FARMING PRACTICES

Joint environmental and social benefits from diversified agriculture

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Agricultural simplification continues to expand at the expense of more diverse forms of agriculture. This simplification, for example, in the form of intensively managed monocultures, poses a risk to keeping the world within safe and just Earth system boundaries. Here, we estimated how agricultural diversification simultaneously affects social and environmental outcomes. Drawing from 24 studies in 11 countries across 2655 farms, we show how five diversification strategies focusing on livestock, crops, soils, noncrop plantings, and water conservation benefit social (e.g., human well-being, yields, and food security) and environmental (e.g., biodiversity, ecosystem services, and reduced environmental externalities) outcomes. We found that applying multiple diversification strategies creates more positive outcomes than individual management strategies alone. To realize these benefits, well-designed policies are needed to incentivize the adoption of multiple diversification strategies in unison.

The simplification of farming systems continues to grow at the expense of more diversified agriculture, contributing to the crossing of planetary boundaries due to the excessive use of chemical inputs, as well as increased greenhouse gas emissions, biodiversity loss, and water use (*1*). To address these challenges, a new paradigm for farming systems is needed that focuses on providing food security and nutrition while minimizing negative environmental, health, and social impacts (*2*). This transformation is particularly pertinent as countries in different stages of economic development navigate through distinct challenges. Economically advantaged nations need to reverse simplification to recover from environmental and social damage already done, whereas lower-income nations need to minimize these externalities in their development transitions (*3*). Historically, the architects of the Green Revolution were primarily concerned with breeding crops and developing agronomic inputs to increase staple crop yields and respond to food security needs. However, the focus of their policies on simplifying agricultural systems came with unintended large and negative environmental impacts such as pollution, as well as social side effects such as farmer indebtedness, reduction of peoples' dietary diversity, and reduced resilience (*4*, *5*). This has led to widespread calls for a change in agricultural development policy that addresses the negative side effects directly through the action of biologically diversified farming systems.

Biologically diversified farming systems, meaning those that intentionally increase the number of agricultural and nonagricultural crop and livestock species (and their genetic diversity), are a promising solution to bring about more sustainable food production because in theory they offer an ecological mechanism for higher resource use efficiency, less pollution, improved food sovereignty, and reduced vulnerability to climate change (*6*–*8*). Much research has examined the empirical effects of agricultural diversification on environmental outcomes (*9*–*12*). This research includes recent quantitative syntheses demonstrating the positive effects of agricultural diversification on biodiversity and ecosystem services and showing that diversification practices increase yields as often or more often than they decrease them (*11*–*13*). However, although evidence of the environmental benefits of agricultural diversification is accumulating, our knowledge of social outcomes beyond yields is limited to studies focusing on selected dimensions of social sustainability such as income (*14*) or employment, but with limited attention to other facets such as social networks (*15*, *16*). Therefore, broad trade-offs between social and environmental outcomes from agricultural diversification are poorly understood and largely unquantified (*9*, *17*, *18*). To determine whether there are advantages to scaling up diversified agricult systems (*19*), we need evidence that diversification does not privilege certain outcomes (e.g., nonagricultural biodiversity) at the expense of others (e.g., yields) (*20*). Here, we draw on data from 11 countries to take the next step, building on prior syntheses examining how diversification affects biodiversity, ecosystem services, and yields (*12*–*14*, *21*, *22*) to include other social outcomes such as food security and human well-being.

Interdisciplinary and participatory data synthesis

We examined environmental and social outcomes resulting from multiple agricultural diversification strategies, both separately and in combination. We focused our assessment on five types of diversification strategies: (i) livestock inclusion and diversification (e.g., managed mammals, fowl, bees, and fish); (ii) temporal crop diversification (e.g., crop rotation and cover crops); (iii) soil conservation and fertility management (e.g., compost application); (iv) noncrop plantings (e.g., hedgerows); and (v) water conservation (e.g., contour farming). We chose these five diversification strategies (table S2) inductively to classify the wide array of farming practices represented across the 24 datasets (table S5) included in our analysis. Soil conservation practices such as compost addition are considered to represent a diversification strategy if they create habitat conditions that enhance biodiversity or trophic complexity belowground (*23*). Likewise, water conservation practices are considered to represent diversification if they affect plant and microtopographic heterogeneity that influences biodiversity (*24*). We investigated how these five strategies can lead to trade-offs and/or synergies between targeted environmental (e.g., nonagricultural biodiversity, regulating ecosystem services such as crop pollination, and reduced environmental externalities or harms) and social (e.g., yields, human well-being, and food security) outcomes (tables S1 to S7 and figs. S7 to S10). Our six environmental and social outcomes each measure specific dimensions of sustainability to account for interconnections and assess the overall sustainability of diversified farming from a systems perspective.

We harmonized 24 datasets covering 2655 farms and various farming types across five continents, including smallholder farming in rural Africa, plantation crops in Southeast Asia, and both small- and large-scale farming in North America, Europe, and Latin America (Fig. 1). The harmonized dataset combines individual studies to cover a broad range of farming practices, geographies, and environmental and social contexts to develop a synthesis broadly applicable across multiple farming systems. All 24 datasets measured at least one agricultural diversification practice, as well as one environmental

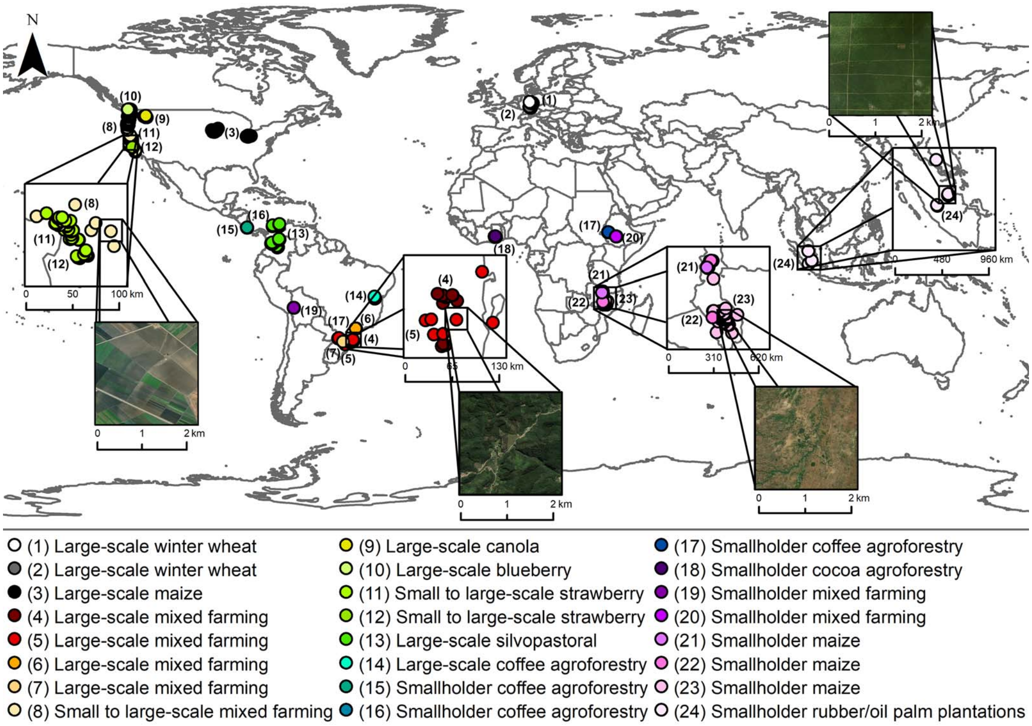

Fig. 1. Geographic distribution of 24 datasets spanning five continents and a wide range of landscapes. Our analysis of agricultural diversification strategies covers 2655 farms across five continents. Insets depict satellite images of agricultural systems (left to right: leafy greens in the US West Coast, mixed farming in Brazil, smallholder maize in Malawi, and oil palm plantations in Indonesia). Colored dots indicate farm locations within each study. The commonly used 2-ha threshold for differentiating smallholder farming from farming that is less reliant on subsistence was applied (*45*).

and one social outcome, and thus are inherently interdisciplinary (mostly collected by ecologists and social scientists working together and merging their "ways of knowing" and methods). Also, each dataset studied farm sites with varying levels of diversification, including farms without any diversification practices. Unlike data synthesis approaches that extract values from published materials, our data synthesis is based on a participatory, iterative process, including multiple group meetings and exchanges with data contributors during all stages of variable selection, data analysis, and result interpretation. Although our sample size of 24 studies would be relatively small for a standard meta-analysis, it is ideal for an approach requiring extensive interaction with data contributors working across disparate geographies and farming systems to confirm and contextualize results. Fig. S5 provides an example illustration that we used to confirm and contextualize results with data contributors who worked with Malawian smallholders.

We first tested how agricultural diversification strategies affected each of the six targeted social and environmental outcomes. For each of the five diversification strategies, we

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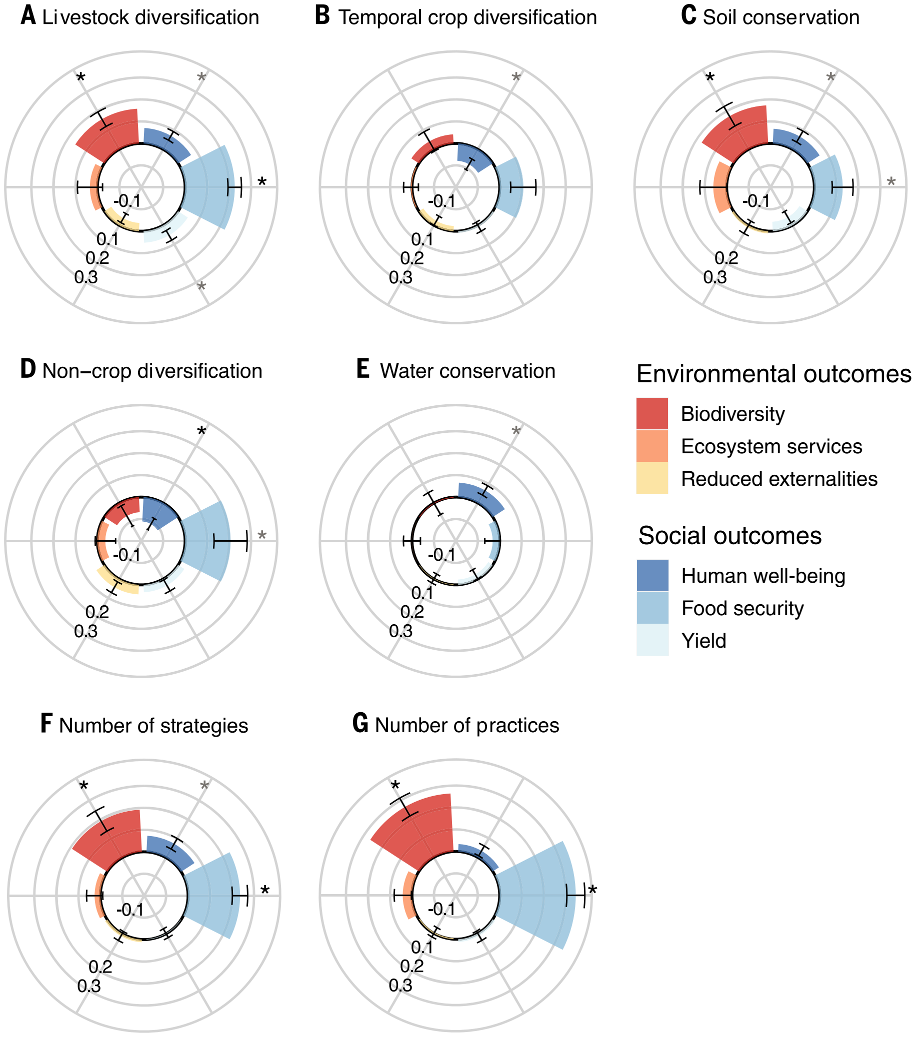

Fig. 2. Effects of agricultural diversification on environmental and social outcomes. (**A** to **G**) Agricultural diversification strategies include livestock diversification, temporal crop diversification, soil conservation, noncrop diversification, and water conservation. Flower diagrams indicate the effects of diversification strategies on three environmental outcome variables (nonagricultural biodiversity, regulating ecosystem services, and reduced environmental externalities) and three social outcome variables (human well-being, food security, and yield). Also shown are the effects of the total number of diversification strategies (up to a total of five) and their associated diversification practices (up to a total of 23, excluding livestock diversification) applied (table S2). Effect sizes are measured in units of SD, with the black circle indicating an effect size of 0.0. The size of the flower petals is proportional to the effect size; error bars indicate ± 1 SE. Asterisks indicate statistically significant effects of diversification strategies on outcomes (gray asterisks, $P < 0.05$; black asterisks, $P < 0.00119$ using Bonferroni correction for multiple comparisons; 42 estimates).

identified the number of distinct practices adopted by farmers at the field or farm level that were recorded by each study. For example, noncrop diversification included practices such as windbreaks, flower strips, and hedgerows. In addition, we recorded the total number of strategies (maximum of five) and the total number of practices recorded by each study (calculated by summing all practices applied within each strategy). For example, a farm with noncrop diversification in the form of hedgerows and flower strips, in combination with soil conservation through application of green manure and biochar, would score 2 for strategies and 4 for practices (fig. S1 shows examples of coverage of agricultural diversification strategies within farms). We then modeled outcome variables as a function of (i) the degree of diversification of each strategy (i.e., the number of practices used within each strategy), (ii) the total number of diversification strategies used, and (iii) the total number of diversification practices applied across all strategies (linear mixed-effects models with study IDs as a random effect; see the materials and methods and tables S12 and S13).

We also examined the effect of landscape composition on diversification outcomes (figs. S2 to S4). To this end, we refitted the same model set described above but allowed the effects of diversification strategies and practices to differ depending on landscape composition (interaction = diversification × composition). We then compared the effects of diversification for farms situated in cleared, simple, and complex landscapes using the amount of seminatural habitat in a 3000-m radius as a measure of landscape complexity. We considered cleared to mean that <5% of natural habitat remains, simple that 5 to 20% remains, and complex that >20% remains (*25*) (tables S8 to S10). Farmers' adoption of diversification strategies occurred in our study through choices rather than experimental manipulation (fig. S6), so this is a synthesis of observed associations on real-world farms, not experimental field trials.

More diversification strategies or practices are better

We found that applying a higher number of diversification strategies or practices had a greater likelihood of beneficial outcomes than using individual strategies or practices. Specifically, we showed that combining five diversification strategies or practices had overwhelmingly strong benefits across outcomes, with positive effects especially on nonagricultural biodiversity and food security (Fig. 2, F and G). Farmers who integrated multiple strategies or practices more likely experienced benefits for nonagricultural biodiversity (effect sizes of 0.19 ± 0.05 and 0.26 ± 0.05 for strategies and practices, respectively), moderate increases in human well-being (effect size of 0.07 ± 0.03) for number of strategies, and comparatively stronger increases in food security (0.24 ± 0.03 and 0.35 ± 0.04 for strategies and practices, respectively). Positive effects of diversification strategies and practices on biodiversity were driven by effects on large, but not small, farms (tables S11 and S12). This may be due to the availability of stronger contrasts in management intensity between large-scale simplified farms and similar-sized farms that have adopted diversification strategies (*26*). We also found that increases in food security were driven by small farms, which might suggest that new market opportunities could be more beneficial than diversification for food security on large farms (*27*).

All results for nonagricultural biodiversity and regulating ecosystem services should be taken with caution because these outcomes were measured by only 11 and 12 studies, respectively (table S9). Also, a potential criticism of the type of analysis that we report here is that hierarchical models place more weight on studies with more observations. Therefore, we also created a weighting scheme in which we kept the total number of observations constant but artificially up- or down-weighted studies so that all were equally represented in the model fitting. In the equalized

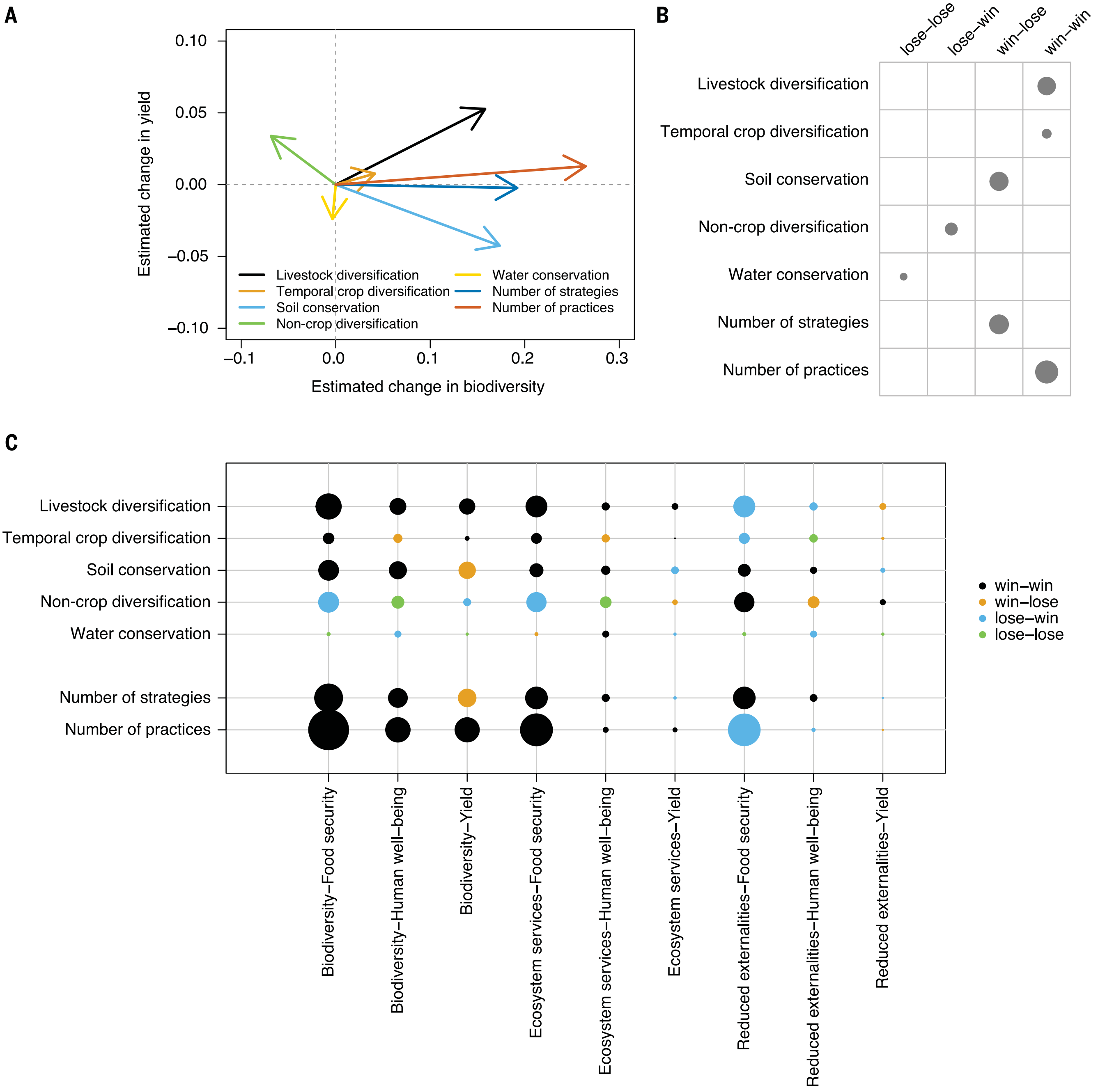

Fig. 3. Synergies and trade-offs among environmental and social outcomes of agricultural diversification. (**A** and **B**) Methodological approach to identify synergies and trade-offs based on the example of nonagricultural biodiversity and crop yield. (**C**) Synergies and trade-offs for all pairwise combinations of studied environmental and social outcome variables. (A) shows the effects of agricultural diversification strategies on nonagricultural biodiversity and crop yield. Arrow tips are located at the predicted change in nonagricultural biodiversity and crop yield, respectively, with an increase of 1 SD of a given diversification strategy. The *x-y* coordinates of the arrow tips are numerically similar to the effect sizes shown in Fig. 2. The resulting arrow directions indicate trade-offs and synergies of diversification strategies, with arrows pointing in the upper right corner indicating win-win outcomes, and arrows pointing in the other quadrants indicating either trade-offs (top left quadrant, lose-win; bottom right quadrant, win-lose) or lose-lose (bottom left quadrant) outcomes. (B) shows outcomes by diversification strategy. Circle size is proportional to arrow length in (A) and indicates the effect strength, that is, the conjoined change in nonagricultural biodiversity and crop yield with diversification. In (C), colored circles indicate outcome combinations of environmental and social outcome variables (black, win-win; orange, win-lose; blue, lose-win; green, lose-lose). Circle size is proportional to the joint change of the paired environmental and social variables.

model, we observed some difference in results for specific outcomes (e.g., ecosystem services) and diversification strategies (e.g., livestock diversification); however, equalizing the influence of each study did not alter the key finding that multiple diversification strategies and practices maximized benefits across environmental and social outcomes (fig. S9). We interpreted the results from both model sets as suggesting that different outcomes, trade-offs, and synergies may be more present in different contexts, but that the overall best strategy to maximize environmental and social outcomes is to apply multiple diversification strategies and practices in tandem.

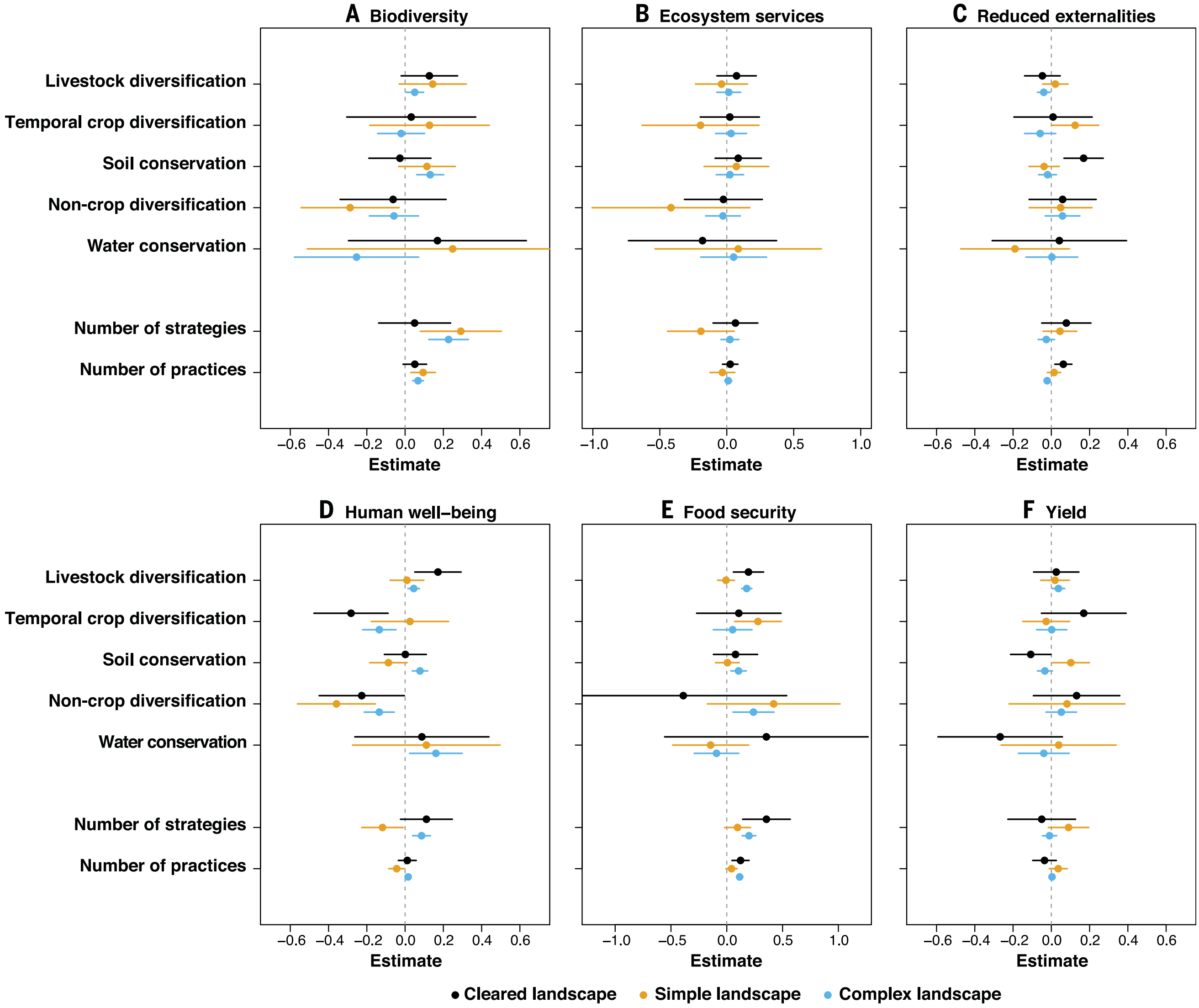

Fig. 4. Landscape composition moderates the outcomes of agricultural diversification strategies. (**A** to **F**) Shown are standardized effect sizes (means and 95% confidence intervals) of the five diversification strategies and the total number of diversification strategies or practices applied, depending on the proportion of seminatural habitat in a 3000-m-radius surrounding farms (cleared, <5%; simple, 5 to 20%; complex, >20%). When the confidence interval is not overlapping with the 0 line, there is a significant effect in a given landscape.

Maximizing win-wins, minimizing trade-offs

We further examined the extent to which the five diversification strategies might promote pairs of environmental and social win-win outcomes and also which are particularly promising for achieving paired benefits. Overall, applying a high number of diversification strategies or practices was associated with more potential for win-win outcomes (Fig. 3, B and C). Livestock diversification and soil conservation were the two strategies that appeared to consistently elicit multiple positive outcomes (Fig. 2, A and C), especially win-win outcomes of nonagricultural biodiversity and multiple social outcomes (Fig. 3C). Half of the farms in our study practiced some form of livestock integration (14 studies surveyed farms with livestock integration). Livestock diversification had the largest positive effect on food security (0.23 ± 0.03), which is more than four times as large as the effect on yields. Livestock diversification promoted nonagricultural biodiversity, but with a lower effect size than for food security (0.16 ± 0.04) (Fig. 2A). Soil conservation practices also promoted synergies through gains in all three environmental outcomes, accompanied by enhanced human well-being and food security (Fig. 3C). Overall, three of the five assessed agricultural diversification strategies offered potential win-win outcomes regarding food security and nonagricultural biodiversity. Conversely, many national strategies and programs focusing on agricultural intensification did not achieve win-wins (*28*).

We also observed trade-offs, such as soil conservation practices leading to gains in biodiversity but potential yield losses, although the latter were not statistically significant (Figs. 2C and 3, A to C). For noncrop diversification, we did not observe a consistent positive effect on biodiversity (Fig. 2D), potentially driven by divergent responses of taxa. However, positive effects on food security can readily arise from such practices. For example, having trees on-farm can support peoples' diets by providing edible products, including fruits, nuts, and leaves (*29*–*33*). Five of our studies (corresponding to 810 farms) used dietary diversity scores (counting the number of food groups consumed) to proxy dietary quality, a key component of food security and a metric likely to capture effects of having trees on-farm (*34*). The positive effect of noncrop diversification on food security was pronounced (0.21 ± 0.08), almost twice the size as the negative effect of noncrop diversification on human well-being (Fig. 2D). Explanations for this negative effect include longer crop rotations or the implementation of practices such as hedgerows, which could lead to a smaller area planted with cash crops, potentially leading to lower production and/or higher labor demands. Although we did not detect significant effects of single diversification strategies on ecosystem services, several large meta-analyses have shown strong positive effects of diversification practices on many ecosystem services (*12*, *13*).

Role of landscape composition in diversification outcomes

The "intermediate landscape complexity hypothesis" states that agricultural diversification is unlikely to result in improvements in cleared landscapes because the regional species pool available to colonize crop fields and provide ecosystem services is limited (*25*). Similarly, in complex landscapes, diversification may not lead to measurable increases in nonagricultural biodiversity and/or ecosystem services on farms because sufficient alternative resources and habitats are already present in the farm surroundings to support these species and services. Instead, the predicted environmental benefits from agricultural diversification strategies are largest in simple landscapes containing 5 to 20% of seminatural habitats or noncrop areas (*25*). We tested this hypothesis and found that landscape composition (the proportion of seminatural habitats in a landscape) moderated the outcomes of agricultural diversification strategies (see Fig. 4 and table S10 for sample sizes). We observed that the number of diversification strategies applied had strong positive effects on food security (Fig. 4E) in cleared landscapes, indicating benefits even in landscapes lacking natural habitat. However, we also observed positive effects in complex landscapes. For example, livestock diversification showed the strongest positive effects on human well-being in cleared landscapes (Fig. 4D). However, although we found positive social outcomes in cleared landscapes, diversification practices there did not result in positive environmental outcomes, which is partially consistent with the hypothesis. Finally, we observed that the number of diversification strategies and practices applied had positive effects on biodiversity in both simple and complex landscapes (Fig. 4A). These results partially agree with the intermediate landscape complexity hypothesis, but indicate that diversification strategies on farms can be beneficial for biodiversity even in complex landscapes.

Outlook

At a time when the outlook for simultaneously improving and protecting the environment and social conditions for farmers often seems bleak (*2*), our findings present a promising avenue for shaping global agricultural policy by showing how applying a suite of diversification strategies or practices can create win-win scenarios. Our results support the notion that a diversified farming system is often more beneficial than specific diversified farming strategies or practices in isolation (*13*, *14*). This finding emphasizes the need for more explicit evidence about which combinations of diversification strategies and practices are most complementary in different social and ecological contexts. Most of our present findings, which are based on working farm data, support the growing body of literature linking agricultural diversification strategies with better outcomes for nonagricultural biodiversity and regulating ecosystem services without compromising yields (*12*, *13*).

Our study advances existing knowledge about how diversification affects agricultural system sustainability by (i) considering how a multitude of diversification strategies, not just crop diversification, may affect sustainability outcomes (including both individual and combined effects of diversification strategies); (ii) examining how diversification influences multiple social and environmental outcomes while highlighting trade-offs and/or synergies within and between environmental and social outcomes; and (iii) examining how landscape composition moderates the effects of diversification on environmental and social outcomes. Thus, we have moved beyond existing studies that typically assess the effects of diversification strategies in isolation and on selected output variables (*35*–*37*), preventing the systemic understanding needed for informing policy debates on how to produce food while maintaining a safe operating space for humanity. By focusing on agricultural working landscapes, our work complements earlier studies examining environmental and social trade-offs and/or synergies of protected areas (*38*) and considers working land conservation approaches affecting a broader area (*39*). Because we include diverse datasets representing multiple world regions, our flexible approach can be replicated and expanded to incorporate additional datasets in the future.

How can and should policy-makers and practitioners encourage the adoption of specific types of diversified farming systems? Although we recognize the benefits of diversification, it is also critical to acknowledge that many farmers are working "against the odds" (*8*). Structural factors are often the main barrier for adopting diversification practices, and include high land rents, the predominance of short-term leases, stringent food safety regulations, trade agreements exacerbating corporate concentration in global food systems, and other supply chain pressures (*40*). Transitions to diversified farming systems often require financial support because of potential initial yield declines or implementation costs (*8*). Indeed, current policies often lock in simplified, conventional farming rather than enabling durable transitions to diversified farming, and investments are needed to develop appropriate seeds, crop mixes and rotations, and equipment to promote the profitability of diversified farms.

Effective policies for encouraging the adoption of diversification strategies and practices likely vary with cropping system and region and include incentives, regulations, and combined approaches. The use of incentives can be seen in the European Union, where farmers are financially compensated on a per-area basis (*41*, *42*) for some diversification practices such as noncrop plantings. Also, a recent synthesis from Ghana shows that incentivizing noncrop diversification has cascading positive effects on adoption patterns (*43*). Regulatory mechanisms can be used for soil or water conservation through policies requiring farmers to use diversification practices to reduce pollutants on their farms (e.g., for water quality) (*44*). Finally, the benefits of combining incentives with regulatory mechanisms can be seen in California, where increasing adoption of diversification practices on larger farms may require supplementing the "pull" of incentives with the "push" of regulatory mandates (*44*).

Our study suggests several contexts in which desirable local outcomes occur most frequently, with a key example being the positive effect on human well-being and food security from applying a high number of diversification strategies in cleared landscapes and on small farms (table S12). However, researchers have much more to discover about the variability of outcomes that can occur across different agricultural diversification strategies, landscapes, and social contexts, and future work should use quasiexperimental methods that control for possible underlying differences between farmers that choose more versus fewer diversification strategies.

The future of agriculture faces great challenges: large increases in demand for agricultural commodities must be met while at the same time minimizing agriculture's negative environmental, health, and social impacts (*2*). Our interdisciplinary analysis spanning a wide array of regions provides convincing evidence that agricultural diversification is a promising win-win strategy for providing social and environmental benefits.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S10
Tables S1 to S13
References (*47–91*)
MDAR Reproducibility Checklist

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