Landscape context affects the sustainability of organic farming systems

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Organic agriculture promotes sustainability compared to conventional agriculture. However, the multifunctional sustainability benefits of organic farms might be mediated by landscape context. Assessing how landscape context affects sustainability may aid in targeting organic production to landscapes that promote high biodiversity, crop yields, and profitability. We addressed this using a meta-analysis spanning 60 crop types on six continents that assessed whether landscape context affected biodiversity, yield, and profitability of organic vs. conventional agroecosystems. We considered landscape metrics reflecting landscape composition (percent cropland), compositional heterogeneity (number and diversity of cover types), and configurational heterogeneity (spatial arrangement of cover types) across our study systems. Organic sites had greater biodiversity (34%) and profits (50%) than conventional sites, despite lower yields (18%). Biodiversity gains increased as average crop field size in the landscape increased, suggesting organic farms provide a "refuge" in intensive landscapes. In contrast, as crop field size increased, yield gaps between organic and conventional farms increased and profitability benefits of organic farming decreased. Profitability of organic systems, which we were only able to measure for studies conducted in the United States, varied across landscapes in conjunction with production costs and price premiums, suggesting socioeconomic factors mediated profitability. Our results show biodiversity benefits of organic farming respond differently to landscape context compared to yield and profitability benefits, suggesting these sustainability metrics are decoupled. More broadly, our results show that the ecological, but not the economic, sustainability benefits of organic agriculture are most pronounced in more intensive agricultural landscapes.

agriculture | biodiversity | yield | profitability | meta-analysis

Organic agriculture promotes socioecological sustainability with practices such as crop rotation, natural pest management, diversified crop and livestock production, and addition of compost and animal manures in place of synthetic inputs (1). Generally, organic farms produce lower yields than conventional farms (2, 3) but are more profitable (4). Organic agriculture also typically promotes biodiversity (5–7), natural pest control (8), pollination (5), soil quality (9, 10), and energy efficiency (10) while reducing pesticide use and other negative externalities that are associated with conventional agriculture (1). Due to recognition of these benefits and growing demand, organic farming has experienced rapid growth, with global sales of organic foods and beverages increasing by more than fourfold to $89.7 billion between 2001 and 2016 (11).

Organic farming is practiced in 178 countries on six continents (11). In turn, landscape context, such as the extent of crop production and the diversity of crop and noncrop habitats around fields or farms, varies across systems. Increasingly, studies show landscape context can mediate effects of farming practices on biodiversity (5–7, 12–20). Yet, whether landscape context mediates effects of organic agriculture on other sustainability metrics, such as crop yield and profitability, remains largely unknown. While one meta-analysis assessed landscape context effects on yields for organic and conventional farms, it focused on biological pest control (20); studies have also assessed effects of organic production on yield or profitability, but in a single country (14, 18). Studies that simultaneously quantify landscape context effects on biodiversity, yield, and profitability benefits of organic farming are needed to identify the landscape context(s) where organic agriculture may provide the greatest multifunctional benefits to sustainability.

To address this knowledge gap, we conducted a global meta-analysis to quantify the effects of landscape context on the sustainability of organic versus conventional agriculture using four socioecological sustainability metrics: 1) biotic abundance, 2) biotic richness, 3) crop yield, and 4) profitability. These metrics span ecological and economic dimensions of sustainability and are key indicators for evaluating sustainability of farming systems and directing policy (21, 22). We assessed how each metric was affected by landscape metrics that reflected composition (amount of land cover types), compositional heterogeneity (diversity of land cover types), and configurational heterogeneity (spatial arrangement of land cover types) (13). The landscape metrics were percent cropland (composition), crop field size (configurational heterogeneity), Shannon's habitat diversity

Significance

Organic agriculture promotes environmental and socioeconomic sustainability to a greater degree than conventional agriculture. However, it is unknown whether effects of organic agriculture on sustainability metrics such as biodiversity, crop yields, and profitability vary across the diverse landscapes where organic farming is practiced. We addressed this using a global meta-analysis spanning 60 crops. Organic sites had greater biodiversity than conventional ones, with the largest benefits in landscapes with large field sizes. In contrast, while organic sites also had greater profits, the largest benefits occurred in landscapes with small fields. The ecological sustainability benefits of organic agriculture are most pronounced in landscapes typified by more intensive agriculture, while economic benefits are likely influenced by socioeconomic factors and yields.

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index (compositional heterogeneity), and patch richness (compositional heterogeneity) (*SI Appendix*, Fig. S1 and Tables S1–S6). While studies assessing effects of landscape context on agroecosystems often focus solely on composition, it is recognized that landscape composition, configurational heterogeneity, and compositional heterogeneity can mediate ecological processes on farms (13–19). For example, a study of 435 landscapes along gradients of crop diversity and mean field size in Europe and Canada found that multitrophic biodiversity was more affected by crop field size than seminatural habitat (17). Similarly, crop field size affected profitability of organic compared to conventional farms in Germany after World War II (18). By including a diversity of landscape variables in analyses we were able to test various mechanisms by which landscapes might affect sustainability of organic compared to conventional systems (12–17).

We hypothesized landscape context would mediate biotic abundance and biotic richness differences between organic and conventional systems (5–7, 12–20), increased biodiversity benefits of organic farming would lead to smaller yield gaps (14, 23), and decreased yield gaps would boost profits in organic vs. conventional systems (4). Thus, we expected the sustainability metrics would respond to landscape features as coupled processes. Moreover, the effects of alternative systems, such as organic agriculture and agri-environment schemes, on promoting biodiversity compared to conventional systems may often occur most strongly in simple (80 to 95% cropland) compared to cleared (>95% cropland) or complex (<80% cropland) landscapes, also known as the "intermediate landscape-complexity hypothesis" (12, 15). Effects of landscape composition may also interact in nonadditive ways with configurational (crop field size) or compositional heterogeneity (Shannon's diversity index or patch richness) metrics (16, 17). However, whether such nonlinear and nonadditive effects of landscape context extend to crop yield and profitability differences between organic and conventional farms remains unknown.

To address these questions, we compiled metadatasets spanning 60 crops on six continents (Fig. 1) across a range of agronomic practices and landscape contexts (*SI Appendix*, Tables S7–S10), although profitability studies came only from the United States. We calculated 102, 94, 159, and 37 effect sizes for biotic abundance, biotic richness, yield, and profitability, respectively (Datasets S1 and S2 and *SI Appendix*, Tables S11–S14); each effect size represented one comparison between an organic and conventional system. The majority of studies in the metadataset were conducted in homogenous landscapes (for example, plots at an experimental station) (*SI Appendix*, Table S15 and Figs. S2–S9). However, some studies included data from multiple fields across a gradient of landscape complexity. For these studies, we averaged landscape metrics across all sites sampled in the study to represent the average landscape where the study was conducted. For each sustainability metric tested, our metadataset included a range of between-study landscape complexity gradients (*SI Appendix*, Figs. S2–S9). More simple landscapes were characterized by large crop fields, high percent cropland, low patch richness, and/or low Shannon's diversity index, while complex landscapes were characterized by small crop fields, low percent cropland, high patch richness, and/or high Shannon's diversity index.

For each sustainability metric we calculated log-response ratios as effect sizes comparing organic and conventional systems (24). Data for biotic abundance and richness were the number of individuals or taxa, respectively, for organismal groups in each field or adjacent field borders. Our data spanned Archaea, arthropods, bacteria, birds, earthworms, fungi, mammals, nematodes, plants, and protozoa (*SI Appendix*, Tables S8, S11, and S12). Data for yield were based on the same crop grown in both systems and spanned various annual and perennial crops (*SI Appendix*, Tables S9 and S13). Profitability data were costs and gross returns including premiums, which were used to calculate benefit/cost ratios for each system (4) (*SI Appendix*, Tables S10 and S14). For each sustainability metric we tested the overall effect size against 0 (representing no difference between farming systems) using one-sample *t* tests. We then tested whether various landscape factors mediated these effects using metaregression.

Results and Discussion

Effects of Organic and Conventional Agriculture on Sustainability Metrics. Overall, organic systems had greater biotic abundance (mean effect size = 0.32, 90% CI: 0.19 to 0.45) ($t_{101} = 4.01$, $P = 0.0001$) and biotic richness (mean effect size = 0.32, 90% CI: 0.22 to 0.43) ($t_{93} = 5.88$, $P < 0.0001$) than conventional systems (Fig. 2). These results are consistent with previous meta-analyses on the effects of organic compared to conventional agriculture on abundance and diversity of many organismal groups (5–7). Compared to conventional systems, organic agriculture had lower overall yields (mean effect size = −0.27, 90% CI: −0.32 to −0.22) ($t_{158} = -9.03$, $P < 0.0001$) but greater profitability (mean effect size = 0.59, 90% CI = 0.45 to 0.73) ($t_{36} = 7.15$, $P < 0.0001$) (Fig. 2), as also shown by other meta-analyses (2–4).

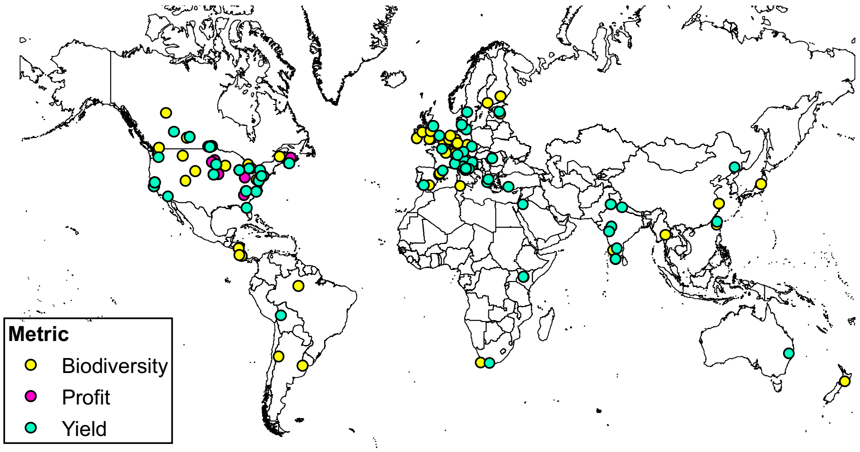

Fig. 1. Global distribution of studies. Map showing distribution of studies on biotic communities (biodiversity) (*n* = 81), yield (*n* = 78), and profit (*n* = 9).

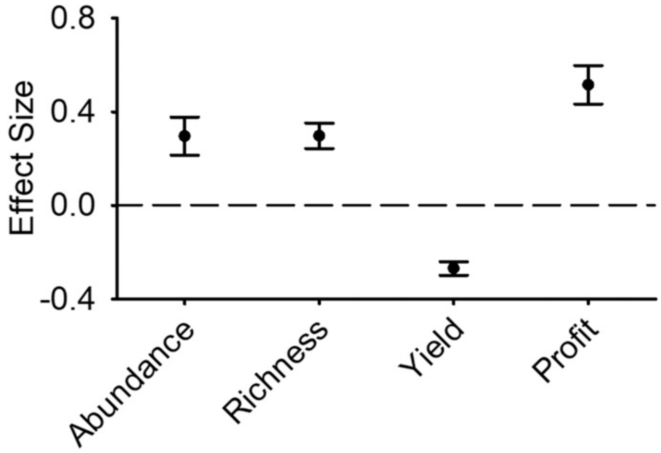

Fig. 2. Effect size (mean ± SE) in organic vs. conventional systems. Shown are results for biotic abundance ($n = 102$), biotic richness ($n = 94$), yield ($n = 159$), and profit ($n = 37$). An effect size of 0 indicates no difference between organic and conventional systems. Values above 0 indicate a higher value for the sustainability metric in organic systems; values below 0 indicate a higher value for the sustainability metric in conventional systems.

Effects of Landscape Context on Biotic Communities. The benefits of organic farming for biotic abundance and richness were best predicted by average crop field size in the landscape (abundance: *SI Appendix*, Tables S16–S21; richness: *SI Appendix*, Tables S22–S27; Fig. 3 *A–D*). The Akaike weight (ω) for field size was >0.67 for all abundance models and >0.85 for all richness models, and field size had regression coefficients that did not overlap 0 in all models (*SI Appendix*, Tables S16, S18, S20, S22, S24, and S26); field size was also included in the most well-supported models ($\Delta AICc < 2.0$) for abundance and richness (*SI Appendix*, Tables S17, S19, S21, S23, S25, and S27). Other landscape metrics, including percent cropland (including the quadratic term), Shannon's diversity index, and patch richness had ω values <0.39 in all cases; these variables were also not included in the well-supported models except for percent cropland in abundance models (*SI Appendix*, Tables S16–S27). Overall, a one-unit increase in average crop field size resulted in a 3.1% and 2.3% increase in the biotic abundance or richness, respectively, in organic relative to conventional systems (Fig. 3 *A* and *B*). Effects of field size on abundance in organic compared to conventional systems were consistent across organism groups ($\chi^2 = 9.5$, degrees of freedom [df] = 7, $P = 0.22$), functional groups ($\chi^2 = 8.1$, df = 7, $P = 0.32$), continents ($\chi^2 = 0.61$, df = 4, $P = 0.96$), biomes ($\chi^2 = 3.5$, df = 4, $P = 0.47$), crop types ($\chi^2 = 4.2$, df = 7, $P = 0.76$), and level of development ($\chi^2 = 0.0060$, df = 1, $P = 0.93$). Similarly, effects of field size on richness differences between organic and conventional systems were consistent across organism groups ($\chi^2 = 5.2$, df = 8, $P = 0.73$), functional groups ($\chi^2 = 7.7$, df = 10, $P = 0.66$), continents ($\chi^2 = 4.5$, df = 3, $P = 0.22$), biomes ($\chi^2 = 0.69$, df = 3, $P = 0.87$), crop types ($\chi^2 = 0.92$, df = 6, $P = 0.99$), and level of development ($\chi^2 = 0.66$, df = 1, $P = 0.42$).

Studies conducted in conventional and organic farming systems show that crop field size often has a negative correlation with the abundance and diversity of taxa such as plants, birds, and arthropods (17, 18, 25, 26). Our results show a similar effect of crop field size in boosting the biodiversity benefits of organic farms, but we found that percent cropland, the most widely used landscape context variable in the agroecological literature (5–7, 12, 13), was not significant. These results occurred despite the low resolution of the global field size layer (1 km) compared to the percent cropland layers for the United States and Europe (~30 m). Moreover, our data did not strongly support the intermediate landscape complexity hypothesis, as quadratic effects of percent cropland or crop field size were not significant or of high weight in any biotic models (*SI Appendix*, Tables S16–S27). While the intermediate landscape complexity hypothesis has typically been evaluated only in the context of percent cropland, crop field size can also reflect intensification, but the lack of quadratic effects of both of these variables suggest trends were largely linear. Nonetheless, our results provide further evidence supporting recent studies that show that aspects of landscapes associated with configurational heterogeneity, such as crop field size, can affect communities as much or more than compositional heterogeneity variables such as percent cropland (17, 18, 25, 26).

Crop field size may reflect agricultural intensification, as areas with larger fields often have greater agricultural investment, mechanization, and labor intensity (27). We show that crop field size was also positively correlated with the percent cropland (Fig. 4*A*) but negatively correlated with crop patch richness (Fig. 4*B*), crop diversity (Fig. 4*C*), and natural habitat diversity (Fig. 4*D* and *SI Appendix*, Table S28). This suggests regions with larger crop fields were more intensified. Crop fields were largest in North America and smallest in Asia, with South America and Europe having intermediate-sized fields (*SI Appendix*, Fig. S10*A*). Crop fields were also larger in developed relative to less-developed countries (*SI Appendix*, Fig. S10*B*) and in temperate compared to tropic or desert biomes (*SI Appendix*, Fig. S10*C*). These trends match observations that agricultural intensification has occurred most extensively in temperate regions such as North America and in more developed countries (28). This may be important because larger conventional crop fields are often associated with a greater use of synthetic inputs (fertilizers and pesticides) (29) that can harm biological communities (30, 31). As organic farms typically use fewer pesticides than conventional farms (1), our results may reflect that organic farming is most beneficial in boosting biodiversity in landscapes where biological communities have been harmed by agricultural intensification (i.e., landscapes with large crop fields). Put another way, our results suggest that organic agriculture may provide a refuge for organisms in intensified landscapes. Our maps suggest that organic agriculture in the upper midwestern United States, eastern Europe, and western Asia may promote biodiversity to the largest degree compared to conventional systems (Fig. 3 *C* and *D*), although our data extent makes it difficult to extrapolate these results to tropical or less-developed regions (*SI Appendix*, Tables S11 and S12).

Small fields also have greater edge-to-area ratios than large fields, and a greater proportion of the area of small fields resides in close proximity to a field border. This can benefit organisms that require multiple cover types, as they can move more easily between small compared to large fields (landscape complementation) (17, 18). One study showed the majority of organisms in agroecosystems accumulate near field edges, and regions with small fields received the greatest benefits from organic practices because organisms had access to the majority of field borders (18). Our results instead show the opposite trend: large fields promoted the greatest biodiversity benefits of organic sites. This may occur if organisms can more easily move from conventional fields into natural habitat patches following disturbances, such as pesticide sprays, if fields are small compared to large. If organisms are less capable of escaping conventional farms when they are large they could incur greater harm from disturbances, which could elevate the biodiversity benefits of organic systems. This would support the hypothesis that boundary zones connecting habitats are key for supporting biodiversity in agroecosystems (32, 33).

Effects of Landscape Context on Yield. Empirical studies show that greater biodiversity on farms can promote higher crop yield

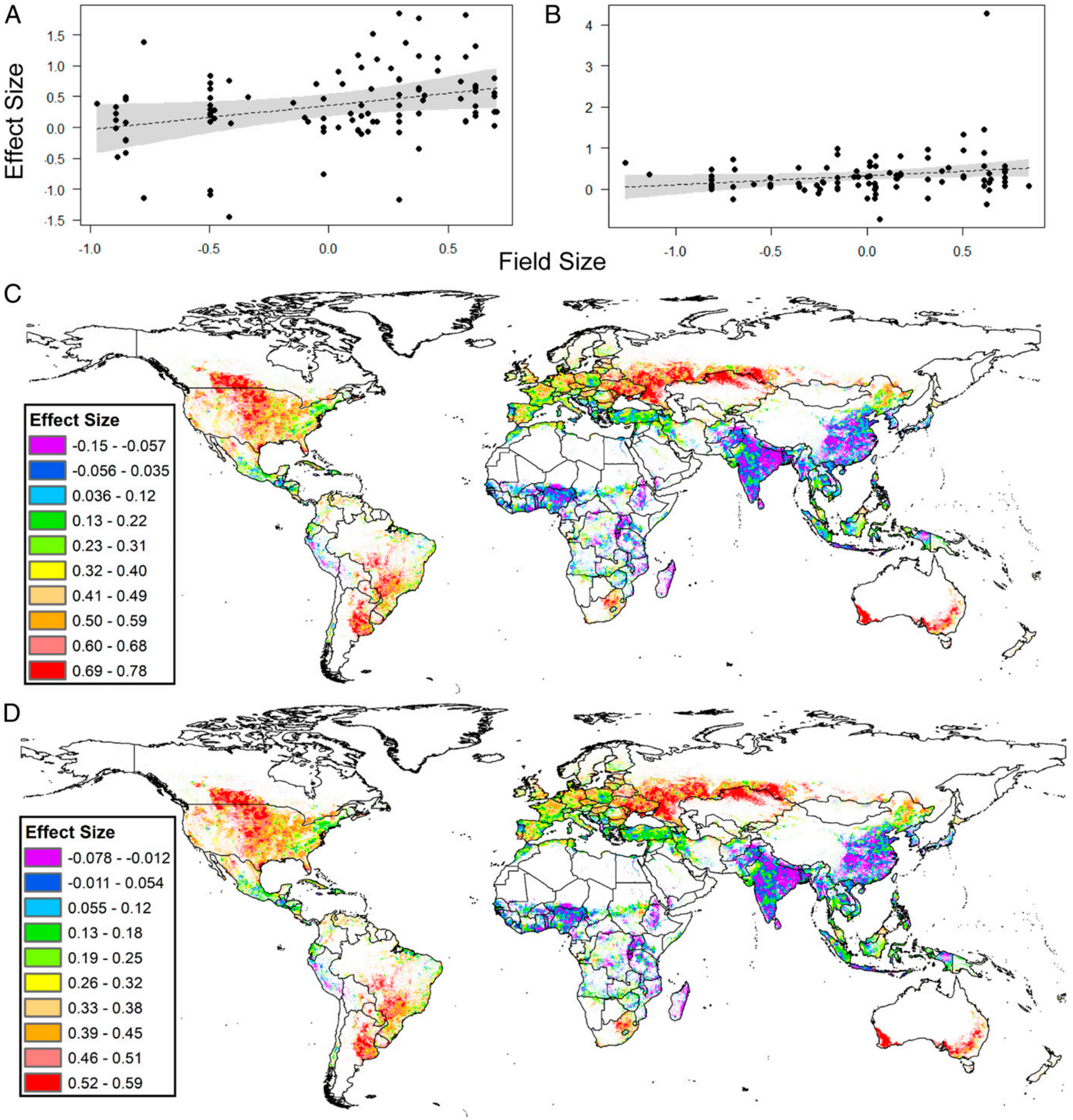

Fig. 3. Relationship between crop field size, biotic abundance, and biotic richness. (*A* and *B*) Best-fit regression (and 90% CIs) showing relationship between average crop field size based on Fritz et al. (49) and the log response-ratio effect sizes for (*A*) biotic abundance and (*B*) biotic richness. (*C*) Map showing predicted effect size of biotic abundance in organic vs. conventional systems with varying field sizes (*SI Appendix*, Fig. S14*A*) and (*D*) map showing predicted effect size for biotic richness in organic vs. conventional systems with varying field sizes (*SI Appendix*, Fig. S14*A*). Coefficients used to generate regressions and maps were based on the most-well-supported simple statistical models (biotic abundance: *SI Appendix*, Table S16; biotic richness: *SI Appendix*, Table S22).

(34–37). In turn, positive effects of organic farming on biodiversity might translate into greater yields on organic compared to conventional farms. This could occur due to more effective pest control if organic farms contain more natural enemy species (ref. 34, but see ref. 20), or if organic farms with greater pollinator diversity have increased fruit set (36). Moreover, greater plant diversity in agroecosystems is often associated with decreased pest densities (35). However, while organic systems boosted biotic abundance and richness particularly in landscapes with large crop fields, the yield gap between organic and conventional systems was not strongly affected by landscape metrics in the simple models (*SI Appendix*, Tables S29 and S30). However, in more complex models that included compositional heterogeneity metrics (either Shannon's diversity index or patch richness), the quadratic term for field size had a significant negative coefficient, indicating a downward-facing curve (*SI*

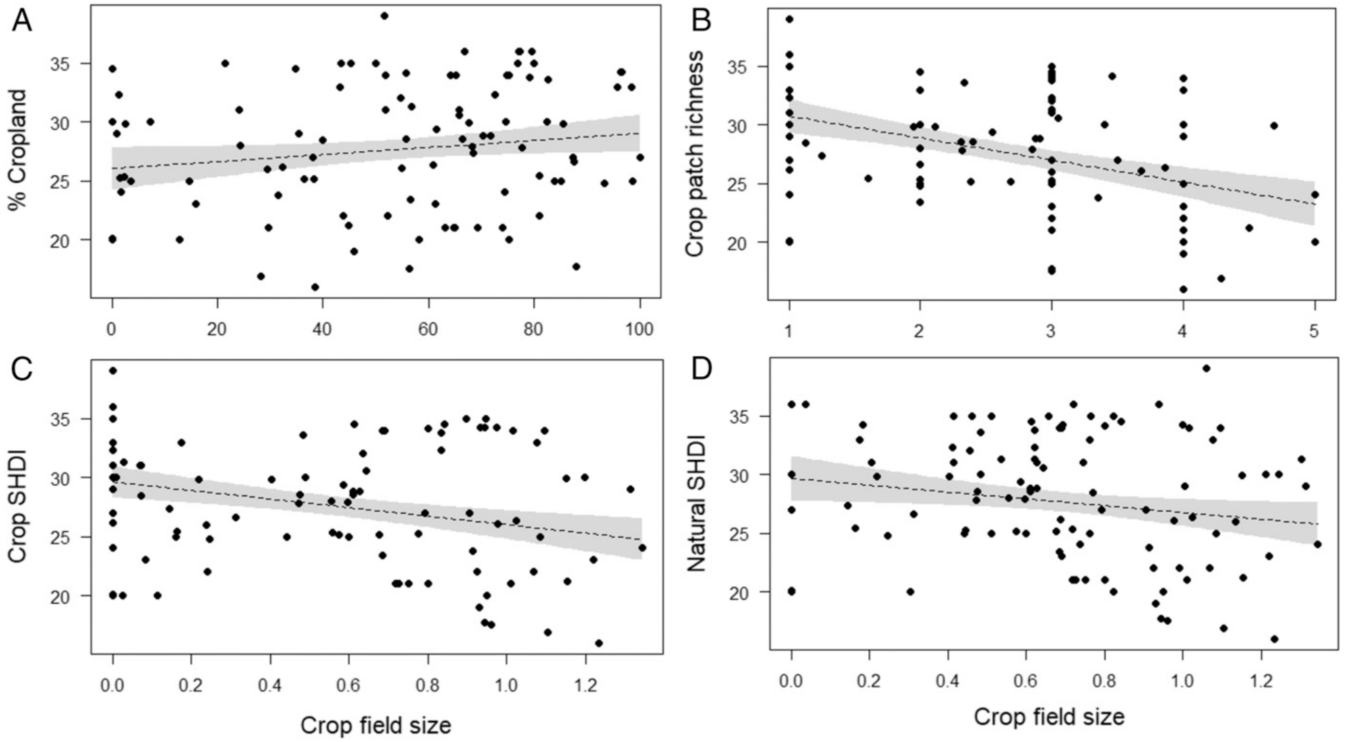

Fig. 4. Relationship between crop field size and various metrics of landscape context. Correlations (and 90% CIs) showing the relationship between average crop field size and (*A*) percent cropland, (*B*) crop patch richness, (*C*) crop diversity (Shannon's diversity index, SHDI), and (*D*) natural habitat diversity (SHDI) in the broader landscape. See *SI Appendix*, Table S28 for statistical output of models.

Appendix, Tables S31–S34). In simple and complex model sets, the field size metric had the highest ω and was included in most well-supported models (*SI Appendix*, Tables S29–S34 and Fig. S11). Effects of field size on yield were robust across continents ($\chi^2 = 4.7$, df = 3, $P = 0.20$), biomes ($\chi^2 = 5.0$, df = 3, $P = 0.17$), crop types ($\chi^2 = 12.5$ df = 7, $P = 0.084$), and development level ($\chi^2 = 1.1$, df = 1, $P = 0.29$).

We could not explore direct relationships between effects of organic systems on yield and biotic abundance or biotic richness compared to conventional agriculture, given that too few studies examined all of these metrics. However, the differential responses of these sustainability metrics to landscape context suggests that they may not be strongly linked in the field. One possible explanation is that the benefits of organic farming are typically greatest for rare species (7), and these rare species may not play key roles in providing ecosystem services (7, 38). If the benefits of organic compared to conventional farming primarily accrue for rare species that contribute little to ecosystem services such as yield, this may explain why benefits of organic farming for biodiversity did not translate into greater yields on organic farms. Moreover, it remains unclear whether biotic abundance and biotic richness gains in organic compared to conventional farms were primarily due to beneficial taxa, such as pollinators and predators, or harmful pests, or a combination of both. If gains to abundance and richness of ecosystem service providers are offset by similar gains in pest densities at the same sites, benefits to yield may be minimal (8, 20, 22). Yet, if gains to abundance and richness on organic farms are greatest for pests, it may partially explain why biodiversity metrics and yield responded in the opposite direction to crop field size. Prior meta-analyses show that weeds are more abundant in organic systems (6), but pollinators and natural enemies are boosted (5, 7), suggesting simultaneous gains in pest and beneficial species likely occur on organic farms.

We only observed strong effects of landscape context on yield in complex models, such that our results for effects of crop field size were not as robust as with the biodiversity metrics; the magnitude of the field size effect was also smaller for yield (*SI Appendix*, Fig. S11) compared to biotic abundance and richness (Fig. 3 *A* and *B*). This suggests that the productivity of organic compared to conventional farms is mediated primarily by on-farm management. Organic farmers may be able to reduce yield gaps with comparable conventional systems by using multicropping, longer crop rotations, and more nitrogen fertilizers (2, 3). Yield gaps can also be reduced when organic farms incorporate perennial crops or legumes, when soils have a neutral pH, and in rain-fed systems (2, 3). Farms with high water-use efficiency and effective weed control also typically have higher yields (22). Yield gaps between conventional and organic farms may also be dependent on crop type; fruit crops tend to have little to no yield gap, while vegetable and cereal crops tend to have the largest gap (2, 3). Overall, our results suggest that yield gaps may be more influenced by on-farm practices than by landscape context, the former of which can be controlled by growers.

Perhaps the biggest criticism of organic farming is its lower yields relative to conventional agriculture (39, 40). However, some contend that environmental advantages of organic systems far outweigh lower yields and that increasing research and breeding resources for organic systems would reduce yield gaps (41, 42). Globally, enough food is produced to more than feed the world's population, but inequities in food distribution do not allow for adequate access to all individuals (43). More and more, scientists are arguing that we need to consider multiple sustainability indicators other than crop yield to better promote global food security (44, 45). In that light, although organic systems produce lower yields than conventional agriculture, they are more profitable and environmentally friendly and deliver equal or more nutritious foods with fewer pesticide residues (1–4). Our study suggests that a singular focus on yield may cause other factors that differ between organic and conventional farms to be overlooked.

Effects of Landscape Context on Financial Performance. While yield gaps were not strongly affected by landscape context, the relative profitability of organic systems had a significant negative relationship with crop field size (Fig. 5 and *SI Appendix*, Tables S35, S37, and S39 and Fig. S12). Average crop field size had a ω >0.79 in both simple and complex models (*SI Appendix*, Tables S35, S37, and S39). Crop field size was also the only factor retained in the most-well-supported models (*SI Appendix*, Tables S36, S38, and S40). The percent cropland, Shannon's diversity index, patch richness, and interactions between these variables and field size always had a ω <0.27 (*SI Appendix*, Tables S35–S40). Effects of field size on profitability were stronger in cereals and oil crops than in vegetables, with intermediate effects for fruits and legumes ($\chi^2 = 16.5$ df = 4, $P = 0.0024$).

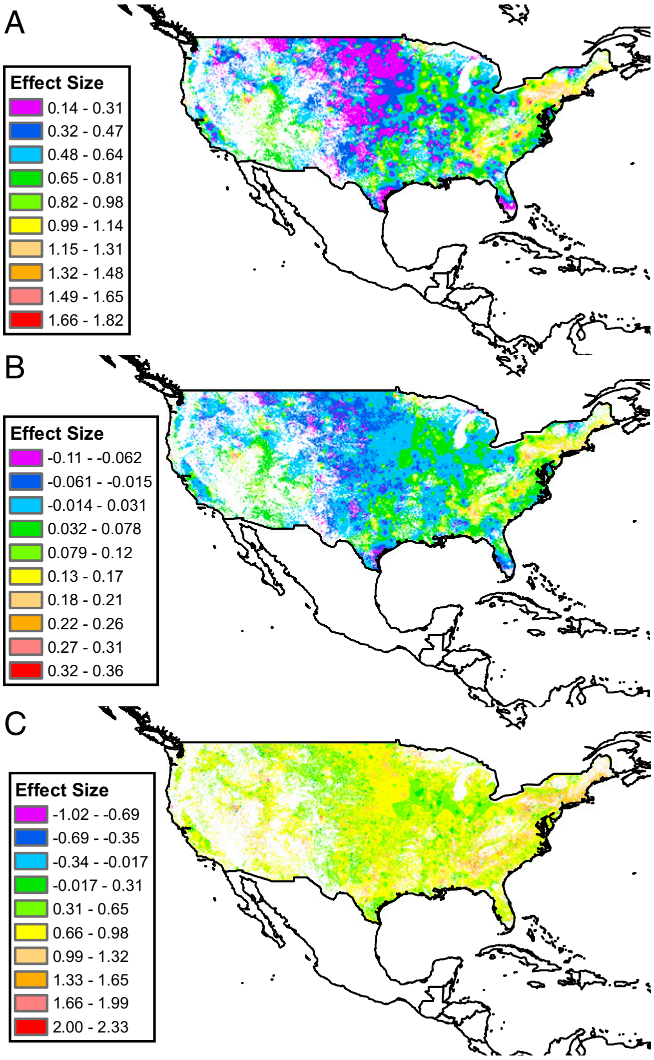

Fig. 5. Relationship between landscape context, profitability, costs, and price premiums. Maps showing predicted effect sizes comparing organic vs. conventional farming for (*A*) profits, (*B*) production costs, and (*C*) organic price premiums (based on crop field size and/or percent cropland; see *SI Appendix*, Fig. S14; regression coefficients for these landscape factors were taken from most-well-supported simple statistical models; see *SI Appendix*, Tables S35, S41, and S47). All of these variables were highly correlated. Only the predictions for the United States are shown given that this was the geographic scope of our input studies; interpolations beyond this region would not be supported by our dataset.

However, our metadataset for profitability only contained studies conducted in the United States. Few studies on profitability were conducted outside this country, and most of those that existed did not contain landscape coordinates. Thus, while our biotic abundance, biotic richness, and yield analyses reflected global trends (although data were primarily from the United States, Canada, and Europe, hindering inference about tropical systems), our results for profitability were limited to the United States. To our knowledge, the only other study that has examined the influence of landscape context on agricultural system profitability was conducted on wheat production in landscapes of West and East Germany following World War II (18). This study found that organic farming experienced the greatest profit gain in less-intensified landscapes of West Germany that had smaller field sizes compared to East Germany, in line with our findings.

The main factors that determine the profitability of organic agriculture are price premiums, crop yields, labor costs, and potential cost savings from reduced inputs (4). Our results reinforce this finding, given that increased profitability of organic compared to conventional systems was positively correlated with reduced costs (*SI Appendix*, Fig. S13*A*), lower yield gaps (*SI Appendix*, Fig. S13*B*), and greater price premiums (*SI Appendix*, Fig. S13*C*); the negative effect of crop field size on profitability also mirrors the effect on yields (*SI Appendix*, Fig. S11). Thus, we assessed how each of these metrics responded to landscape context to assess mechanisms that might explain the complex relationship between landscape context (crop field size, percent cropland, and landscape heterogeneity) and profitability. Production costs, price premiums, and benefit/cost ratios responded in qualitatively similar ways to average crop field size, although percent cropland and landscape diversity (Shannon's diversity index and patch richness) were also included in some of the most-well-supported models for costs and price premiums unlike benefit/cost ratios (Fig. 5 and *SI Appendix*, Tables S35–S52). Thus, variation in crop yields, farm production costs, and organic price premiums across landscapes appears to be the primary driver of landscape-level effects on profitability of organic compared to conventional systems.

Given that profitability varies across landscapes in response to production costs and price premiums received in different landscapes, understanding factors that shape organic markets for producers (which differ from consumer markets) and consumer willingness to pay a premium for organic foods is critical. Profitability will be highest in areas with large numbers of consumers of organic foods, or greater supplies of organic inputs, which may often occur in areas with greater population density and median income (46). Moreover, areas with lower property taxes and those closer to interstates tend to have larger organic markets for producers (46). In more rural areas with less infrastructure, consumer density may be too low to support markets for organic goods with premiums, and farmers who sell their crops in these regions may receive lower premiums.

Win–Win Scenarios and Knowledge Gaps. We found that large crop field sizes were associated with greater biotic abundance and biotic richness benefits in organic compared to paired conventional systems (*SI Appendix*, Tables S16–S27 and Fig. 3) but lower yield and profitability benefits (Fig. 5 and *SI Appendix*, Tables S29–S40 and Figs. S11 and S12). However, while benefits of organic farming for biodiversity were greatest in landscapes with large crop fields, organic farming promoted biodiversity across all landscape contexts analyzed (effect sizes >0 for any crop field size; Fig. 3 *A* and *B*). Areas with small crop fields also had the lowest yield gap between organic and conventional farms and greatest profitability benefits. Regions with small crop fields may thus promote "win–win" scenarios where organic farming boosts biodiversity and profitability with minimal yield gaps compared to conventional farming. Yet, our dataset only allowed us to assess such "win–win" scenarios in the United States and are limited in predicting such scenarios for other regions, particularly the tropics, from which we have few data and in which systems may be quite different (Fig. 1). More specifically, our datasets for biotic communities (81 total studies) and yield (78 total studies) were considerably larger than our profitability dataset (9 studies), with more data being needed for profitability from systems outside the United States to more effectively explore potential "win–win" scenarios.

We note that we compared the magnitude of differences in biodiversity and profitability in organic vs. conventional systems rather than absolute values. Thus, biodiversity may be relatively impoverished in organic systems in more-intensified landscapes compared to organic systems in less-intensified regions, such as shade-grown organic coffee, while profits in the United States might be higher than in other regions. Moreover, although most of our studies were conducted in homogeneous landscapes with little variability across sites (*SI Appendix*, Table S15), some studies were conducted along landscape gradients such that we calculated average landscapes per study. This may confound results if average landscape metrics poorly characterized the overall landscape, which might occur if landscape variables such as crop field size were nonnormally distributed. Finally, we note that our results may have been biased by different resolutions of land cover data used in the United States, where all of our profitability studies were conducted, compared to the more global analysis of biotic communities; however, we used the best available data by region. More studies that assess the benefits of organic farming on biotic communities, yield, and profitability in the same ecological context, but spanning landscape gradients, would aid in identifying "win–win" scenarios for farmers in areas with growing organic markets.

Conclusion

Recent studies call for a multiecosystem service approach to study sustainable agriculture (1, 22, 47). While the literature shows strong links between agricultural landscapes and effects of organic vs. conventional agriculture on biological communities (5–7), few studies have assessed effects of landscape context on relative yield or profitability of organic farms. Our results show that landscape factors that mediate biotic abundance and biotic richness differences between organic and conventional farming are not necessarily the factors that impact yield or profitability differences. Our results, therefore, suggest that these processes may be largely decoupled, lending further support that different sustainability metrics can respond to different landscape metrics (48) or respond to the same landscape metric in opposite directions (18). Moreover, our results provide evidence that some sustainability metrics may respond strongly to on-farm practices rather than landscape context. Studies that examine multiple sustainability metrics simultaneously are increasingly needed to identify potential "win–win" scenarios for organic farmers across the diverse landscapes where organic agriculture is practiced worldwide.

Methods

Literature Search. We searched for studies reporting organic vs. conventional abundance, richness, yield, and profit comparisons. First, we searched references from 12 prior meta-analyses (*SI Appendix*) and then used ISI Web of Knowledge to search for additional studies published after the last date of the most recent meta-analysis from which metadata were available for biotic communities, yield, and profitability. Our search was performed in December 2017 using the terms "organ* AND conven* AND diversity* OR rich* OR abund*" from 2013 to 2017 for biotic abundance and biotic richness, "yield AND organ* AND conven*" from 2013 to 2017 for yield, and "profit* AND organ* AND conven*" for 2015 to 2017 for profitability. Our search yielded 2,700 studies for biodiversity, 4,161 studies for yield, and 266 studies for profitability; each study was a single published manuscript. Our preliminary screening of these studies yielded 714 that appeared to meet our criteria for inclusion, which we then reviewed in more depth (Dataset S3).

We used 11 inclusion criteria: 1) the study reported one or more responses on individual crop species in organic and conventional treatments for yield and profitability; 2) the study reported primary data not in another included paper; 3) the organic systems were those that authors stated were organically certified or followed certification standards, meaning that although study sites were not certified by an accredited organic certification body they followed all practices necessary for certification; this was most typical of plots on field stations. Conventional systems were those that the authors stated were conventional or used recommended rates of synthetic chemical inputs and included low-input conventional systems (meaning reduced use of off-farm materials, such as fertilizers and pesticides, but increased on-farm inputs, such as manures and cover crops). However, if studies reported data for both high- and low-input conventional systems, we only used data from the high-input conventional systems; 4) the organic and conventional treatments were spatially interspersed in a landscape or at the same experimental station to eliminate bias in landscape context; 5) there were more than two replicates of organic and conventional treatments; 6) the study reported coordinates, or they were provided, to degrees minutes seconds. We emailed all corresponding authors for coordinates if they were not available in publications (we do not provide locational data to protect privacy but the number of coordinates associated with each study is shown in Datasets S1 and S2). We excluded studies that only reported degrees minutes as this only provided a spatial resolution of ∼1.5 to 1.8 km, which could have confounded measurements of landscape context that were taken in 1.0-km buffers; coordinates in degrees minutes seconds provided site locations to within the nearest 0.03 km; 7) the study was peer-reviewed; 8) the study did not include "subsistence" agriculture or integrated systems (a blend of both organic and conventional practices) instead of conventional or organic farming; 9) biotic studies reported data from within plots, fields, or farms, or adjacent field borders; we excluded data collected from natural habitat surrounding organic and conventional sites; 10) the study reported the mean as numerical or graphical data or it could be calculated. For biotic data, we further required studies to report biotic richness data in both organic and conventional systems for $n > 2$ taxa identified to order, family, genus, species, or morphospecies; and 11) the study was in English. One hundred forty-eight studies met these criteria, representing 102 biotic abundance comparisons from 50 studies, 94 biotic richness comparisons from 59 studies, 159 yield comparisons from 78 studies, and 37 profit comparisons from 9 studies (Fig. 1 and Datasets S1–S3). An additional two profit comparisons from two studies (one in Africa, one in Asia) were suitable but were excluded to avoid extrapolating our inference beyond the scope of the vast majority of the dataset (Dataset S3).

Each included study compared an organic system (or systems) to a directly comparable conventional system (or systems). This meant that none of the included studies compared organic systems to conventional systems that involved different treatments. For example, if the organic system measured yield of a particular crop in a monoculture (such as corn), the conventional system also measured the yield of that particular crop in the same monoculture. All of our included studies met this criterion, and data on the management practices that were common to the systems are detailed in Datasets S1 and S2 and *SI Appendix*, Tables S11–S14.

Study Variables. We gathered data on 20 categorical and 10 continuous variables from each study (*SI Appendix*, Tables S7–S14); mean and SD of organic and conventional treatment biotic abundance, biotic richness, yield, and profitability; and 28 continuous landscape variables from public land cover maps generated from remote-sensed data (*SI Appendix*, Table S1). For each study, we assessed landscape context in a 1-km radius buffer around the coordinates for each site (7) (*SI Appendix*, Fig. S1). If studies included more than one sample site (most commonly biodiversity studies on fields/farms), we calculated the landscape in a 1-km buffer around each site and averaged them to generate one metric per study. We calculated mean percent cropland using relevant land cover databases: 1) CORINE for Europe (∼30 m resolution, 89.7% accuracy), 2) the NASS (National Agricultural Statistics Service) cropland data layer for the United States (30 m resolution, 85 to 95% accuracy of crop cover classes), and 3) the IIASA-IFPRI (International Institute for Applied Systems Analysis–International Food Policy Research Institute) cropland percentage map for other countries (1-km resolution, 82.4% accuracy). We calculated average crop field size using the IIASA-IFPRI global field size map (1-km resolution, 78% overall accuracy) (49). A global reference map showing the percent cropland and average field size maps from (49) used in our analysis is shown in *SI Appendix*, Fig. S14. We calculated composition of crop and natural/seminatural habitat types (13) for studies in the United States and Europe (68% of biotic abundance, 81% of biotic richness, 71% of yield, and 100% of profit studies were from these regions; other regions did not have these data). We reclassified data from the CORINE and NASS Cropland Data Layer Databases to match the Global Land Cover-SHARE database for all cover types except for crop types. For crop types, we reclassified NASS Cropland Data Layer data to match the CORINE database (Dataset S4).

We considered 28 landscape variables that captured aspects of landscape composition and configuration (13) (*SI Appendix*, Table S1). Landscape composition was the amount of different cover types and included variables such as percent cropland, percent urban, and percent natural land (*SI Appendix*, Table S1). Landscape compositional heterogeneity was the number and diversity of crop cover types (13) and included variables such as patch richness, Shannon's diversity index, and Shannon's evenness index (*SI Appendix*, Table S1). Landscape configurational heterogeneity was the spatial arrangement of cover types (13) and included variables such as field size, edge density, mean patch area, and interspersion juxtaposition index (*SI Appendix*, Table S1). We assessed multicollinearity among these metrics based on Spearman's rank correlation and Pearson's correlation coefficient and retained eight variables that captured landscape composition and configuration gradients across the dataset (*SI Appendix*, Fig. S15) and were uncorrelated ($P > 0.05$) (*SI Appendix*, Figs. S16–S19). We then evaluated variance inflation factors of these eight variables using the usdm package in R (50, 51) and selected the four variables that were not strongly autocorrelated (variance inflation factors <4.0) (*SI Appendix*, Tables S2 and S3). These variables also were chosen based on their widespread use as important landscape attributes that may strongly affect agroecosystems (5–7, 12–20, 25): 1) percent cropland (percent cropland), 2) average crop field size in the landscape, 3) Shannon's habitat diversity index of all cover types, and 4) patch richness of all cover types.

Meta-Analysis. For each study, we compiled data on the abundance of taxa, the richness of taxa, crop yield, and profitability in organic and comparable conventional systems. Abundance was the number of individual organisms (of a particular taxonomic group such as pollinators), and richness was the number of unique taxa within the taxonomic group in each system. Crop yield reflected plant biomass, seed set, or fruit production within each site, and profitability reflected the benefit/cost ratio (ratio of gross returns with organic premiums to production costs) in each system. For those studies conducted across multiple years, we averaged values across years. For studies conducted across multiple crops or different independent management treatments (for example variation in tillage or crop rotation), we calculated values independently for each crop or management treatment as long as the treatment was equally applied to organic and conventional systems. These data were used to calculate effect sizes for biotic abundance, biotic richness, crop yield, profitability, production costs, and price premiums in paired organic vs. conventional systems.

To compare effects of farm management on biotic abundance, biotic richness, crop yield, profitability, production costs, and price premiums, we used the log-response ratio as an effect size metric (24). We used this metric, rather than a weighted effect size, for four reasons. First, weighted effect sizes could not be calculated for studies that did not report variability around the mean. Second, our biotic abundance and richness studies classified organisms at varying levels of taxonomic resolution. Studies classified at a coarser taxonomic resolution had less variability in general, and a weighted metric would give these studies greater weight. Third, studies were conducted at varying scales, from experimental plots to fields to farms. Studies conducted in plots on experimental stations typically had more replication than on-farm studies, but the scale of measurement for each replicate was often considerably smaller. Using a weighted effect size would have given studies conducted on small plots more weight than studies conducted at the scale of entire farms. Finally, preliminary analysis showed that weighted and unweighted analyses (for the subset of studies that reported variance) were qualitatively similar.

Once log response-ratios effect sizes were calculated, we used one-sample *t* tests (4, 7) to determine whether the mean effect sizes for biotic abundance, biotic richness, crop yield, and profitability differed from 0 (indicating no difference between organic and conventional systems). We also used Pearson's correlation coefficients to explore associations among profitability, production costs, and organic price premiums. We used $\alpha = 0.10$ to describe effect sizes that appeared ecologically important but did not meet the somewhat arbitrary $\alpha = 0.05$. This accords with a recent policy statement by the American Statistical Association (52) which notes that reliance on an arbitrary alpha value of 0.05 can lead to erroneous conclusions and prevent discussion of findings that may be ecologically relevant.

In subsequent analyses, we used metaregression to examine whether effect sizes were influenced by variables reflecting the landscape context. For each response variable, we ran generalized linear mixed effects models with a Gaussian error distribution in the lme4 package (5, 53). Each model was based on the general structure

$$\text{Effect size} = \beta_0 + \beta_1 X_1 + \ldots + B_N X_N,$$

where X_i are the covariates (landscape variables and their interactions), B_i are the partial regression coefficients for each i covariate, and B_0 is the intercept when covariates are zero. Each model included a random effect of study to control for studies that reported multiple responses and to avoid pseudoreplication. To interpret the main effects in the presence of interactions and improve model stability, continuous fixed effects were standardized prior to fitting the model using a generic scale function, which first mean-centered continuous covariates and then divided each value by two times the SD of the entire vector for each fixed effect (54, 55).

To test for fixed effects of landscape variables on each effect size response variable, we developed three candidate model sets. Our "simple" model set included four main effects (percent cropland, percent cropland^2, average crop field size, and average crop field size^2) and the interaction between percent cropland and average crop field size. This approach follows Sirami et al. (17), who considered quadratic effects of percent cropland and crop field size on biodiversity to account for potential nonlinear relationships but only included interactions between linear factors. The simple model set was applied to the entire dataset for each response variable, given that percent cropland and crop field size were calculated for every study (*SI Appendix*, Table S4). We then developed two "complex" model sets. The first "complex" model set included five main effects (percent cropland, percent cropland^2, average crop field size, average crop field size^2, and Shannon's diversity index) and all two-way interactions between percent cropland, field size, and Shannon's diversity index (*SI Appendix*, Table S5). The second "complex" model set included five main effects (percent cropland, percent cropland^2, average crop field size, and average crop field size^2, and patch richness) and all two-way interactions between percent cropland, field size, and patch richness (*SI Appendix*, Table S6).

We ranked models based on AICc and identified the top models for each response based on a criteria of ΔAICc <2.0 from the most-well-supported model (5). We also calculated associated Akaike weights (ω) and model-averaged partial regression coefficients for each covariate based on the 90% confidence set (5). The relative importance of each covariate on the log response-ratio effect sizes was determined from the sum of Akaike weights across the entire model set, with 1 being the most important (present in all models with weight) and 0 the least important. We considered covariates as strong drivers of the response variable if they appeared in top models (ΔAICc <2) and had a relatively high summed Akaike weight ($\omega > 0.5$) (5). Covariates were additionally considered statistically significant if their unconditional 90% confidence interval did not overlap with zero (5).

In subsequent analyses, we used metaregression to assess whether effects of crop field size (which was consistently the most important landscape variable) differed based on organismal group (for biotic metrics only), functional group (for biotic metrics only), continent (for biotic metrics and yield; profitability studies were from one continent), biome (for biotic metrics and yield; all but one of the profitability effect sizes were from one biome), level of development (for biotic metrics and yield; profitability studies were from a highly developed country), and crop type (for all metrics). For these analyses, models included percent cropland, percent cropland^2, one of the six covariates mentioned above, and the interaction between percent cropland and the covariate. All analyses were performed using R version 3.5.1 (50) using the packages lme4 (53) and MuMIn (56). We generated maps showing predicted effect sizes using maps from Fritz et al. (49), which provided the percent cropland and the average crop field size. The values for these variables across regions of interest were multiplied by the regression coefficients and added to the intercepts from the best supported models to generate the maps.

Data Availability. The data supporting the findings of this study are available within the paper, *SI Appendix*, and Datasets S1–S4.

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