity function was parametrized using field data collected from a total of 19 farms, ten organic and nine conventional farms, distributed across the two studied agricultural regions (Fig. 1). We surveyed flowering plants in two cereal fields, two leys and two semi-natural grasslands on each farm in 2017 (see Carrié et al., 2018). This data enabled the biodiversity function to estimate the flowering plant species richness in an agricultural landscape based on the three most common agricultural land uses in the regions (Statistics Sweden, 2017).

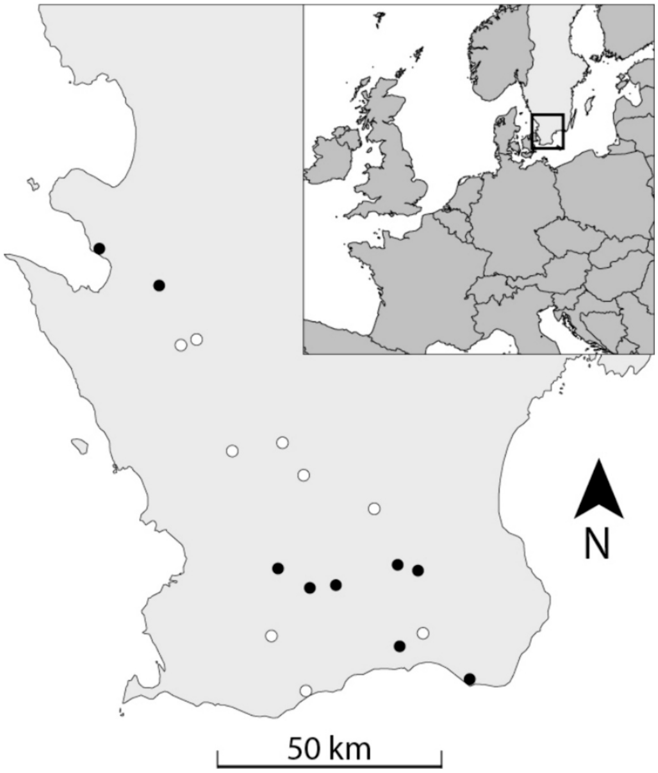

Fig. 1. Locations of the studied organic (white circles) and conventional farms (black circles) in southern Sweden and Europe (square insert).

The objective of the biodiversity function was to model the change in flowering plant species richness at the landscape scale in response to conversion of arable land from conventional to organic farming, relative to the proportion of semi-natural grasslands in the landscape. The main principles of the biodiversity function are explained below, whereas a more detailed description is available in the Appendix.

We used a probabilistic model of species-area relationship (Olsson et al., 2021) to estimate total species richness for agricultural landscapes with different proportions of organically and conventionally farmed arable land and semi-natural grasslands. The probabilistic model is based on the classical assumption that the probability of species occurrence increases with the habitat size, but in addition weighs the probability of occurrence by the species' density in the given habitat. Based on species densities, the model can thus estimate the landscape scale species richness for a given landscape configuration and scale. We estimated the species-specific density distributions based on data from the field study.

We used the probabilistic model of the species-area relationship to estimate species richness for different landscape configurations. The landscape scales were set at 100, 1000 and 2000 ha, and the proportion of semi-natural grasslands within each landscape was set to 5 % and 25 % respectively to reflect the average proportions of semi-natural grasslands in the studied regions. For each landscape scale, as well as proportion of semi-natural grasslands, we assessed how species richness responded to different farming configurations, ranging from 0 to 100 % organically farmed arable land, with the remaining percentage being farmed conventionally. We assumed that there is no difference between semi-natural grasslands under conventional or organic management because these are managed in similar ways (i.e. neither are treated with pesticides nor fertilizers).

We fitted the generated configurations and estimates of species richness using a model based on a negative exponential function, because it allows an estimation of an asymptote and the speed of species accumulation (Tjørve, 2003). We considered that the proportion of organic land would influence the asymptote of the accumulating effect of increasing the proportion of semi-natural grasslands on flowering plant species richness. Moreover, landscapes dominated by organic farming are likely to have more plant species than conventional ones, but we expected some species turnover when converting to organic farming, as some species are well adapted to intensive practices such as high nitrogen and herbicide inputs (Carrié et al., 2022). As a result, the conversion effect to organic farming on plant diversity is likely to be hump-shaped, with a maximum located towards high proportions of organic land. We therefore chose to model the effect of conversion to organic farming on plant diversity using a Ricker function, which is well adapted to model skewed hump-shaped relationships (Bolker, 2008).

3.3. *Empirical economic model*

To model farmers' optimal land use in response to a biodiversity target, we developed a mathematical programming model of a representative landscape in each of the studied regions. This approach was chosen, rather than an econometric (statistical) approach, because of its flexibility to model outcomes beyond those represented in the data (e.g. large proportions of organic agriculture) and its suitability for integrating ecological relationships within an optimization framework (Carpentier et al., 2015). A traditional limitation of the mathematical programming approach is calibration and validation that relies on expert judgement. To overcome this limitation we used an objective calibration procedure known as Positive Mathematical Programming (PMP) to automatically calibrate the economic model to observed farmer behaviour in the calibration year 2021 (Howitt, 1995a, 1995b). The approach takes maximum advantage of the available data on agricultural production as reflected in official agricultural statistics and research findings for the studied regions (Mérel and Howitt, 2014). Rather than introducing, e.g. arbitrary constraints to force the model to reproduce observed behaviour, and therefore potentially overly restricting farmers' land use possibilities, it relies on a non-linear cost term to infer unobservable costs, such as production risks, declining productivity of land, additional labour, etc. to explain farmers' observed production choices, which are provided in Table 1 for our studied regions. This term corresponds to the nonlinear cost term $h_j(X_j)$ in the theoretical model, Eq. (1). The calibration procedure is explained in the Appendix.

With this optimization approach it becomes possible to infer marginal values of limited resources such as land, or policy constraints such as a biodiversity target, through shadow pricing (Mérel and Howitt, 2014). It therefore makes it possible to infer values that farmers put on resources that are otherwise difficult to estimate, which can be used to calibrate farmers' behaviour in models to predict their response to environmental policies (Buysse et al., 2007; Mérel et al., 2014). Furthermore, the PMP approach also solves another problem, which is that organic farming according to enterprise budgets (i.e. ostensibly) is more profitable than conventional (e.g. Ramankutty et al., 2019), yet so little area in the regions are actually farmed organically. This suggests that there are costs perceived by farmers that are not accounted for in enterprise budgets, but which can be inferred by the PMP approach. This is based on the premise that observed production levels reflect farmer's profit optimizing behaviour.

The economic model was implemented in General Algebraic Modelling System (GAMS).

3.4. *Empirical ecological-economic modelling*

We created an ecological-economic optimization model by integrating the biodiversity function with the economic optimization model as a constraint on the farmers' decision problem. To adapt to the scale of the biodiversity function we normalized all observed production levels to landscapes of 100, 1000 and 2000 ha. This allowed for an assessment of how the optimal land use solution for achieving biodiversity targets depends on the landscape scale.

To generate a benchmark, or baseline solution, to evaluate the cost-effectiveness of organic farming in a particular landscape context, it was necessary to exclude the current agricultural policy payments for organic farming from the optimization (i.e. once the model had been calibrated), because these represent transfers to farmers and not social opportunity costs. Thereafter we solved the ecological-economic model without a constraint on biodiversity to generate the baseline solution for each landscape scenario to be evaluated. This counter-factual solution represents farmers' profit maximizing choices (optimal land use) excluding the current payments to organic farming or biodiversity targets. In this modelled solution, the optimal proportions of organic arable land were estimated to approximately 1 % in the high-productive region and 5 % in the low-productive region, irrespective of landscape size. This contrasts with the actual allocation when farmers obtain policy payments, where organic farming currently accounts for 5 % and 11 % of the arable land in the high- and low-productive region, respectively, while the areas of semi-natural grasslands remain identical. We modelled the baseline proportion of organic farming and species richness for each of the landscape scales in both agricultural regions (Fig. 2).

Table 1
Observed agricultural production and proportion (%) organic management in the studied regions in 2020 (Statistics Sweden, 2020a, 2020b).

	High-productive region		Low-productive region	
	Area	Organic	Area	Organic
	Hectare/ head	Proportion (%)	Hectare/ head	Proportion (%)
Agricultural land				
Arable land	317,699	5	312,587	11
Semi-natural grassland	16,803	–	107,239	–
Arable land use				
Winter wheat	97,879	3	58,145	8
Other grains	86,402	6	78,581	9
Winter rape	37,005	2	16,369	6
Sugar beet	33,497	1	22,803	2
Protein crops	4950	21	7823	13
Grass silage	34,006	11	104,236	17
Arable pasture	14,090	13	14,090	12
Fallow/set-aside	9870	0	10,540	0
Total arable	317,699	5	312,587	11
Livestock				
Dairy cows	24,462	8	60,005	10
Suckler cows	11,129	14	29,750	16
Beef cattle[a]	17,756	9	63,642	7
Recruitment heifers	12,011	9	29,952	11
Ewes	13,196	14	59,765	23
Total livestock units	56,090	10	157,864	12

[a] The proportion of organic beef is lower than the proportions of organic dairy cows because it is common for calves from organic dairy cows to be fattened conventionally, due to the high opportunity cost of raising these calves organically.

For the three different landscape scales (100, 1000 and 2000 ha) in both the high- and low-productive regions, we modelled the marginal conservation cost of increasing flowering plant species richness in the landscape from the baseline by converting conventional to organic arable land use. We used this to compare how the marginal conservation cost of converting conventional to organic land use is affected by agricultural region and landscape scale. For each landscape scale and region, we ran the model until the total benefit of organic farming to species richness reached its maximum (Fig. 3).

The ecological-economic model was coded in GAMS to find optimal solutions regarding land uses and impacts on marginal conservation costs based on the PMP approach. All costs were converted from the Swedish crown (SEK) to Euro based on the average exchange rate for January through June 2023 (1 SEK = €0.0885).

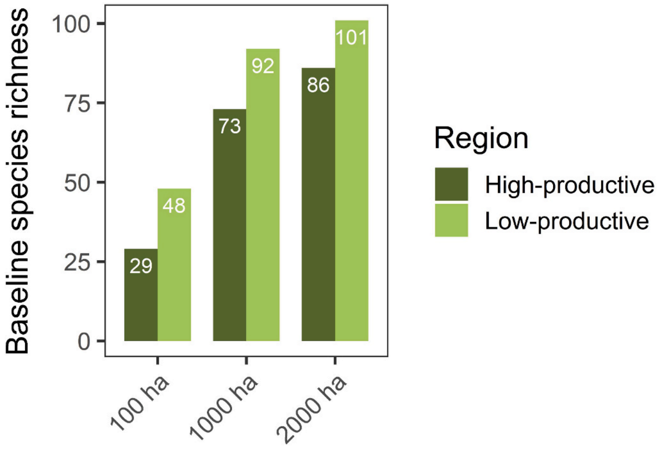

Fig. 2. Modelled species richness in the baseline solution in the high-productive and low-productive region for each of the assessed landscape scales. Besides landscape scale, species richness is affected by the proportion of semi-natural grasslands within the landscape (5 % in the high-productive region and 25 % in the low-productive region) and the proportion of the arable land managed organically, which in the baseline solution is 1 % in the high-productive region and 5 % in the low-productive region.

4. Results

According to our baseline levels, the proportion of organic arable land that maximized profit without the current organic policy payments was only 1 % in the high-productive region and 5 % in the low-productive region. Increasing the proportion of organic arable land beyond that level was associated with an increasing marginal conservation cost and thus profit loss.

We found that higher biodiversity targets (i.e. increased species richness compared to the baseline solution) could be reached most cost-effectively by increasing organic farming in the high-productive region. This was demonstrated by a lower marginal conservation cost, which we present as an average per hectare to provide a reference framework (Fig. 4). This finding was driven by a stronger biodiversity effect from increased organic farming in the high-productive region (Fig. 3), where the baseline biodiversity was much lower due to fewer semi-natural grasslands in the landscape (Fig. 2). On the other hand, for lower biodiversity targets, it proved most cost-effective to increase biodiversity by promoting organic farming in the low-productive region (Fig. 4). This trend was particularly pronounced at larger landscape scales, where there was more available land with low opportunity costs, and where an increased proportion of arable land farmed organically had a greater impact on species richness (Fig. 3). Regardless of region, organic farming was more cost-effective in reaching conservation objectives at larger landscape scales.

As expected, the marginal conservation cost showed an upward trend

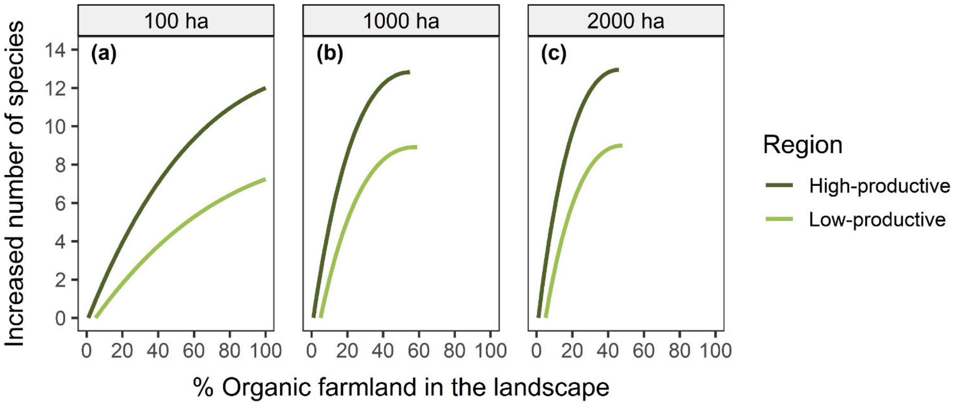

Fig. 3. Increase in number of species from the baseline when increasing the proportion of organic arable land in the landscape. Estimates are modelled from the baseline to maximum species increase from converting to organic farming in the high-productive and low-productive region at each of the three landscape scales 100 ha (a), 1000 ha (b) and 2000 ha (c).

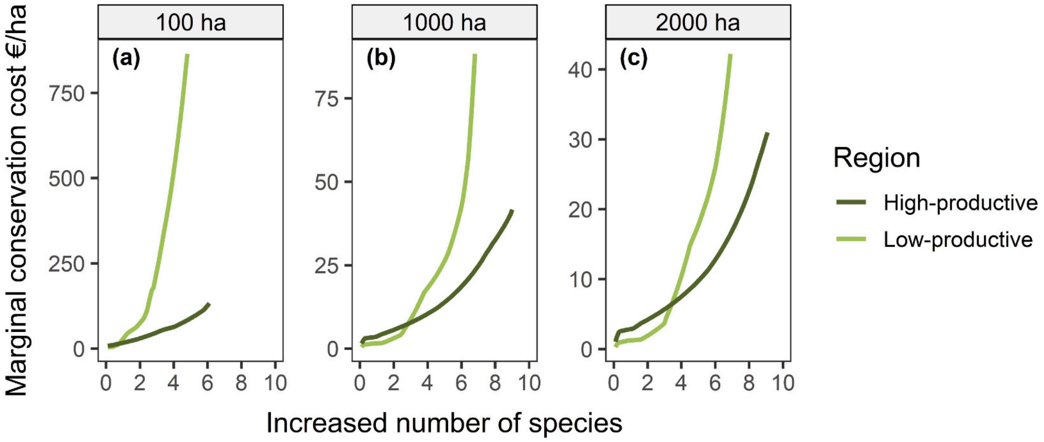

Fig. 4. The average marginal conservation cost per ha for converting conventional arable land to organic to increase the number of flowering plant species from the baseline. Estimates are modelled for the high-productive and low-productive region at each of the three landscape scales 100 ha (a), 1000 ha (b) and 2000 ha (c).

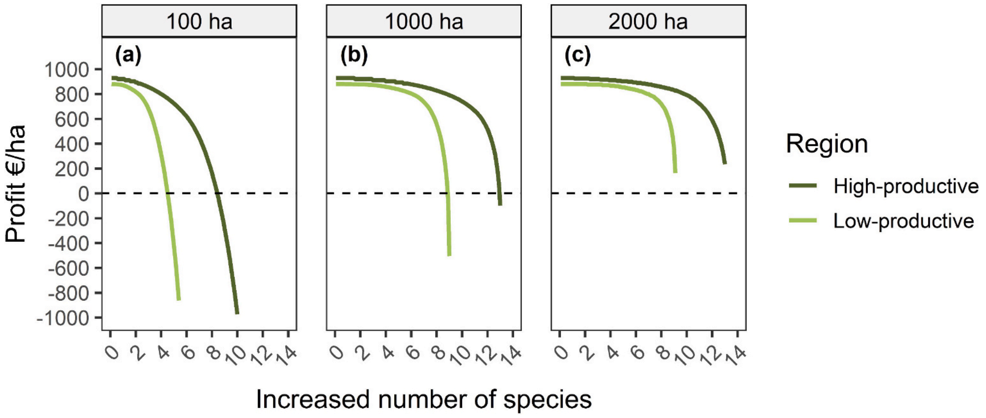

Fig. 5. Relationship between profit per hectare and increased number of species from the baseline. As more arable land is managed organically, the species richness increases and the profit per hectare decreases. Estimates are modelled for the high-productive and low-productive region at each of the three landscape scales 100 ha (a), 1000 ha (b) and 2000 ha (c).

with increasing targets for added flowering plant species in both regions and across landscape scales. The slopes of the marginal conservation cost curves indicate that the cost of increasing species richness in the landscape escalates rapidly with higher conservation targets, especially in the low-productive region and at smaller landscapes scales (Fig. 4).

We found that converting up to 10 % of arable land to organic management increased biodiversity with a negligible impact on profit (less than a 4 % decrease). For conversion rates up to 20 %, a modest profit impact was observed, with a decrease of approximately 6 % in the low-productive region and 15 % in the high-productive region (Fig. S3). Yet, specific biodiversity targets could be reached with a lower foregone profit in the high-productive compared to the low-productive region, because it required less land to be converted to organic (Fig. 5).

At the larger landscape scales, the availability of more land with lower opportunity costs enabled species targets to be reached via conversion to organic farming with lesser impact on profitability (Fig. 5). As an illustration, increasing species richness by 10 species in the high-productive region required 65 % organic land in the smallest landscape (100 ha), resulting in a net loss of -€950/ha. Conversely, in the larger landscapes, the same species target was achieved by converting only 25 % (1000 ha) and 20 % (2000 ha) of land to organic, maintaining positive profits (€750 and €800/ha respectively) (Figs. 5 and S3).

5. Discussion

Our study demonstrates that flowering plant species richness could generally be increased more cost-effectively through organic farming in the high-productive region compared to the low-productive region, and by allocating agricultural land-use across larger landscapes, i.e. at larger spatial scales.

The differences in the cost-effectiveness of organic farming in preserving biodiversity can be explained by both ecological and economic factors. Ecologically, the impact of organic farming on flowering plant species richness was greater in the high-productive region, primarily because the region had fewer semi-natural grasslands. Many plant and animal species can occur in both semi-natural habitats and arable land (Lüscher et al., 2016), which reduces the potential of adding species through increasing the areas of organic farming in the low-productive region where the species richness is already high due to the high proportion of semi-natural grasslands.

At all evaluated landscape scales (100, 1000 and 2000 ha), the increase in species richness from converting additional arable land to organic farming diminished the greater the area being farmed organically. Consequently, achieving higher biodiversity targets required larger proportional increases in organic farming; hence resulting in steeply increasing marginal conservation costs for increasing species. This result aligns with the general understanding that species richness tends to increase with habitat area but at a declining rate (Rosenzweig, 1995). Thus, our results showing a decreasing contribution of organic farming to flowering plant species richness with increasing proportions of land managed organically, could also be expected for other organism groups benefiting from organic farming, such as insects and spiders (Stein-Bachinger et al., 2021; Tuck et al., 2014). The dependence of species richness on habitat area further explains why at larger landscape scales a smaller proportion of arable land needs to be converted to organic farming to achieve specific biodiversity targets, as compared to a smaller landscape scales.

Although organically managed arable land was found to be more species-rich than its conventional counterpart, the contribution to the landscape-wide biodiversity was maximized when approximately half of all arable land was managed organically in the landscapes measuring 1000 and 2000 ha (Fig. 3). In contrast, in the landscape measuring 100 ha, species richness was maximized by managing all arable land organically. This observation is interesting because it implies that the optimal proportion of organically farmed land for species conservation will vary between regions and depending on the landscape scale biodiversity is measured at. For biodiversity conservation, it is typically more important to preserve species richness at larger spatial scales to safeguard a broad array of species and ecological interactions (Gering et al., 2003; Sidemo-Holm et al., 2022). Our results thus suggest that a mix of conventional and organic farmland management is optimal for biodiversity conservation.

While organic farms typically have lower yields than conventional ones (De Ponti et al., 2012), organic farming is not necessarily less profitable than conventional farming due to higher market prices for organic products and lower input costs (Crowder and Reganold, 2015). However, despite financial incentives for organic farming, only 9 % of all utilized agricultural land in the EU is managed organically (Eurostat, 2023). This suggests that there are substantial opportunity costs associated with farming organically compared to farming conventionally, which we could demonstrate and subsequently infer through our PMP calibration approach. According to our baseline levels, the proportion of organic arable land that maximized profit without the current organic policy payments was only 1 % in the high-productive region and 5 % in the low-productive region. Increasing the proportion of organic arable land beyond that level was associated with an increasing marginal conservation cost and thus profit loss.

Our ecological-economic model accounted for the fact that farmers within each region would achieve biodiversity targets by converting land with the lowest possible opportunity cost. Achieving higher biodiversity targets therefore entailed converting land with increasingly higher opportunity costs (Fig. 4). The variability of opportunity costs within regions was driven by the observed areas of different crops, the number of livestock, and the profit difference for these in organic and conventional farms (Appendix). As demonstrated in Figs. 4 and 5, lower biodiversity targets could be achieved with a relatively low marginal conservation cost and profit loss. Reaching a higher biodiversity target entails increased opportunity costs as land with more profitable crops, such as sugar beets and rapeseed (Appendix), must be converted to organic management.

At the two larger landscape scales, it was most cost-effective to increase species richness with up to three species in the low-productive region (Fig. 4). For higher targets at these landscapes scales, and in general at the smallest landscape scale, the greater impact of organic farming on biodiversity in the high-productive region outweighed the higher opportunity costs, making it most cost-effective to increase biodiversity in the high-productive region. This implies that policy payments for organic farming should be differentiated across regions to reflect biodiversity benefits, i.e. be higher in high-productive regions, measured as average crop yield.

As the marginal conservation cost escalates as more land is used for organic farming, other land uses may offer more cost-effective opportunities to promote biodiversity. Our results show that presence of semi-natural grasslands had a high positive impact on species richness. The low-productive region with semi-natural grasslands composing 25 % of the agricultural land had 15 to 19 more species (depending on the landscape scale) at the baseline level compared to the high-productive region that had 5 % semi-natural grasslands (Fig. 2). Therefore, adding semi-natural grasslands, by for instance restoring shrub-encroached grasslands (Pittarello et al., 2016), or incentivizing better management of existing grasslands, may be comparatively cost-effective ways to promote species richness of flowering plants and biodiversity in general (Tscharntke et al., 2021). However, it should be noted that the potential for restoration of semi-natural grasslands of high biodiversity value may often not be a viable solution, because of legacies of present land-use (Le Provost et al., 2021; Piqueray et al., 2011). Instead, in high-productive landscapes where these restoration opportunities may be particularly scarce, creating novel semi-natural habitats of high biodiversity value such as flower strips or permanent grassy set asides might represent better alternatives, but their cost-effectiveness for conservation targets have yet to be evaluated.

It is important to acknowledge that the biodiversity function was parameterized with a relatively small dataset. It was also based on a crude characterization of landscapes, e.g. with biodiversity being generalized to what occurs in arable fields and semi-natural grasslands. This may limit the transferability of the results to other regions. In addition, we used a space-for-time substitution approach that may result in issues with unknown biases in uptake of organic farming and not well represent the dynamic of biodiversity after organic transitions. Furthermore, the biodiversity function did not account for ecological habitat interactions, which may be important for processes such as metapopulation and source-sink dynamics as well as landscape supplementation and complementation (Smith et al., 2014). Thus, further development of the biodiversity function to allow the inclusion of interactions between habitats and parameterization with larger datasets will be important to enhance transferability to other regions.

Our modelling approach focused on the total number of species in the landscape, but not their identity or abundance, which are important to know to better understand the conservation and functional values of species promoted in the different scenarios. Still, regarding conservation values, species richness is often associated with an increase in rare species (see Heegaard et al., 2013; Lichtenberg et al., 2017), which are generally more dependent on conservation interventions to persist in anthropogenic environments than common species (Pimm and Jenkins, 2010). Also, high species richness is likely positive for the amount and resilience of ecosystem functioning and services provisioning (Tscharntke et al., 2012b).

While our focus was on flowering plants, a diversity of such non-cultivated flowering plants in agricultural landscapes contributes to structural habitat heterogeneity (Tscharntke et al., 2005) and provides food resources for other organisms, including pollinators (Bretagnolle and Gaba, 2015), and biological control agents (Wäckers and Van Rijn, 2012). Yet, there is a need to consider multiple organisms groups, especially those that respond differently to farming practices (Lichtenberg et al., 2017), to fully comprehend how biodiversity can be promoted cost-effectively by organic farming.

In addition to biodiversity, organic farming is associated with benefits such as reduced human exposure to pesticides, enhanced animal welfare, reduced spreading of pesticides, better soil health, and increased pollination and biological pest control (Reganold and Wachter, 2016; Seufert and Ramankutty, 2017). Therefore, while this study makes an important contribution to assessing cost-effective biodiversity conservation, further research is needed for a more holistic understanding of how landscape contexts influence the cost-effectiveness of organic farming to achieve multiple objectives.

6. Policy impact

The EU's ambitious goal of increasing the area of utilized agricultural land under organic farming from the current 9 % to 25 % by 2030 (European Commission, 2020; Eurostat, 2023) presents a unique opportunity to revamp policy schemes and achieve improved results from organic farming. However, our research findings underscore the need for a nuanced approach to such a broad objective.

We show that area goals for organically farmed land need to be spatially differentiated to be cost-effective. Notably, the optimal ratio of organically farmed land for biodiversity conservation varies significantly between high- and low-productive regions and according to the scale at which biodiversity is measured at. In this respect our findings indicate that a general goal of 25 % organic across the entire EU is likely to be highly inefficient for biodiversity conservation. Instead, a more cost-effective strategy would be to customize this goal based on regional characteristics and biodiversity targets.

Currently, the environmental payments provided to farmers for adopting organic farming practices in the EU are based on fixed rates determined by the farmer's total area under organic cultivation and the number of livestock. This approach primarily incentivizes organic farming based on economic feasibility and profitability compared to conventional farming. As a result, organic farming has predominantly been adopted in low-productive regions where the opportunity costs are lower (Eurostat, 2019; Gabriel et al., 2009; Rundlöf and Smith, 2006).

However, our research highlights that organic farming can have the most significant positive impact on biodiversity in high-productive regions. To encourage the adoption of organic farming in such contexts, incentives need to account for biodiversity benefits as well as opportunity costs, i.e. cost-effectiveness. One potential solution is to introduce spatially differentiated incentives, where payment rates are adjusted based on contextual factors such as landscape complexity and productivity (Lundberg et al., 2018; Sidemo-Holm, 2022). This approach could be facilitated by introducing region/landscape specific payment rates, based on the proportion of land composed of semi-natural habitats and the average crop yields. As a result, payments would align more closely with the actual biodiversity-enhancing potential of organic farming.

Alternatively, a forward-looking approach involves compensating farmers based on projected biodiversity outcomes using predictive models (Bartkowski et al., 2021; Sidemo-Holm et al., 2018). By linking payments to modelled results, this approach naturally promotes organic farming in regions where it can enhance biodiversity most cost-effectively. Moreover, by using models to project the impact of organic farming on various organism groups and ecosystem services, payments can be adjusted to reflect the multifaceted benefits of organic farming (Reganold and Wachter, 2016; Tuck et al., 2014). This approach aligns promotion of organic farming with the optimal interests of society. However, the effectiveness of such systems hinges on the development of precise, transferable models with easily quantifiable parameters (Bartkowski et al., 2021; Elmiger et al., 2023).

In the process of designing new policy schemes, it is important to account for the spatial dimensions of biodiversity. As underscored by our research findings, the cost-effectiveness of attaining specific biodiversity targets through organic farming varies considerably depending on the scale at which biodiversity is assessed. Furthermore, in extensive and environmentally heterogeneous regions like the EU, policies need to consider beta-diversity, such that organic farming is encouraged across areas with high species turnover and not only in areas with similar species assemblages (Socolar et al., 2016).

In conclusion, to ensure that organic farming delivers cost-effective biodiversity benefits, policies need to align incentives for organic farming with expected biodiversity outcomes. These policies should account for regional variation in opportunity costs and biodiversity benefits, as well as the spatial aspects of biodiversity targets. Therefore, we suggest that policies incorporate tailored incentives, either based on regional contexts or model-derived outcomes from organic farming, to steer the adoption of organic farming to locations where it is not only economically viable but also capable of maximizing biodiversity benefits. However, we also acknowledge that organic farming has multiple aims such as other environmental targets (Reganold and Wachter, 2016), that needs to be factored in for a complete valuation of spatial targeting.

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CRediT authorship contribution statement

William Sidemo-Holm: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mark V. Brady:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Romain Carrié:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johan Ekroos:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Henrik G. Smith:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110624.

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