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REVIEW ARTICLE

Semi-natural habitats and their contribution to crop productivity through pollination and pest control: a systematic review

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Abstract
Context Semi-natural habitats (SNHs) play a vital role in delivering key ecosystem services, such as crop pollination and biological pest control, which are essential to support agricultural productivity. However, the evidence of the economic benefits of SNHs is scattered, and their impacts on productivity in agricultural landscapes are not well understood, limiting their adoption and integration into farming practices and agricultural policies.
Objectives In this study, we qualitatively assess the benefits of SNHs for pollination and biological pest control, as well as their translation into economic outcomes. Our objective is to determine whether the spatial scale of the study and the type of metrics used influence the relationship between SNHs and productivity.
Methods We conducted a systematic review and identified 68 peer-reviewed studies from which we extracted 355 relationships that evaluated the effects of SNHs on productivity. For each relationship, we identified the spatial scale (local or landscape) and the metrics used to measure productivity, pollination or pest control. We conducted a qualitative analysis of the relationships and categorized them as positive, negative, or no evidence for a relationship based on the results reported in the primary studies.
Results We found that SNHs typically enhance pollination and pest control, with 70% of studies reporting a benefit for diversity of pollinators, flower visitation rates and pest predation. However, the link between SNHs and ecosystem services did not consistently translate into increased productivity. Increase in pollination supply translated into higher productivity when indirect metrics (e.g., flower visitation rate) were measured. In contrast, pest control benefits were largely confined to reductions in pest pressure, with limited evidence of increases in productivity. Importantly, the economic benefits and costs of reallocating

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land for SNHs remain underexplored, with only 15% of relationships addressing these aspects.

Conclusions Understanding ecosystem service provision and productivity is challenged by the variability in measures used, mismatches in scale across studies that limit the comparability, and a limited availability of economic data. Advancing this field will require the development of standardized measures that effectively connect biodiversity enhancements with economic outcomes, facilitating quantitative analysis to improve policymaking and the integration of SNHs into sustainable agricultural practices.

Keywords Non-crop areas · Agricultural Productivity · Yield · Ecosystem service supply · Pollination · Pest control · Biodiversity

Introduction

The global human population has rapidly increased to eight billion in less than a century, following a rise from just two billion (Adam 2022). Meanwhile, nature and biodiversity are under pressure, raising urgent questions about how to sustainably feed humanity while ensuring responsible agricultural production (Crist et al. 2017). Agricultural production has been intensified primarily through in-field measures, including increased use of chemical inputs, soil management practices such as mechanized tillage (often ploughing deeper than in the past), mechanical weeding, and a reduction in crop diversity. Beyond in-field measures, agricultural expansion also modified landscapes by increasing field sizes and reducing natural and semi-natural areas that are not directly used for production. This process leads to more uniform landscapes, characterized by large, consolidated fields with fewer non-crop habitats (Robinson & Sutherland 2002; Benton et al. 2003; Kleijn et al. 2011). Despite governmental efforts to mitigate environmental impacts through incentives to maintain or re-create local-scale measures (e.g., organic farming and restrictions on synthetic pesticides), the intensification of agriculture has led to a decline in semi-natural habitats (SNHs) and biodiversity (Mupepele et al. 2021). While there are policies promoting SNHs within agricultural landscapes, many farmers are reluctant to adopt them due to additional management costs and concerns about potential drawbacks, such as the risk of attracting pests that could harm adjacent crops (Rosa-Schleich et al. 2019; Raatz et al. 2021).

SNHs are areas within agricultural landscapes that are not primarily used for production (Holland et al. 2016). These habitats encompass a variety of types that differ according to their historical use and management, which is reflected in their vegetation structure and function (Holland et al. 2017). SNHs can be classified by the type of vegetation they consist of (grassy or woody plants) and by their shape (linear or non-linear). Historically, linear SNHs, such as hedgerows or herbaceous strips along field borders, were used to fence livestock and mark land boundaries (Marshall & Moonen 2002). Conversely, areal SNHs such as tree islands, bushes, or remnants of natural habitats have served as refuges for many species from disturbance (e.g., mowing, tillage, and pesticide usage) or extreme weather conditions (Landis et al. 2000; Duelli & Obrist 2003; Pywell et al. 2005). SNHs play a vital role in supporting species otherwise absent in agricultural landscapes and delivering ecosystem services by sustaining beneficial organisms such as pollinators and natural enemies of pests (Howlett et al. 2023). Natural enemies benefit from woody linear habitats (Bartual et al. 2019), while pollinators are often associated with herbaceous SNHs containing diverse flowering species (Eeraerts et al. 2019). Nevertheless, SNHs are frequently located on soil of poor quality or areas inaccessible to agricultural machinery, and not necessarily in areas with high potential for ecological benefits (Rosa-Schleich et al. 2019; Alarcón-Segura et al. 2023), missing on the opportunity to significantly halt biodiversity losses among pollinators (Potts et al. 2010; Zattara & Aizen 2021) and natural enemies (Chaplin-Kramer et al. 2011; Letourneau et al. 2011).

The benefits of SNHs for crop production are especially critical for insect-pollinated crops, as maintaining and enhancing on-farm pollinator diversity is associated with stable, year-to-year yields (Garibaldi et al. 2016; Senapathi et al. 2021). Studies have shown that restoring SNHs, such as native woody vegetation or flower strips, can increase pollination-dependent yields by 5–6% in berry crops (Blaauw & Isaacs 2014; Feltham et al. 2015) and by 1.5 kg per tree in mango cultivars (Carvalheiro et al. 2012). Benefits for pest control have also been documented. For example, Gurr et al. (2016) reported that planting nectar-producing plants adjacent to rice fields in Thailand increased grain yields by 5%, reduced insecticide use by 70%, and provided an overall economic benefit of 8% compared to fields without SNHs. The impact of SNHs on agricultural yields can be understood through multiple mechanisms. Depending on the interplay between ecosystem services and disservices, SNHs may either enhance or diminish crop yields in adjacent fields. On one hand, SNHs can support key ecological functions such as pollination and natural pest regulation, contributing to increased agricultural productivity (Estrada-Carmona et al. 2022). On the other hand, SNHs may also generate disservices, including the potential spillover of pests and weeds, competition for essential resources such as water and nutrients, and shading effects that limit crop access to sunlight (Tscharntke et al. 2016). Additionally, while SNHs may reduce short-term yield potential by occupying land that could otherwise be cultivated, they may enhance long-term yield stability by mitigating soil erosion, improving water retention, and buffering crops against extreme climatic conditions (Redhead et al. 2020). The scale at which these mechanisms are studied, along with the metrics used to quantify ecosystem service provision and agricultural productivity, significantly influence how scientific findings can be translated into policy implications. Ultimately, the net effect of SNHs on agricultural yields is highly context-dependent, driven by intricate ecological and economic interactions.

The economic implications of establishing (or maintaining) SNHs can be decomposed into three main components. The first component captures the opportunity costs associated with the land that is no longer available for crop production (Delphia et al. 2019). This is determined by multiplying the area designated for SNHs by the counterfactual yield (the potential crop yield that would have been achieved if the land had been cultivated) along with the associated gross margin per unit of output. The second component relates to the net economic benefits of managing SNHs, and is estimated by calculating the potential revenue derived from harvestable outputs, such as woody biomass, while subtracting the costs linked to maintenance (e.g., pruning, Morandin et al. 2016). If the costs of maintaining SNHs exceed the income generated from these outputs, the resulting net benefits will be negative. The third component captures how SNHs influence crop yields (and thus economic output) in adjacent cropland by modifying ecosystem services (e.g., pollination and pest control Raderschall et al. 2021; Boldorini et al. 2024), ecosystem disservices (risk of weed and pest spillovers, Boinot et al. 2019; Raatz et al. 2021) and microclimate (e.g., shading, (Kuemmel 2003; Schäfer et al. 2021)). These interactions are complex, and the overall yield impact is context-dependent and thus could result in both positive and negative yield effects.

The ecological value of SNHs is often evaluated according to their capacity to support beneficial organisms that supply ecosystem services. It is often estimated with the help of different ecological indicators. For instance, the fruit set of flowers (proportion of a plant's flowers that develop into mature fruits or seeds) with and without pollinators is a commonly used proxy to determine the direct effect of the benefits of pollination for crop yield (Garibaldi et al. 2013; Siopa et al. 2024). Additional metrics such as pollinator abundance, species richness, and evenness, are often employed to infer how increased biodiversity may enhance flower visitation rates and, consequently, fruit set. However, sometimes studies consider such biodiversity metrics as a proxy of ecosystem service (indirect) without exploring the direct relationship between pollinator richness and ecosystem service, making it difficult to determine whether the biodiversity enhancement can translate into actual yield outcomes. Moreover, the link between biodiversity enhancement and service provision is not always straightforward (Cardinale et al. 2012), for example, increased fruit set resulting from higher pollinator diversity can reach a plateau when additional pollinators no longer contribute to yield increases (e.g., due to pollen saturation) or may even negatively impact fruit set through pollen excess (Chacoff et al. 2008; Garibaldi et al. 2011). On the other hand, while pollinator evenness may enhance fruit set through complementary interactions among species, it could also have a negative effect if the most efficient pollinator, such as the honey bee, dominates the pollinator species assemblage (Hillebrand et al. 2008).

Metrics measuring pest control are linked to yield outcomes in various ways (Waterfield & Zilberman 2012). The influence of pest pressure on crop yield is well documented, as numerous pesticide alternatives have been developed to stabilize yields (Pingali 2012; Washuck et al. 2022). However, research on integrated pest management often does not sufficiently account for ecological principles or the functional dynamics of agro-ecosystems (Deguine et al. 2021). Nonetheless, SNHs can enhance pest control, thus providing a potential win–win scenario for biodiversity conservation and agricultural productivity (Dainese et al. 2019). The proximity of SNHs to crop fields or on surrounding farms can support pest predator populations, yet, there is considerable variation in natural enemy responses, and their effects on pest populations remain inconclusive (Karp et al. 2018). This variability may stem from biological factors or differences in how habitat characteristics and biocontrol effectiveness are measured, as sometimes the metrics used to explain changes in yield following a shift in pest control may only relate to yield indirectly (Karp et al. 2018). Additionally, it is also expected that the overall impact of improved pest management on agricultural production can be negative, as some crop pests may also benefit from non-crop habitats (Tscharntke et al. 2016).

In this systematic review, we aim to synthesize current knowledge on the effects of SNHs on agricultural productivity, with a particular focus on the roles of pollination and pest control as key ecosystem service mediators. Our objective is to assess whether the impact of SNHs varies based on the ecosystem service examined and the metrics used to evaluate both ecosystem services and productivity outcomes. We use the term “productivity” as a broad conceptual framework encompassing various measures, such as marketable or harvestable yield per area, yield quality affecting market value, and overall (cumulative) profitability. We aim to qualitatively assess the following four hypotheses. 1) SNHs consistently support beneficial organisms by enhancing the abundance or richness of pollinators and natural predators; 2) Gains in crop productivity depend on the specific ecosystem service being assessed; 3) The direction and magnitude of the response depend on the type of metric used (direct vs indirect). Specifically, we anticipate stronger and more detectable benefits when direct metrics, such as fruit set, are employed; 4) The positive effects of SNHs on productivity are expected to be more pronounced in studies evaluating the allocation or restoration of non-crop areas directly adjacent to crop fields, which we define as local scale.

Methods

In March 2025 we conducted a systematic review based on a literature search in the Web of Science Core Collection and Scopus using the search string: (”Landscape heterogeneity” OR “non-crop area” OR “non-crop habitat” OR “semi-natural cover” OR”semi-natural habitat*" OR “semi-natural area*” OR “seminatural habitat*" OR “seminatural area*” OR “wildflower strip” OR "field margin" OR “hedgerow” OR “buffer strip” OR “fallow” OR “set-aside”) AND (“pollinat*” OR “bio* control” OR “natural enem*” OR “natural pest control” OR “predation” OR “parasitism”) AND (“farm income” OR “income” OR “cost” OR "productivity" OR "yield*" OR "crop yield" OR "loss" OR "profit"). We included peer-reviewed studies that reported: (i) the type of semi-natural area, (ii) the type of crop, (iii) the ecosystem service indicator related to pollination or pest control, and (iv) a productivity measure. We screened 540 abstracts (Fig. 1) and included 68 studies that met our inclusion criteria (Appendix S1). From each study, we extracted all relationships between SNHs, pollination and/or pest control and economic outcomes that were given. We treated each relationship recorded as an independent observation. When models included different predictions, we extracted only the outcome of the focal variable i.e., related to SNHs.

We identified all relationships that evaluated the impact of SNHs on economic outcomes either directly or mediated by pollination or pest control. We categorized relationships into ‘positive’, ‘negative’ or with ‘no evidence for a relationship’ based on the direction of the response between an explanatory (e.g. a measure related to SNHs) and a response variable (e.g. a measure related to ecosystem service supply or productivity) following the statistical analysis of the original publication. For each relationship, we documented: (i) the scale at which SNHs were studied (local or landscape scale); (ii) the crop type, (iii) the ecosystem service indicator, related to pollination or pest control, and (iv) the measure of productivity or economic outcome.

We categorized the ecosystem service indicators related to pollination in direct and indirect metrics. Direct metrics, such as fruit set or seed set, can be directly translated and linked to economic outcomes, while indirect metrics, such as visitation rate, pollinator abundance or richness are missing the direct link to

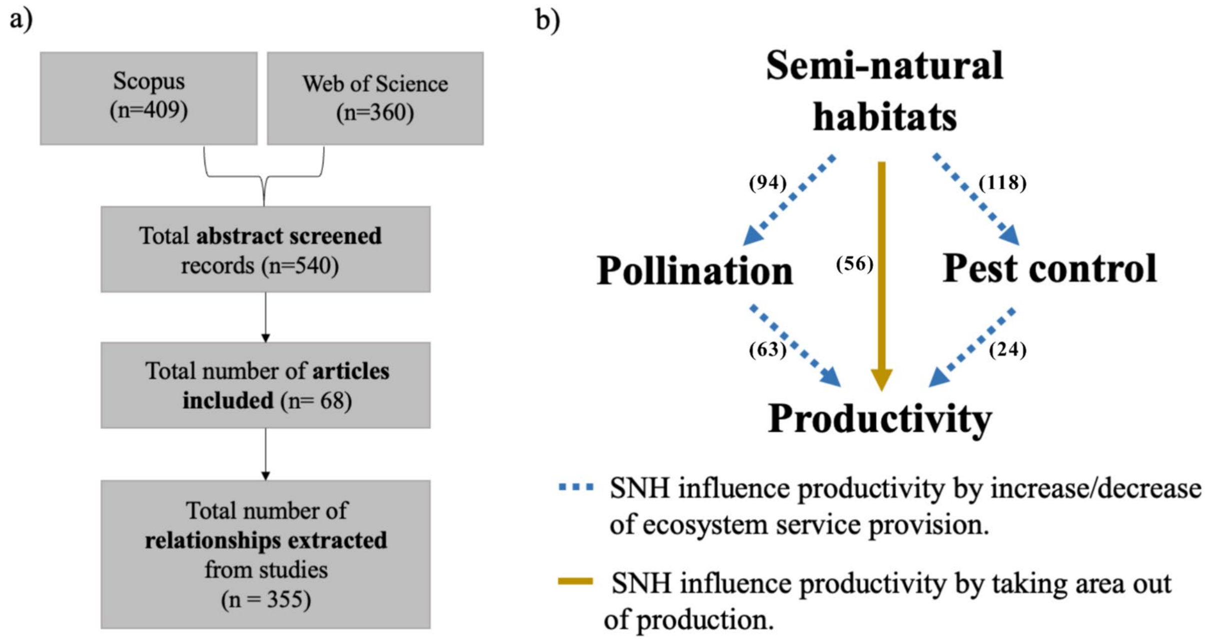

Fig. 1 **a**) Flow diagram of the synthesis search. **b**) Relationships examined in the model. Blue and dashed arrows show relationships that link SNHs and productivity via pollination or pest control. Yellow and continuous arrows represent relationships between SNHs and productivity. The numbers in parentheses indicate the total number of relationships considered in the analysis of each relationship

the crop and as such the productivity or economic outcome. For clarity on the direction of the relationships, pest control indicators were grouped into pest predation and pest pressure. From a farmer's perspective, pest predation is beneficial and should thus increase, while pest pressure is undesirable and should thus be decreased. Positive relationships related to pest predation will translate into benefits for productivity, while positive relationships related to pest pressure will translate into disadvantages for productivity. We used R and the R packages Bibliometrix to extract the literature and delete duplicates from the two search engines (Aria & Cuccurullo 2017; R Core Team 2021). We manually extracted relationship outcomes from the published models from each paper and used the R packages ggplot (Wickham 2016) and dplyr (Wickham et al. 2023) to create the graphs and perform our qualitative analysis.

Results

Review data

We qualitatively analysed 355 relationships from 68 studies that met our inclusion criteria. The majority (80%) of the studies originated from temperate regions (Fig. 2a), aligning with the fact that the concept of semi-natural areas is predominantly used in temperate agricultural landscapes or regions with a long history of agricultural practices. Germany accounted for the highest number of studies (n = 9), followed by the United States (n = 8), France (n = 6) and Sweden (n = 5). The remaining countries were represented by three or less studies (Fig. 2a).

Wildflower areas, field margins, and hedgerows were the most frequently studied SNHs (Fig. 2b). Detailed descriptions of SNHs types, such as

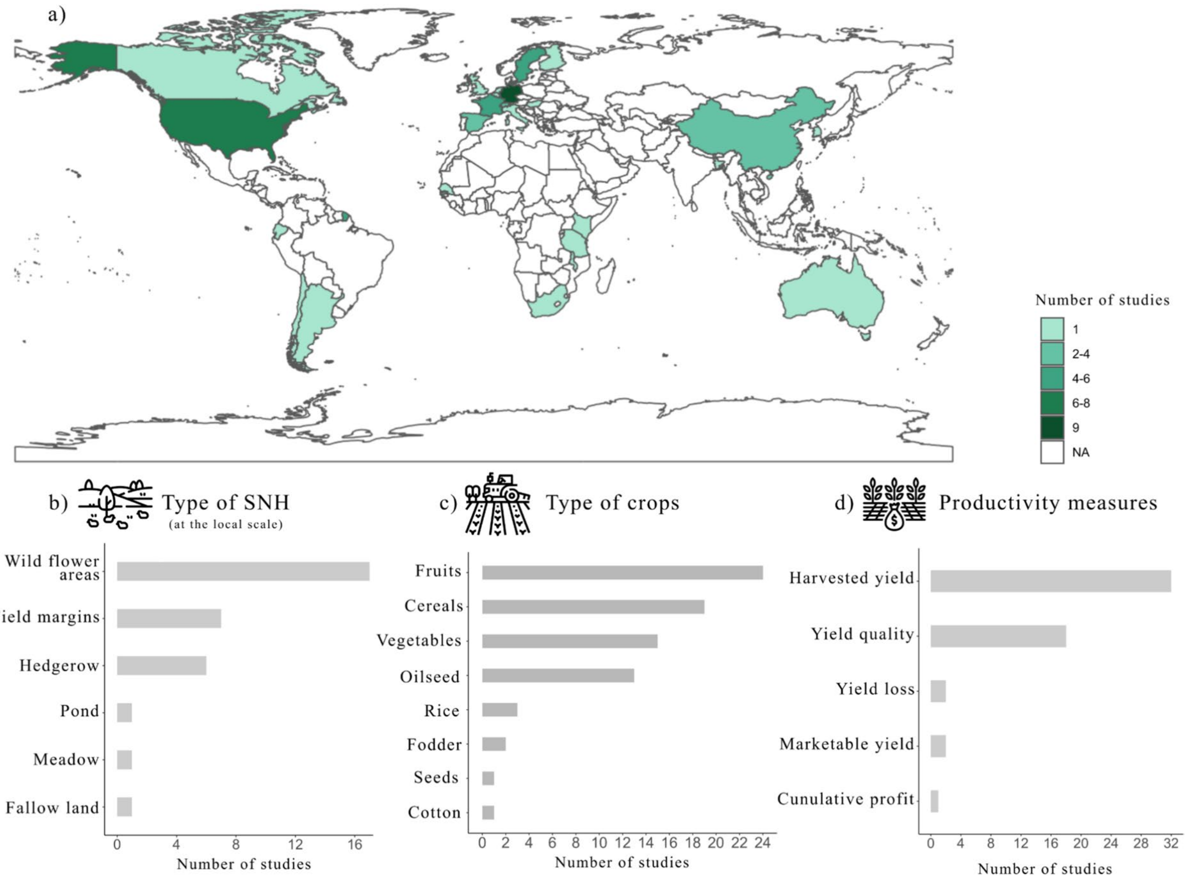

Fig. 2 **a**) Map showing the global distribution of studies included. Number of studies investigating each type of **b**) SNHs examined in studies assessing their influence at the local scale **c**) crop, and **d**) productivity measures

distinguishing between hedgerows and wildflower areas, were provided only in studies conducted at a local scale, particularly when the research focused on the effects of SNHs adjacent to a crop field. At the landscape scale, studies often aggregated different types of SNHs under the umbrella term "semi-natural covers", "proportion of non-crop areas" or "proportion of semi-natural habitats". The spatial scales used in the studies ranged from 100 to 1,000 m, often corresponding to assumed dispersal distances of the focal insect groups. Commonly studied crops were fruits (mostly apples and strawberries), cereals (mostly wheat), and vegetables (mostly beans) (Table S1). Productivity was more frequently assessed using agronomic or biophysical indicators (e.g., harvested biomass per unit area) rather than economic metrics. Among the studies that incorporated monetary terms, cumulative profit was the only economic indicator employed (Fig. 2d).

The effects of SNHs on productivity have been investigated primarily through their contributions to pollination (n = 63) and pest control (n = 24). In contrast, a smaller number of studies (n = 56) have directly evaluated the economic impacts of SNHs (Fig. 1b). Conversely, when assessing the extent to which SNHs enhance ecosystem service supply, more studies have focused on pest control (n = 118) than on pollination (n = 94). Overall, SNHs enhanced both pollination (Fig. 3) and pest control (Fig. 4). However, the magnitude of these effects varied depending on the spatial scale and the type of metrics employed.

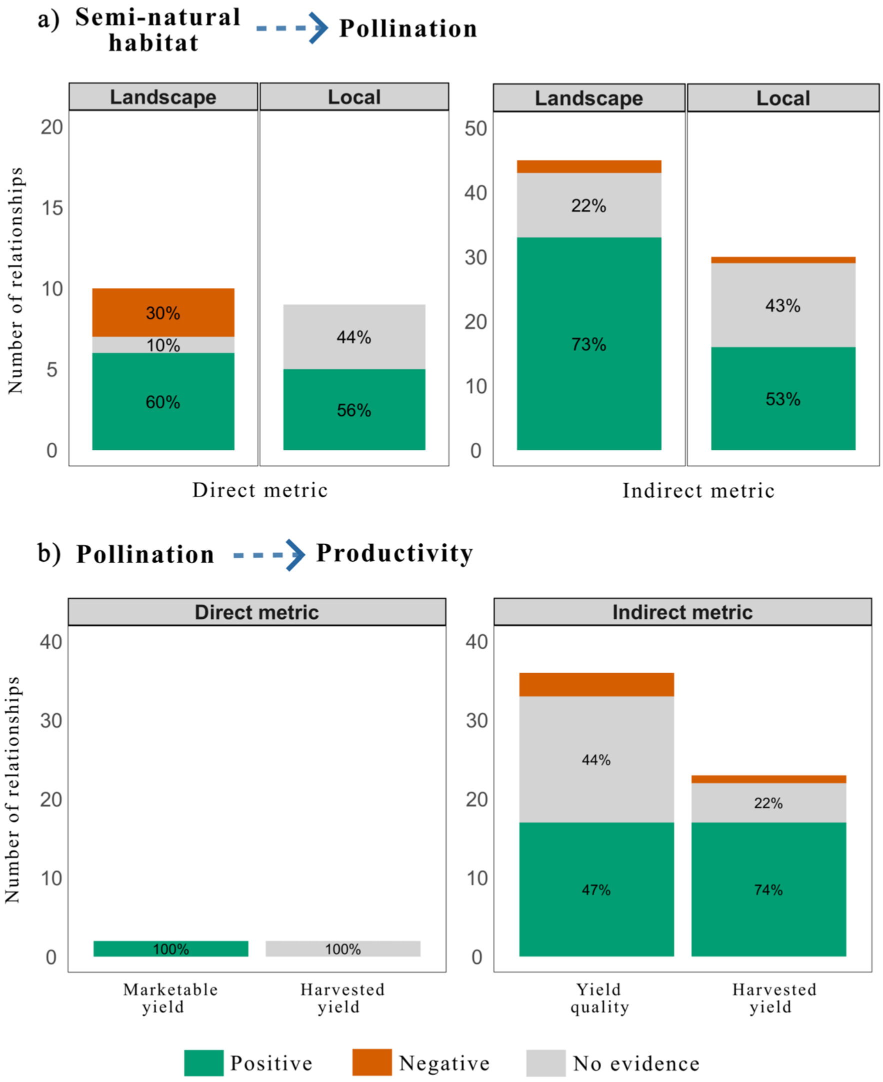

Fig. 3 Number of relationships (as percentages) assessing the effects of SNHs at the local or landscape scale on productivity via pollination. The distinction between *direct* or *indirect* metrics classifies pollination into measures directly linked to the crop and thus productivity, e.g. fruit set, or measures that can only indirectly be related to crops and productivity, such as pollinator abundance. Green bars indicate a simultaneous increase in both variables. Red bars represent a decrease in the response variable as a result of an increase in the explanatory variable. Grey color represents relationships that were tested but no significant relationships were found. Percentages lower than 10% are not depicted

SNHs effect mediated by pollination

The presence of SNHs adjacent to a field (local scale) or in the surrounding landscape (landscape scale) benefited pollination, measured in the form of direct as well as indirect metrics (Fig. 3a). However, indirect metrics were most frequently analysed (n = 75), than direct metrics (n = 19). Indirect metrics of pollination (e.g., visitation rates, pollinator diversity) were most frequently analyzed in relation to the proportion of SNHs in the surrounding landscape, typically within a 1 km radius of crop fields. For direct pollination metrics, up to 60% of models indicated positive responses to increased SNHs at either scale. However, 30% of models at the landscape scale showed negative effects, and 44% at the local scale found no significant relationship. Notably, when using indirect metrics, the proportion of negative responses was lower than when using direct metrics.

Translation of pollination metrics into economic outcomes

Indirect metrics of pollination (n = 59) were more often used than direct metrics (n = 4) to translate pollination supply into economic outcomes (Fig. 3b). Direct metrics were only used in four relationships showing positive or no evidence for a relationship. Regarding the economic outcomes, yield quality increased when it was assessed with the exclusion

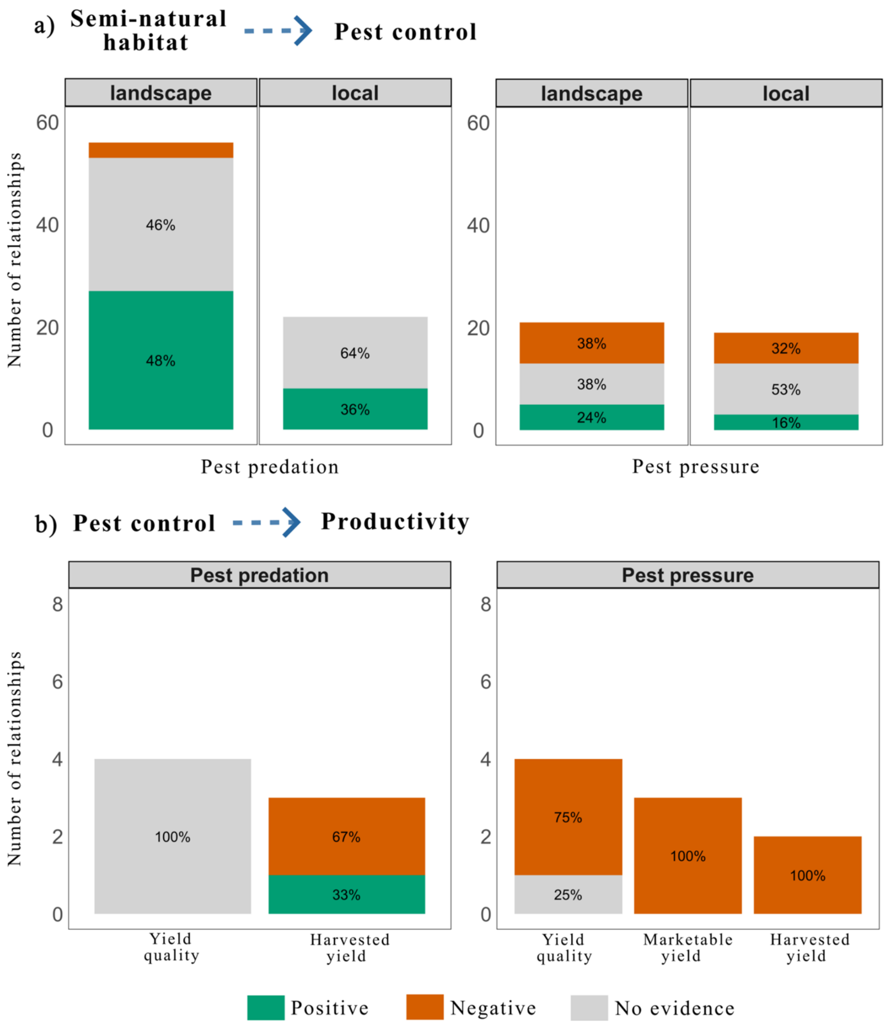

Fig. 4 Number of relationships (as percentages) assessing the effects of SNHs at the local or landscape scale on productivity via pest control. Pest predation refers to variables reducing pest densities (e.g., natural enemy abundance, predation rates), while pest pressure measures crop damage caused by pests. Green bars indicate a simultaneous increase in both variables. Red bars represent a decrease in the response variable as a result of an increase in the explanatory variable. Grey color represents relationships that were tested but no significant relationships were found. Percentages lower than 20% are not depicted

method, i.e., comparing flowers that were open to pollination to caged flowers, or when flowers had increased visitation rates (Table 1). Pollinator abundance was more frequently related with increase in harvested yield (n = 5) than yield quality (n = 1), while pollinator richness only showed positive results for harvested yield only in one model (Table 1). Direct metrics of pollination (e.g., seed/fruit set) were seldom related to economic outcomes and showed positive results only in terms of increase in marketable yields (Table 1).

SNHs effect mediated by pest control

Pest control (n = 142) was evaluated similarly often as pollination (n = 157). However, we found stronger differences in the model results depending on the outcome measured (Fig. 4a). Among these, pest predation at the landscape scale was the most frequently studied outcome. Overall, SNHs reduced pest pressure in only one-third of the relationships at the landscape (38%) and local (32%) scales. Conversely, pest predation increased due to SNHs in less than 50% of the relationships at the landscape scale and only in 36% of the relationships at the local level (Fig. 4a).

Translation of pest control metrics into economics outcomes

A relatively small number of relationships (n = 16) examined the link between pest control metrics and economic outcomes (Table 1). Among these, only one study (Duflot et al. 2015) found that increased natural enemy abundance led to higher harvested yields. As

Table 1 Number of models and corresponding directional effects (represented by colors) assessing the influence of pollination or pest control on productivity. Green squares denote positive relationships, red squares indicate negative relationships, and grey squares represent no evidence of a relationship

Ecosystem service	Metric category	Metric name	Effect on productivity								
			Harvested yield			Yield quality			Marketable yield		
Pollination	Direct	Seed set			⬜ 1				🟩 1		
		Pollinated achenes							🟩 1		
		Fruit set			⬜ 1						
	Indirect	Open pollination	🟩 9		⬜ 2	🟩 11		⬜ 5			
		Pollinator abundance	🟩 5	🟥 1	⬜ 2	🟩 1	🟥 1	⬜ 4			
		Visitation rate	🟩 2			🟩 5	🟥 2	⬜ 7			
		Ricness of pollinators	🟩 1		⬜ 1						
Pest control	Pest predation	Natural enemy abundance	🟩 1	🟥 1							
		Pest predation						⬜ 2			
		Richness of natural enemies		🟥 1				⬜ 2			
	Pest pressure	Crop damage		🟥 1						🟥 2	
		Pest abundance		🟥 1			🟥 3	⬜ 1		🟥 1	

The numerical values within the squares reflect the total number of relationships evaluated

anticipated, variables indicating pest pressure were associated with reduced productivity in 90% of the relationships. In contrast, when assessed, variables related to pest predation showed no significant associations with economic outcome metrics (Table 1).

SNHs benefits directly linked with productivity

Only 16% (n = 56) of the 335 relationships assessed the effect of reallocating land to SNHs on productivity and economic outcomes, without using ecosystem services or biodiversity enhancements as intermediate proxies (Fig. 5). Productivity was mainly measured in terms of harvested yield or yield quality, with limited consideration given to other productivity measures (Table S2). Fields adjacent to SNHs showed increased harvested yields in 62% of cases while an increase of SNHs at the landscape level benefited productivity outcomes only in 26% of the cases (Fig. 5). Only two studies included in this review have quantified the direct economic benefits of SNHs. Blaauw & Isaacs (2014), examining wildflower strips, reported cumulative profits of up to $10,000 for a 4-hectare blueberry field located near a 0.8-hectare wildflower planting. In the case of hedgerows, Boinot et al. (2024) observed increased profit

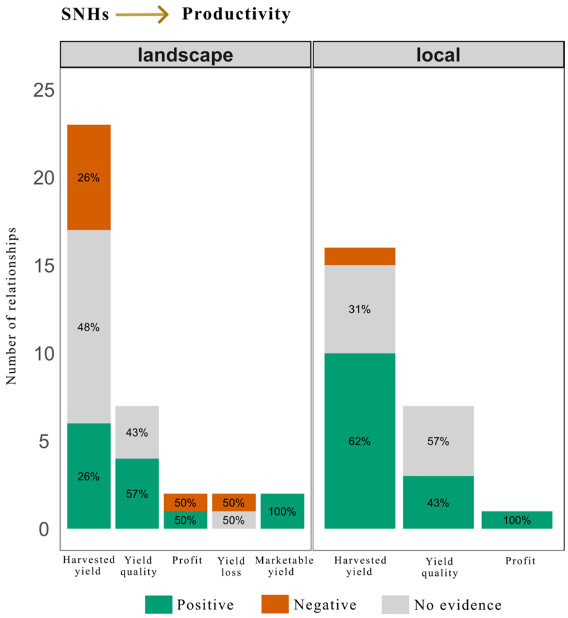

Fig. 5 Number of relationships (as percentages) between SNHs at the local or landscape scale and productivity. Green bars indicate a simultaneous increase in both variables. Red bars represent a decrease in the response variable as a result of an increase in the explanatory variable. Grey bars represent relationships that were tested but no significant relationship was found. Percentages lower than 20% are not depicted

margins—specifically, an additional €79 per hectare—in winter cereal fields with longer hedgerow lengths. Finally, McCullough et al. (2022) found that marketable yields of winter squash and strawberry consistently increased on farms with higher SNH cover, despite variation in pest control and pollination services across crops.

Discussion

SNHs are critical components of agricultural landscapes, as they support biodiversity, including organisms that contribute significantly to the delivery of ecosystem services. Nevertheless, assessments of their economic impacts remain limited and inconsistent. Our findings indicate that SNHs consistently enhance the biodiversity of beneficial organisms involved in pollination and pest control, in line with previous studies (Estrada-Carmona et al. 2022; Mohamed et al. 2024; Priyadarshana et al. 2024). However, the extent to which these ecosystem services translate into measurable productivity gains—and thus economic benefits—varies considerably across studies. On one hand, the positive effects of SNHs on crop productivity via enhanced pollination are well-documented, with several studies reporting clear benefits (Dainese et al. 2019; Aguilera et al. 2020; Eeraerts et al. 2021). On the other hand, evidence supporting a positive relationship between pest control and productivity remains relatively scarce (Albrecht et al. 2020; Boldorini et al. 2024). Moreover, the specific contributions of individual SNH types or their diversity to productivity outcomes are not well understood (Holland et al. 2016; Herzon et al. 2021). Most existing research tends to focus on aggregated effects at the landscape level or on SNH elements supported by agricultural policy—such as hedgerows (Montgomery et al. 2020; Staley et al. 2023) and flower strips (Blaauw & Isaacs 2014; Delphia et al. 2019; Albrecht et al. 2020; McCullough et al. 2022)—leaving substantial knowledge gaps regarding the productivity impacts of other, less-studied SNH types that are not currently supported by policy measures.

The effects of SNHs on productivity are often evaluated based on their contributions to the support of beneficial organisms, with relatively few studies translating this effect on the economic implications of restoring land with SNHs. The benefits of SNHs for pollination were more often linked to productivity gains. Nevertheless, uncertainty persists, as many studies (c.a 40%) report negative or non-significant results. Although the benefits of SNHs for pest control are evident, few studies have specifically examined the link between pest control and productivity. When this relationship was analysed, most of the studies reported contrasting or inconclusive results, aligning with previous findings that suggest the economic potential of SNHs for biological pest control may be limited in certain contexts (Griffiths et al. 2008; Tscharntke et al. 2016; Karp et al. 2018; Zamorano et al. 2020). The benefits of SNHs for productivity remain uncertain due to an incomplete understanding of the relationships between biodiversity, ecosystem service provision, and farm productivity, particularly regarding how the abundance, diversity, and identity of beneficial arthropods predict pollination or pest control service provision (Herzon et al. 2021). The mechanisms underlying these relationships are complex. Generally, high diversity among beneficial organisms may enhance pest control or pollination through facilitative interactions but could also lead to competition, reducing service provision (Greenleaf & Kremen 2006). Additionally, when ecosystem services are primarily driven by dominant species (e.g., honeybees or classical biological control agents), biodiversity itself may have limited influence on service supply (Straub & Snyder 2006; Kleijn et al. 2015). Identifying combinations of SNHs that simultaneously support both pollination and pest control may be challenging due to the different ecological mechanisms underlying these services. For instance, mutualistic interactions such as pollination generally have a positive impact on plants, whereas predation-based pest control often involves omnivory, which can sometimes result in direct damage to crops or grains (Kremen 2005; Kremen et al. 2007). Additionally, intraguild predation may weaken top-down control by natural enemies, further complicating the balance between these ecosystem services (Tscharntke et al. 2016). Given the complexity of these interactions, additional studies that address the synergies and tradeoffs of pest control and pollination services are necessary (see Classen et al. 2014; Martínez-Salinas et al. 2022; Merle et al. 2022 Hohlenwerger et al. 2024).

The scale at which studies were conducted influenced the outcome. Studies examining SNHs at the landscape scale were more common and often demonstrated positive, but also contrasting, effects. These findings align with previous studies that show both positive (Dainese et al. 2019) and inconsistent (Karp et al. 2018) impacts of landscape composition on yields. However, aggregating diverse SNH covers into a single land-cover category can obscure the ecological responses of specific taxa to specific landscape structures (Duflot et al. 2015), contributing to inconsistent links between pollination or pest control metrics and productivity. SNHs supported by agricultural policies are typically established along field margins, such as flower strips or hedgerows. However, our results do not support the hypothesis that the productivity gains of SNHs through ecosystem service provision—specifically pollination and pest control—are stronger at the local scale when these elements are located adjacent to crop fields. In contrast, direct effects (i.e., from studies that assessed the influence of SNHs on productivity without explicitly considering ecosystem services such as pollination or pest control as mediating mechanisms) were more frequently positive at the local scale. This suggests that other beneficial mechanisms, beyond pollination and pest control, may play an important role in mediating the positive effects of SNHs on crop productivity. Additionally, as study outcomes are often aggregated at the landscape or field level, relatively few investigations explicitly link their findings to specific farms. This gap complicates the translation of research evidence into targeted policy recommendations (Isbell et al. 2017) and undermines efforts to translate findings into actionable policies, as interventions may require cooperation among neighboring farmers or fail to account for variations in farm size, field shape or field area (Batáry et al. 2011). Overall, considerable uncertainty remains regarding the relationship between SNHs and agricultural productivity. While a few studies have reported productivity gains (d'Albertas et al. 2024), many have found non-significant effects, and there is a notable lack of ecological research that accounts for the implementation costs of SNHs within farmland systems.

Yield changes in terms of harvested production or yield quality, were the most frequently utilized metric or proxy for productivity in our review. However, increases or decreases in yield do not necessarily correspond to higher or lower profits, as profitability is also influenced by variations in input costs and market prices (Debertin 2012). From a strictly economic standpoint, productivity is defined as the ratio of output to inputs, with land representing only one of several contributing factors, including labor, capital, water, nutrients, and pesticides, among others (Debertin 2012). Accordingly, to accurately refer to land productivity, all other inputs should be held constant (Debertin 2012). However, ecological studies may employ the term productivity more flexibly than economists, and only in rare cases biodiversity enhancements have been considered as an agricultural input (see Garratt et al. 2018). In the context of our review, referring simply to "productivity" is appropriate, as the yield metrics found in our analysis encompass various dimensions, including crop productivity, agricultural productivity and land productivity, the latter of which accounts for different crop types. A lack of studies addressing concrete economic outcomes may stem from data privacy concerns, as farmers are often reluctant to share yield data due to uncertainty about who will access their data and how it will be used or monetized, or simply because farm-level economic data is protected by governments (Zhang et al. 2021; Sullivan et al. 2024). Furthermore, the multidisciplinary nature of studying both ecological and economic implications within a single study can make it challenging for researchers to effectively integrate these perspectives, potentially hindering the development of a balanced approach that maintains conceptual clarity (Gurr et al. 2016).

Additional factors such as pesticide use and crop or cultivar identity are critical determinants of productivity outcomes (Ricci et al., 2019; Tscharntke et al., 2024). However, in our review, fewer than 10% of the studies examined the effects of SNHs in organic or diversified farming systems. Although previous studies have investigated the relationship between SNHs and yield stability (see Redhead et al. 2020), these typically relied on satellite-derived land cover maps as proxies for ecosystem service supply, rather than experimental field data. Our review specifically focused on studies that directly collected field-based data on pollination and pest control indicators. Among these, only a few studies collected data over multiple years, limiting the ability to assess the role of SNHs in stabilizing yields over time (Blaauw & Isaacs 2014; Garibaldi et al., 2014). This static approach may fail to account for long-term effects such as the contribution of SNHs to yield stability by enhancing soil structure, reducing erosion, and mitigating the impacts of extreme weather events. Finally, the economic value of SNHs can also be linked to the access they provide to alternative financial incentives, such as carbon sequestration credits (Jones et al. 2024), payments under agri-environmental schemes (Batáry et al. 2015) and other sources such as market-based instruments for biodiversity conservation (Bücheler et al. 2024; Streit et al. 2025). However, these aspects have received limited attention, as have the technological implications associated with the establishment of SNHs. Such implications include potential reductions in machinery efficiency (e.g., increased turning space requirements for tractors) and greater farmland fragmentation, which can lead to increased travel time and higher overall production costs. Overall, we observed positive effects of SNHs and ecosystem services on productivity; however, further investigation is required to determine the dominant economic mechanisms driving these effects. Specifically, it remains unclear whether our findings are primarily attributable to short-term yield reductions due to a decrease in cultivated area or to long-term yield stability. While we recognise that a quantitative analysis would have provided a more systematic and potentially rigorous synthesis, the wide variation in measures and methodological approaches across the studies prevented a direct quantitative comparison. Therefore, we adopted a qualitative approach to emphasise, first, the limited number of studies that collect data on economic impacts, and second, how the choice of scale and metrics can influence the results.

Conclusions

This review demonstrates that SNHs can enhance pollination and pest control at local and landscape scales. However, their direct translation into economic benefits and ecosystem service provision remains unclear. Our findings underscore critical knowledge gaps in the economic evaluation of SNHs and the disconnection between study scales and practical agricultural policy applications. More interdisciplinary studies incorporating an ecological and economic perspective to inform policies that balance productivity and biodiversity conservation are needed. Future research should prioritize quantitative meta-analysis of farmer-relevant productivity measures, such as marketable yields or profit, and evaluate ecological-economic trade-offs at farm and regional scales relevant for policy makers and farmers.

Author contributions V.A.S, A.C.M, I.G, A.F, and A.G.C. contributed to the conceptualization and design of the study. Data collection, and analysis were performed by V.A.S. V.A.S. wrote the first draft of the manuscript. All authors commented on previous manuscript versions, contributed critically to the drafts, and gave final approval for publication.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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