nature ecology & evolution

ARTICLES
DOI: 10.1038/s41559-017-0272-x

The former Iron Curtain still drives biodiversity–profit trade-offs in German agriculture

Péter Batáry[1,2*], Róbert Gallé[1,3], Friederike Riesch[1,4], Christina Fischer[5], Carsten F. Dormann[6], Oliver Mußhoff[7], Péter Császár[3], Silvia Fusaro[1,8], Christoph Gayer[1,9], Anne-Kathrin Happe[1,10], Kornélia Kurucz[1,11], Dorottya Molnár[1], Verena Rösch[1,12], Alexander Wietzke[13] and Teja Tscharntke[1]

Agricultural intensification drives biodiversity loss and shapes farmers' profit, but the role of legacy effects and detailed quantification of ecological–economic trade-offs are largely unknown. In Europe during the 1950s, the Eastern communist bloc switched to large-scale farming by forced collectivization of small farms, while the West kept small-scale private farming. Here we show that large-scale agriculture in East Germany reduced biodiversity, which has been maintained in West Germany due to >70% longer field edges than those in the East. In contrast, profit per farmland area in the East was 50% higher than that in the West, despite similar yield levels. In both regions, switching from conventional to organic farming increased biodiversity and halved yield levels, but doubled farmers' profits. In conclusion, European Union policy should acknowledge the surprisingly high biodiversity benefits of small-scale agriculture, which are on a par with conversion to organic agriculture.

Agricultural intensification greatly gained momentum after World War II due to increasing use of agrochemicals and mechanization[1–3] to mitigate starvation in almost the whole of Europe[4]. The vision was, at that time, to produce as much food as possible to overcome hunger and poverty in both the Eastern and the Western blocs (Supplementary Fig. 1). This led to increased yields, but was and still is coupled to biodiversity loss[5,6]. In the Eastern bloc, intensification was combined with a vast collectivization of farms, as farmers were forced to hand over their fields to state-owned cooperatives[7]. This practice aimed at increasing the efficiency of production through landscape-scale homogenization, including the removal of minor field roads, field margins, hedgerows and any semi-natural habitat inhibiting the ambitious production goals leading to large fields. This process was implemented in East Germany during 1953–1960 and resulted in a rapid change from small-scale agriculture, with more than 800,000 family farms, to large-scale agriculture, with fewer than 20,000 cooperatives. Meanwhile, such drastic change did not happen in the West[8]. After the German reunification in 1990, field sizes remained almost unchanged[9], while ownership changed from cooperatives to private, often Western or foreign farmers. This marked field-size difference is still visible along the former 'Iron Curtain'[10] (Fig. 1). At the same time, European Union (EU) legislation under the Common Agricultural Policy started providing financial support through agri-environmental schemes (AES) with, for example, organic management[11]. Although some studies questioned the effectiveness of AES in terms of biodiversity gains[12,13], both meta-analytical studies and large-scale field studies show that organic management supports threatened farmland biodiversity generally better than conventional farming[14,15], while also producing healthier food and less contamination of soils and groundwater[16]. Biodiversity advantages of small-scale farming and landscape heterogeneity have been acknowledged widely in ecology[17–21]. However, to the best of our knowledge, the ecological and economic role of large-scale versus small-scale farming has never been studied together. Further, we compared ecological and economic consequences of small-scale agriculture with those of organic farming for the first time.

The historical East–West division enabled us to test the effectiveness of organic cereal management for biodiversity in large-scale versus small-scale agriculture. We measured the diversity of plants and arthropods (Methods) and hypothesized that (1) biodiversity is higher in small-scale cropland[1] and (2) the effect of field size is more important for biodiversity than conversion to organic management. In 2013, we selected nine pairs of organic and conventional winter wheat fields in small-scale agricultural landscapes in former West Germany and in large-scale agricultural landscapes in former East Germany, respectively, all along the former inner German border (2 regions × 9 field pairs = 36 study fields; Supplementary Fig. 2). These two neighbouring study regions are representative of the farmland areas of the former East and West Germany[22,23]. We aimed to explore how biodiversity patterns change from field edges to field centres with the following within-field sampling design. We designated transects at field edges

[1]Agroecology, University of Goettingen, Grisebachstraße 6, 37077 Göttingen, Germany. [2]GINOP Sustainable Ecosystems Group, MTA Centre for Ecological Research, Klebelsberg Kuno utca 3, 8237 Tihany, Hungary. [3]Department of Ecology, University of Szeged, Közép fasor 52, 6726 Szeged, Hungary. [4]Institute of Grassland Science, University of Goettingen, von-Siebold-Straße 8, 37075 Göttingen, Germany. [5]Restoration Ecology, Department of Ecology and Ecosystem Management, Technische Universität München, Emil-Ramann-Straße 6, 85354 Freising, Germany. [6]Biometry and Environmental System Analysis, University of Freiburg, Tennenbacher Straße 4, 79106 Freiburg, Germany. [7]Department of Agricultural Economics and Rural Development, University of Goettingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany. [8]Department of Biology, Padua University, via Ugo Bassi 58, 35121 Padua, Italy. [9]Environment and Urban Planning, University of Applied Science Nürtingen-Geislingen, Schelmenwasen 4-8, 72622 Nürtingen, Germany. [10]Ecological Networks, Technical University Darmstadt, Schnittspahnstraße 3, 64287 Darmstadt, Germany. [11]Szentágothai Research Centre, University of Pécs, Ifjúság útja 20, 7624 Pécs, Hungary. [12]Institute for Environmental Science, University of Koblenz-Landau, Fortstraße 7, 76829 Landau, Germany. [13]Plant Ecology and Ecosystem Research, University of Goettingen, Untere Karspüle 2, 37073 Göttingen, Germany. *e-mail: pbatary@gmail.com

Fig. 1 | Illustrative map of West and East Germany (scale 1:30,000) at 25 May 2012. Field-size differences are shown between West and East Germany along the former Iron Curtain (red line) in the study area (around the villages of Weissenborn and Hohes Kreuz, southeast of Göttingen, on the border of Lower Saxony (West) and Thuringia (East)). Source of the photo: ESRI, World Imagery, DigitalGlobe.

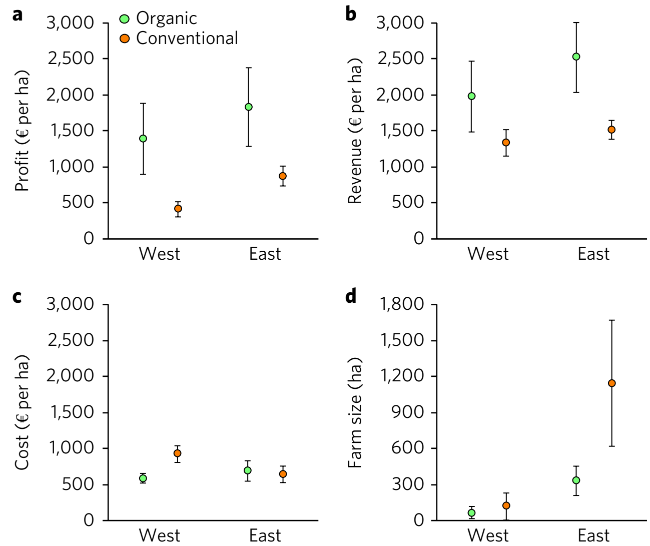

Fig. 2 | Effects of region and management on profit, revenue, cost and farm size. a–c, Farmers' profit (**a**), revenue (**b**) and cost (**c**) are measured in € per ha ($n=28$ fields). **d**, Farm size is measured in ha ($n=18$ farms). Organic farmers' revenue contained the subsidy for organic farming, which was €170 and €210 per ha in West and East Germany, respectively. Bars represent mean ± standard error of the mean. See Supplementary Table 1 for test statistics.

(directly next to narrow grassy field margins bordering dirt roads), field interiors (15 m from field edge) and field centres (120 m and 75 m from field edge in East and West, respectively). We performed our study in the agricultural matrix, minimizing the area and potential effect of non-agricultural habitats (Table 1)[24]. Landscape structure was very different between the two neighbouring regions, with fields more than six times larger in the East, and >70% longer field edges in the West. Conventional farmers in both regions used about five times the amount of nitrogen fertilizer compared with organic farmers, applied synthetic pesticides about five times per year (versus never) and had approximately two times higher yields than organic farmers[25,26]. This large difference in winter wheat yield between organic and conventional farmers is typical for the rich soils farmed in the study region[27].

We also performed a detailed economic survey of our study farms based on farmer interviews (Methods). Total costs included expenses for mechanical field work, seeds, soil analyses, chemical plant protection, chemical growth regulators, synthetic and organic fertilizers, agricultural wage enterprises and working time. Total revenues included grain and straw revenues as well as subsidies for organic agriculture. Total profit was calculated by deducting total costs from total revenues per field per hectare. We hypothesized that (1) large-scale agriculture is more profitable due to lower variable costs[28] and (2) organic agriculture is more profitable due to better marketing possibilities[29,30].

Table 1 | Landscape structure (in 500 m buffer) around and local management intensity of study fields in small- (West) versus large- (East) scale agricultural systems with organic versus conventional management (mean ± standard error of the mean) during 2013 ($n=36$ fields)

Model	West		East		Estimate ± 95% CI		
	Organic	Conventional	Organic	Conventional	Region	Management	R × M
Landscape structure							
Field size (ha)	3.7 ± 0.7	3.3 ± 0.4	21.7 ± 5.5	18.3 ± 2.1	**−14.14 ± 6.90**	2.16 ± 7.74	−1.55 ± 10.95
Edge length (km)	18.3 ± 1.3	19.5 ± 1.6	11.0 ± 0.8	10.8 ± 0.6	**8.38 ± 3.67**	0.02 ± 2.90	−1.52 ± 4.10
Grassy field margin (km)	7.2 ± 0.5	7.3 ± 0.4	5.5 ± 0.6	5.0 ± 0.9	**2.09 ± 1.90**	0.42 ± 1.73	−0.54 ± 2.45
Land-use diversity	1.4 ± 0.1	1.3 ± 0.0	0.9 ± 0.1	0.9 ± 0.1	**0.43 ± 0.26**	0.07 ± 0.22	−0.03 ± 0.31
Agricultural area (%)	73.9 ± 4.1	76.9 ± 6.2	81.0 ± 5.1	85.5 ± 4.5	−9.25 ± 16.11	−5.49 ± 13.55	2.90 ± 19.17
Management intensity							
Fertilizer (kg N ha^{-1})	21.6 ± 10.9	199.3 ± 6.3	65.3 ± 11.7	193.6 ± 8.6	−8.47 ± 33.76	**−129.61 ± 33.76**	**−57.10 ± 22.40**
Pesticide application (#)	0.0 ± 0.0	4.3 ± 0.4	0.0 ± 0.0	5.2 ± 0.7	0.19 ± 1.03	-	-
Yield (dt ha^{-1})	40.9 ± 2.5	85.2 ± 3.3	48.3 ± 2.5	85.3 ± 1.6	0.54 ± 8.25	**−37.91 ± 8.25**	−7.91 ± 11.67
Study field size (ha)	3.0 ± 0.5	3.1 ± 0.4	21.8 ± 3.6	20.0 ± 3.0	**−16.95 ± 7.18**	1.23 ± 5.59	−1.35 ± 7.90

Effects of region (R), management (M) and their interaction are shown as effect estimates ± 95% confidence intervals (CIs) from general and generalized linear mixed-effects models. N: nitrogen. #: number. Significant effects ($P<0.05$) are marked in bold.

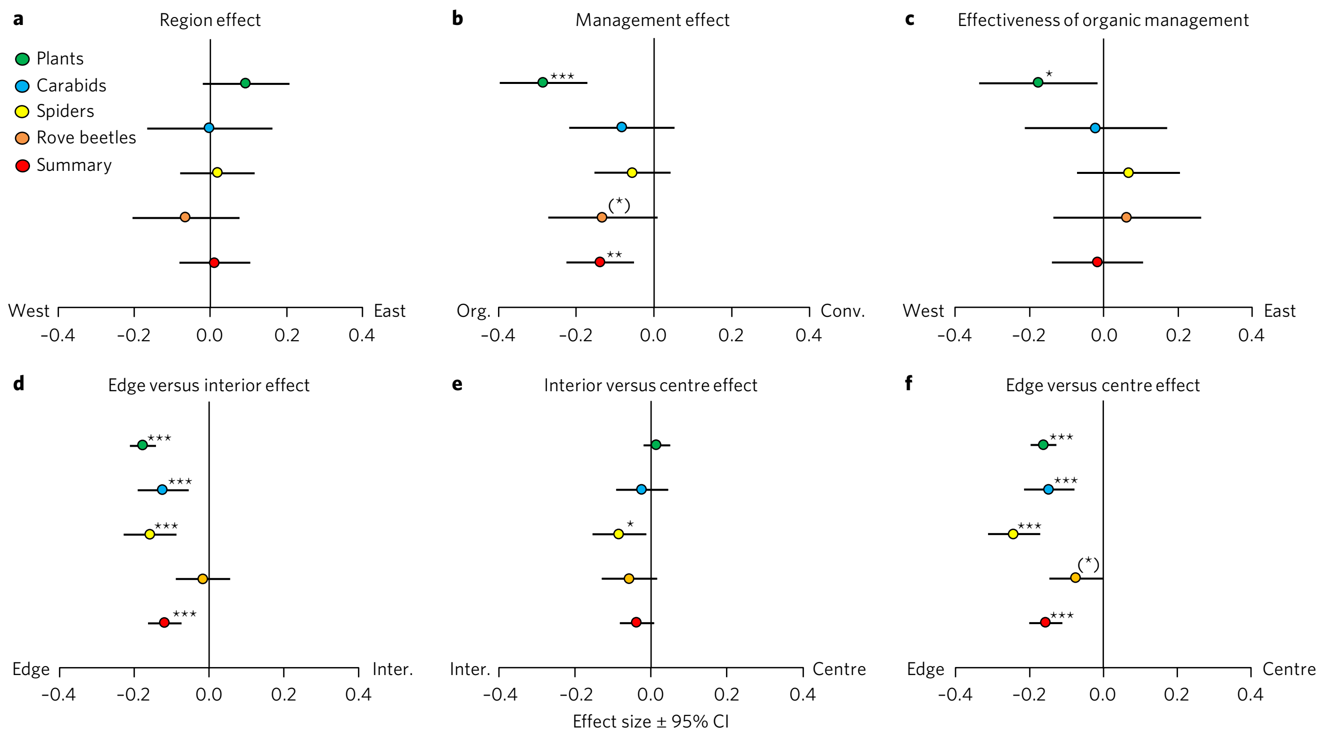

Fig. 3 | Effects of region and management, their interaction and edge effect on plant and arthropod species richness. a–f, Effects of region (**a**) and management (**b**), their interaction, that is, effectiveness of organic management (**c**), and edge effect (edge versus interior (**d**), interior versus centre (**e**) and edge versus centre (**f**)) on plant and arthropod species richness, as well as the summary effect from meta-analysis, expressed as effect estimate ± 95% confidence interval (CI) (n = 36 fields). Org.: organic; Conv.: conventional; Inter.: interior. Significance levels: (*)P < 0.1, *P < 0.05, **P < 0.01, ***P < 0.001.

Results

We found that farmers' profit from winter wheat was more than 100% higher per hectare under organic than conventional management (Fig. 2 and Supplementary Table 1). Subsidies for organic agriculture were €170 and €210 per ha in East and West (AES and subsidies vary among German federal states[31]), respectively, suggesting that these subsidies contributed to the difference in profit between the two management types. Although subsidies were a substantial part of profit for organic farmers, large differences between the two management regimes remain without these subsidies (mean values for West organic: €1,181 per ha; West conventional: €412 per ha; East organic: €1,663 per ha; East conventional: €874 per ha). We also found significantly higher profits per farmed area (~50–60%) in the large-scale than in the small-scale agricultural region. This is because of higher production costs in Western conventional farms due to current labour costs and higher revenues in Eastern organic farms[32] probably associated with better marketing possibilities (Fig. 2 and Supplementary Table 1).

There was no effect of region on species richness of plants and arthropods (carabids, rove beetles, spiders), as well as no overall effect of region when all groups were considered together in a fixed-effect meta-analysis[33] (Fig. 3, Supplementary Fig. 4 and Supplementary Tables 2–6) (Methods). The same was true when analysing arthropod abundances and plant cover (Supplementary Figs. 5 and 6). Organically managed fields harboured more species and individuals of all groups than conventionally managed fields. This effect was strongest for plants, which drove the overall summary effect resulting in 44% higher overall species richness in organically than conventionally managed fields. The statistical interaction of region and management was due to a higher effectiveness of organic management in the West for plant richness as well as spider abundances. Interestingly, both species richness and abundances were reduced by about 25% when comparing field edges with field interiors, but there was no further drop towards the field centres (except for spider richness). Hence, most farmland species and their populations were confined to the very edge of crop fields. This also implies that the higher biodiversity in the small-scale agricultural system in the West can be linked to the much higher amount of field edges[1,17,19].

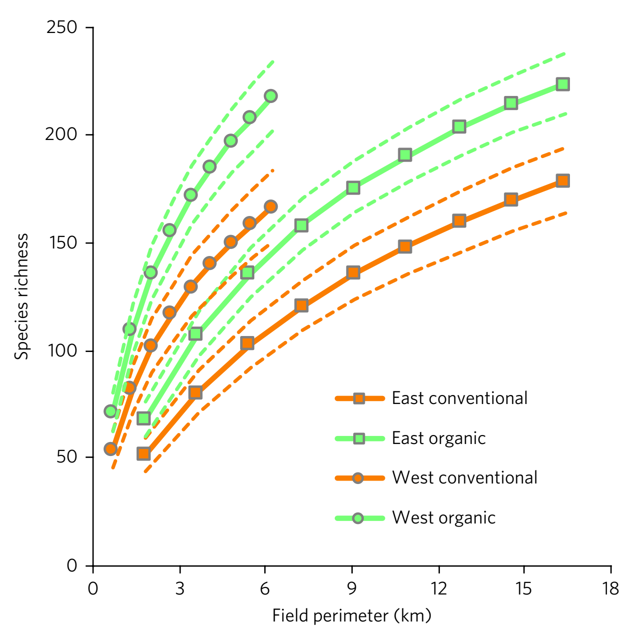

Fig. 4 | Effects of region and management on overall species richness. We used sample-based rarefaction curves standardized for perimeter per field (n = 36 fields; dashed lines represent 95% confidence intervals).

To further explore this pattern, we performed sample-based rarefaction curves[34,35] on incidence data of all taxa in field edges combined by standardizing for field perimeter (field perimeters originate from the mean field size per region, Table 1). The rarefied species richness observed in different types of management (organic over conventional) and region (West over East) was significantly different ($P < 0.05$; Fig. 4). Small-scale conventional management in the West supported higher biodiversity than large-scale organic management in the East (Fig. 4). Although the species richness per field was similar in both regions (Fig. 3), having only nine small fields in the West gives a much higher species richness than four large fields with the same length of field perimeter in the East regardless of management type. This means that the species richness in the fields, that is, alpha diversity, of these two contrasting regions was similar, whereas the species turnover, that is, between-field beta diversity, was much higher in the West than in the East. In addition, richness was higher in organic than in conventional management.

Discussion

Our study showed how the former Iron Curtain between East and West Germany and the associated divide in large-scale and small-scale agriculture are still shaping economic–ecological trade-offs in agriculture. We quantified the great contribution of small-scale agriculture to biodiversity, which was more important than organic management. Yield levels were the same across the East–West divide, but large-scale agriculture led to the highest profit (despite similar yield), and organic farming even doubled profit (despite halved yield). Although large-scale farms allow higher profits, which is in line with economies of scale[28], future restructuring of agricultural landscapes towards small fields with field margins would probably be an economically viable option under an EU-subsidized policy on enhancing farmland biodiversity[31]. We emphasize the importance of quantifying ecological–economic trade-offs for a politically balanced view. Further, the long-term stability of former East–West contrasts in agricultural politics and farming practices suggests that evaluations of ecological and economic costs and benefits need to be regionally adapted, taking into account agricultural traditions and potential legacy effects[36].

Methods

Biodiversity survey. In June 2013, we surveyed plants by estimating the relative cover per species in three plots (5 m × 1 m in size and 10 m distance between them) per transect (n = 324 plots). Arthropods (carabids, spiders and rove beetles) were collected with two funnel traps per transect in two one-week periods from May to June (n = 432 funnel traps; for the trapping method see Duelli et al.[37]).

Economic comparison. The following cost factors were considered per study field: field preparation, including sowing and harvesting (for example, costs due to the use of cultivator, milling machine, plough, harrow, chipper, curry comb, seed drill, harvester and baler), seeds, soil analyses, chemical plant protection (for example, fungicides, insecticides, herbicides, rodenticides or molluscicides), chemical growth regulators, synthetic and organic fertilizers, agricultural wage enterprises and working time. If costs of preparation, sowing (including seed costs) and harvesting were not tractable by farmers, we noted working steps and machine data, and later calculated expenses by the use of the online plant process calculator of the agricultural advisory board for engineering and building[38]. In doing so, we considered field size, workability of soil (medium or heavy soil), mechanization (kW, machine type, working width of machines or sowing quantity), field-to-farm distance (set up to 1 km) and farming system (organic or conventional). In terms of other parameters (for example, machine costs such as fuel requirement, repair costs and depreciation), we used standardized settings of the online calculator. If farmers' data did not fit exactly into the online calculator (for example, sometimes in the case of kW, field size or machine width), we used the next closest setting. In terms of farm-saved seed, we assumed €0.40 per kg of seed for conventional and €0.47 per kg of seed for organic farming systems (Association for Technology and Structures in Agriculture, personal communication) because statements of farmers showed a huge variation. Machine costs emerging through fertilization and chemical plant protection were calculated by using the default setting of the online calculator[38] while considering the farming system (organic or conventional), field size, workability of soil (heavy or medium) and cultivation method (direct sowing method, non-plough tillage or conventional soil cultivation with plough). If farmers provided information only about the kind and quantity of product used without prices (four farmers), then costs for chemical plant protection products and growth regulators were derived from different price lists[39–42]. If farmers were unable to provide prices for synthetic fertilizers, cost calculation was based on individual average prices of the fertilizers in Germany for the marketing year 2013–2014 (Agrarmarkt Informations, personal communication). Because farmers used organic fertilizers originating from their own enterprises, they were able to tell us just the quantity and the type of organic fertilizer. Average prices were derived from our own survey of regional companies (Nährstoffverwertung Oldenburger Raum Münsterland, Naturdünger Verwertungs, Agrovermittlungsdienst Emsland-Bentheim, Bioenergiedorf Jühnde), which deal with or use natural fertilizers. Prices for liquid manure and digested residue were generally set with €4 per t or €4 per m^3 (Lower Saxony) and €5 per t or €5 per m^3 (Thuringia), and solid dung with €10 per t. To calculate the costs of working time, we recorded the estimated working hours of each farmer (with reference to the whole winter wheat season 2013–2014). Working time was related to hectares and multiplied by €15 (this amount was based on our own experiences as well as on a farmer's estimate) to calculate costs per hectare.

In addition to the costs, we also considered the revenue side of the winter wheat season 2013–2014. Here, we recorded grain and straw yield as well as additional state grants for organic agriculture per study field. Grain yield was multiplied by actual proceeds stated by the farmers. Grain yield was sold or used as fodder, as seed or for baking purposes. If a crop was still not sold or used at the time of the survey, calculations were based on the estimated proceeds of each farmer. If straw was not left on the field, we also calculated the proceeds of straw (sold or used as fodder or litter). If not stated by the farmers (nine farmers), we used the average German sales price of straw (€73.8 per t) with reference to the marketing year 2013–2014 (Agricultural Market Information Company, 2015). Besides grain and straw proceeds, we also took into account state grants for organic agriculture as a source of revenue. Here, we considered federal state-specific subsidy rates of the business year 2013–2014 (cultural landscape programme of Thuringia: €170 per ha if organic farming was practised ≥six years; agri-environmental programme of Lower Saxony: €210 per ha if organic farming was practised ≥three years; Lower Saxony Ministry of Food, Agriculture and Consumer Protection and Thuringian Ministry of Infrastructure and Agriculture, personal communication).

All matters of costs and proceeds were calculated per hectare and year for each field. To obtain total revenue (€ per ha, field and business year), aggregated costs were subtracted from overall proceeds.

Statistical analysis. Due to limited availability of organic farms in the East (fewer organic farms in the East, but with an order of magnitude larger size than in the West[43]), we applied a so-called partly cross-nested design by selecting from half of the farmers two fields and from the other half only one field: in both regions we had three villages with two organic–conventional pairs and three villages with one organic–conventional pair (see Supplementary Figs. 2 and 3). Therefore, we applied linear mixed-effects models by using the 'lme4'[44] package of the statistical software R[45]. All biodiversity data were pooled per sampling year and per transect before analysis by taking the mean cover for arable plants and the sum for arthropods. Response variables, if needed, were either log (carabid and rove beetle abundances) or logit (plant cover) transformed to achieve a normal error distribution and/or avoid heteroscedasticity and to get a better model fit. Additionally, all response data were standardized from zero to one[46] to allow for direct comparisons of effects on the different dependent variables and to perform fixed-effect meta-analyses for getting the overall effects (see next paragraph). The partly cross-nested study design was taken into account in the random structure of the models. Accordingly, each model included the random effects: field (n = 36) nested in farm (n = 24), nested in village (n = 9); and field (n = 36) nested in pair (n = 18), nested in village (Supplementary Fig. 3). In addition, models contained the following fixed effects: region (East versus West), management (organic versus conventional), transect position (edge, interior or centre) and the interaction between region and management. This model formula in R-syntax is

$$\text{lmer}(y \sim (\text{Region} + \text{Management})\hat{}2 + \text{Transect position} + (1|\text{Village / Farm / Field}) + (1|\text{Village / Pair / Field}))$$

Marginal and conditional R^2 values for species richness and abundance models were calculated using the 'r.squaredGLMM' function of the 'MuMIn'[47] package of R. We did not simplify the models, to be able to directly compare their effect estimates among the different taxa and to summarize these estimates in a meta-analysis (see below).

One of the main interests was, besides investigating the environmental effects on each individual group, whether these environmental effects showed an overall effect. Therefore, we performed a series of unweighted fixed-effect meta-analyses for each effect type (region effect, management effect, effectiveness of organic management, edge versus interior effect, interior versus centre effect, edge versus centre effect) per measure type (species richness, abundance) with the 'metafor'[48] package of R. Weighting was not used, because data originate from the same experimental design with the same sample size per measure. This enabled us to get an effect estimate of all groups expressed as summary effect sizes with their corresponding 95% confidence intervals (presented in Fig. 3 and Supplementary Fig. 5).

We analysed the effects of region and management and their interaction on count data from economic surveys (profit, revenue and cost) with generalized linear mixed-effects models based on a negative binomial distribution for avoiding overdispersion. Random-effect terms correspond to the biodiversity analyses above without the random factor field, because that was the lowest level. This model formula in R-syntax is

$$\text{glmer}(y \sim (\text{Region} + \text{Management})\hat{}2 + (1|\text{Village} / \text{Farm}) + (1|\text{Village} / \text{Pair}))$$

We analysed the effects of region and management and their interaction on farm size with linear regression based on a normal distribution (no random effect). Finally, we analysed the effects of region and management and their interaction, presented in Table 1 with generalized linear mixed-effects models based on a normal distribution for all non-integer continuous data based on a normal distribution. One exception was the only count variable, namely, number of synthetic pesticide applications, which was analysed based on a negative binomial distribution for avoiding overdispersion. The structure of random effects was the same as in the case of economic survey data. In the case of number of synthetic pesticide applications, where effect of management could not be analysed (organic fields excluded because synthetic pesticides are not allowed), only village was used as a random factor.

Code availability. A complete description of the main model is provided in the Methods, and all code is available on request from the authors.

Data availability. Species presence data are available in the Supplementary Information (Supplementary Tables 3–6). The biodiversity and environmental data used in the analyses are archived at the research data repository Zenodo (https://doi.org/10.5281/zenodo.810513).

Received: 23 November 2016; Accepted: 3 July 2017;
Published online: 21 August 2017

References

1. Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I. & Thies, C. Landscape perspectives on agricultural intensification and biodiversity — ecosystem service management. *Ecol. Lett.* **8**, 857–874 (2005).
2. Smil, V. Detonator of the population explosion. *Nature* **400**, 415 (1999).
3. Foley, J. et al. Global consequences of land use. *Science* **309**, 570–574 (2005).
4. Kesternich, I., Siflinger, B., Smith, P. J. & Winter, K. J. The effects of World War II on economic and health outcomes across Europe. *Rev. Econ. Stat.* **96**, 103–118 (2014).
5. Kareiva, P., Watts, S., McDonald, R. & Boucher, T. Domesticated nature: shaping landscapes and ecosystems for human welfare. *Science* **316**, 1866–1869 (2007).
6. Ellis, E. C. et al. Used planet: a global history. *Proc. Natl Acad. Sci. USA* **110**, 7978–7985 (2013).
7. Iordachi, C. & Bauerkamper, A. (eds) *The Collectivization of Agriculture in Communist Eastern Europe: Comparison and Entanglements* (Central European Univ. Press, Budapest, 2014).
8. Schöne, J. in *The Collectivization of Agriculture in Communist Eastern Europe: Comparison and Entanglements* (eds Iordachi, C. & Bauerkamper, A.) 147–180 (Central European Univ. Press, Budapest, 2014).
9. Baessler, C. & Klotz, S. Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agric. Ecosyst. Environ.* **115**, 43–50 (2006).
10. Fischer, C. et al. Mixed effects of landscape structure and farming practice on bird diversity. *Agric. Ecosyst. Environ.* **141**, 119–125 (2011).
11. Petrick, M. & Zier, P. Regional employment impacts of Common Agricultural Policy measures in Eastern Germany: a difference-in-differences approach. *Agric. Econ.* **42**, 183–193 (2011).
12. Kleijn, D., Berendse, F., Smit, R. & Gilissen, N. Agri-environment schemes do not effectively protect biodiversity in Dutch agricultural landscapes. *Nature* **413**, 723–725 (2001).
13. Schneider, M. K. et al. Gains to species diversity in organically farmed fields are not propagated at the farm level. *Nat. Commun.* **5**, 4151 (2014).
14. Tuck, S. L. et al. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. *J. Appl. Ecol.* **51**, 746–755 (2014).
15. Gabriel, D. et al. Scale matters: the impact of organic farming on biodiversity at different spatial scales. *Ecol. Lett.* **13**, 858–869 (2010).
16. Barański, M. et al. Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: a systematic literature review and meta-analyses. *Br. J. Nutr.* **112**, 794–811 (2014).
17. Benton, T. G., Vickery, J. A. & Wilson, J. D. Farmland biodiversity: is habitat heterogeneity the key? *Trends Ecol. Evol.* **18**, 182–188 (2003).
18. Marshall, E. J. P., West, T. M. & Kleijn, D. Impacts of an agri-environment field margin prescription on the flora and fauna of arable farmland in different landscapes. *Agric. Ecosyst. Environ.* **113**, 36–44 (2006).
19. Fischer, J. et al. Should agricultural policies encourage land sparing or wildlife-friendly farming? *Front. Ecol. Environ.* **6**, 380–385 (2008).
20. Perfecto, I. & Vandermeer, J. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proc. Natl Acad. Sci. USA* **107**, 5786–5791 (2010).
21. Mendenhall, C. D., Karp, D. S., Meyer, C. F. J., Hadly, E. A. & Daily, G. C. Predicting biodiversity change and averting collapse in agricultural landscapes. *Nature* **509**, 213–217 (2014).
22. Thiele, H. & Brodersen, C. M. Differences in farm efficiency in market and transition economies: empirical evidence from West and East Germany. *Eur. Rev. Agric. Econ.* **26**, 331–347 (1999).
23. Happe, K., Balmann, A., Kellermann, K. & Sahrbacher, C. Does structure matter? The impact of switching the agricultural policy regime on farm structures. *J. Econ. Behav. Organ.* **67**, 431–444 (2008).
24. Batary, P., Baldi, A., Kleijn, D. & Tscharntke, T. Landscape-moderated biodiversity effects of agri-environmental management: a meta-analysis. *Proc. R. Soc. London Ser. B* **278**, 1894–1902 (2011).
25. Seufert, V., Ramankutty, N. & Foley, J. A. Comparing the yields of organic and conventional agriculture. *Nature* **485**, 229–232 (2012).
26. Seufert, V. & Ramankutty, N. Many shades of gray — the context-dependent performance of organic agriculture. *Sci. Adv.* **3**, e1602638 (2017).
27. Clough, Y., Kruess, A. & Tscharntke, T. Organic versus conventional arable farming systems: functional grouping helps understand staphylinid response. *Agric. Ecosyst. Environ.* **118**, 285–290 (2007).
28. Duffy, M. Economies of size in production agriculture. *J. Hunger Environ. Nutr.* **4**, 375–392 (2009).
29. Crowder, D. W. & Reganold, J. P. Financial competitiveness of organic agriculture on a global scale. *Proc. Natl Acad. Sci. USA* **112**, 7611–7616 (2015).
30. Reganold, J. P. & Wachter, J. M. Organic agriculture in the twenty-first century. *Nat. Plants* **2**, 1–8 (2016).
31. Batáry, P., Dicks, L. V., Kleijn, D. & Sutherland, W. J. The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.* **29**, 1006–1016 (2015).
32. Hill, B. & Bradley, B. D. *Comparison of Farmers' Incomes in the EU Member States* (European Commission, DG Internal Policies, 2015).
33. Borenstein, M., Hedges, V. L., Higgins, P. T. J. & Rothstein, R. H. *Introduction to Meta-analysis* (Wiley, Hoboken, NJ, 2009).
34. Colwell, R. K. EstimateS: statistical estimation of species richness and shared species from samples version 8.0 http://purl.oclc.org/estimates (2006).
35. Gotelli, N. J. & Colwell, R. K. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecol. Lett.* **4**, 379–391 (2001).
36. Sutcliffe, L. M. E. et al. Harnessing the biodiversity value of Central and Eastern European farmland. *Divers. Distrib.* **21**, 722–730 (2015).
37. Duelli, P., Obrist, M. K. & Schmatz, D. R. Biodiversity evaluation in agricultural landscapes: above-ground insects. *Agric. Ecosyst. Environ.* **74**, 33–64 (1999).
38. KTBL *Online Verfahrensrechner des Kuratorium für Technik und Bauwesen in der Landwirtschaft* [Online calculator of Association for Technology and Structures in Agriculture] http://daten.ktbl.de/vrpflanze/home.action (2015).
39. Agravis *Pflanzenschutz- und Schädlingsbekämpfungsmittel, Preisliste 2014* [Pesticides, Price List 2014] (Agravis Raiffeisen AG, 2014).
40. Landi *Bayer Detailpreisliste 2014* [Bayer Price List 2014] (LANDI Bachtel, Landw. Genossenschaft, 2014).
41. Schweiger *Pflanzenschutz Preisliste Frühjahr 2014* [Pesticide Pricelist Spring 2014] (Schweiger Agrar-, Bau-, Brennstoffhandel, 2014).
42. TopAgrar *Getreideherbizide gegen Unkräuter und Ungräser* [Cereal Herbicides against Weeds and Weed Grasses] (Landwirtschaftsverlag Münster, 2013).
43. Köpke, U. & Küpper, P. *Marktanteile im Segment Bio-Lebensmittel – Folgen und Folgerungen* [Market Shares in the Organic Food Segment – Consequences and Conclusions] (Institut für Organischen Landbau, 2012).
44. Bates, D., Maechler, M., Bolker, B. & Walker, S. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 1–48 (2015).
45. R Development Core Team R: a language and environment for statistical computing version 3.2.0 (2015).
46. Legendre, P. & Legendre, L. *Numerical Ecology* (Elsevier Science, Amsterdam, 1998).
47. Bartoń, K. MuMIn: multi-model inference R package version 1.14.0 (2015).
48. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48 (2010).

Acknowledgements

This paper is the product of the project 'Biodiversity and associated ecosystem services in small- vs. large-scale agriculture' by the German Research Foundation (DFG BA 4438/1-1).

We are grateful to L. Ádám for the identification of rove beetles, and to D.W. Crowder, A. Iverson and D. Kleijn for valuable comments on the manuscript. P.B. was supported by the Economic Development and Innovation Operational Programme of Hungary (GINOP–2.3.2–15–2016–00019).

Author contributions

P.B. and T.T. conceived the study; P.B., C.F., O.M. and T.T. developed the study; P.B., R.G., F.R., S.F., C.G., A.-K.H., K.K., D.M., V.R. and A.W. collected data; R.G. and P.C. identified arthropods; P.B. analysed data with substantial input from C.F.D.; and P.B. wrote the paper with substantial input from all authors.

Competing interests

The authors declare no competing financial interests.

Additional information

Supplementary information is available for this paper at doi:10.1038/s41559-017-0272-x.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to P.B.