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Improving ecosystem services through applied agroecology on German farms: costs and benefits

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Abstract

Under the EU's new "Farm to Fork" strategy, crop production systems should rapidly become more environmentally friendly. In particular, by adopting agroecological measures that support functional biodiversity and improve ecosystem services for crop production, this paper contributes to the ongoing efforts in characterizing the socio-economic effects that the upscaling of these measures entails, by looking into two key measures: flower strips and mulching. One important socio-economic aspect of their adoption is their potential impact on agricultural income; however, knowledge on costs and benefits of measures enhancing functional biodiversity at the farm level is still limited. In order to improve these shortcomings our approach makes use of data from field experiments completed with interviews to provide cost–benefit results for flower strips and organic mulching. The estimations show that for "flower strips," on average costs could be covered by compensation payments. Regarding the in-crop measure "organic mulching," the benefits potentially outweigh the costs under the frame conditions of organic agriculture. The analysis also highlights some obstacles and knowledge gaps in the estimation of benefits, especially for off-crop measures like flower strips.

Keywords: Flower strips, Functional biodiversity, Organic mulching, Socio-economics, Sustainable farming systems, Agri-environment schemes, Pollination, Natural pest regulation

Introduction

European agriculture faces the major challenges of biodiversity loss, climate change, and the need for transition to (more) sustainability. This need for change has been recognized by the European Commission and addressed in the Farm to Fork Strategy (Directorate-General for Health and Food Safety 2020) and the Biodiversity Strategy (Directorate-General for Environment 2021). The ambitious goals for more sustainable agriculture and reversing biodiversity loss include the reduction of chemical pesticide

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use by 50% and the use of fertilizers by 20% as well as an increase of organic farming to 25% (Directorate-General for Health and Food Safety 2020).

This is in line with the wider concept of agro-ecology, the use of functional biodiversity, i.e. the positive effects resulting from spatial and temporal combinations of the components of agroecosystem biodiversity (pollinators, predators and parasites, herbivores, non-crop vegetation, soil life) (Altieri 1999). Crop production systems need to be adapted according to these requirements by integrating appropriate agricultural measures and strategies. In particular, focus should be on those measures and strategies that improve regulatory ecosystem services such as pollination, or pest control, and thus support crop production at the same time (Dainese et al. 2019; Dollacker et al. 2021; Tschumi et al. 2016a).

Measures that enhance ecosystem services can be divided into "off-crop" and "in-crop" measures. Off-crop measures include the enhancement and combinations of structural elements (e.g. flower strips, field margins, and hedgerows) within the agricultural landscape. They aim at creating habitat for beneficials such as pollinators or natural enemies of pests resulting in biodiversity conservation, improved pollination, and pest control. This can lead to a reduction in pesticide use and protection against surface water contamination as well as reduction of soil erosion by wind or water (Marshall 2005; Wezel et al. 2014). In-crop measures or crop management practices address specific cultivation methods (e.g. no-tillage), fertilization, irrigation, and weed, pest and disease management practices (e.g. organic mulching, drip irrigation), as well as increasing the diversity of species and varieties of crops (e.g. cultivar mixture, companion cropping). They aim at increased efficiency of agronomic inputs (water, pesticides, and fertilizers) and improved crop productivity (Wezel et al. 2014).

Despite the increase in agro-ecological research, its adoption by European farmers is still limited and high input agriculture remains as the dominant agricultural system (Casagrande et al. 2017; González-Chang et al. 2020). The reasons for this are manifold, ranging from policies and regulations that have so far favored mono-cropping systems, to farm-specific endowments of capital, machinery, and labor force (Casagrande et al. 2017).

The relevance to assess and quantify costs and benefits of ecosystem services has been often pronounced to communicate the importance of biodiversity conservation (Atkinson et al. 2018). However, in a review on the cost-effectiveness of agri-environment schemes (AES), Ansell et al. (2016) found that less than half of the reviewed studies made any reference to the costs and fewer than 15% included any measure of cost-effectiveness. One reason for this is the difficulty to evaluate biodiversity with quantitative indicators, in general, and in particular in economic terms (Bartkowski et al. 2015). In their review on semi-natural habitats and pest control, Holland et al. (2017) concluded that only a small share of studies examined yields, although the impact on pests and yields was regarded as the most compelling evidence for farmers and needed for wider adoption of semi-natural habitats.

The systematic evaluation of the socio-economic impacts of agroecological strategies is a key element to convey the value of ecosystem services and support their implementation, but it is also indispensable to provide economic reasoning to farm-level decision-makers who have to opt in or out of measures. However, knowledge on their costs and benefits, as well as perception of obstacles, is still very limited. Therefore our aim is to shed light on the costs and benefits of agro-ecological measures enhancing ecosystem services.

We base our analysis on two exemplary options, the off-crop measure "flower strips" and the in-crop measure "organic mulching," because these practices can be implemented both individually (compared to more complex measures such as changing crop rotations) at the field level as well as systemically at the farm and landscape levels. In Germany, flower strips receive funding through AES, whereas organic mulching is not part of an AES or other greening subsidies.

Flower strips have become a common measure within agri-environmental schemes in Europe to improve functional biodiversity (Haaland et al. 2011). For implementation, flowering seed mixes are planted or sown on a strip of agricultural land. Flower strips can be planted just for one year, but under most AES longer periods up to five years are compulsory. Seed mixes are composed of wild and/or cultivated plants. In some cases, it is also possible to plant them on irregular field edges or in field corners (Budde-von Beust et al. 2019; MLUK 2020a). Costs of flower strips consist of labor and machinery costs for installation, (wild)flower seeds, and the opportunity costs for the crop area that is planted with the strip. Perennial strips usually need additional management steps such as mowing (Mayer et al. 2009; Pfiffner et al. 2018).

Organic mulching, also called transfer mulching, is a measure familiar to organic vegetable producers, but not yet well-established in organic agriculture (Jacob et al. 2022). Organic material, such as straw or cut clover-grass, is spread under and between the main crops, e.g. potato. In the case of clover-grass and other fresh plant materials, this is done by the "cut and carry" method, where the cut plant material is promptly transferred to a receiving area. Particularly organic farms without livestock use mulching to recycle nutrients of aboveground biomass in their crop rotation (Junge et al. 2020) to improve soil fertility (Jacob et al. 2022), enhance water use efficiency of the crops (Li et al. 2018), and suppress weeds (Teasdale and Mohler 2000).

This paper contributes to socio-economic evaluations of agroecological measures. Our approach (1) identifies and systemizes the expected positive and negative effects of measures enhancing functional biodiversity, (2) makes use of a variety of data sources including field experiments considering crop yields and perceptions, and (3) provides cost–benefit results for flower strips and organic mulching. Moreover, we aim to address where socio-economic costs and benefits arise regarding farm and society level. Finally, we describe obstacles of the socio-economic evaluation of enhancing biodiversity as well as knowledge and data gaps and ways to address them.

Materials and methods

Costs and benefits

We conducted a cost–benefit analysis (CBA) for the selected measures at farm level. This allows a systematic evaluation and comparison of the different measures. In a CBA, costs and benefits can only be estimated in comparison with a defined reference system or baseline scenario. In our case, the baseline scenario means that no specific biodiversity enhancement measures are taken.

To estimate the costs and benefits, the changes and impacts that are likely to occur as a result of the introduction of the measures were identified and systemized based on evaluated literature. By costs we mean negative (monetary) effects associated with the introduction of practices, mainly input costs for the implementation and/or maintenance of the measures (labor, capital, machinery, material), opportunity costs, and transaction costs. Opportunity costs describe the loss of value or benefit from using resources (e.g. land, money, labor) in a particular way compared to an alternative that provides greater value or benefit. When implementing a flower strip, opportunity costs are the loss of the contribution margin of a crop that could be planted instead on a specific area.

To determine costs for inputs, labor, and machinery, we used data and tools provided by the Kuratorium für Technik und Bauwesen in der Landwirtschaft, KTBL (Achilles et al. 2020; KTBL 2022b), such as KTBL field work calculator (KTBL 2022a) and KTBL contribution margin database (KTBL 2024).

Transaction costs occur as search costs, application for funding, and further administration costs such as for monitoring and documentation (Mettepenningen et al. 2009; Uthes and Matzdorf 2013). We have calculated transaction costs, such as obtaining information on funding programs and regulations of flower strips or for the acquisition of suitable mulch material, here in simplified terms as one working hour set at the hourly wage for qualified employees (21 €/h) (KTBL 2022b).

By benefits, we generally mean the positive effects of biodiversity measures, whether monetary and non-monetary. We also consider subsidy payments in case of agri-environmental measures (AEM) as a proxy to express benefits in monetary terms. The data for quantifying costs and benefits were derived from a broad range of sources (see next section).

As a measure for the outcome of the cost–benefit comparison, the Net Benefit was calculated by subtraction of calculated costs from the estimated monetary benefits.

Assessment of costs and benefits of flower strips

Due to the general lack of economic data from field trials with flower strips, we decided to use exemplary and secondary data for calculating the implementation of flower strips at farm scale. We contacted farmers using perennial flower strips in the German Federal states Brandenburg and Saxony, who provided us with actual data on costs of seeds, labor, and machinery for the installation of flower strips on their conventional farms. Data were collected during one on-farm visit and face-to-face interview, two telephone interviews, and additional open questions were verified via e-mail. Data for an annual flower strip in Lower Saxony as well as cost data under organic farming conditions were provided by project partner Kompetenzzentrum Ökolandbau Niedersachsen (KÖN).

The four different flower strips implemented in three different regions in Germany represent annual and perennial, organic and non-organic, high and low yielding locations and crops. They are situated in different German Federal states with differing frame conditions and AEM premiums.

To show the range of foregone yield due to the strip, we calculated the opportunity costs for different crops (wheat and rye) either as provided by farmers or with data from the KTBL contribution margin database (KTBL 2024). The KTBL contribution margin database provides average contribution margins for different crops per year and region in Germany. We averaged values from 2017 to 2020. Input costs of different seed mixtures, labor and machinery costs for soil cultivation, seeding, and further work steps were included as provided by farmers. These anecdotal data are discussed in comparison with data from the evaluated literature.

We used the AEM premium as a proxy for monetary benefits, because it represents a benefit of adoption from the farmer's point of view and is the value that society is currently willing to pay for its services. The amount of the AEM premium may vary depending on the German Federal State's incentive program (Budde-von Beust et al. 2019; Kompetenzzentrum Ökolandbau Niedersachsen 2019; MLUK 2020b; SMUL 2021).

Assessment of costs and benefits of organic mulching

In the field trials on organic mulching, the focus was particularly on the benefits regarding functional biodiversity (plant protection) and biodiversity enhancement. In addition, yields were recorded. Organic mulching of potatoes was tested in farm scale field experiments on the organic farm *Biolandhof Reulein & Schöne GbR* in Ellershausen, Bad Sooden-Allendorf about 30 km east of Kassel in 2021 (a) and the organic farm *Naturhof Stieg* in Reiffenhausen, Friedland about 15 km south of Göttingen in 2021 (b) and 2022. All trials were set up as Randomized Block Design with four (2021a and 2022) and three (2021b) blocks, respectively. The organic mulch materials (straw, triticale/vetch, grass-silage), which were selected in pre-trials as the most favorable in terms of availability and effectiveness, were applied with a manure spreader. The time of application varied from year to year but was always at or shortly before emergence of potato plants. Weeds were controlled three times (2021) and twice (2022) before mulch application and once after mulch application in the untreated control (for details see Online Appendix Table S1). For the yield assessment, four 3 m row sections, randomly distributed over each plot, except for a 3 m wide edge, were harvested, resulting in an area of 9 m^2. Product prices of potato yields were calculated at an average price of 600 €/t for organic potatoes (Achilles et al. 2020). Data on work processes and mulch material were derived directly from the trials. For the cost of mulch, we used the purchase price of bedding-straw (100 €/t) or the price of rye-vetch green fodder (33 €/t) (Achilles et al. 2020).

In our field trials, the mulch was applied with a small manure spreader, which required a lot of labor time. Since no data on labor and machinery costs were available from the field trials, we used the KTBL field work calculator for straw application with manure spreader for small application rates (KTBL 2023) and the KTBL field work calculator for application of wilted clover-grass with manure spreader (KTBL 2023), respectively.

Additional data on labor and machinery costs for weed management were determined according to the Kuratorium für Technik und Bauwesen in der Landwirtschaft, KTBL (Achilles et al. 2020; KTBL 2022a, 2022b, 2024). The fertilizing effects depend on the material and the quantities applied: For straw, no fertilizing effect was assumed. For calculating the fertilizing effect of triticale-vetch mulch, we used the average nutrient content of legume-intercrop mixture (kg per t wet weight): 4.6 kg N, 1.4 kg P, 5 kg K (LfL 2022) multiplied by pure nutrient prices in organic agriculture for 2021 and 2022 taken from price lists of the Bayerische Landesanstalt für Landwirtschaft, LfL (LfL 2023). Only 35% of the nitrogen contained were attributed to the fertilization effect, since only a variable proportion of the nitrogen is made available to the plants through mineralization in the year of utilization (Möller and Schultheiß 2014; Sradnick and Feller 2020). This reduction was also applied to the nutrients P and K, as data on their availability in the first year were lacking.

Perception of measures among target user group

In addition to the economic analysis, we collected data on the implementation of measures and the perception of incentives and obstacles by farmers on different occasions.

A survey was conducted among farmers who participated in a nationwide online information session on organic mulching in arable farming on February 22, 2023, organized by two of the authors. This survey focused on the implementation and perceived benefits and barriers of organic mulching, but also asked about the use of other agroecological measures. In total, around 100 individuals from all over Germany took part in the event, but only participants, who previously stated that they were farmers, were taken into account in the survey. The survey took place in the second half of the event, when participants had already gained some insights in the practice of organic mulching. First, general questions were asked on the adoption of agroecological measures. Then we asked questions on the advantages and obstacles of organic mulching, providing five predefined answer options and one subsequent open question (see results section for answer options). Multiple answers were possible.

Another event was an on-site workshop with seven organic farmers in Lower Saxony on February 10, 2023, where some feedback was obtained on perceptions of agro-ecological measures, including organic mulching and flower strips. Interactive surveys were conducted during the workshop and notes were taken on the discussions.

The interviews with two farmers on flower strips in Saxony and Brandenburg also asked about the advantages and disadvantages of flower strips.

Results and discussion

Costs and benefits of flower strips

Monetary

Planting flower strips incurs costs for the seed, labor, and machinery costs for seeding and later for maintaining the strip, transaction costs, and opportunity costs for foregone yields. In Table 1, we present the costs and benefits of four different flower strips in Germany. They are based on three different perennial seed mixtures applied on farms in Brandenburg and Saxony, and one annual strip on an organic farm in Lower Saxony.

Our results in Table 1 and Fig. 1 show that seed mixes account for a large part of the costs of flower strips, because in many German Federal States such as Brandenburg it is mandatory to use approved seed mixtures, which are rather costly. Filling material is required when the seeding machine is not suitable for very small wildflower seeds. Another option is to repeatedly mix the segregated seed by hand, but this prolongs the sowing process.

The second major cost factor is opportunity costs of the production area that is used for the flower strip. Crops with high contribution margins such as wheat cause high opportunity costs, opposed to low profit crops such as rye. Labor and machinery costs for tillage and seeding, as well as for strip maintenance or turn-over, account for a

Table 1 Calculation of costs for different exemplary flower strips in Germany

Permanence	Strip 1		Strip 2		Strip 3		Strip 4	
	Perennial		**Perennial**		**Perennial**		**Annual**	
Location	Brandenburg, low to medium yielding area		Brandenburg, low to medium yielding area		Saxony, low yielding area		Lower Saxony, medium to high yielding area	
Production system	Non-organic		Non-organic		Non-organic		Organic	
Transaction costs	21€ in year 1		21€ in year 1		21 € in year 1		21 €	
Seed	283 €/ha		243 €/ha		410 €/ha		141 €/ha	
Preparation and Seeding	129 €/ha		98 €/ha		155 €/ha		174 €/ha	
Maintenance or removal	25 €/ha		45 €/ha		35 €/ha from year 2		56 €/ha for removal	
Opportunity costs (€/ha)	Wheat	Rye	Wheat	Rye	Wheat	Rye	Wheat	Rye
Wheat	530		530		328		723	
Rye		174		174		200		300
Sum of costs Year 1	988	632	937	581	914	786	1115	692
Sum of costs Year 2 and following	555	199	575	219	363	235	1094	671
AEM premium (benefit)	700 €/ha		700 €/ha		909 €/ha		700 €/ha	
Net Cost – Benefit Year 1	*− 288*	**68**	*− 237*	**119**	*− 5*	**123**	*− 415*	**8**
Net Cost – Benefit Year 2	**145**	**501**	**125**	**481**	**546**	**674**	*− 394*	**29**

Bold numbers denote a positive benefit - cost difference

For additional information and sources, see Online Appendix Table S2

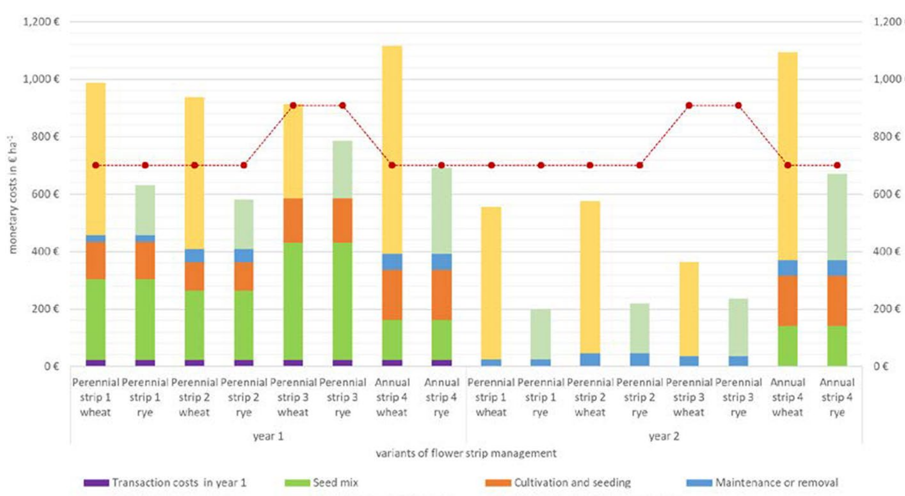

Fig. 1 Calculation of costs of flower strips for Brandenburg, Saxony and Lower Saxony with different variants: All strips differ regarding seed mix, seedbed preparation and costs for mowing/mulching (see Table 1 and Online Appendix Table S2). Strip 4 is an annual flower strip in organic agriculture. Variants are given for high (wheat) and low (rye) opportunity costs and for the installation year 1 in comparison with year 2. The dashed line marks the threshold at which the current agri-environmental measures (AEM) payments by the German Federal states cover the costs of flower strips

comparatively smaller share of the total costs, but must be considered with respect to peak workloads and the machinery available on the farm.

From Fig. 1, it can be seen that all strips have relatively high costs in the year of planting, but perennial strips are less costly and labor intensive from the second year, while annual strips have almost the same costs.

To estimate the monetary value for the benefit, we used in our calculation the compensation payments that farmers receive depending on the AEM program of the respective Federal State. In our examples, the compensatory payments for flower strips were able to cover the costs for the low-profit crop rye in all cases and for the perennial strip from the second year onwards also for higher profit wheat. Annual strips on organic high-yield sites in Lower Saxony did not cover costs.

In summary, major costs arise for the establishment of flower strips, in particular in the first year. Opportunity costs are the second major cost factor. For the case of Germany, compensation payments could cover these costs, especially when the strips were located on low-yield sites. Additional or indirect benefits of biodiversity enhancement were not measured and could not be calculated in monetary terms. They are discussed in the next section.

Non-Monetary

While most of the costs accruing from off-crop measures such as flower strips clearly occur at farm level, a large share of the benefits are more easily observed at the societal level or landscape level than at the farm level. Examples of the societal benefits are the pleasing aesthetic qualities of flower strips and the services they offer in terms of habitats and biotope connectivity (Buhk et al. 2018; Fuchs and Stein-Bachinger 2008; Kremen and Merenlender 2018). This is not the case at farm level where the economic benefits from ecosystem services that these measures provide are more difficult to unequivocally demonstrate (Garbach and Long 2017; Kleijn et al. 2019).

The services of flower strips that are usually assigned to the societal level will also be provided at farm level. These may be either reduced risks of water stress, floods and soil erosion from water retention services, or better opportunities for (eco) tourism businesses due to the aesthetic benefits and improved image, which along with the benefits of biodiversity conservation can strengthen the local economies in many ways. According to Dollacker et al. (2021), the value of flower strips varies by region and is higher in a densely populated region than in a remote, simplified agricultural region. So far, monetary values of these benefits are hardly available (Albrecht et al. 2020; Blaauw and Isaacs 2015; Pfiffner et al. 2018; Tschumi et al. 2016a) and they can mostly only be taken into account in qualitative terms. In the following we try to disentangle this complex question.

Literature shows that improved pollination and pest control can be expected from the adoption of flower strips (Herbertsson et al. 2018; Marshall and Moonen 2002; Tschumi et al. 2016b; Wezel et al. 2014). Of all the services provided by flower strips mentioned above, pollination and pest control series are perhaps the easiest to measure; nevertheless, the respective calculations are not without some challenges, which we address next.

Pollination services from flower strips

Flower strips can harbor pollinator insects for a number of flowering crops, such as oilseed rape. The quantification of pollination services aims to show which proportion of the yield can be attributed to pollination generated by the flower strip (see Winfree et al. 2011 for an account of different valuation methods). If that proportion is known, the estimation of benefits from pollination services can be described by the increase in yield and monetized by the market value of the crop. For example, Woodcock et al. (2016) report yield increases of 0.4 t/ha in oilseed rape due to insect pollinators and Pywell et al. (2015) discovered that field bean yields increase in the vicinity of wildlife friendly habitats. In their discussion of the valuation of pollination services, Melathopoulos et al. (2015) reveal that intensive oilseed crops are the most problematic in these estimates. Perrot et al. (2018) found certain values of pollinator diversity to increase oilseed rape yield such as increasing the number of bee genera, which was associated with an increase in yield of about 1 t/ha or 37.5%. However, Ouvrard and Jacquemart (2019) also pointed out that there are opposing reports from studies with winter oilseed rape varieties where no yield effect of insect pollination could be confirmed.

Enhanced pest control services but not yields

The economic benefit of pest control services is usually perceived in terms of less pest damage, changes in yield or savings in the use of plant protection measures such as pesticide application. In our analysis, we were not able to quantify or monetize these benefits for the flower strips. For this purpose, a direct comparison of a crop with and without neighboring flower strips would be needed to estimate for both (a) the crop damage and maybe yield loss by pest species, (b) the abundance of predators/beneficial organisms, (c) the necessity of plant protection measures to cope with pests and their associated costs. Such a comparison requires similar or even equal conditions since pest occurrence and the need for control vary greatly across growing seasons, regions, and countries (Menzler-Hokkanen 2006) due to climatic and edaphic variations and evolving landscape context. Moreover, Penvern et al. (2019) suggest self-monitoring methods to assess functional biodiversity with relevant indicators (or biodiversity-related parameters) adapted to farmers and farming conditions to further enhance the ability of growers to evaluate these practices on their own, to evaluate impacts and adjust practices.

Regarding pest management services, the success rates of flower strips will heavily depend on adequate selection of seed mixes (Uyttenbroeck et al. 2015; Woodcock et al. 2016). The species composition of the seed mix, as well as the life stage of the flower strips (their resources are not constant throughout the years), leads to high variations of possible effects. Positive examples include a study by Pfister et al. (2017) who found that a greater flower abundance on the field edges of pumpkin fields significantly increased the density of natural enemies and tended to reduce aphid densities.

In their global synthesis on the effectiveness of flower strips and hedges on pest control, pollination services, and crop yield, Albrecht et al. (2020) reported that flower strips enhanced pest control services in crop fields adjacent to flower strips by 16% on average, compared to fields without flower strips. Pest control services were quantified as pest parasitism or crop damage. However, within their meta-analysis they did not detect significant effects of flower strips on crop yields. Nonetheless, Pywell et al. (2015) discovered that yields were maintained despite the loss of arable land for flower strips.

The difficulties in estimating benefits of flower strips are not the same for all crops. For fruit orchards, the benefits seem to be easier to estimate. Albrecht et al. 2020; Blaauw and Isaacs 2015; Christmann et al. 2017; Pfiffner et al. 2018; and Walton and Isaacs 2011 reported that the costs of perennial flower strips could be recouped through higher yields, fewer insecticide treatments, and/or improved pollination, and there were no opportunity costs associated with set aside (Albrecht et al. 2020; Blaauw and Isaacs 2015; Christmann et al. 2017; Pfiffner et al. 2018; Walton and Isaacs 2011).

Besides habitat conservation, flower strips can be used as buffer strips against pesticide drift or erosion with impacts on water protection and environmental health aspects (Haddaway et al. 2018; Marshall and Moonen 2002; Wezel et al. 2014). They can provide hunting lanes (BMEL 2020) and contribute to the improvement of landscape aesthetics for recreation (Hauck et al. 2014; Reich and Rode 2016; Syngenta, Arcadis, and Biodiversity International 2018) as well as of the public image of farmers and farming (Bockholt 2018; Degenbeck 2020; Deubert et al. 2017; Joormann and Schmidt 2017).

Implementation and perception of flower strips among users

Flower strips are a popular AEM practice in Germany. In 2018, farmers planted more than 117.000 ha of flower strips, i.e. one percent of the arable land (Deutscher Bauernverband e.V. (DBV) 17.05.2019).

Among the 57 farmers surveyed in the online information event, 41 (72%) had applied flower strips. In the on-site workshop with seven organic farmers, three farmers stated that they had planted flower strips. Others were not using them because of disadvantages such as problematic weeds and bureaucracy. When asked for the main reasons in favor of using agro-ecological measures (not specific flower strips), participants primarily listed the factors that increase soil fertility or facilitate their work such as organic matter buildup, nitrogen fixation, improved trafficability, or less workload. Image gain, subsidies, and biodiversity were also mentioned, but not prioritized. Regarding obstacles of implementing agro-ecological measures, participants drew on their own experiences with measures and named specific problems encountered. The monetary costs played a role in their evaluation, but were only one factor among others.

Cost and benefits of organic mulching

Monetary

The costs for mulching potatoes consist of costs for mulching material and for spreading the mulch and transaction costs (see Table 2). We found that implementation costs are lower for straw mulch (481–692 €/ha) than for triticale-vetch-mulch (1326–2245 €/ha).

Field trials on organic mulching focused on benefits regarding functional biodiversity (plant protection) and biodiversity enhancement, but yields were also recorded. Figure 2 shows potato yields of farm scale experiments in 2021 and 2022. They varied greatly between years, averaging up to 34.9 t ha^{-1} in the 2022 trial and only 21.79 t ha^{-1} (a) and 17.29 t ha^{-1} (b) in the 2021 trials. Yields were higher in all trials in the

Table 2 Cost example for transfer mulching in organic potato cropping in Hesse, Germany

Trial designation	Unit	Control	Straw mulch		Triticale-vetch transfer mulch ("cut and carry")		
		2021a 2021b 2022	2021a straw	2021b straw	2021 a triticale/ vetch	2021 b triticale/ vetch	2022 triticale/ vetch
Amount and costs for organic mulch material[a,b]	t/ha	0	4	6	35	60	50
	€/ha	0	400	600	1,155	1,980	1,650
Spreading of mulch material[c]	€/ha	0	60	71	150	244	205
Transaction costs	€	0	21	21	21	21	21
Sum of costs	€/ha	0	*481*	*692*	*1326*	*2245*	*1876*
Fertilizing effects, fertilizer saving[d]	€/ha	n.a	n. a	n.a	430	737	736
Savings weed control[e]	€/ha	n.a	50	50	50	50	50
Yield deviation from control[a]	t/ha	0	1.8	2.4	2.5	4.9	2.1
Yield deviation at market price[f]	€	0	1,080	1,440	1,500	2,940	1,260
Sum of benefits	€/ha	0	1,130	1,490	1,980	3,727	2,046
Benefit–cost difference	€/ha	0	**649**	**798**	**654**	**1,482**	**170**

Bold numbers denote a positive benefit - cost difference

Sources: (a) EcoStack project data from field trials in Germany, (b) Calculated for bedding-straw (100 €/t) or rye-vetch green fodder (33 €/t) (Achilles et al. 2020), (c) KTBL field work calculator (KTBL 2023), (d) Average of nutrient content of legume-intercrop mixture such as triticale-vetch (kg per t wet weight): 4.6 kg N, 1.4 kg P, 5 kg K (LfL 2022); calculated with pure nutrient prices in organic agriculture for 2021 and 2022 (LfL 2023). Only 35% of the nitrogen contained were attributed to the fertilization effect. This reduction was also applied to the nutrients P and K, (e) One operation of harrowing/ridging was saved compared to control (KTBL 2022a), (f) Average price of 600 €/t for organic potatoes (Achilles et al. 2020)

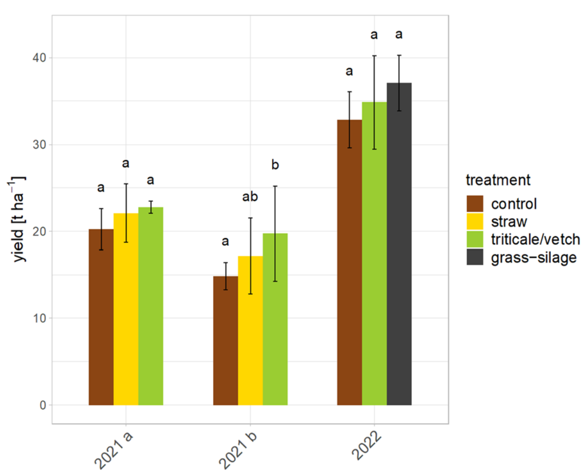

Fig. 2 Potato yields of on-farm field experiments 2021 and 2022. Treatment refers to the application of organic mulch material. Details of the experiments in Online Appendix Table S1. Values represent means ± standard deviation. Different letters indicate significant differences within one experiment ($p < 0.05$; linear mixed-effects model including the specific error structure; with 16 and 12 observations, respectively)

mulched treatments, although there was a significantly higher yield only in triticale/vetch mulch in trial 2021b compared to the control.

In Table 2 and Fig. 3, we present the costs and benefits for two different mulch materials and application rates, based on the farm scale experiments. The costs for

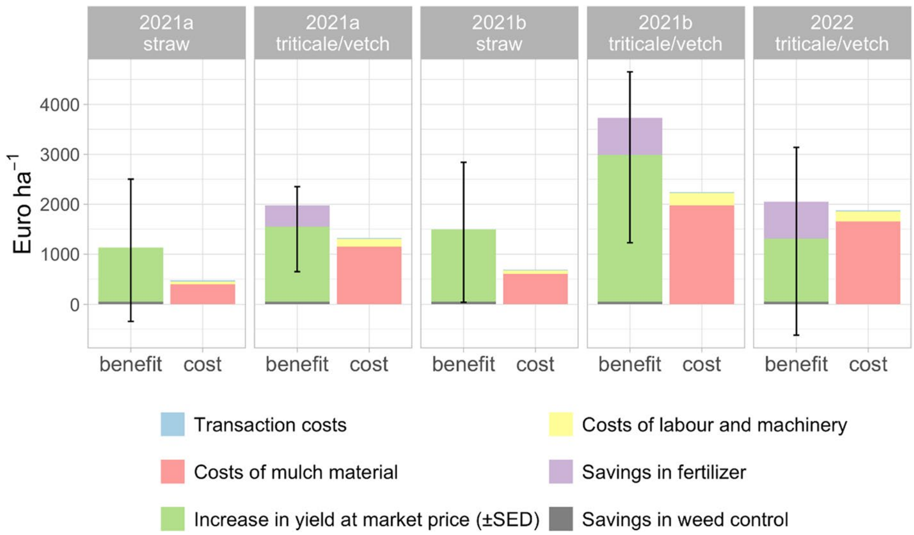

Fig. 3 Calculation of costs and benefits of organic mulching using results of farm scale experiments in Hesse, Germany. For details of the calculation and additional sources, see Table 2. The error bars refer to the yield deviation from control (standard error of the difference (SED) between means at market price)

the organic mulch material and the application of the material in the field depend on the quantities used.

The benefits include the fertilizing effect, the reduction of weed pressure and yield effects. The fertilizing effect of triticale-vetch mulch led to savings between 430 and 737 €/ha; for straw no effect was assumed. Regarding weeds, the use of all mulch materials was found to reduce weed pressure. On average one mechanical weed control measure, in this case harrowing (50 €/ha), could be saved. Finally yet importantly, higher yields were measured. Yield deviation from control was on average 2.7 t/ha higher, bringing an additional benefit of 1620 €/ha (calculated with an average selling price for organic potatoes).

The benefit–cost difference was positive in our calculations of the field trials, ranging from 170 to 1482 €/ha, averaging at 626 €/ha. However, depending on local soil and weather conditions, mulching and yield effects can lead to different cost–benefit ratios. In summary, we found that under organic farming conditions, the costs of organic mulching could be offset by the monetary benefits of the practice.

Non-monetary

The different yields between the two trial years, and the different effect of mulch on yield, may be strongly related to the amount of water available. Mulch has been shown to improve the water supply in many past trials (Kar and Kumar 2007; Li et al. 2018) by reducing the evaporation (Zribi et al. 2015) and lowering the soil temperature (Cook et al. 2006). The potatoes suffered less from drought, which was expressed, among other things, by earlier row closure and delayed senescence, which had an effect on yield (Millard and Mackerron 1986; Möller et al. 2007). During rain events, improved erosion control can be observed, compared to control fields without mulch (Döring et al. 2005). Also in our survey, farmers interested in organic mulching, including those already practicing organic mulching most frequently noted these benefits. This could be because these advantages can be very yield increasing and/or because they are relatively easy to see in the field.

Organic mulching in the field trials led to reduced aphid infestation and aphid-transferred virus diseases (data not published yet), resulting in improved plant health. These results correspond with earlier studies (Saucke and Döring 2004). Even higher benefits are possible in seed potato production, as lower aphid infestations make it easier to meet virus-level standards (Kirchner et al. 2014). Furthermore, mulching is able to reduce infestation with Colorado potato beetles (Junge et al. 2022; Winkler et al. 2024; Zehnder and Hough-Goldstein 1990) (Zehnder and Hough-Goldstein (1990); Junge et al. 2022 and to promote natural enemies (Brust 1994). Other benefits concern weed suppression (Genger et al. 2018), enhanced soil moisture (Hooks and Johnson 2004), erosion protection (Döring et al. 2005; Král et al. 2020), and soil fertility (Brown and Gallandt 2018; Döring et al. 2005; Finckh et al. 2021; Jäckel and Hoff 2021; Key et al. 2020).

Implementation and perception of organic mulching among the target group of users

Among the 57 farmers surveyed in our online information event on organic mulching, 22 (39%) had applied organic mulching. In the other workshop, three of seven organic farmers indicated they use organic mulches. Although these results are not representative, they do indicate a tendency for these practices to be used.

Of the 57 farmers, 45 responded to the survey on perceived advantages and 40 responded to the survey on perceived obstacles, with about three quarters of them identifying themselves as organic farmers. Of the respondents, 16 and 11 farmers, respectively, had already practiced mulching on their farms. Among the proposed benefits, "soil water availability" was the most frequently mentioned (Fig. 4).

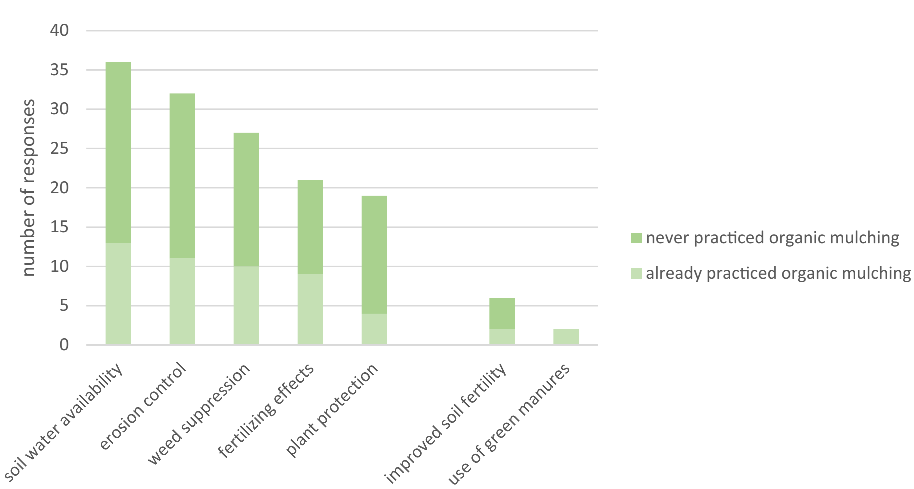

Fig. 4 Advantages of organic mulching as perceived by farmers who have either already practiced or never practiced organic mulching. Each of the five response options on the left was pre-defined, while the two on the right were added in an open query

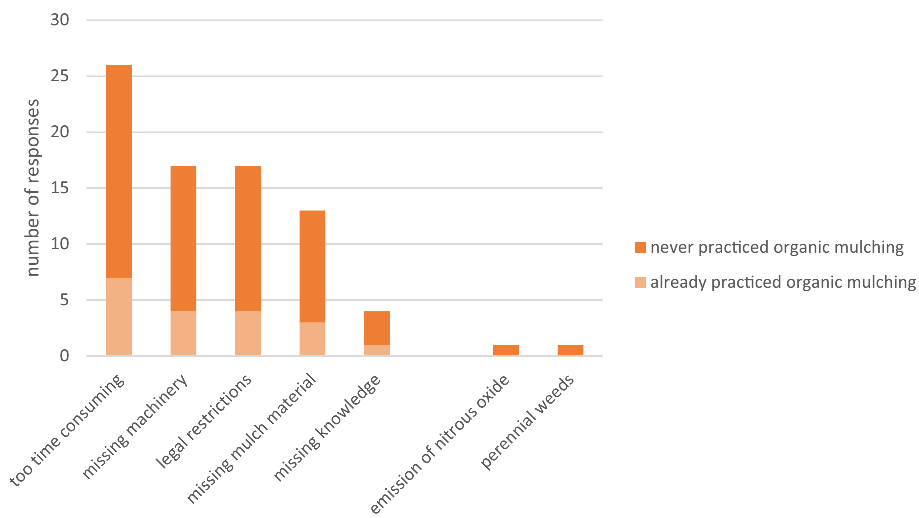

Fig. 5 Obstacles of organic mulching as perceived by farmers who have either already practiced or never practiced organic mulching. Each of the five response options on the left were pre-defined, while the two on the right were added in an open query

Obstacles were seen mainly in the high time requirement and, by those who had not applied mulch before, the lack of machinery and material as well as legal restrictions (Fig. 5).

Discussion of findings on costs and benefits of flower strips

In our cost–benefit analysis of flower strips, we found that major costs arise for the establishment of flower strips, but relatively high compensation payments for agri-environmental measures in Germany could cover these costs. It further indicates that adopting measures to enhance biodiversity can yield multiple ecosystem services. These services include increased biologically based pest control and enhanced pollination. Demonstrating the return on investment for such practices is crucial for encouraging their adoption among farmers, especially when they can experience benefits (Blaauw and Isaacs 2015).

A high share of the total costs is accounted for by the purchase of seed, which is due to the regulations for flower strips in Germany that require the use of certified regional seed and is in line with the results of other studies in Germany (Bosse et al. 2022). Whether such high demands on seed mixtures and high prices are appropriate, depends on the purpose of the flower strip. If certain species are to be protected or promoted, e.g. for conservation, pollination, or pest control, consideration must be given to their particular habitat and forage requirements (Haaland et al. 2011; Tschumi et al. 2015, 2016b). Preliminary results of EcoStack field trials on flower strip mixtures in the UK, Serbia, and Bulgaria show differences in performance of the same species between pedoclimatic regions, indicating that flower mixtures to attract certain ecosystem service providers in different regions need careful design. This is in line with results of Tschumi et al. (2016b). To obtain the desired effects and benefits, prescribing of certain seed mixes may be justified.

Some authors reject seeded flower strips as a biodiversity measure and advocate self-vegetation as a cost-effective way to promote native flora and fauna (Sommer and Zehm 2020). However, our survey among farmers showed that in their experience sown flower strips with seed mixtures of regional wildflowers but also commercial flowering plants were more successfully established and more robust to weed pressure. This was supported by local studies (Gäbert and Preuße 2021; Mayer et al. 2009).

The second major cost factor in our calculations is opportunity costs which is in line with findings of Bosse et al. (2022). They strongly depend on the local conditions regarding soil fertility, farm management, and product prices. One common approach to mitigate this effect already applied by farmers is to use areas for biodiversity measures that are less productive. Our surveys of farmers additionally revealed that they preferably plant flower strips on marginal sites or forest edges, which are less valuable in terms of yield potential and soil quality.

If biodiversity measures are needed in highly productive areas, another approach could be to either raise the AEM premium in general or to adapt it to the yield potential of a specific area in order to cover the costs. Raising the premiums in general has partly been implemented, for example in Lower Saxony, Germany, where from 2023, premiums will increase, e.g. up to 1,373 €/ha for annual flower strips in organic agriculture (Niedersächsisches Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz 2022). A third strategy, developed in low- and middle-income countries, is to plant flower strips not in addition to or instead of field crops, but as in-crop measure through marketable flowering plants, such as herbs, sunflowers, oilseed rape, vegetables, or alfalfa, that attract pollinators and benefit from them (Christmann et al. 2021). However, this strategy would entail increased complexity in planning and implementation.

At the moment, according to German regulations, it is not allowed to use the biomass of AEM flower strips, neither as fodder, nor for energy production or even for composting (Budde-von Beust et al. 2019). Revising these restrictions of the use of the biomass would incentivize further adoption of the measure.

While comparably high AEM premiums make flower strips attractive to farmers in Germany, the administrative burden is an obstacle to implementation. In Germany, the compensation payments for flower strips range according to the funding schemes of the Federal States between 250 and 800 €/ha (Appel et al. 2020). Additional or alternative premiums for flower strips are paid e.g. in contract nature conservation or in organic farming (Budde-von Beust et al. 2019). Regulations for the promotion of flower strips, e.g. in the German Federal States, are very complex and the application procedures time-consuming. They require a great deal of interest and initiative from farmers to familiarize themselves with the regulations and therefore give rise to transaction costs. In some schemes the compensation of transaction costs is already included (Geisbauer and Hampicke 2012). However, simplifying regulations and application procedures, as well as advisory services, could reduce these costs.

Compensation payments, in the case of flower strips AEM premiums, can be seen as the monetary value of agro-ecological measures to society. They should therefore cover all costs that are not covered by higher yields or improved pollination, and be at the same level as the benefits to society, such as aesthetic improvements or increased biodiversity. Our results show that in most cases the benefits cover the calculable costs, but do not greatly exceed them. Non-monetary benefits can therefore be seen as a bonus for farmers who take the risk of trying something new. In summary, in the cases observed, the level of compensation appears to be a fair deal for both farmers and the rest of society.

Discussion of costs and benefits of organic mulching

The on-farm trials have shown that mulching of organic potatoes can result in higher yields. This leads to a high monetary benefit and makes it possible to compensate for high material and labor costs. Organic mulches are currently mainly used in horticulture and only to a lesser extent in arable farming. Due to the higher contribution margins in horticultural crops, small increases in quality and quantity already have a large effect on the financial benefits. However, our results show that organic mulching, in our case of potatoes, can also be profitably applied in arable farming.

Regarding procurement and costs of mulch material, high costs of the mulch material can be reduced, if self-harvested mulch material is used. If this is done, however, opportunity costs for the material as well as labor, and machinery costs must be taken into account (Albus 2022). Straw has the advantage over mulch material cut at a younger green stage in that it does not require costly preservation or composting. Freshly cut clover-grass, on the other hand, offers advantages in terms of plant nutrition, but must be harvested promptly before application by "cut and carry" (Heilmeier and Jacob 2021). Clover-grass is a common component of the crop rotation on organic and extensive farms and requires regular cutting. If the cuttings remain on the field, they are decomposed and the nitrogen content in the soil increases, which leads to a decrease in the fixation rate of the root bacteria. If the cuttings are removed and used, e.g. for mulching, the activity of the root bacteria increases, resulting in elevated gross nitrogen fixation in the field. This, in turn, makes the alternative more profitable (Jacob et al. 2022). Organic mulching is therefore most suitable for farms that do not have alternative uses for their green manure or straw, which means that the costs of the measure consist only of the cutting or baling of the mulch material and the labor and machinery costs for spreading the mulch.

Nevertheless, even if clover-grass or other green manure crops are available on the farm, the availability of mulch may be limited due to dry conditions in the spring. Moreover, existing problems with perennial weeds are more difficult to control when using organic mulch (Finckh et al. 2018). Fertilizer regulations that severely limit the amount of mulch, such as those that exist in some Federal States in Germany, can be further hindrances, since they place "cut and carry" mulch in the same category as liquid manure (slurry) in Germany (Jacob et al. 2022).

The farmers surveyed also saw these obstacles, but considered the excessive amount of work and time as well as the lack of machinery to be a greater problem. A lack of mulch material, on the other hand, was seen as an obstacle by only about one-third.

Compared to our field trials, where a relatively small manure spreader was used, a larger manure spreader could be used for a larger application rate. However, a larger manure spreader would require tracks, which means, for example, that two rows of potatoes would have to be omitted every 12 m, reducing the cultivated area by about 15%.

The fertilizing effect is difficult to quantify, as it can vary greatly from one mulch material to another and reliable information is often only available for nitrogen. Straw, for example, was assumed to have no nitrogen fertilizing effect. However, under particularly broad C-N ratios and certain weather conditions, it can actually have a nitrogen binding effect (Döring et al. 2005). For triticale-vetch mulch, the average nutrient content (N, P, and K) of a legume-green manure mixture (LfL 2022) was assumed. Here, too, the proportion of mineralized nitrogen can vary greatly depending on soil and moisture conditions. In the interviews, farmers spoke of 40–60%, which they could attribute to the mulch material based on nitrogen measurements in the soil. We have very cautiously calculated 35% nitrogen and assumed the same for the other nutrients, because this corresponds to an average value from various sources (Möller and Schultheiß 2014; Sradnick and Feller 2020).

Thus, due to the weed suppressing and fertilizing effects, transferred mulch could enable the introduction of reduced tillage in organic or low-input farming systems (Junge et al. 2020). In a changing climate that favors aphids (Kim and Kwon 2019) and complicates seed production, that accelerates Colorado potato beetle development (Wang et al. 2017) and threatens yields, that endangers crop quality by increasing abiotic stress (Pulatov et al. 2015), mulch could be an adaptive strategy. We can draw the conclusion that mulch can not only contribute to climate-resilient cultivation and plant health in a profitable way, but also increases soil functions through the input of organic nutrients (Bulluck and Ristaino 2002; Junge et al. 2020). In addition, the development of suitable mechanical support and an increase in the effectiveness of the application should be the focus of subsequent research. In particular, the long-term, systemic effect on succeeding crops caused by the improvement of ecosystem services should be included and quantified in multi-year crop rotation trials to achieve greater farmer acceptance and wider application.

Comparison of off-crop and in-crop measures

Off-crop measures like flower strips are comparably costly and need to be incentivized to be adopted. Thus, a sensible application of flower strips is limited to areas where such compensation payments are made. They provide habitat for biodiversity conservation and water protection at farm and at landscape level. However, functional biodiversity benefits in adjacent fields are difficult to derive in monetary terms as so far studies have often not been aimed at collecting yield parameters. In Germany, flower-strip AEM are attractive for farmers, because they can avoid income risk and provide image enhancement. However, transaction costs of administrative procedures can be perceived as obstacles by farmers. In comparison, the in-crop measure organic mulching is labor and cost intensive, but the cost can be recovered at farm level through yield increases, improved soil fertility, and benefits in pest and weed control. Additional benefits at landscape level occur due to erosion control. Organic mulching can be used in areas where mulch material is available with low transportation costs. However, farmers lack information on the viability of these measures.

The two measures represent two different approaches to supporting and promoting biodiversity. The main benefit of the flower strips provides long-term habitat and buffer zones outside the field area, while the benefit of organic mulching is to increase yields and soil fertility. In-crop measures, such as mulching, can be implemented in a cost-neutral manner over larger areas than off-crop habitats. Apart from that, one cannot speak of a superiority of one of the two measures. The two measures can be combined well on one farm and even on one and the same field and can complement each other excellently.

Conclusions

With our socio-economic evaluation of biodiversity-enhancing measures in agricultural landscapes, we want to contribute to filling the existing knowledge gaps in this field. A systematic analysis of the positive and negative effects of such measures is crucial to identify factors for the evaluation of costs and benefits occurring at both farm and societal level. Based on a cost–benefit analysis applied to the off-crop measure "flower strips" and the in-crop measure "organic mulching" we were able to estimate the net benefits of the measures. The results show that for off-crop measures such as flower strips, in our example, installation costs and opportunity costs are the major cost factors, but that on average costs could be covered by compensation payments. Regarding the in-crop measure organic mulching, the benefits could outweigh the costs under conditions of organic agriculture in our trials. Beyond that, however, there are other agro-ecological benefits to be expected that have not yet been priced in. Acknowledging these limitations is essential when, as was done here, cost–benefit analysis is used as a tool to examine the trade-offs farmers make for these ecologically valuable options.

While in our examples costs could be determined quite clearly, we observed obstacles and knowledge gaps especially in quantifying and monetizing benefits of off-crop structures where data on pest damage and pest management, the enhancement of beneficials or yield data were not available. Therefore, researchers should consider the collection of socio-economic data in addition to ecological data in their research design, especially in farm scale experiments.

Our findings support the importance of socio-economic evaluation in terms of assessing measures and their effects, for the economic use of resources, for famer decision making concerning the implementation of biodiversity-enhancing measures, and increasing public awareness of the costs and benefits at the farm as well as at societal level.

Abbreviations

AEM	Agri-environmental measures
AES	Agri-environment schemes
KÖN	Kompetenzzentrum Ökolandbau Niedersachsen/Competence Center Organic Agriculture Lower Saxony
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft/Association for Technology and Structures in Agriculture
LfL	Bayerische Landesanstalt für Landwirtschaft/Bavarian State Institute for Agriculture

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40100-024-00326-6.

Additional file1.

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Author contributions
BW, HK, FA, SK, and JW conceived the original research idea and designed the research methods. BW and PM collected the data on flower strips. JW, SK, SJ did experiments to collect data on organic mulching. BW, JW, SK, SJ, and PM performed and interpreted the analysis. BW wrote the first draft of the manuscript. BW, JW, SK, PM, HK, SJ, and FA contributed to and substantially revised the manuscript. All authors have approved the final version of the manuscript and agree with its submission to *Agricultural and Food Economics*.

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Availability of data and materials
The data used and/or analyzed during this study can be made available upon request to the authors.

Declarations

Ethics approval and consent to participate
All participants taking part in workshops and interviews agreed to the scientific use of the collected data. This manuscript is an original contribution and has not been published elsewhere, nor has it been submitted simultaneously for publication elsewhere.

Competing interests
The authors declare that they have no competing interests.

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