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2
3 **Gains to species diversity in organically farmed fields are not propagated at the farm**
4 **level**

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1 **Abstract**

2 Organic farming is promoted in order to reduce environmental impacts of agriculture, but
3 surprisingly little is known about its effects at farm level, the primary unit of decision making.
4 We assessed effects of organic farming on species diversity at field, farm and regional levels
5 by sampling plant, earthworm, spider, and bee species in 1470 fields of 205 randomly selected
6 organic and non-organic farms in twelve European and African regions. Species richness was,
7 on average, 10% higher in organic than non-organic production fields, with highest gains in
8 intensive arable fields (around +45%). Gains to species richness were partly caused by higher
9 organism abundance and were common in plants and bees but intermittent in earthworms and
10 spiders. Average gains faded to insignificant +4.6% at farm and +3.1% at regional level, even
11 in intensive arable regions. Additional, targeted measures are therefore needed to fulfill the
12 commitment of organic farming to benefit farmland biodiversity.

13

14 **Introduction**

15 Biodiversity is threatened, both at global and regional scales^{1,2}. During the past decades,
16 agriculture has been a key driver of the loss of biodiversity through intensification of existing
17 farmland and conversion of natural land into cropland³⁻⁵. However, farmland also hosts many
18 species that depend on appropriate agricultural management for their survival^{6,7}. Organic
19 agriculture is intended to be a biodiversity-friendly and sustainable farming system⁸ and is
20 promoted by many countries as a way of reducing the environmental impacts of agriculture⁹.
21 Although debated, better food quality¹⁰ and less environmental impact¹¹ are persuasive
22 arguments that have encouraged an increasing number of consumers to buy organic products.
23 Organic farming is also considered a key strategy for land sharing, i.e. the promotion of
24 biodiversity and food production on the same area of land^{5,12-14}.
25 Evidence generally suggests that organic farming has beneficial effects on biodiversity, but
26 the magnitude of these effects is highly variable^{11,15-22}. This is due to two major challenges in

1 quantifying the effects of a farming system on biodiversity. First, biodiversity is prohibitively
2 expensive to capture comprehensively and therefore only inferable using proxies, e.g. species
3 richness of certain ‘indicator’ taxonomic groups^{23,24}. A recent meta-analysis indicated that
4 organic farming increases species evenness and that organic farming gains to species richness
5 are mainly effects of the abundance of individuals²⁵. The second challenge is that, while
6 research investigates biodiversity mostly at the field scale, a farmer considers his entire farm
7 when making management decisions²⁶. Farms are highly diverse in their internal organization
8 and spatial layout, even within the same geographical region and production type. Farming
9 effects at the field level do not necessarily translate directly to the farm or landscape
10 level^{12,15,18,19,27}. Hence, studies at multiple scales are crucial to understanding impacts of
11 farming systems on biodiversity²⁸.

12 In one of the largest comprehensive studies on farmland biodiversity, we aimed to quantify
13 the benefits organic farming has on species diversity at field, farm and regional levels across a
14 range of environments from boreal to tropical. In order to address the challenge of the
15 intangible nature of ‘biodiversity’ as a whole, we analyzed organism abundance, species
16 richness, and species evenness in four taxonomic groups: plants, earthworms, spiders and
17 bees. The groups were selected to represent different habitat compartments (soil, soil surface,
18 and above-ground structures), trophic levels, mobility, and expected responses to agricultural
19 management^{15,16,19,20,29,30}. In order to cope with the heterogeneity of agriculture, we sampled
20 species in 205 farms in twelve contrasting regions in Europe and Africa using standardized
21 methods (Fig. 1a; Supplementary Table S1). The regions represented various production types
22 with a low to medium intensity of farming (regional average N input ranging from 5 to 215 kg
23 N ha⁻¹; Fig. 1b), thus accounting for a relatively large portion of global agriculture³¹. The
24 twelve regions were homogeneous with regard to environmental conditions, and from each
25 region 12 to 20 farms were randomly selected, approximately half of them certified organic
26 (Supplementary Table S2). No additional constraints were set on the non-organic farms,

1 which could therefore comply with various other statutory or voluntary standards of
2 environmental care³². This provided us with representative samples of present-day organic
3 and non-organic farms in every region, thereby avoiding the problematic, and ultimately
4 impossible, exercise of pairing organic and non-organic farms.

5

6 --- Fig. 1 near here ---

7

8 **Results**

9 *Organic farming gains to species diversity in production and non-production habitats*

10 Since habitats present in each region differed, a comparison at the field level was only
11 possible for the most frequently observed habitats per study region. Depending on the region,
12 the most frequent habitats managed with the primary aim of agricultural production were
13 winter or summer-sown non-entomophilic crop fields, fertile grasslands, vineyards or olive
14 groves (Supplementary Table S3). The most frequent non-production habitats, e.g. managed
15 for access to land, wind shelter or as part of an agri-environmental scheme, were grassy or
16 shrubby strips along field or water edges.

17 Organic farming was beneficial to species richness of plants and bees in production fields in
18 many regions, but differences were rarely significant if tested within each region separately
19 (Fig. 2a). Mixed-effects models estimated by maximum likelihood show that in all regions
20 combined organic farming gains to species richness in production habitats were +17.1% ($P\chi_1^2$
21 < 0.01) for plants, +6.3% (ns) for earthworms, +1.2% (ns) for spiders, +13.6% (ns) for bees.
22 Across all four taxonomic groups and all regions, 10.5% ($P\chi_1^2 < 0.02$) more species were
23 found in organic than in non-organic production fields. This significant positive effect of
24 organic farming on species richness arises from the fact that all groups responded positively,
25 although only the difference in plants was significant. Organic farms were further

1 characterized by lower mean nitrogen inputs (-22.4%, $P\chi_1^2 < 0.02$; Fig. 1b), fewer mechanical
2 field operations (-9.3%, $P\chi_1^2 < 0.08$; Fig. 1c), and fewer pesticide applications (-75.9%, $P\chi_1^2 <$
3 0.001 ; Fig. 1d) than in their non-organic counterparts. Differences in species richness between
4 organic and non-organic production fields were highest in arable and horticultural fields in
5 Marchfeld, Gascogne, Gelderland, and Southern Bavaria (+45.5%, $P\chi_1^2 < 0.001$ on average
6 across these four regions and the four taxonomic groups). Effects were similar if the
7 regionally most frequent crops (winter wheat or alfalfa) were compared (Supplementary
8 Figure S1). The four regions also showed significant differences in management intensity
9 between organic and non-organic farms (as illustrated by N input, the number of mechanical
10 operation per ha and the number of pesticide applications per ha; Fig. 1b-d). Average regional
11 gains to species richness in production habitats were positively correlated to regional average
12 N input per ha (Spearman's $\rho = 0.68$, $P < 0.05$).

13 Organic farming gains to organism abundance and to species richness were strongly
14 correlated (Spearman's $\rho = 0.67$, $P < 0.001$, over all four groups in production and non-
15 production habitats and at farm level; Supplementary Table S4). Consequently, trends for
16 organic farming gains were also detected for the cumulated cover abundance of plants
17 (+9.0%, ns) and the number of individuals of earthworms (3.8, ns), spiders (+5.7%, ns) and
18 bees (+23.8, ns) in production habitats (Supplementary Fig. S2a). As with species richness,
19 organic farming gains to organism abundance across all four taxonomic groups were highest
20 for the four regions with intensive arable or horticultural fields (+25.6%, $P\chi_1^2 < 0.05$ vs.
21 +8.5%, ns, across all regions). Rarefying species richness shows that a positive put
22 insignificant gain of organic farming remains (+6.9%, ns, for bees; +2.0% for spiders and
23 +9.8% for bees; Supplementary Fig. S3) Organic farming had no significant effect on species
24 evenness in production habitats, with the exception of plants in the four most intensive region
25 (+0.13, $P\chi_1^2 < 0.01$; Supplementary Fig. S4a).

1 In contrast to production habitats, organic farming did not alter species richness in non-
2 production habitats (-3.6% (ns) for plants, +13.4% (ns) for earthworms, -7.1% (ns) for
3 spiders, +9.1% (ns) for bees, and -0.7% (ns) overall; Fig. 2b). Organic farming also had no
4 significant effects on abundance or evenness in non-production habitats (Supplementary Fig.
5 2b and 4b). In addition, organic farms did not, on average, have a higher number of habitat
6 types or a higher areal proportion of semi-natural elements (Fig. 1e).

7

8 *Organic farming gains to species diversity at the farm level*

9 As assessed by hierarchical preferential sampling, organic farms tended to have higher total
10 species richness than non-organic farms. Across all regions, organic farming gains were
11 +4.8% (ns) for plants, +3.1% (ns) for earthworms, +3.2% (ns) for spiders, +12.8% ($P\chi_1^2 <$
12 0.05) for bees, and +4.6% ($P\chi_1^2 < 0.1$) across all four taxonomic groups. Gains to total species
13 richness were strongest in Bavarian mixed farms, as well as in olive farms in Extremadura,
14 and were consistently positive in the grassland farms in Obwalden, Hedmark, and Wales (Fig.
15 2c). No significant organic farming gains were found for the abundance of organisms at the
16 farm level.

17

18 --- Fig. 2 near here ---

19

20 These results reflect diminished organic farming gains when observed at the farm level as
21 compared to the field level. A weighted random resampling procedure with the areal
22 proportion of different habitats per farm as weights indicated that organic farming gains to
23 species richness decrease as more of the smaller habitats on the farm are included (Fig. 3a-d).
24 The resampling mimicked random species sampling, in which samples are more likely drawn
25 in habitats with larger areal proportion, in this case, predominantly production habitats. The

1 fading was especially pronounced where organic farming gains to production habitats were
2 large, namely with plants and bees and in regions with arable cropping (Fig. 3e). Gains to
3 species richness of spiders also tended to decrease with more sampled habitats.

4

5 --- Fig. 3 near here ---

6

7 *Organic farming gains to species richness at regional level*

8 There were considerable differences in species richness between regions for the four
9 taxonomic groups. However, in the majority of regions, species accumulation curves from
10 samples in organic and non-organic farms had similar shapes (Supplementary Figs. S6-S9).
11 Extrapolated regional species numbers from these curves differed little between organic and
12 non-organic farms (Supplementary Fig. S5) and overall organic farming gain to extrapolated
13 regional species richness was +3.1% (ns).

14

15 **Discussion**

16 The evidence from 205 European and African farms suggests substantial organic farming
17 gains to species richness of plants and bees in production habitats in intensive arable regions,
18 which is in agreement with several other studies conducted at the field level^{11,15-20,22}. Organic
19 farming benefits to species richness in production fields increased with regional average
20 nitrogen input, as well as with difference in nitrogen input between organic and non-organic
21 farms. This supports a recent meta-analysis²² as well as an investigation in wheat fields,
22 which indicated that organic farming gains in biodiversity are proportional to losses in yield²¹.
23 However, organic farm gains to species richness at the field level fade when observed at the
24 farm level, from a significant +10.5% overall taxa at the field level to an insignificant +4.6%
25 at the farm and +3.1% at regional level. This is in agreement with the few studies that
26 compared organic and non-organic practices at farm or landscape level and found weaker

1 effects at higher levels of aggregation^{12,19}. In contrast to earlier studies, we aimed at a
2 comprehensive assessment of all habitats affected by farming activities, including non-
3 productive habitats, such as unpaved tracks or field margins. This allowed us to account for
4 possible differences in habitat composition between farms, which are of crucial importance
5 for biodiversity at farm level^{28,33–35}.

6 Species richness at the farm level is a combination of farming effects at the field level and the
7 composition of farmland habitats on each farm. This interaction is exemplified by comparing
8 data from Extremadura and Veneto. In Extremadura, organic and non-organic olive groves
9 did not differ in species richness because in both farming systems, the primary management is
10 harrowing to control weeds and reduce competition for soil water³⁶. Herbicides are primarily
11 used to control weed invasion from margins and reduce species richness in non-organic non-
12 production strips of grass and shrubs. Consequently, more species are found in organic than in
13 non-organic farms. In contrast, herbicide use in non-organic vineyards in Veneto reduced
14 floral species richness³⁷, whilst the application of natural pesticides and organic weed control
15 may have reduced richness of faunal groups in organic vineyards³⁸. Similar habitat richness in
16 organic and non-organic farms resulted in higher floral but lower faunal species richness on
17 organic than non-organic farms.

18 Habitat composition was taken into account in the resampling procedure, which highlights a
19 continuous decrease in the positive effects of organic farming on plant and bee species
20 richness as more farm habitats are sampled. Such fading from field to farm may be explained
21 by two processes: the regional pool of farmland species may be limited and simply attained
22 faster on organic farms, or additional species in organic production habitats are ubiquitous,
23 invading more easily from boundaries into fields and contribute little to the total species
24 richness per farm. Ubiquity of species appears to be more likely than limited pools since the
25 individual farms contained, on average, only 27% ($\pm 6.8\%$ standard deviation) of all plant
26 species and 24% ($\pm 13.2\%$) of all bee species found in the region. We further calculated the

1 occurrence of each plant and bee species relative to all samples in a region as a measure of
2 species rarity, but did not find organic farming effects on species rarity. This suggests that the
3 higher species richness in organic production fields is mostly due to common species, which
4 contribute relatively little to total farm species richness because they are frequently found in
5 other habitats of each farm.

6 There was a striking correspondence between gains to species richness and organism
7 abundance across all regions and taxonomic groups. While this is not surprising and is a well-
8 known property of species richness^{25,39}, it shows that a higher abundance of individuals is
9 likely the most important effect of organic farming on species richness. Hence, organic
10 farming is not significantly increasing the number of species present in a given number of
11 individuals but sustains a higher number of individuals in a given sampling unit.

12 Investigating species diversity across multiple regions and taxonomic groups using
13 standardized methodology also substantially complements our understanding of the effects of
14 organic farming on biodiversity by showing where there are no significant effects. Most
15 prominently, organic farming contributed little to habitat heterogeneity, which is of key
16 importance for farmland biodiversity^{28,33-35}. Organic and non-organic farms did not differ in
17 average habitat richness and thereby, in their potential to host exclusive species in any of the
18 investigated regions. Organic farming effects on earthworm and spider richness and
19 abundance were highly region-specific but marginal over all regions. Furthermore, we found
20 significant gains to species evenness in plants in arable fields only, in contrast to a recent
21 meta-analysis based on 81 studies²⁵. This shows that any evaluation of farming effects on
22 biodiversity requires critical consideration of the investigated taxonomic groups and
23 geographical coverage⁴⁰.

24 Organic farming gains in the two investigated African regions were surprisingly small and did
25 not differ from European regions. Interestingly, plant species richness in both regions tended
26 to be lower in organic than in non-organic production fields. Due to the costs of organic

1 certification and market access, organic growers may invest more labor in weed control than
2 some of the non-organic counterparts⁴¹. In addition, inputs to agriculture are relatively low in
3 both regions and, hence, differences between organic and non-organic management are
4 small⁴².

5 Despite substantial variation between taxonomic groups and regions, the majority of the
6 average effects of organic farming on species diversity demonstrate a positive tendency. This
7 is true for most of the non-significant effects on species richness, abundance and evenness in
8 productive fields and at farm and regional level. Hence, organic farming tends to sustain
9 species diversity to a higher degree than non-organic farming by allowing more individuals to
10 survive in a given unit of agricultural habitat.

11 We conclude that organic farming represents a step in the right direction toward preserving
12 farmland biodiversity. Yet, the gains fade at the farm level due to the equilibrating effect of
13 non-production habitats, which are similar in both farming systems. Therefore, land sharing
14 by present-day organic farming alone is unlikely to halt the current global decline in farmland
15 biodiversity^{1,14}. Additional land-sparing measures that maintain and increase habitat diversity
16 and quality, such as directed agri-environment schemes^{6,18,27}, set-aside areas^{29,34}, and
17 management contracts for habitats of rare species⁷ are urgently needed. Implementation of
18 these measures in organic farming guidelines should be intensified in order to boost its
19 performance in terms of promoting farmland biodiversity. Our study highlights that only by
20 means of such targeted measures it is possible to accommodate the dual objectives of food
21 production and biodiversity conservation on farmland.

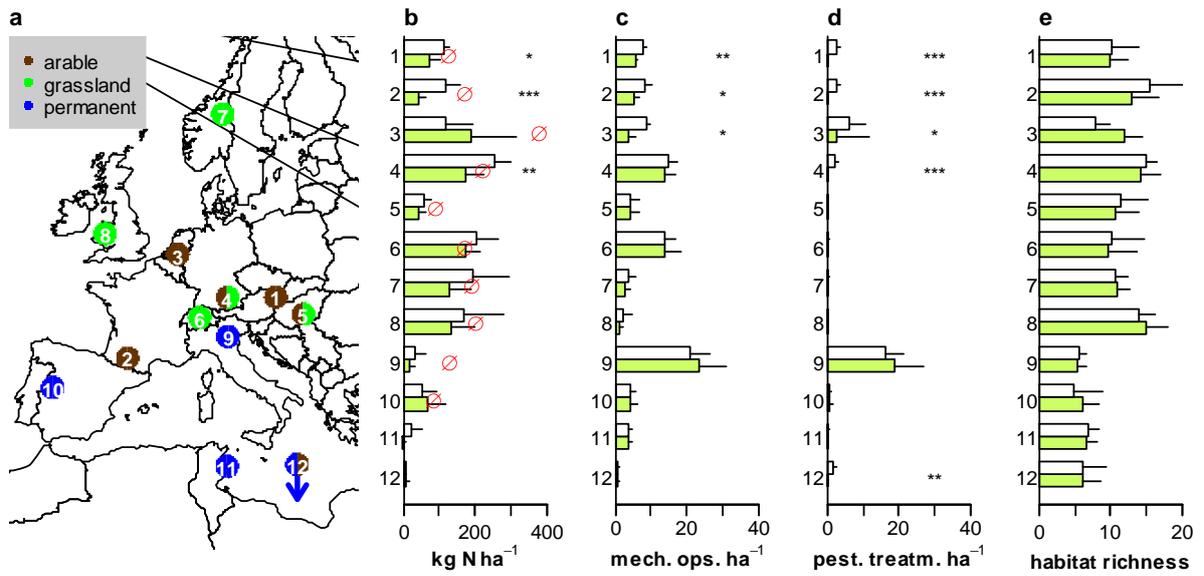
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1 **Figure 1 | Management of organic and non-organic farms in twelve regions on two**
2 **continents. a,** Location of study regions with predominant type of agricultural land use.
3 Regions with bicolor symbol have mixed land use. Region 12 is located in Uganda and not
4 shown on map. **b-d,** Average nitrogen input per hectare (+ standard deviation) (b), average
5 number of mechanical operations (c), average number of pesticide applications (d), and
6 average number of habitats (e) in non-organic (white bars) and organic farms (green bars) in
7 the twelve regions. Red \emptyset are national average N inputs in 2008⁴³. Significant differences within
8 regions (U-Test) at 0.05, 0.01, and 0.001% are indicated by *, **, and ***, respectively.

9
10 **Figure 2 | Organic farming gains and losses (OFG) to species richness in twelve regions.**
11 Organic farming gains/losses (\pm standard deviation) to species richness in the regionally most
12 frequent production habitat (a), in the most frequent non-production habitat (b), and on total
13 species richness per farm (c), for the four taxonomic groups of plants, earthworms, spiders,
14 and bees in the twelve regions shown in Fig. 1a. X-axis is log-scaled to equalize distances on
15 both sides of parity. Significant differences within regions (U-Test) at 0.05, 0.01, and 0.001%
16 are indicated by *, **, and ***, respectively.

17
18 **Figure 3 | Organic farming gains and losses to species richness fade from field to farm.**
19 **a-d,** Species numbers of plants (a), earthworms (b), spiders (c), and bees (d) depending on the
20 number of resampled habitats in the twelve regions shown in Fig. 1a. Lines show average
21 organic farming gains/losses estimated from mixed-effects models, shaded areas are
22 approximate 50% and 95% confidence intervals. **e,** species numbers depending on the number
23 of resampled habitats for the twelve individual regions. Y-axes are log-scaled to equalize
24 distances on both sides of parity.

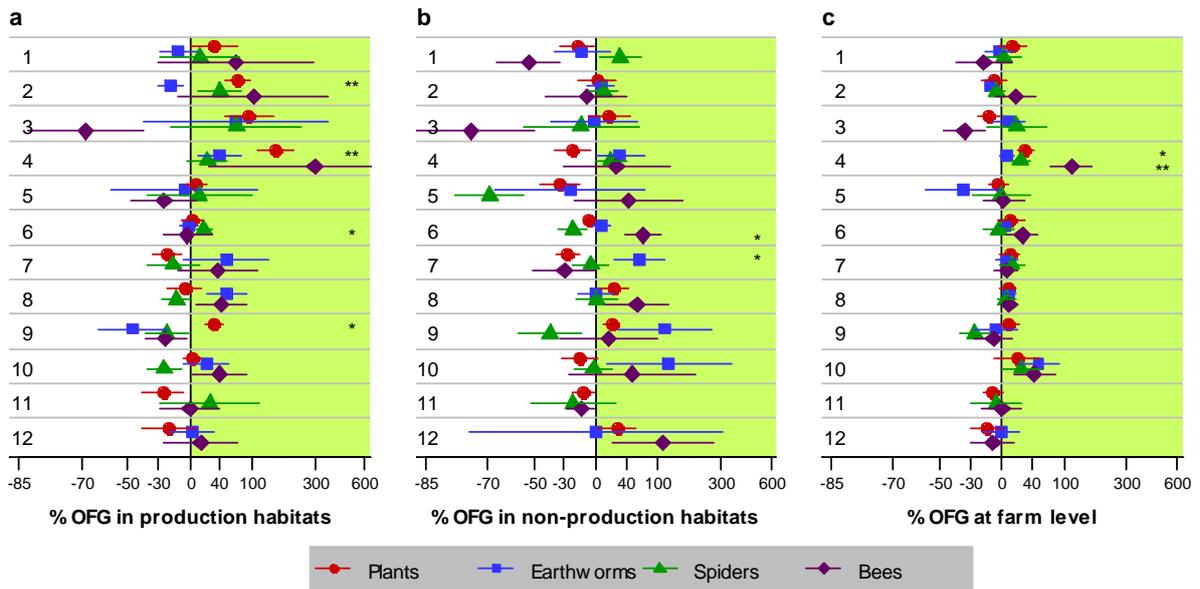
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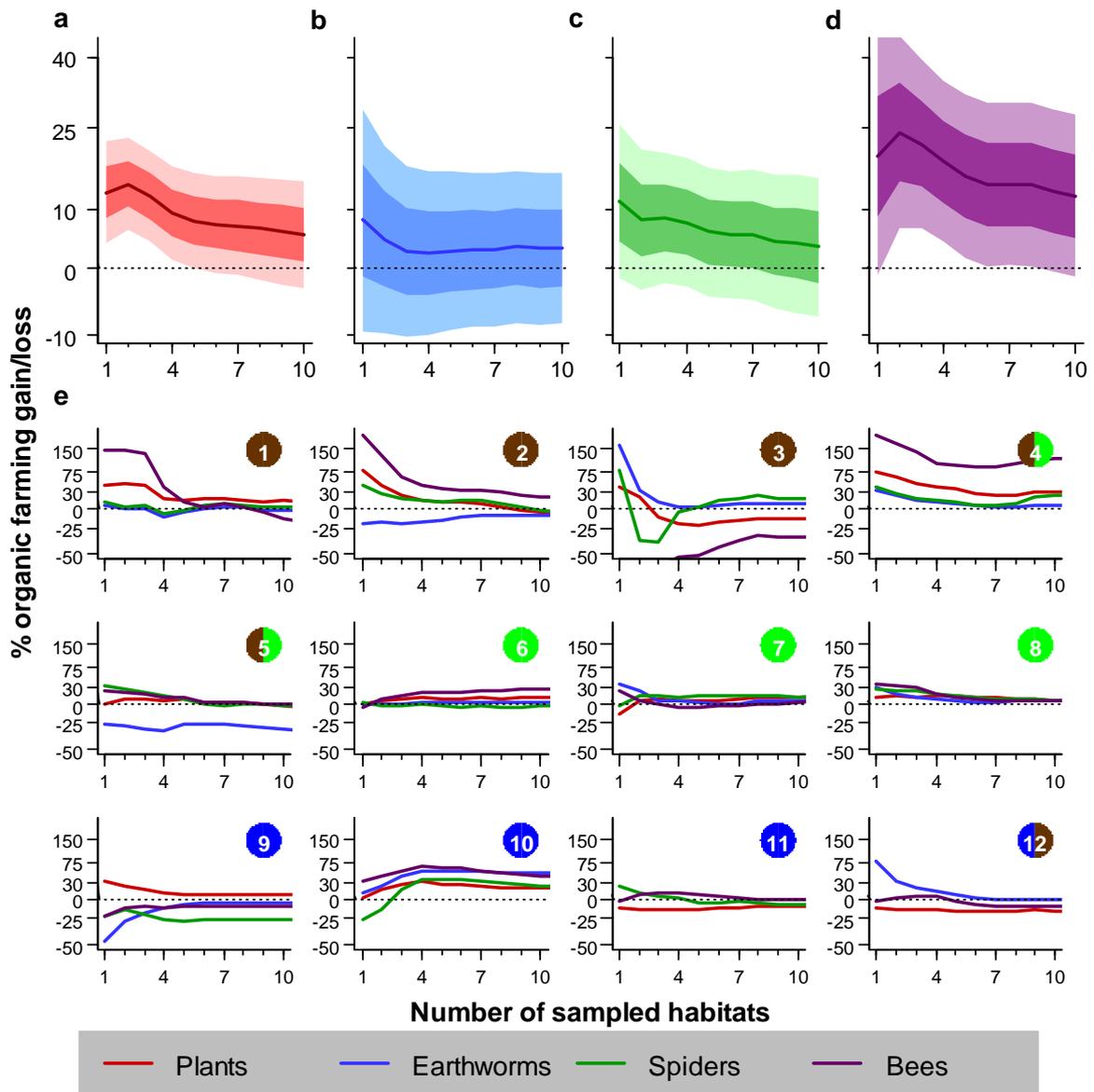
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1 Figure 3



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1 **Methods**

2 Study regions and farms

3 Study regions were selected to reflect major organic farming types in Europe and Africa as
4 well as a large gradient of climatic conditions (Supplementary Table S1) and farm
5 information obtained from local sources (Supplementary Table S2). To reduce farm selection
6 bias within study regions, the regions needed to be as homogeneous as possible with respect
7 to environmental conditions (soil, temperature and precipitation) and contain a sufficient
8 number of organic and non-organic farms. Furthermore, specific exclusion criteria were
9 applied to all farms in each study region, e.g. a minimum portion of area under arable
10 cropping for farms in regions with mixed land use. Out of the eligible farms in each region, 8
11 to 10 organic and an equal number of non-organic farms were selected at random
12 (Supplementary Table S2). Organic farms were required to have been certified organic for at
13 least five years prior to the study. No additional constraints were set on the non-organic farms.
14 Hence, sampled farms were representative for a specific combination of region and
15 agricultural types, e.g. vine producers in Veneto, but not for all farms in a region.

16 In the Hedmark region, the total number of farms studied was limited to 12 due to sampling
17 time constraints caused by the short growing season and the complex habitat structure. In the
18 entire Gelderland region, only three non-organic horticultural farms within the study region
19 agreed to participate in the study, in comparison to eleven organic farms. In Homokhatsag,
20 only seven organic farms were available for investigation and in Obwalden, a non-organic
21 farmer ceased participation during the study. In Veneto, farms had to be selected from three
22 separate vine areas because there were not enough organic farmers within one single area. In
23 Wales and Hedmark, organic and non-organic farms were selected in pairs because they were
24 located along a geographical and intensity gradient that made it difficult to get an unbiased
25 subset by random sampling.

1 Management information was gathered during structured interviews with farmers. Nitrogen
2 input in kg N ha⁻¹ included nitrogen from mineral and organic fertilizers as well as estimated
3 N₂ fixation and was compared to national average nitrogen inputs in kg N ha⁻¹ in 2008³¹.
4 Counts of mechanical operations included e.g. mowing, turning, bale making and loading.
5 Counts of pesticide applications included natural pesticides. N input, mechanical operations
6 and pesticide applications on fields were totaled and the area-weighted averages per farm
7 were calculated. Gathering of management information in African countries involved more
8 uncertainty than in Europe.

9 Hierarchical preferential sampling

10 The entire area of each study farm was mapped according to the EBONE methodology, a
11 standard habitat mapping procedure for the European scale^{44,45}. This method is based on a
12 generic system of habitat definitions, General Habitat Categories (GHCs). The habitat
13 qualifiers, which characterize individual habitats with respect to their ecological features,
14 include categories specifically related to farming areas. For our study, the method has been
15 adapted with refined GHC definitions to deal with the specific characteristics of farm
16 holdings. The most important adaptation was the division of the annual crop GHC into four
17 subcategories, namely summer or winter-sown non-entomophilic annuals, entomophilic
18 and/or bee-attracting annuals, and perennials. In addition, the three dominant plant species
19 were recorded and allowed for comparisons within the regionally most frequent crops
20 (Supplementary Figure S1).

21 The first step in mapping was the assessment of the farm area, i.e. all land managed by a
22 farmer. In the second step, the area was mapped to either areal or linear elements. The
23 minimum mappable area for an areal element was 400 m², with minimum dimensions of 5 x
24 80 m. If the width of an element was smaller than 5 m it was recorded as a linear element with
25 a minimum mappable length of 30 m. Third, based on life form and non-life form categories,

1 a GHC was assigned to every areal and linear element. A farm class (farmed and non-farmed
2 land) and specific environmental and management qualifiers were attributed to all areal
3 elements. The GHCs and qualifiers were chosen from a limited list using specific rules in
4 order to avoid potential multiplicity of codes and mosaics, and to provide a lowest common
5 denominator for linking datasets across study regions. The combination of GHCs and
6 qualifiers allowed a specific separation of habitats with distinct species compositions (e.g.
7 grasslands of different management intensity), while still being general enough for
8 comparison within regions. Across all twelve study regions, the habitat mapping yielded 167
9 distinct habitats on farmed land, with an average of 26 (range of 13-58) in each region and an
10 average of 7.2 (1-15) per farm (Supplementary Table S3).

11 Out of all areal or linear elements of a specific farmed habitat on each farm, one plot was
12 randomly selected. On the selected plots, the species of the four taxonomic groups were
13 sampled using standardized protocols⁴⁶.

14 Species sampling

15 Plant species in selected plots of areal habitats were recorded in squares of 10 x 10 m², well
16 away from the plot edges. In linear habitats, which were by definition less than 5 m wide,
17 plant species were recorded in a rectangular strip of 1 x 10 m².

18 Earthworms were extracted at three random locations per plot in all regions except Madhia,
19 where they were completely absent. When soil was humid, 2 liters of a solution of allyl
20 isothiocyanate (AITC), a commercially produced metabolite of glucosinolate, were poured
21 into a metal frame (30 x 30 cm²) twice at 5 minutes interval⁴⁷ and earthworms appearing at
22 the surface were collected. Thereafter, a soil core of 30 x 30 x 20 cm³ deep was excavated,
23 and a single person hand-sorted earthworms from the soil for a duration of 20 minutes.

24 Spiders were caught with a vacuum shredder (Stihl SH 86-D, Andreas Stihl & Co., Dieburg
25 64807, Germany) with a tapering gauze bag inserted into the intake nozzle⁴⁸. On each of three

1 sampling dates, five sub-samples were collected for 30 seconds within a sample ring of 0.357
2 m internal diameter haphazardly pre-placed on the target vegetation within each plot. Sub-
3 samples were immediately transferred to a cool-box. Since a taxonomic catalog of spiders is
4 lacking in the Kayunga region, the region was not sampled for spiders.

5 Bees were captured with a standard entomological aerial net along a transect of 100 m length
6 and 2 m width during 15 minutes^{49,50}, either identified in the field or immediately transferred
7 into a kill jar. Domesticated bees were counted in the field but not captured. Each plot was
8 surveyed three times during the growing season, but specific timing depended on local
9 conditions.

10 Metrics of species diversity

11 Organism abundance and species richness at the field level was calculated by summing all
12 individuals and species per sample, respectively. Species evenness was calculated as

$$13 \quad E_{\text{var}} = 1 - \frac{2}{\pi} \arctan \left[\frac{\sum_{i=1}^S (a_i - \bar{a})^2 / S}{\bar{a}} \right] \quad (1)$$

14 where a_i is the log-transformed abundance of species i , \bar{a} is the mean of all a_i and S is the total
15 number of species in the sample^{25,51}. Data points without or with only one sampled species
16 were omitted from the evaluation of evenness, as no meaningful values could be calculated.

17 Total species richness at the farm level was calculated by counting all species observed in all
18 sampled habitats on each farm. Abundance at the farm level was calculated by totaling all
19 individuals in all sampled habitats on each farm. Species richness was rarefied to the smaller
20 value between two and the lowest number of individuals present in all samples of one region
21 using Hurbert's method⁵² implemented in package `vegan` 2.0-10 in R 3.0.1⁵³.

22 Total species richness at the regional level was calculated by extrapolating the species-area
23 curves (Supplementary Figures S4-S7) using the jackknife method of first order⁵³.

1 Furthermore, moment-based species accumulation curves together with unconditional
2 standard deviations⁵⁵ were calculated for all samples collected on organic and non-organic
3 fields in each region.

4 Statistical analysis

5 Differences between organic and non-organic within individual regions were tested using
6 Mann–Whitney U Tests. Because interpreting the significances of these tests is not trivial in
7 light of the numerous comparisons⁵⁶, we relied on mixed-effects models for assessing the
8 impact of organic farming. In these models, farming effects on each metric of species
9 diversity (S) were calculated for each taxonomic group over all 12 regions. For organism
10 abundance and species richness, the data were $(S_{ij} | \beta, b, x) \sim \text{Poisson}(\mu_{ij})$ from $i=1, \dots, 205$
11 farms in $j=1, \dots, 12$ regions. The model is:

$$12 \quad \log(\mu_{ij}) = \beta_0 + \beta_1 x_{1ij} + \beta_2 x_{2ij} + b_{1j} + b_{2ij} \quad (2)$$

$$13 \quad b_q \sim N(0, \sigma^2), \quad q=1, 2$$

14 where β_0 is a fixed intercept, β_1 a fixed effect of farming treatment x_{1ij} (organic versus non-
15 organic), β_2 is a fixed effect of the number of sampled habitats per farm x_{2ij} , b_{1j} are random
16 intercepts for country j , and b_{2ij} are random intercepts for farm ij . Random effects b_1 to b_2 are
17 normally distributed with mean 0 and variance σ^2 . Random intercepts b_{2ij} accommodate extra-
18 Poisson variance due to over-dispersion⁵⁷. The significance of term β_1 was calculated by log-
19 likelihood ratio tests with 1 degree of freedom^{58, p.83}. For species evenness, mixed-effects
20 analogous to eq. 2 but with a Gaussian error structure were tested.

21 Since the number of sampled habitats on each farm was not equal across farms, it was
22 incorporated into the model for species richness at the farm level as a linear covariate x_{2ij} ^{59, p.}
23 ¹¹². The number of samples had no effect on both measurements of species richness at the
24 field level and was omitted from these models.

1 Maximum likelihood estimation was carried out in R 3.0.1⁵³ using package lme4 (Version
2 0.999999-2).

3 The models over all four taxonomic groups are more complex and, hence, offer several
4 possible structures of random effects. For each metric of species diversity, we started
5 therefore with a complex structure of random effects (full model) and subsequently simplified
6 it using sequential log-likelihood ratio tests⁵⁸. The most parsimonious model was finally used
7 for inference on the overall organic farming gain to species richness. For each evaluated
8 measure of species richness and abundance (S), the data were species richness ($S_{kij} | \beta, b, x$) ~
9 Poisson(μ_{kij}) of $k=1, \dots, 4$ taxonomic groups from $i=1, \dots, 205$ farms in $j=1, \dots, 12$ regions. The
10 full model is

$$11 \quad \log(\mu_{kij}) = \beta_0 + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \beta_{3k} + b_{1j} + b_{2jk} + b_{3ij} + b_{4ijk} + k \cdot b_{5ij} \quad (3)$$

$$12 \quad b_q \sim N(0, \sigma_q^2), \quad q=1, \dots, 4$$

$$13 \quad b_{5ij} \sim N_k(0, \Sigma)$$

14 where β_0 is a fixed intercept, β_1 is a fixed effect of farming treatment x_{1ij} (organic versus non-
15 organic), β_2 is a fixed effect of the number of sampled habitats x_{2ij} in farm ij , and β_{3k} is a fixed
16 intercept for the taxonomic group k . The term b_{1j} is a random intercept for country j , b_{2jk} is a
17 random intercept for the combination of country j and taxonomic group k , and b_{3ij} is a random
18 intercept for farm ij . The term b_{4ijk} is a random intercept for observations of taxonomic group
19 k in farm ij and accommodates extra-Poisson variance due to over-dispersion⁵⁷. Random
20 effects b_1 to b_4 are normally distributed with mean 0 and variance σ^2 . Term b_{5ij} is a random
21 effect of taxonomic group k within farm ij . In order to account for the nestedness of the
22 observations of the four taxonomic groups within farm ij , b_{5ij} is multivariate normal, with
23 mean 0 and covariance matrix Σ .

24 The most parsimonious models of both measurements of species richness and organism
25 abundance at field level were full models without the fixed term β_2 and without random terms

1 b_2 and b_3 . The most parsimonious models of species richness and organism abundance at farm
 2 level was the full model without random terms b_1 , b_3 and b_4 . Significance of term β_1 was
 3 calculated by a log-likelihood ratio test with 1 degree of freedom⁵⁹.

4 Calculation of organic farming gain/loss

5 For individual regions and taxonomic groups, organic farming gains (OFGs) and losses were
 6 calculated as percent difference of organic farms (OFs) relative to non-organic farms (NOFs)

$$7 \quad \text{OFG} = 100 \cdot \frac{\bar{Y}_{\text{OF}}}{\bar{Y}_{\text{NOF}}} - 100, \quad (4)$$

8 where \bar{Y} is the mean species richness in organic and non-organic farms in each region.

9 The standard deviation⁶⁰ of the OFG is

$$10 \quad \text{sd}_{\text{OFG}} = 100 \cdot \sqrt{\frac{\text{sd}_{\text{OF}}^2}{n_{\text{OF}} \bar{Y}_{\text{OF}}^2} + \frac{\text{sd}_{\text{NOF}}^2}{n_{\text{NOF}} \bar{Y}_{\text{NOF}}^2}}, \quad (5)$$

11 where sd is the standard deviation and n is the number of observations in each group.

12 Organic farming gains and losses across regions and taxonomic groups were calculated based
 13 on coefficients estimated from mixed-effect models (eqs. 2 and 3). At the population mean,
 14 the expected effect of organic farming is $e^{\beta_0 + \beta_1} / e^{\beta_0} = e^{\beta_1}$ and hence

$$15 \quad \text{OFG} = 100 (e^{\beta_1} - 1) \quad (6)$$

16

17 Weighted random resampling

18 In order to assess the diminishing of organic farming gains to species richness from field to
 19 farm, we resampled fields according to their proportion of total farm area. Specifically, we
 20 generated 100 random sequences of all sampled habitats per farm weighted by their areal
 21 proportion^{61, p. 111}. This resulted in random sequences of habitats predominantly starting with

1 those habitats with high areal proportions. We then calculated the accumulation of species
2 richness along each sequence and, based on the 100 realizations, the mean accumulation of
3 species richness per farm. Finally, we fitted mixed-effects models for each taxonomic group
4 at each number of sampled habitats using equation 2 and calculated organic farming gains
5 using equation 6.

6

7

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