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OPINION PAPER

Scale-dependent effectiveness of on-field vs. off-field agri-environmental measures for wild bees

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Abstract

The effectiveness of agri-environment schemes depends on scheme type, taxon and landscape. Here, we show how spatial scale, i.e. studied transect, field or farm level, and controlling for yield loss, can drastically change the evaluation of biodiversity benefits of on-field (organic farming) vs. off-field (flower strips) schemes. We selected ten agricultural landscapes in Central Germany, each with a triplet of winter wheat fields: one organic, one conventional with flower strip, and one conventional without flower strip as a control. We surveyed the abundance of wild bees at field edges for two years. We found that comparing data at the transect level may lead to misleading conclusions, because flower strips, covering only 5% of conventional fields, support fewer bees than large organic fields. However, a 50% cereal yield loss of organic farming can be considered as equivalent to yield levels of 50 ha conventional plus 50 ha flower strip. This would promote 3.5-times more bees than 100 ha organic farming. In conclusion, considering various scales in the evaluation of agri-environment scheme measures is necessary to reach a balanced understanding of their ecological and economic effects and their effectiveness.

Keywords: Agri-environment scheme; Biodiversity; Farm; Flower strip; Landscape structure; Organic farming; Pollinators; Yield

Introduction

There has been a decades-long discussion on how the landscape may be designed to deliver both high agricultural productivity and biodiversity conservation (Landis, 2017; Zhang et al., 2007). To address these challenges, various agri-environment schemes (AES) have been introduced (Batáry et al., 2015; Marja et al., 2019; Sutcliffe et al., 2015). The AES exhibit a positive effect on species richness and abundance of farmland biota, but these effects depend on landscape structure and ecological contrast between the treated and the control site (Batáry et al., 2015; Marja et al., 2019). Recently, Batáry et al. (2015) reviewed the broad range of European AES with a meta-analysis and compared their relative contributions to biodiversity conservation. AES approaches can focus on non-productive areas, such as field boundaries and wildflower strips (off-field practices Garibaldi et al., 2014), or productive areas, such as arable crops or grasslands (on-field practices). Schemes promoting off-field areas include hedgerows (often for bird conservation Batáry et al., 2012), sown or naturally regenerated field margins (e.g. flower strips for pollinators Pywell et al., 2012) or simply taking land out of production (e.g.

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abandoned land for great bustard conservation in Hungary Kovács-Hostyánszki et al., 2011). In contrast, on-field practices support environmentally sensitive approaches to managing land used to grow crops or feed livestock. For example, they might reduce or prohibit the use of agrochemicals or confine management, such as mowing grassland within specified points in time. The most widespread on-field scheme is organic farming (Reganold & Wachter, 2016; Seufert & Ramankutty, 2017). Batáry et al. (2015) found that off-field schemes were much more effective at enhancing species richness than on-field schemes. The conversion of crop monocultures to semi-natural habitat, such as field margins, results in a much larger increase in resource availability (i.e. creates a larger ecological contrast to the untreated control) for a broader range of species than on-field schemes, such as reducing stocking rates or restricting fertiliser and pesticide application in organic farming (Marja et al., 2019; Tscharntke et al., 2021, 2022). Furthermore, schemes promoting the establishment of wildflower strips might be better targeted to the conservation of a given species group than on-field schemes because they often specifically address a resource that is limiting population growth or size, e.g. floral resources for flower-visiting insects (Warzecha et al., 2018). Thus there can be substantial differences in AES preferences between major arthropod groups (Marja et al., 2022).

However, the meta-analysis by Batáry et al. (2015) has limitations in comparing off- vs. on-field practices, as it combines very different studies, which refer to biodiversity gains at very different spatial scales. For example, insect and plant surveys cover typically only a minor part of a study field (e.g. the field margin) without considering how best to upscale the effects to the whole field or farm. Further, biodiversity-yield trade-offs have rarely been considered. In a large scale UK study, Gabriel et al. (2013) showed that arthropod diversity did not differ between organic and conventional cereal fields after correcting for the more than 50% yield loss in organic farming. In a follow-up study comparing the same dataset to grassland nature reserves (land sparing), Hodgson et al. (2010) found that to support butterfly population via organic farming (land sharing) instead of land sparing with reserves, the organic yield has to achieve 87% of conventional one. Here, we focus on different spatial scales of two popular AESs in Germany (Lakner et al., 2019), namely organic farming as an on-field measure and planted flower strips as an off-field measure, leading to contrasting assessments of their biodiversity value.

Organic farming is generally applied at farm scale, and organic farmers do not apply for flowering strip (FS) schemes. Hence, FS as an AES is typically used by conventional farmers. FS are usually sown with seed mixtures of wild flowers and/or flowering crop species on arable land along field boundaries (Marshall & Moonen, 2002; Warzecha et al., 2018). The width, the species mixtures and strip management vary between countries and even between states. FS are most often targeted for insect conservation, especially favouring flower visitors to ensure crop pollination and natural enemies contributing to biological pest control (Blaauw & Isaacs, 2014; Tschumi et al., 2015; Wratten et al., 2012). In their review, Haaland et al. (2011) found that sown wild FS support higher insect abundances and diversity than cropped habitats.

In this study, we illustrate four different scenarios of scale-dependence of these AES by using wild bee data from surveys of three types of farmland management (organic wheat field, conventional wheat field and conventional wheat fields with FS) from ten landscapes replicated in two years. We investigated whether the effectiveness of the two AES (relative to the control, i.e. conventional fields) depends on the spatial scale considered. We supposed that scaling up the transect level data to field or farm level by considering their larger contribution due to their larger area, as well as the yield loss, might significantly change the whole picture.

Materials and methods

For illustrating the different scenarios, we used wild bee data surveyed in 2016 and 2017 along the field borders of winter wheat fields (for details of study design and survey methods, see Geppert et al., 2020). We selected ten agricultural landscapes in Central Germany (Lower Saxony) with a triplet of winter wheat fields: one conventional wheat field with an annual flower strip (AES subsidy for flower strip area: 875 €/ha) and one control conventional wheat field without flower strip owned by the same farmer, and one organic wheat field from another farmer (AES subsidy for organic farming area: 234 €/ha). In each landscape, the selected fields were situated close to each other with a maximum distance of 3.7 km (1636 ± 176 m in 2016 and 1666 ± 197 m in 2017; mean ± SEM), in order to minimize edaphic and climatic differences among them. In Lower Saxony, the area covered by flower and buffer strips was 209 km^{2,} and the area covered by organic farming was 1172 km^2 in 2016 (Lakner et al., 2019). We designated 50 m long and 2 m wide transects (100 m^2) along the field border (1 m in the grassy margin and 1 m into the field), i.e. in the case of flower strip fields, directly next to the flower strips, and in the case of control conventional wheat fields and organic fields, directly next to the wheat fields (n = 60 transects). The fields in a triplet were situated in the same landscape with similar environmental conditions except for the above-described design variable. We surveyed wild bees (honeybees were not considered) three times between June and July 2016 and 2017 by two different methods. First, we surveyed bees by a 15 min transect walk along the transect, and then we performed a sweep-net sampling standardised with 60 sweeps per transect. All specimens caught were brought to the laboratory and identified to species level.

Altogether we caught 1052 bee individuals belonging to 41 species. Here we focus on abundance. First, because extrapolation to higher scales with species numbers is difficult, especially in the case of flower strip fields, which consist of both the flower strip and wheat. Second, because species numbers are generally strongly correlated to abundance, at least at smaller scales. At the transect level, species number correlated strongly with abundance in our dataset (Pearson's $r = 0.80$, df = 58, $t = 10.28$, $P < 0.001$).

We used the following procedure to calculate abundances for the four scenarios. For Scenario 1, we pooled the data within transect and year by summing the number of individuals across the two survey methods and three survey rounds. Then we calculated the bee density in 100 m^2 transect (hereafter bee abundance) by dividing the pooled data by three and rounded up to the nearest integer. For Scenario 2, we estimated the bee abundance for a 1-hectare field by extrapolating the bee abundance in 100 m^2 to 10 000 m^2 (caution that surveys were performed at the field margins thus, extrapolation to whole fields may have overestimated bee abundances). In the case of the flower strip field, where we sampled only the flower strip, we used the data from the flower strip transect and from the conventional control field to estimate the bee abundance in the whole field. Thus, in this case, first, we calculated the share of flower strip and wheat for flower strip fields, then we extrapolated the flower strip transect data to the share of flower strip per 1-hectare, and the conventional control transect data to the share of wheat in flower strip field per 1-hectare. The 20 flower strips studied covered 15% of flower strip fields on average, representing the current, typical situation at the field level in our study area. For Scenario 3, we estimated the bee abundance for 100-hectare organic and conventional farms by applying the same extrapolation process as in the previous scenario with the exception that for conventional farming, we took uniformly 5% flower strip cover, which corresponds to the minimum area criterion of greening measures in the Common Agricultural Policy (CAP) of the EU (Zinngrebe et al., 2017). As flower strips can be and are typically accounted for the obligatory greening measure, we think that this 5% area is justified, which is supported by the fact that flower strips covered 5.37% of the arable land of our study farms. Finally, scenario 4 differs from scenario 3 only in that the flower strip cover was taken uniformly as 50%, which corresponds to the average yield difference of conventional vs. organic wheat in the study area (Batáry et al., 2017; Clough et al., 2007).

We tested the effect of treatment on bee abundance at all scales by generalised linear-mixed effects models using the R-package 'lme4' package (Bates et al., 2015). In the case of scenarios 1 and 2, we included nested random effects, with 'field' nested in 'farmer', 'farmer' nested in 'landscape' and 'landscape' nested in 'year'. In all scenarios, we fitted a model based on negative binomial distribution due to overdispersed count data. In the case of scenarios 3 and 4, we also included nested random effects, with 'farmer' nested in 'landscape' and 'landscape' nested in 'year'. Additionally, we rounded them up to the nearest one thousand before analysing these data.

Scenarios of different scales

In their meta-analysis, Bengtsson et al. (2005) found that organic management supports 30% higher species richness and 50% higher abundance of organisms than conventional management. Flower strips adjacent to conventional fields are more species-rich with higher bee abundances than organic fields without such strips (Geppert et al., 2020; see also Gayer et al., 2021). Batáry et al. (2015) quantified this in their meta-analysis in that off-field practices (often flower strips) were more effective measures in maintaining or restoring biodiversity than measures on productive areas, such as organic farming on arable land or grassland; effect size of off-field practices was about two times higher than that of on-field practices. However, these findings might depend on the studied spatial scale.

In the first scenario, comparisons consider the transect level, i.e. sampling of pollinator data at the transect level of organic vs. conventional vs. FS (adjacent to conventional fields) (Geppert et al., 2020), exhibiting an eight times higher effectiveness of FS than organic management (Fig. 1). Finally, we have to note, however, that bee densities observed in transects do not necessarily reflect the local population densities accurately but rather bees' response to floral food resource densities, as shown in Geppert et al. (2020).

The second scenario focuses on the field level, considering the area share of sown flowers in the case of FS fields (Fig. 1). When considering the situation in our study (Geppert et al., 2020), FS occupied 15% of our conventional fields on average. However, the effectiveness of conventional management with FS was still 43% higher than the effectiveness of organic management (compared to conventional fields without FS). Hence, the difference at the field level is much less expressed than in the transect scenario. Buhk et al. (2018) showed in a replicated long-term study that flower strips covering 10% of a conventionally managed agricultural landscape massively increase bee abundances and species numbers up to three to five times after two years. This suggests that a high amount of flower strips not only sustain but significantly increase bee populations (Häussler et al., 2017, but see Ganser et al., 2019).

In the third scenario, we further scaled up pollinator abundance data to farm level with a farm size of 100 ha (Fig. 1). In the case of conventional farming with FS, this extrapolation of the field to a 100 ha farm level considered 5% area taken out for FS. We took 5% FS, as it corresponds to the minimum area of the greening measure of the CAP (Zinngrebe et al., 2017) and the actual share of our study farms. We found that 100 ha organic farming, usually characterised by a much higher cover of flowering weeds than

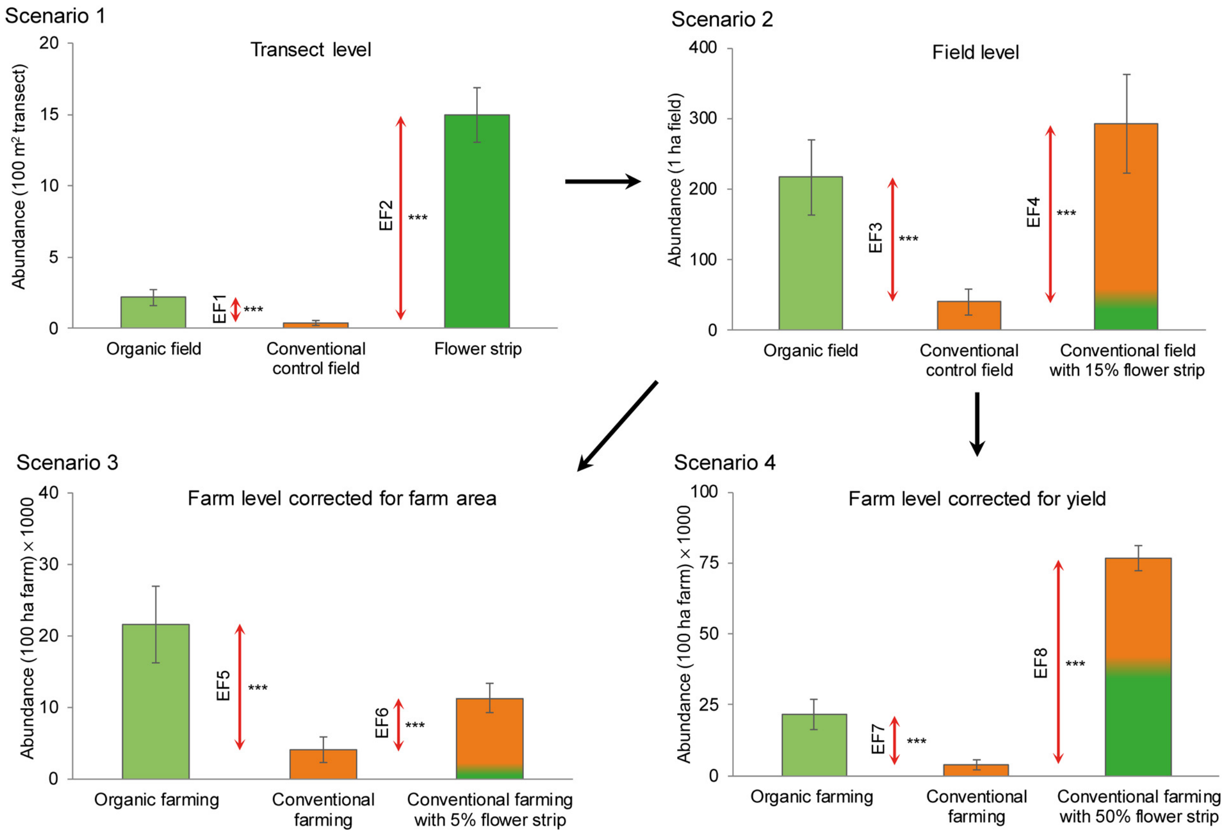

Fig. 1. Bee abundance sampled at transect level in organic field, conventional control field and flower strip, and their upscaling to field and farm scales with different scenarios. Scenario 1: At transect level, the effectiveness of the flower strip (FS) scheme (EF2: compared to the conventional field) was eight times higher than the effectiveness of organic management (EF1: compared to the conventional field). Scenario 2: At the field level, when FS occupied 15% of a conventional field, the effectiveness of conventional management with FS (EF3) was 43% higher than the effectiveness of organic management (EF4). Scenario 3: Based on the same farm area (100 ha), organic farming was more effective (EF5) than conventional farming containing 5% FS and 95% conventional fields (EF6). Scenario 4: Based on the same farm area (100 ha) and same yield loss, i.e. conventional farming with ca. 50% FS (EF8) was more efficient than organic farming (EF7) (n = 60 transects and fields; n = 40 farms). Error bars represent the standard error of mean. Significance levels of effectiveness of AES (EF) compared to conventional control: ***$P < 0.001$. Abundance closely correlated with species numbers in our dataset (Pearson's $r = 0.80$, $P < 0.001$).

conventional fields (Batáry et al., 2013), was about twice as effective as 100 ha of conventional farming, including FS in supporting pollinator abundance. This is because organic management promotes bee abundance with a 20 times larger area than the small area (5 ha) of flower strips, as shown here. Holzschuh et al. (2008) showed that increasing the area with organic farms per landscape from 5 to 50% triples the number of bee species on surrounding fallows.

The last scenario controls yield loss in organic compared to conventional farming (Gabriel et al., 2013) (Fig. 1). As the productivity of organic wheat in the study area is, on average, 50% lower (Batáry et al., 2017), 100 ha organically managed farm may be compared with 50 ha conventional farm with 50 ha flower strips (or more realistically spared fallow land; Tscharntke et al., 2011), thereby producing equal crop yield. In this situation, the same yield per 100 ha farm is the target, and we found that conventional farming supported 3.5-times more pollinators than organic farming due to the large area of flowering strips/fields allowed in conventional farming. Finally, one might consider other scenarios that we could not test with our data, such as other crop species with lower yield differences between organic and conventional farming (Seufert & Ramankutty, 2017). For example, when organic farmers manage their farms with higher crop diversity and longer crop rotations than conventional farmers, biodiversity might further increase with crop yield kept at a high level (Sirami et al., 2019).

Conclusions

A plethora of studies addresses the ecological effectiveness of different agri-environment schemes, with nearly all of them focusing exclusively on the transect level (Batáry et al., 2015), whereas upscaling to higher spatial scale (field or farm level) is rare (Batáry et al., 2017). Although small-scale off-field measure can have a very positive biodiversity outcome at that scale, such as in the case of flower strips, upscaling to field and farm level can reveal that the biodiversity benefit of FS is on par or even lower than that of on-field measures such as organic farming (Geppert et al., 2020). Studies focusing on the transect scale can thus give misleading results, as FS make up typically only ca. 5% of a conventional farm, they enhance bee populations less than would an organic farm of the same size. This can be turned around again when we control for yield losses from organic farming (Chave, 2013). As yield in organic wheat is on average 50% lower, 100 ha organic farm has the same productivity as 50 ha conventional farm with 50 ha flower strips, which supports much higher biodiversity than organic farming. In conclusion, considering various scales and taxonomic groups in the evaluation of AES measures is necessary to get a balanced understanding of their ecological and also economic effects for further development of their effectiveness.

Declaration of Competing Interest

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

Statement of authorship

Péter Batáry: Conceptualization, Visualization, Data curation, Formal analysis, Writing − original draft. **Teja Tscharntke:** Conceptualization, Visualization, Writing − original draft.

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