nature plants

ARTICLES

https://doi.org/10.1038/s41477-022-01191-1

Farm size affects the use of agroecological practices on organic farms in the United States

Jeffrey Liebert[1]✉, Rebecca Benner[2], Rachel Bezner Kerr[3], Thomas Björkman[4,5], Kathryn Teigen De Master[6], Sasha Gennet[7], Miguel I. Gómez[8], Abigail K. Hart[9], Claire Kremen[6,10], Alison G. Power[11] and Matthew R. Ryan[1]

Organic agriculture outperforms conventional agriculture across several sustainability metrics due, in part, to more widespread use of agroecological practices. However, increased entry of large-scale farms into the organic sector has prompted concerns about 'conventionalization' through input substitution, agroecosystem simplification and other changes. We examined this shift in organic agriculture by estimating the use of agroecological practices across farm size and comparing indicators of conventionalization. Results from our national survey of 542 organic fruit and vegetable farmers show that fewer agroecological practices were used on large farms, which also exhibited the greatest degree of conventionalization. Intercropping, insectary plantings and border plantings were at least 1.4 times more likely to be used on small (0.4–39 cropland ha) compared with large (≥405 cropland ha) farms, whereas reduced tillage was less likely and riparian buffers were more likely on small compared with medium (40–404 cropland ha) farms. Because decisions about management practices can drive environmental sustainability outcomes, policy should support small and medium farms that already use agroecological practices while encouraging increased use of agroecological practices on larger farms.

Transformative changes are urgently needed to increase the sustainability of agri-food systems[1]. In the United States, the prevailing 'conventional' model of agriculture is input-intensive and narrowly focused on maximizing crop yield. Landscape and management simplification, product standardization and consolidation of farms and agribusinesses have resulted in tremendous production outputs. Yet, the practices associated with this agricultural paradigm have also been major drivers of biodiversity loss, soil degradation, water pollution and greenhouse gas emissions[2–6].

As a series of mutually enabling trends, synthetic fertilizer and pesticide use, mechanization and farm size have increased since the 1940s. Fewer farmers are now working larger farms, a change that was encouraged by policy, research and development. Championing this transition in the 1970s, former US Secretary of Agriculture, Earl Butz, declared that farmers should 'get big or get out'[7]. Since then, the average size of US farms has increased. By 2000, the majority of cropland had shifted from being managed by small- and medium-scale farmers to large-scale farmers on operations of at least 405 ha. As a result of market forces and policies that disproportionately reward economies of scale and particular commodity crops[8], the majority of cropland is now managed on large farms, primarily at the expense of medium farms (Fig. 1).

In the United States, organic farms are smaller (135 ha), on average, than conventional farms (180 ha)[9,10]. Over 2.2 million hectares of farms and ranches are certified organic, with 1.4 million hectares dedicated to crop production. Although it comprises less than 1% of all farmland in the United States, organic agriculture has been promoted as a management approach that can help ameliorate the deleterious effects associated with conventional agriculture[11,12]. Compared with conventional production, organic farming performs better across an array of sustainability metrics—such as energy use, soil quality and the provision of ecosystem services—largely through the use of practices that support biodiversity and minimize negative impacts on the environment[11,13,14]. These benefits reflect the focus of the United States Department of Agriculture (USDA) National Organic Program (NOP) standards, which were designed to maintain or enhance soil health and 'promote ecological balance'[15]. Many of the practices commonly used on organic farms are also characteristic of agroecology and other alternative approaches to agriculture. Agroecology can be described as a scientific discipline, suite of practices and social movement[16]. Although the focus is on practices here, we understand agroecology to integrate these three dimensions.

Agroecological practices

Agroecological practices aim to maintain the ecological integrity of farming systems, which in turn provide ecosystem services such as nutrient cycling, pollination and biological pest control[17–19]. Such services not only undergird the resilience of a farming system, but can also reduce the need for off-farm inputs. In this study, we focused on eight agroecological practices that range from within-field to landscape-level implementation: compost or manure application, intercropping, insectary plantings (for example, flower strips), reduced tillage (a decrease in tillage intensity or frequency),

[1]Soil & Crop Sciences Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, USA. [2]The Nature Conservancy, Highland, NY, USA. [3]Department of Global Development, Cornell University, Ithaca, NY, USA. [4]Horticulture Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, USA. [5]Cornell Agritech, Cornell University, Geneva, NY, USA. [6]Environmental Science, Policy, and Management, University of California, Berkeley, Berkeley, CA, USA. [7]The Nature Conservancy, Arlington, VA, USA. [8]Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY, USA. [9]The Nature Conservancy, Sacramento, CA, USA. [10]Institute for Resources, Environment and Sustainability, Department of Zoology, Biodiversity Research Centre, University of British Columbia, Vancouver, British Columbia, Canada. [11]Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY, USA. ✉e-mail: jal485@cornell.edu

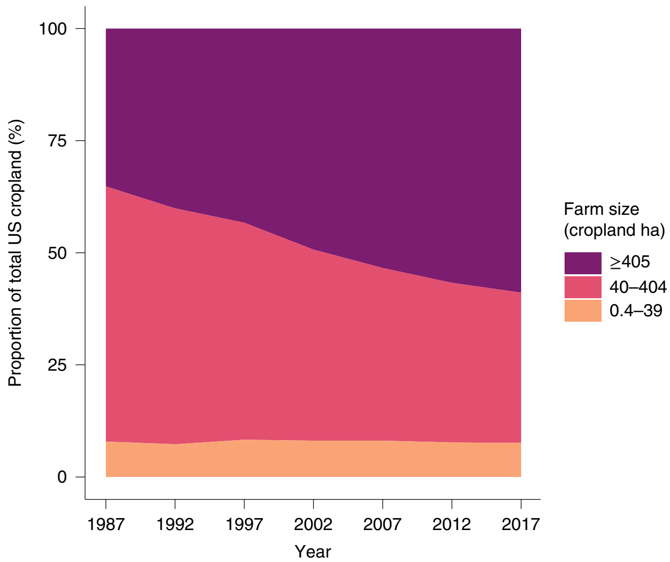

Fig. 1 | The proportion of total US cropland managed by farms in different size categories: 0.4–39, 40–404 and ≥ 405 ha. Farm size categories are adapted from the 2017 Census of Agriculture (Methods). Data were compiled by J. MacDonald (USDA Economic Research Service) and represent all crop farms in the United States[42].

diverse crop rotations (three or more crops), cover cropping, border plantings (for example, hedgerows) and riparian buffers (Fig. 2).

Because biological diversity is a key element in ecosystem function and maintenance, it is notable that all eight practices support greater above- or below-ground biodiversity[20]. Crop rotation is among the most fundamental practices in this regard. Diversified crop rotations reduce yield loss and the risk of crop failure under climatic stresses, as well as increase yields during more productive growing conditions[21]. Crop rotations can also limit the frequency and severity of pest outbreaks, support more diverse soil biota and enhance nutrient cycling, among other benefits[17,19]. With intercropping and cover cropping, leveraging plant functional traits through crop species and cultivar selection and management can yield a range of ecosystem services, including weed suppression and nitrogen fixation[22,23]. The application of compost or manure enhances numerous indicators of soil health[24], such as organic matter[25] and soil microbial community composition and activity[26]. Reducing tillage can also improve soil health through increased aggregate stability, microbial biomass C and soil respiration, among other characteristics[27–29]. Diversifying an agroecosystem with insectary plantings and semi-natural, perennial or other flower-rich habitats along field edges (border plantings) can enhance pest control and pollination services[6,30–33], although context and landscape complexity are important mediating factors[34]. Riparian buffers also provide habitat for beneficial organisms and movement corridors or stepping stones for wide-ranging species, but they are primarily used by farmers to prevent sediment, nutrient and pesticide transport via run-off[35].

Because these agroecological practices are applicable to all types of farm management, organic farms that integrate multiple practices can serve as models for transforming agriculture[11,17,36]. However, as cropland becomes increasingly consolidated among fewer farmers and market opportunities entice conventional farmers to enter into organic production, concerns about the conventionalization of organic agriculture have emerged[37–39].

Conventionalizing organic agriculture

The process by which organic agriculture is becoming more similar to the dominant industrial model of farming has been termed 'conventionalization'[37]. The conventionalization process is characterized by larger farm sizes, simplified agroecosystems, greater mechanization, standardized crop production and a reliance on input substitution (that is, replacing a prohibited input with an NOP-approved input)[38,39]. Social, economic and political consequences of conventionalization include the use of more non-family labour, less full-time farmworker employment, increased contract growing, a decline in direct marketing, vertical integration and a weakening of organic standards[40,41].

Similar to the trends observed among all farms in the United States, the consolidation of land among a decreasing number of increasingly large farms has also occurred in the organic sector. Because of conventionalization, organic agriculture is bifurcating into two distinct groups: large-scale operations mass-producing a few crops for wholesale; and small- to medium-scale farms using more ecological practices to grow a diverse array of crops for direct sale. In 2017, crop farmers who primarily sold organic products managed 49% of organic cropland while representing 73% of all farms with NOP-certified sales. By contrast, farmers who primarily sold non-organic products managed the remaining 51% of organic cropland, but represented just 27% of all farms with NOP-certified sales[42,43]. In other words, a small number of large-scale farmers—predominantly conventional but whose operations include a fraction of organic land—manage the majority of organic cropland in the United States.

Some researchers have emphasized the importance of distinguishing between different types of organic management[14,17,44], but such differentiation is still uncommon in empirical studies. Universally ascribing benefits or drawbacks to organic agriculture might obscure the uneven potential among organic farms of varying sizes and management types to contribute to the transformation of agriculture. This lack of distinction among organic farms could, in turn, mislead research agendas or hinder more effective policy interventions. If organic agriculture is to scale up in a way that avoids many of the drawbacks of conventional production, it will be important to better understand the effects of conventionalization on organic farms. We use results from a national survey of organic fruit and vegetable farmers to discern whether relationships exist between farm size and the use of agroecological practices and to assess the degree to which conventionalization is occurring among organic farms in the United States.

Results

A total of 542 organic fruit and vegetable farmers from 43 states completed our survey. Farm sizes based on cropland ranged from 0.4 to 9,737 ha, with a mean size of 8, 128 and 1,904 cropland ha for small (0.4–39 ha, $n=394$), medium (40–404 ha, $n=109$) and large (≥405 ha, $n=39$) farms, respectively. The farmers represented here grow as few as a single fruit or vegetable crop to more than 50 different species.

Practice-use among organic farmers. Farmers who managed small or medium farms used more than five of eight agroecological practices on average (Fig. 3), which was a greater number of practices than large-scale farmers (small versus large, $P=0.0004$, and medium versus large, $P=0.02$). Over half of the small- and medium-scale farmers used at least six of the eight practices.

The relationship between farm size and the use of specific agroecological practices varied among (Fig. 4 and Supplementary Table 1) and within (Supplementary Table 2) size categories. Across all three size groups, the probability that an organic farmer used a diverse crop rotation, cover cropping or riparian buffers was over 75% (Fig. 4). The use of border plantings, by contrast, had among the lowest predicted probability (<63%) across farm sizes. When averaged over all eight practices, small-scale farmers exhibited the highest probability of practice-use (79%), with all practices more

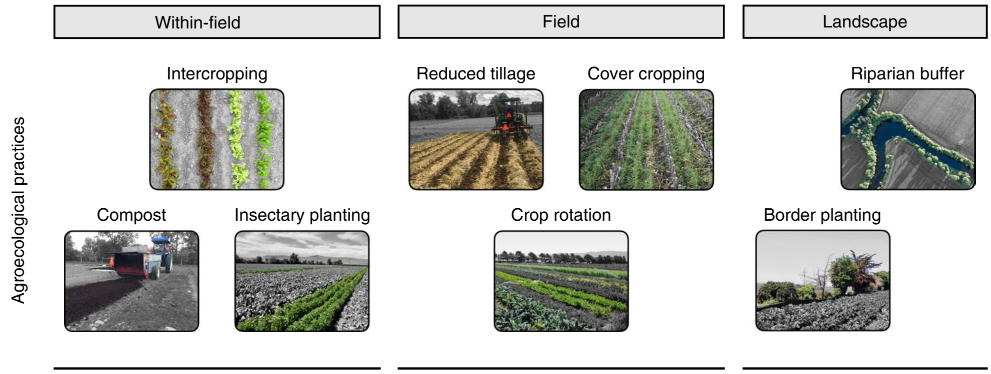

Fig. 2 | Agroecological practices organized by their typical on-farm scale of application. Based on previous reviews of agroecological practices[20,45], this categorization scheme, ranging from within-field to perimeter and landscape-level application, is common. Some practices can be implemented at multiple scales or combined across scales to create a 'diversified farming system'[20]. Photographs provided by R. Maher (compost and reduced tillage), C. Pelzer (cover cropping), F. Leivo (riparian buffer) and J. Liebert (all other practices).

likely than not to be used among this size category (that is, all probabilities were >50%; Fig. 4). By contrast, large-scale farmers were associated with the lowest average probability of practice-use (65%), as well as the only two practices that organic farmers of any size were less likely to use than not use: insectary plantings at 29% ($P=0.03$) and border plantings at 30% ($P=0.04$).

The use of compost, diverse crop rotations and cover crops exhibited no differences among farm sizes within each practice (Fig. 4 and Supplementary Table 1). The only practice that showed a positive relationship with farm size was reduced tillage, increasing from 69% to 81% as farm size increased from small to medium ($P=0.06$; Fig. 4). For intercropping, small-scale farmers were more likely to use the practice (74%; Fig. 4) than either medium-scale (55%, $P=0.004$; Fig. 4) or large-scale farmers (52%, $P=0.04$; Fig. 4). The effect of farm size on the use of insectary plantings was even more pronounced (Fig. 4): the probability of use markedly declined from 80% among small-scale farmers to just 29% among large-scale farmers ($P<0.0001$). Using border plantings was also less likely among large-scale farmers compared with small- and medium-scale farmers (Fig. 4 and Supplementary Table 1). Farmers in the smallest farm size category were most likely to use riparian buffers if a waterway, such as a stream or drainage ditch, was present on or adjacent to their farmland.

Practice-use among medium-scale farmers was generally intermediate. Whereas small-scale farmers were more likely to use intercropping, insectary plantings and riparian buffers than medium-scale farmers ($P\leq0.008$), reduced tillage was the only practice more likely to be used on medium than small farms ($P=0.06$). Medium-scale farmers were, however, more likely to use both insectary plantings and border plantings than large-scale farmers ($P\leq0.02$).

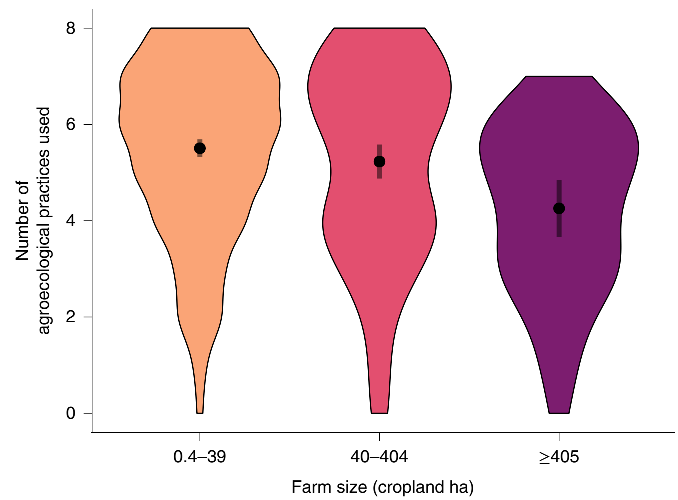

Fig. 3 | Average number of agroecological practices used by farm size (cropland ha). Violin plots display the distribution of the data ($n=542$ farmer respondents), whereby the width indicates the observation frequency. Estimated marginal means (points) are accompanied by 95% confidence intervals (bars).

Indicators of conventionalization. Four features commonly ascribed to conventionalization were assessed in the survey: low crop diversity, high mechanization, wholesale marketing and non-local market access. Together, these qualities describe a farm that uses a standardized, industrial management approach to produce a relatively small number of crops for export-oriented wholesale markets. Among the survey respondents, these attributes were generally associated with larger farms (Fig. 5).

Large-scale organic fruit and vegetable farmers managed the least diverse crop rotations overall, although most of these farmers grew between three and nine crops in a typical rotation (Fig. 5). Although nearly one-third of both small- and medium-scale farmers produced 30 or more crop species, no large-scale farmers managed similarly diverse rotations. The proportion of mechanized farm work increased as farm size increased. Among small-scale farmers, 54% managed their farm with little to no mechanization (0%–25%), whereas just 3% of large-scale farmers did the same (Fig. 5). Conversely, around 6% of small-scale farmers managed highly mechanized (75%–100%) operations, compared with 48% of large-scale farmers.

Wholesale markets, which include selling to processors and distributors, were the primary destination for fruits and vegetables grown on large farms: nearly 90% of large-scale farmers sold over three-quarters of their produce wholesale (Fig. 5). Direct sales, such as farmers' markets, farm stands or community-supported agriculture programmes, comprised over three-quarters of total sales for 74% of small farms, 30% of medium farms and less than 7% of large farms. Relatedly, nearly 30% of the produce grown on small farms was sold to consumers within a radius of 16 km around the farm, with just 12% transported further than 160 km (Fig. 5). In comparison, none of the crops grown on large farms were sold to consumers within 16 km of the farm, and nearly 60% was shipped beyond a radius of 160 km.

Farms of contrasting sizes market their crops in dissimilar ways, potentially serving different consumers. Notably, however, only

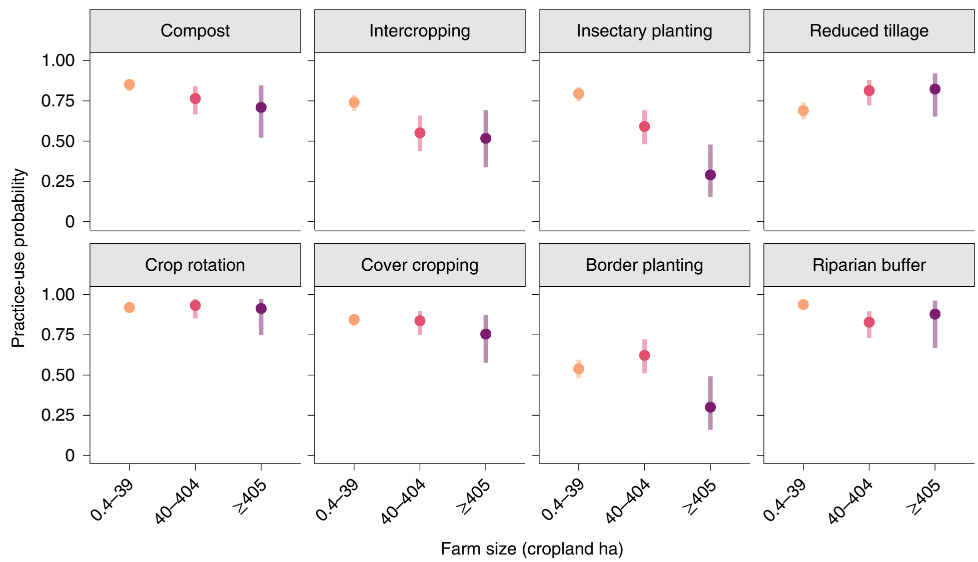

Fig. 4 | Predicted probability that a farmer does use ($y = 1$) or does not use ($y = 0$) a given agroecological practice among farm size (cropland ha) categories. Using responses from all farmers ($n = 542$), estimated marginal means are presented for each practice-size interaction, and accompanying bars are 95% confidence intervals.

17% of small-scale (organic) farmers claimed that other small- or medium-scale organic farmers were their biggest competitors (Fig. 5). Over 40% of small-scale (organic) farmers reported that competition from large organic farms presented the greatest threat, followed by 28% who designated this role to large conventional farms. Among large-scale (organic) farmers, over 50% indicated that large conventional farms were their greatest competition.

In our survey, respondents were asked if they would increase the size of their farm if possible—that is, if all barriers to scaling up were removed in a hypothetical situation. Among small farms, the responses were evenly distributed at around 25% for each option (Fig. 5). More than half of all large farms indicated that they would 'definitely' increase the size of their farm with just 3% definitive about not doing so.

Discussion

Overall, most of the organic farmers in our survey used multiple agroecological practices in a variety of combinations. Small-scale farmers were able to adopt many of these practices, although usually not all eight concurrently, whereas large-scale farmers adopted fewer agroecological practices in general. Other research has shown that organic farmers are likely to use agroecological practices, although many studies do not explicitly distinguish practice-use among organic farms of different sizes[13,17,20,36,45,46]. In a national survey that grouped all organic farms together, it was reported that 29% of organic farmers maintained habitat for beneficial insects[9]; however, our analyses demonstrate that farm size is an important factor for predicting the use of insectary plantings. While the probability of using insectary plantings was 29% for large-scale farmers, it was much higher at 59% and 80% for medium- and small-scale farmers, respectively. Similarly, large-scale farmers were less likely (30%) to use border plantings compared with medium- (62%) or small-scale (54%) farmers.

Insectary plantings provide an illustrative example of how barriers to using agroecological practices can vary substantially by farm size. For instance, crop pollination services have been found to decrease exponentially as the distance from an insectary planting increases[31]. In our survey, the average field size for large farms, at 41 ha, was not only 25 times larger than the average field size on small farms, but it was also greater than the largest possible small farm in that category. This disparity has inherent management implications for optimizing pollination services, as well as for biological pest management[33]. Although insectary plantings are generally scalable[47], large-scale farmers must consider trade-offs that a small-scale farmer might not contend with to the same degree. Integrating enough insectary plantings or border plantings to countervail the suppressive effects of both low semi-natural habitat abundance and low edge density (that is, perimeter-area ratios) on functional biodiversity might present a greater challenge for large-scale farmers, although landscape composition and configuration can interact in complex, context-specific ways[48–50]. Still, taking land out of production is a likely concern on farms of any size, exacerbated by short-term leases and the high value of farmland in many important growing regions in the United States.

In addition to cropping system constraints, marketing can present uneven barriers that differentially affect large- and small-scale growers. Large-scale farmers tend to sell their produce wholesale, thus receiving a lower price per unit than those who sell directly to consumers. To access some wholesale markets, farmers must comply with third-party food safety standards that can be more stringent than national guidelines[51]. In these instances, compliance has resulted in the removal of non-crop vegetation and a notable simplification of agroecosystems[52]. Landscape simplification has been shown to reduce both natural enemy and pollinator richness, indirectly affecting pest control and pollination, resulting in lower crop production[30]. Together, these factors have the potential to affect large-scale farmers negatively through reduced prices, habitat removal and lower yields. Although small-scale farmers engage with different markets, buyers can still demand that they obtain some form of food safety certification[51]; unless they are exempt from these demands, small-scale farmers face prohibitively high costs to comply—costs that are substantially greater than for large-scale farms—given the high fixed costs relative to sales[53].

Conventionalization, competition and certification. Large farms in our survey exhibited more characteristics of conventionalization than smaller farms, including differences in the use of agroecological practices, suggesting a bifurcation based on traits concomitant with size. In early conventionalization research outside the United States, it was suggested that the bifurcated sectors—large-scale

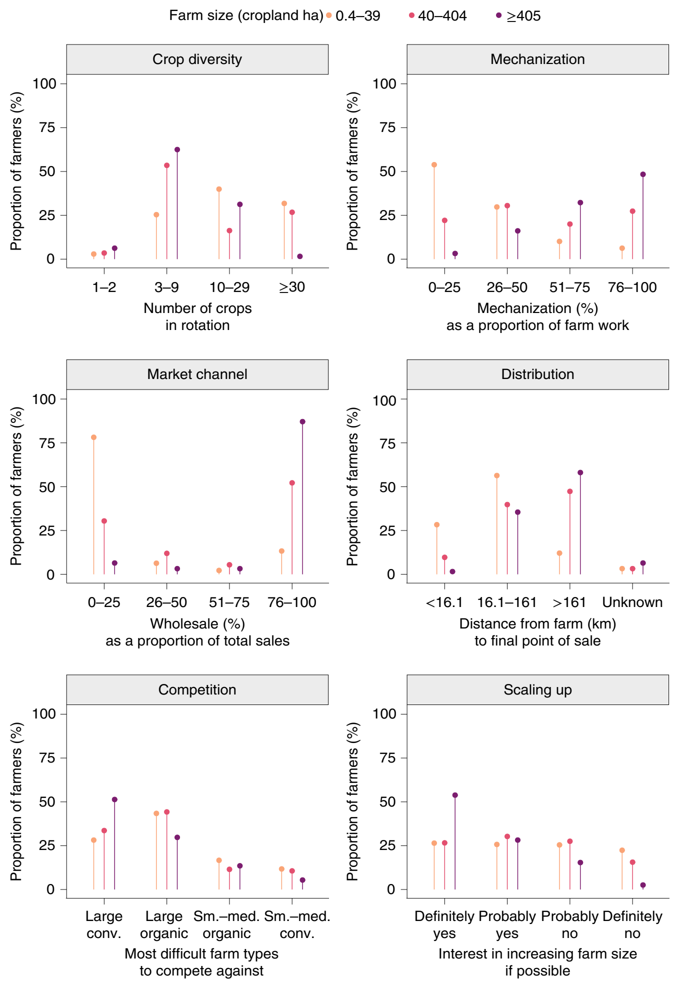

Fig. 5 | Comparing potential indicators of conventionalization among organic farms of different size (cropland ha). Points represent the percentage of farmers ($n=542$ survey respondents) within a size category who selected a specific response among a discrete number of choices for a given survey question. The questions presented here focused on crop diversity (number of crops in rotation), mechanization (proportion of work that is mechanized), market channels (wholesale as a proportion of total sales), distribution (distance to market), competition with other farmers (size and management type) and scaling up (interest in increasing farm size). Conv., conventional; med, medium; sm., small. See Supplementary Table 3 for the associated contingency tables.

production for export markets and small-scale production for local markets—coexist in a dependent relationship in which target markets are both separate and complementary[54]. Despite small and large organic farms serving different consumer niches[55], small-scale farmers in our survey reported a disproportionately high degree of competition from large organic farms. This threat might represent a farm-gate price-squeeze[56], driven by the entry of large-scale conventional farmers into an organic market with few powerful buyers (that is, oligopsony), providing products at a lower cost due to scale efficiencies[57].

The overall, though uneven, dilution of organic standards[58,59]—leading to some products less differentiated from their conventionally produced counterparts—accommodates, if not encourages, increased entry by larger farms[39]. This mainstreaming of organic agriculture has been co-facilitated by big-box retailers and the large-scale farmers who have access to processors, distributors and national wholesale markets, thereby introducing organic products to a much greater number of people, often at a lower cost[60]. Yet, the entry of these large farms can depress the price premium obtained for organic produce, thereby discouraging the very farmers who are most motivated by profitability from converting to organic production[60].

In the United States, reversing the attenuation of organic standards and evolving them beyond minimum requirements[59] to include measurable social and ethical dimensions might help minimize the economic pressure from large farms, but not without consequences for the price of organic products and growth in the sector. Although some alternative certification schemes have been developed to explicitly address social justice shortcomings, others still eschew the inclusion of more rigorous social and ecological principles in favour of regulation compliance, which has been central to the critiques of the NOP[39,40,59–61]. Alternative certifications that do seek to redress the absence of strong commitments to social sustainability typically frame their principles in contrast to conventionalized organic standards. As such, voluntary adoption of these alternative certifications seems more likely among small- and medium-scale farmers, many of whom indicated that large organic farms posed the greatest competition (Fig. 5). By contrast, elective uptake of these more rigorous certifications seems less likely among the large-scale farmers that the organic standards have been softened to accommodate.

It should be noted that the features of organic farms described in this article cannot be extrapolated to other production regions with different socio-economic or political contexts. We also agree with other researchers[54,62,63] who have detailed the limitations of using binary metrics in a heterogeneous organic sector. A large-scale farmer is not inherently less attuned to environmental stewardship, animal welfare or farmworker justice than a small-scale farmer, just as small-scale farmers are not intrinsically or universally more ecologically and socially virtuous.

Identifying the use and disuse of agroecological practices helps illustrate the differences among organic farms, but it does not reveal why or how the practices are being used. Although the reasons why agroecological or similar practices are used have received substantial attention from researchers[64], the different ways in which farmers implement these practices—particularly across farm sizes—is not well understood or documented. Such variations in the application of a given practice can have profound implications for the delivery of ecosystem services, or disservices, as well as the transformative potential of the farming sector as a whole.

Redesigning agroecosystems. Although organic agriculture can serve as a model for transforming agriculture, heterogeneity within the sector in terms of agroecological practice-use and conventionalization highlights the need for a guiding framework that acknowledges the influence of farm size. Conceptualizing the transformation of agriculture as a series of discrete steps can be a valuable analytical approach, despite simplifying the complexity inherent in the process[65,66]. One such framework for envisaging a shift towards increasingly sustainable farming systems involves three nonlinear stages: efficiency, substitution and redesign (E-S-R)[67]. These stages can be sequential, but they are just as likely to occur simultaneously, forwards or backwards, among different practices[68].

Practices that increase the efficiency (E) of a farm usually involve more judicious use of external inputs (for example, most applications of precision and digital agriculture technologies). The substitution (S) approach seeks to replace unsustainable inputs or practices with more sustainable or environmentally benign alternatives (for example, synthetic fertilizers might be replaced with compost). The input substitution approach associated with the conventionalization of organic agriculture involves the use of NOP-approved inputs instead of prohibited ones, which is analogous to the more general description of substitution practices employed by the E-S-R

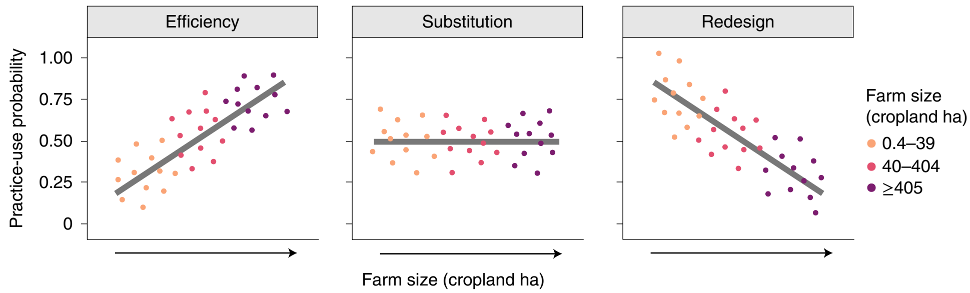

Fig. 6 | Conceptual diagram illustrating the relationship between farm size and agroecological practice-use. Integrative approaches include using an agroecological practice as an efficiency-increasing tactic, as a substitution for a less-sustainable input or as part of the systematic redesign of an agroecosystem. Points are for illustrative purposes only.

framework. As with efficiency-increasing practices, substitution practices do not necessitate major changes to the overall cropping system. Redesign (R), by contrast, explicitly involves reshaping an agroecosystem and leveraging ecological processes to minimize externalities, enhance resilience and optimize the provision of ecosystem services. A redesign approach shifts the focus from reactive interventions—even relatively ecological ones—to prioritizing preventative and regenerative measures on the farm. Whereas the least sustainable farms are input-intensive in this schematic, the most sustainable systems are biodiverse and knowledge-intensive.

Informed by our findings, we propose the following generalized relationships: (1) implementing an agroecological practice simply to increase production efficiency is more likely on large-scale organic farms, (2) using an agroecological practice to substitute for a less-sustainable input or practice is no more or less likely on organic farms of a particular size, and (3) using an agroecological practice as part of a system-level redesign approach to optimize ecological processes is more likely on smaller organic farms (Fig. 6).

In relation to our practice-use diagram, reduced tillage is the only agroecological practice that follows the pattern associated with efficiency (that is, a positive slope from small to large farms; Figs. 4 and 6). Compost, crop rotation, cover cropping and riparian buffers generally follow the pattern of expected use associated with substitution (that is, marginal or no slope; Figs. 4 and 6). Intercropping, insectary plantings and border plantings follow the pattern of expected use associated with redesign (that is, a negative slope; Figs. 4 and 6). In the efficiency and redesign scenarios it is less likely, but not impossible, for the opposite to occur. Most important in this conceptualization, especially as cropland continues to shift from medium- to large-scale farmers, is the limited probability that large-scale farmers will transition (without support) to a system that relies primarily on knowledge- and labour-intensive agroecological practices to redesign their operation. As recent studies have shown, medium-scale farmers can potentially access resources and provide benefits that are distinct from other farm types[69,70]. Accordingly, the ongoing disappearance of an 'agriculture of the middle' is of particular concern[71].

Conceptualizing the E-S-R framework as it relates to farm size and the probability of practice-use has implications for developing policy that is tailored to farm size. In the policy and scientific discourse about how agriculture should minimize or remedy the socio-ecological ills associated with the dominant food system, two distinct approaches have emerged: incrementalism and transformation[36]. The former focuses on increasing efficiency and substitution, whereas the latter prioritizes redesign. In relation to the E-S-R framework, however, incrementalism and transformation are not mutually exclusive. Although greater implementation of agroecological practices can deliver a wide range of social and ecological benefits[45], the use of these practices among farmers is limited, particularly as part of a redesign approach. In light of the relationships between farm size and practice-use, we offer public and private sector decision-makers three pathways for guiding transformative change in agriculture:

(1) Promote increased use of agroecological practices, especially those involving non-crop vegetation, among large-scale organic farmers through enhanced outreach and education to policymakers, private sector actors, extension educators and farmers on the multifaceted benefits of comanaging a farm for biodiversity conservation and food safety.
(2) Support small and, in particular, medium organic farms by increasing access to 'values-based supply chains' and alternative markets, such as regional food hubs, that lie outside the scope of direct competition with large farms.
(3) Develop or revise incentive programmes to provide progressively greater financial assistance for agroecological practice-use that demonstrates characteristics of efficiency (less support) through redesign (more support).

Just as farm size is a proxy, not a prophecy, conventionalization of the organic sector is not an inevitable trajectory. The degree to which an organic farm might be described as conventionalized exists on a gradient, and the probabilities we have presented are calls to action, not predetermined outcomes. Whether an organic farm has become conventionalized through size or management changes or it has exhibited characteristics of conventionalization since its establishment, targeted, scale-appropriate policy interventions can shift both management and sustainability outcomes.

Although this work is focused on organic agriculture, we expect that the farm size and agroecological practice-use relationships we describe within the E-S-R framework exist under other types of farm management. To this end, we recommend that farm size and the way in which agroecological practices are used be positioned more centrally when developing or refining policy and research priorities aimed at generating transformative change in US agriculture.

Methods

Survey design. The survey questions were initially developed to address our broad research objectives and the associated knowledge gaps we identified in the literature. As we designed the survey instrument, we also created an interview guide, which was comprised of themes, questions and prompts that were similar to the survey questions. We used this interview guide to conduct semistructured in-depth interviews with 10–12 farmers in both California and New York. Written informed consent was obtained from all interview subjects who participated in the study. The Cornell Institutional Review Board for Human Participants approved our study (Protocol ID #1612006859).

The interviews provided detailed responses and valuable insight, informing our questionnaire revisions. After these modifications, the questionnaire was tested by a diversity of small- to large-scale farmers from multiple US states. Feedback from this phase was then integrated into a final set of revisions. Numerous question types were used throughout the survey, including multiple choice, text entry, rank order and matrix tables with Likert-scale response options.

Survey distribution. Created with the Qualtrics online survey platform, our electronic survey was accessible with a computer, tablet or smartphone. We primarily used maximum variation sampling (also known as 'heterogeneous sampling'), which is a subtype of non-probability purposive sampling. We used this sampling procedure because probability sampling was not possible for our population of interest, and it was important for our research objectives to obtain responses from organic fruit and vegetable farmers who managed a wide range of farm sizes and were characterized, potentially, by varying degrees of 'conventionalization'.

To ensure that we minimized sampling bias and obtained a sufficient sample of respondents who represented small- to large-scale farmers across a range of conventionalization, we used a highly diverse and purposeful survey outreach approach. This strategy included posting survey invitations on farmer listservs; publishing invitations through various social media platforms, on farming-focused websites and in electronic agricultural newsletters; promoting the survey through trade magazine interviews; contacting farmers directly with email addresses obtained from extension educators, grower associations, non-governmental organizations and public databases; and through referral (snowball) sampling.

Although some of these outreach efforts reached organic farmers of all sizes (for example, USDA Organic Integrity Database), others were more specific. For example, obtaining farmer email addresses from farmers' market managers across the country provided access primarily to small- and medium-scale organic farms because large-scale organic farmers typically sell their produce through wholesale markets. To reach large-scale farms, our approach included promoting our survey through extension educators at land-grant universities who often work with medium- and large-scale farmers (though specific 'small farm' programmes are an exception); crop consultants, who tend to do contract or salaried work for larger farms; farm bureau contacts, some of whom serve on state boards with large-scale farmers; and grower–shipper associations, which cater to large, vertically integrated farms.

Once started, the survey could be completed over any number of sessions within a 2-week timeframe. Because many farmers left the survey open and returned to it multiple times, an accurate calculation of the average length of time required to complete the survey was not possible. Although the survey remained live between February and November 2018, the outreach and distribution efforts were intermittent, rather than continuous, throughout that period.

Data preparation. A total of 1,264 responses from farmers across the United States were obtained. Using R v.4.1.1 (ref. [72]), incomplete surveys were filtered out. More specifically, any surveys that did not include responses to questions about farm size, management type, crops grown or agroecological practices used were excluded because these data were required for the analyses in this paper. Next, we organized the respondents into two management types: conventional, which we excluded from the analyses in this paper; and organic. Here, organic management represented a composite of several subcategories from the survey, including any combination of farmers who were certified organic, farmers who used organic management but were not certified, farmers who managed land in transition to organic certification and farmers who managed some land conventionally and some land organically. Among this organic management group (referred to collectively as 'organic farmers' in the main text), we filtered out farmers who did not grow any fruits or vegetables. In addition to those who exclusively produced fruits and/or vegetables, we retained farmers who produced a mix of fruits or vegetables and field crops, grains, forages or livestock. We refer to all of these farmers as 'fruit and vegetable farmers' for simplicity.

Based on the amount of cropland under production, the responses were then organized into one of three farm size categories: 0.4–39, 40–404 or ≥405 ha. Each of these categories combined several size groups used in the USDA 2017 Census of Agriculture[43]. Our small-scale category (0.4–39 ha) matches the USDA group (<40 ha), which represents a farm size group that was relatively stable over the past three decades with a slight 0.3% decrease in the proportion of cropland managed. Our medium-scale category (40–404 ha) combines three USDA groups (40–80, 81–201 and 202–404 ha), which represents a farm size group that experienced a 23.4% decrease in the proportion of cropland managed. Our large-scale category (≥405 ha) combines two USDA groups (405–809 and >809 ha), which represents a farm size group that experienced a 23.7% increase in the proportion of cropland managed.

All three USDA farm size groups that comprised our medium-scale category saw a decrease and both USDA farm size groups that comprised our large-scale category saw an increase over the three-decade period. Combining farm size groups with consistent long-term trends (for example, all decreasing or all increasing) allowed us to visualize the broader trend of cropland consolidation (Fig. 1) more clearly, as well as conduct meaningful contrasts among farm size groups. In our sample, the proportion of farmers who managed mixed operations (that is, both conventional and organic management) was 7%, 28% and 72% for small, medium and large farms, respectively. On these mixed operations, the mean percentage of cropland that was under organic production was 45%, 33% and 25% across the same farm sizes. Although we refer to the farm size categories as small, medium and large for convenience, we are aware that such qualitative descriptors differ substantially across the United States.

This data preparation process yielded 542 responses from farmers across 43 states for use in our statistical analyses. The representativeness of this sample is supported by the similar demographic composition observed when comparing our national sample with the demographic characteristics reported in the USDA 2017 Census of Agriculture for organic farmers (Supplementary Table 4), as well as the proportion of organic fruit and vegetable production by state (Supplementary Table 5).

Statistical analyses. All analyses and visualizations were completed in R v.4.1.1 with the following packages: 'tidyverse'[73], 'lme4'[74] and 'emmeans'[75]. The total number of practices used was summarised with violin plots. The width of these visualizations represents the observation frequency (width increases as observation number increases). We also predicted the average number of agroecological practices in use on farms of varying size. Based on a linear model in which the number of practices used was the response and farm size was the predictor, we calculated estimated marginal means, which are equally weighted means of the predictions, and 95% confidence intervals (Fig. 3).

Binomial logistic regression was used to predict the probability of whether a farmer does or does not use a given agroecological practice. In the survey, respondents were asked whether they currently use, previously used or never used each of the eight practices. For riparian buffers, a fourth option was available, 'not applicable', so that the responses from farmers without waterways on or adjacent to their farm would not confound the responses from farmers who had never used the practice. Also, farmers who exclusively produced woody perennials, such as fruit and nut trees, were excluded from the analysis of crop rotation. The lifecycle of such crops precludes typical crop rotation. Responses from farmers who previously used a practice, but no longer do so, were grouped with farmers who had never used a practice before. Thus, our binary response variable was current use (1) and current disuse (0).

The response was predicted by an interaction between practice (eight levels: compost or manure application, intercropping, insectary planting, reduced tillage, crop rotation, cover cropping, border planting and riparian buffer) and farm size (three levels: 0.4–39, 40–404 and ≥405 ha), with anonymized respondent identification as a random effect. After establishing a reference grid, which included all combinations of the categorical predictors, we used the binomial logistic regression model to estimate the mean on the response scale for each combination in the reference grid. This process yielded estimated marginal means and 95% confidence intervals (Fig. 4). Note that for binomial logistic regression, the confidence intervals are asymmetrical due to the asymptotic nature of the minimum and maximum values for predicted probabilities (that is, at $y=0$ and $y=1$, respectively). Pairwise comparisons (that is, contrasts) by farm size (Supplementary Table 1) and by practice (Supplementary Table 2) were conducted to compare the estimated marginal means with one another. For these tests, the Tukey Method was used for the P-value adjustment. We note that interpretations of the contrasts were not based exclusively on the threshold of $p<0.05$ (see refs. [76–78]).

To assess whether there were any associations between farm size and a specific indicator of conventionalization, Fisher's exact test[72] was used. This test can accommodate contingency tables (that is, a table with I rows for categories of X and J columns for categories of Y) that are larger than 2×2 ($I\times J$)[79]. Fisher's exact test is also preferred over Pearson's chi-squared test when the sample size is relatively small or when one or more cells in a contingency table has an expected frequency of five or less[79], which was the case in some of our 3×4 tables (Supplementary Table 3). Farm size categories (0.4–39, 40–404 and ≥405 ha) were the rows and conventionalization indicator responses (four discrete choices as a possible survey response) were the columns. For these tests, the null hypothesis is that there is no association between the two categorical variables, farm size and the (potential) conventionalization indicator. The six questions related to conventionalization focused on crop diversity (number of crops in rotation: 1–2, 3–9, 10–29 or ≥30 crops), mechanization (proportion of farm work that is mechanized: 0%–25%, 26%–50%, 51%–75% or 76%–100%), market channel (wholesale as a proportion of total sales: 0%–25%, 26%–50%, 51%–75% or 76%–100%), distribution (distance from farm to the final point of sale: <16.1, 16.1–161, ≥161 km or unknown), competition (most difficult farm types to compete with: large conventional, large organic, small–medium organic or small–medium conventional) and scaling (interest in increasing their farm size: definitely yes, probably yes, probably no or definitely no). After assessing whether farm size and the conventionalization indicators were associated (Supplementary Table 3) using Fisher's exact test (two-sided) with each contingency table of counts (n), we calculated proportions (%), as presented in the Results (Fig. 5) and Discussion, as a more easily interpretable metric for this analysis.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The national farmer survey data that were used in the analyses are available from the corresponding author upon reasonable request. These data are not publicly available as they contain information that could compromise research participant privacy or consent. Data from the USDA NASS 2017 Census of Agriculture were also used to support the findings of this study, and they are publicly available at https://www.nass.usda.gov/Publications/AgCensus/2017.

Code availability

The R code used to generate the results is available from the corresponding author upon reasonable request.

Received: 28 May 2021; Accepted: 7 June 2022;
Published online: 21 July 2022

References

1. Wanger, T. C. et al. Integrating agroecological production in a robust post-2020 Global Biodiversity Framework. *Nat. Ecol. Evol.* **4**, 1150–1152 (2020).
2. Newbold, T. et al. Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45–50 (2015).
3. Amundson, R. et al. Soil and human security in the 21st century. *Science* **348**, 1261071 (2015).
4. Robertson, G. P. & Vitousek, P. M. Nitrogen in agriculture: balancing the cost of an essential resource. *Annu. Rev. Environ. Resour.* **34**, 97–125 (2009).
5. Campbell, B. M. et al. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* **22**, 8 (2017).
6. Kremen, C. & Merenlender, A. M. Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018).
7. Krebs, A. V. *The Corporate Reapers: The Book of Agribusiness* (Essential Books, 1992).
8. Mortensen, D. A. & Smith, R. G. Confronting barriers to cropping system diversification. *Front. Sustain. Food Syst.* **4**, 564197 (2020).
9. *2017 Census of Agriculture – 2019 Organic Survey* (USDA NASS, 2020); https://www.nass.usda.gov/Publications/AgCensus/2017/index.php
10. *Farms and Land in Farms 2019 Summary* (USDA NASS, 2020); https://usda.library.cornell.edu/concern/publications/5712m6524
11. Reganold, J. P. & Wachter, J. M. Organic agriculture in the twenty-first century. *Nat. Plants* **2**, 15221 (2016).
12. Muller, A. et al. Strategies for feeding the world more sustainably with organic agriculture. *Nat. Commun.* **8**, 1290 (2017).
13. Lori, M., Symnaczik, S., Mäder, P., De Deyn, G. & Gattinger, A. Organic farming enhances soil microbial abundance and activity—a meta-analysis and meta-regression. *PLoS ONE* **12**, e0180442 (2017).
14. Seufert, V. & Ramankutty, N. Many shades of gray—the context-dependent performance of organic agriculture. *Sci. Adv.* **3**, e1602638 (2017).
15. USDA AMS. National Organic Program; Final Rule, 7 CFR Part 205. *Fed. Regist.* **65**, 80547–80684 (2000).
16. Wezel, A. et al. Agroecology as a science, a movement and a practice. A review. *Agron. Sustain. Dev.* **29**, 503–515 (2009).
17. Tamburini, G. et al. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* **6**, eaba1715 (2020).
18. Kleijn, D. et al. Ecological intensification: bridging the gap between science and practice. *Trends Ecol. Evol.* **34**, 154–166 (2019).
19. Bommarco, R., Kleijn, D. & Potts, S. G. Ecological intensification: harnessing ecosystem services for food security. *Trends Ecol. Evol.* **28**, 230–238 (2013).
20. Kremen, C. & Miles, A. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* **17**, 40 (2012).
21. Bowles, T. M. et al. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* **2**, 284–293 (2020).
22. Wood, S. A. et al. Functional traits in agriculture: agrobiodiversity and ecosystem services. *Trends Ecol. Evol.* **30**, 531–539 (2015).
23. Faucon, M.-P., Houben, D. & Lambers, H. Plant functional traits: soil and ecosystem services. *Trends Plant Sci.* **22**, 385–394 (2017).
24. D'Hose, T. et al. The positive relationship between soil quality and crop production: a case study on the effect of farm compost application. *Appl. Soil Ecol.* **75**, 189–198 (2014).
25. Fließbach, A., Oberholzer, H.-R., Gunst, L. & Mäder, P. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agric. Ecosyst. Environ.* **118**, 273–284 (2007).
26. Francioli, D. et al. Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies. *Front. Microbiol.* **7**, 1446 (2016).
27. Nunes, M. R., Karlen, D. L., Veum, K. S., Moorman, T. B. & Cambardella, C. A. Biological soil health indicators respond to tillage intensity: a US meta-analysis. *Geoderma* **369**, 114335 (2020).
28. Blanco-Canqui, H. & Ruis, S. J. No-tillage and soil physical environment. *Geoderma* **326**, 164–200 (2018).
29. Willekens, K., Vandecasteele, B., Buchan, D. & De Neve, S. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. *Appl. Soil Ecol.* **82**, 61–71 (2014).
30. Dainese, M. et al. A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* **5**, eaax0121 (2019).
31. Albrecht, M. et al. The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. *Ecol. Lett.* **23**, 1488–1498 (2020).
32. Chaplin-Kramer, R., de Valpine, P., Mills, N. J. & Kremen, C. Detecting pest control services across spatial and temporal scales. *Agric. Ecosyst. Environ.* **181**, 206–212 (2013).
33. Martin, E. A. et al. The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecol. Lett.* **22**, 1083–1094 (2019).
34. Karp, D. S. et al. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proc. Natl Acad. Sci. USA* **115**, E7863–E7870 (2018).
35. Zhang, X., Liu, X., Zhang, M., Dahlgren, R. A. & Eitzel, M. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *J. Environ. Qual.* **39**, 76–84 (2010).
36. Eyhorn, F. et al. Sustainability in global agriculture driven by organic farming. *Nat. Sustain.* **2**, 253–255 (2019).
37. Buck, D., Getz, C. & Guthman, J. From farm to table: the organic vegetable commodity chain of northern California. *Sociol. Rural.* **37**, 3–20 (1997).
38. Guthman, J. Raising organic: an agro-ecological assessment of grower practices in California. *Agric. Hum. Values* **17**, 257–266 (2000).
39. Guthman, J. The trouble with 'organic lite' in California: a rejoinder to the 'conventionalisation' debate. *Sociol. Rural.* **44**, 301–316 (2004).
40. Darnhofer, I., Lindenthal, T., Bartel-Kratochvil, R. & Zollitsch, W. Conventionalisation of organic farming practices: from structural criteria towards an assessment based on organic principles. A review. *Agron. Sustain. Dev.* **30**, 67–81 (2010).
41. Constance, D. H., Choi, J. Y. & Lyke-Ho-Gland, H. Conventionalization, bifurcation, and quality of life: certified and non-certified organic farmers in Texas. *J. Rural Soc. Sci.* **23**, 208–234 (2008).
42. *2017 Census of Agriculture – United States Summary and State Data* (USDA NASS, 2019); https://www.nass.usda.gov/Publications/AgCensus/2017/index.php
43. *2017 Census of Agriculture: Characteristics of All Farms and Farms with Organic Sales* (USDA NASS, 2019); https://www.nass.usda.gov/Publications/AgCensus/2017/index.php
44. Ponisio, L. C. et al. Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B* **282**, 20141396 (2015).
45. Wezel, A. et al. Agroecological practices for sustainable agriculture. A review. *Agron. Sustain. Dev.* **34**, 1–20 (2014).
46. Gomiero, T., Pimentel, D. & Paoletti, M. G. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Crit. Rev. Plant Sci.* **30**, 95–124 (2011).
47. Tittonell, P. et al. Agroecology in large scale farming—a research agenda. *Front. Sustain. Food Syst.* **4**, 584605 (2020).
48. Haan, N. L., Zhang, Y. & Landis, D. A. Predicting landscape configuration effects on agricultural pest suppression. *Trends Ecol. Evol.* **35**, 175–186 (2020).
49. Martin, E. A., Seo, B., Park, C.-R., Reineking, B. & Steffan-Dewenter, I. Scale-dependent effects of landscape composition and configuration on natural enemy diversity, crop herbivory, and yields. *Ecol. Appl.* **26**, 448–462 (2016).
50. Tscharntke, T. et al. Landscape moderation of biodiversity patterns and processes – eight hypotheses. *Biol. Rev.* **87**, 661–685 (2012).
51. Olimpi, E. M. et al. Evolving food safety pressures in California's central coast region. *Front. Sustain. Food Syst.* **3**, 102 (2019).
52. Karp, D. S. et al. The unintended ecological and social impacts of food safety regulations in California's central coast region. *BioScience* **65**, 1173–1183 (2015).
53. Bovay, J., Ferrier, P. & Zhen, C. *Estimated Costs for Fruit and Vegetable Producers To Comply With the Food Safety Modernization Act's Produce Rule*, EIB-195 (U.S. Department of Agriculture, Economic Research Service, 2018).
54. Coombes, B. & Campbell, H. Dependent reproduction of alternative modes of agriculture: organic farming in New Zealand. *Sociol. Rural.* **38**, 127–145 (1998).
55. Hughner, R. S., McDonagh, P., Prothero, A., Shultz, C. J. & Stanton, J. Who are organic food consumers? A compilation and review of why people purchase organic food. *J. Consum. Behav.* **6**, 94–110 (2007).
56. Smith, E. & Marsden, T. Exploring the 'limits to growth' in UK organics: beyond the statistical image. *J. Rural Stud.* **20**, 345–357 (2004).
57. Howard, P. H. *Concentration and Power in the Food System: Who Controls What We Eat?* (Bloomsbury, 2016).
58. Arcuri, A. The transformation of organic regulation: the ambiguous effects of publicization. *Regul. Gov.* **9**, 144–159 (2015).
59. Seufert, V., Ramankutty, N. & Mayerhofer, T. What is this thing called organic? – How organic farming is codified in regulations. *Food Policy* **68**, 10–20 (2017).
60. Guthman, J. in *Alternative Food Politics: From the Margins to the Mainstream* (eds. Phillipov, M. & Kirkwood, K.) 23–36 (Routledge, 2019).

61. Jaffee, D. & Howard, P. H. Corporate cooptation of organic and fair trade standards. *Agric. Hum. Values* **27**, 387–399 (2010).
62. Campbell, H. & Rosin, C. After the 'organic industrial complex': an ontological expedition through commercial organic agriculture in New Zealand. *J. Rural Stud.* **27**, 350–361 (2011).
63. Lockie, S. & Halpin, D. The 'conventionalisation' thesis reconsidered: structural and ideological transformation of Australian organic agriculture. *Sociol. Rural.* **45**, 284–307 (2005).
64. Prokopy, L. S. et al. Adoption of agricultural conservation practices in the United States: evidence from 35 years of quantitative literature. *J. Soil Water Conserv.* **74**, 520–534 (2019).
65. Pretty, J. et al. Global assessment of agricultural system redesign for sustainable intensification. *Nat. Sustain.* **1**, 441–446 (2018).
66. Gliessman, S. Transforming food systems with agroecology. *Agroecol. Sustain. Food Syst.* **40**, 187–189 (2016).
67. Hill, S. B. Redesigning the food system for sustainability. *Alternatives* **12**, 32–36 (1985).
68. Padel, S., Levidow, L. & Pearce, B. UK farmers' transition pathways towards agroecological farm redesign: evaluating explanatory models. *Agroecol. Sustain. Food Syst.* **44**, 139–163 (2020).
69. Esquivel, K. E. et al. The 'sweet spot' in the middle: why do mid-scale farms adopt diversification practices at higher rates? *Front. Sustain. Food Syst.* **5**, 734088 (2021).
70. Brislen, L. Meeting in the middle: scaling-up and scaling-over in alternative food networks. *Cult. Agric. Food Environ.* **40**, 105–113 (2018).
71. De Master, K. New inquiries into the agri-cultures of the middle. *Cult. Agric. Food Environ.* **40**, 130–135 (2018).
72. R Core Team. *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2021).
73. Wickham, H. et al. Welcome to the Tidyverse. *J. Open Source Softw.* **4**, 1686 (2019).
74. Bates, D., Mächler, M., Bolker, B. & Walker, S. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 1–48 (2015).
75. Lenth, R. V. emmeans: Estimated marginal means, aka least-squares means. R package version 1.7.4-1 https://CRAN.R-project.org/package=emmeans (2021).
76. Wasserstein, R. L. & Lazar, N. A. The ASA statement on *p*-values: context, process, and purpose. *Am. Stat.* **70**, 129–133 (2016).
77. Krueger, J. I. & Heck, P. R. Putting the *P*-value in its place. *Am. Stat.* **73**, 122–128 (2019).
78. Wasserstein, R. L., Schirm, A. L. & Lazar, N. A. Moving to a world beyond '$p < 0.05$'. *Am. Stat.* **73**(Suppl. 1), 1–19 (2019).
79. Agresti, A. *Categorical Data Analysis* (Wiley, 2013).

Acknowledgements

This research was conducted as part of the project 'Adoption of Agroecological Farming Practices in Specialty Crops: Incentives, Barriers, and Outcomes', funded by the Cornell Atkinson Center for Sustainability (and awarded to M.R.R. and S.G., along with R.B., R.B.K., T.B., M.I.G., A.K.H., J.L. and A.G.P.). J.L. acknowledges the financial support from the Natural Sciences and Engineering Research Council of Canada. We thank the farmers who participated in the questionnaire pilot study and interviews, as well as those who completed the survey. We also thank S. Parry, E. Mudrak and L. Johnson at the Cornell University Statistical Consulting Unit for their assistance with statistical analyses; and J. MacDonald at the United States Department of Agriculture's Economic Research Service for his assistance with data compilation.

Author contributions

J.L., R.B., R.B.K., T.B., S.G., M.I.G., A.K.H., A.G.P. and M.R.R. contributed to the overall design of the study. All authors collaboratively developed the survey questionnaire and interview guide. J.L. collected the data. J.L. analysed the data with input from M.R.R. The writing of the manuscript was led by J.L., with all authors contributing through comments and revisions.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41477-022-01191-1.

Correspondence and requests for materials should be addressed to Jeffrey Liebert.

Peer review information *Nature Plants* thanks Rebecca Chaplin-Kramer and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

nature portfolio

Corresponding author(s): Jeffrey Liebert

Last updated by author(s): May 11, 2022

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The online survey software Qualtrics was used to collect survey responses from farmers.
Data analysis	R version 4.1.1 was used to conduct all statistical analyses. Three packages were central to the data analysis and visualization: 'tidyverse' for data cleaning, manipulation, and summary (via 'dplyr,' 'forcats,' 'tidyr,' 'purrr,' and 'tibble'), as well as visualization (via 'ggplot2'); 'lme4' for conducting the mixed-effects binomial logistic regression (glmer function); and 'emmeans' for obtaining the estimated marginal means for the predicted practice-use and conducting contrasts, such as in Supplementary Tables 1 and 2, with the Tukey Method for p-value adjustment of the log odds ratio effect size. To analyze categorical contingency table data of conventionalization indicators, Fisher's exact test was used (fisher.test function from the base R package 'stats'). The computer code (R script) that was used to generate the results presented in this study can be made available upon request.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The national farmer survey data that were used in the analyses are available from the corresponding author upon reasonable request. These data are not publicly available as they contain information that could compromise research participant privacy or consent. Data from the USDA NASS 2017 Census of Agriculture were also used to support the findings of this study, and they are publicly available at https://www.nass.usda.gov/Publications/AgCensus/2017.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

This study was a national survey of organic fruit and vegetable farmers in the United States. All data presented in the manuscript were obtained from this survey and are quantitative. However, we also conducted semi-structured in-depth interviews with farmers in both California and New York as part of a pilot study to help inform the survey question development.

Research sample

The sample consisted of 542 fruit and vegetable farmers from across the United States. These farmers, from 43 of 50 states, represent three farm size categories: 0.4-39 ha (n = 394), 40-404 ha (n = 109), and ≥405 ha (n = 39). These farms were characterized by at least some fruit and vegetable production (i.e., they did not exclusively produce non-horticultural crops, such as small grains or livestock) and some organically managed cropland (i.e., they did not exclusively manage their farm conventionally).
To meet the objectives of our study, we aimed to survey a representative sample of organic fruit and vegetable farmers across a range of farm sizes, located throughout the United States. The farmers who completed our survey were primarily male (58%), white (92%), and 55 years of age or older (48%) with at least 11 years of farming experience (57%). As shown in a comparison with the farmer demographics described in the USDA 2017 Census of Agriculture data in Supplementary Table 4, our sample of 542 farmers is representative of organic farmers in the United States.

Sampling strategy

A multi-tactic approach was used for the survey outreach, distribution, and sampling. Probability sampling and a sample size calculation were not possible for our population of interest because the probability of inclusion for each unit (i.e., organic fruit and vegetable farmer, with subgroups defined by cropland-based farm size) was unknown (i.e., such data are not available for this relatively small population). Instead, we primarily used a non-probability sampling approach, maximum variation sampling (also known as "heterogeneous sampling"), which is a sub-type of purposive sampling. It was important for our research objectives to obtain responses from organic fruit and vegetable farmers who managed a range of farm sizes and were characterized, potentially, by varying degrees of "conventionalization." These criteria were based on our theoretical framework and expert elicitation.

Establishing the "sufficiency" of a sample size, whether using probability or non-probability sampling, depends on many factors. Our approach to validating the size of our sample was informed by comparisons with data from the 2017 USDA Census of Agriculture, as well as the use of statistical techniques that moderated inferences through the explicit consideration of variance (i.e., in relation to the sample size of a given categorical factor level).

In terms of comparisons, the USDA 2019 Organic Survey, which is a 2017 Census of Agriculture Special Study, provides aggregate data for broad crop type categories. Our sample of fruit and vegetable farmers (n = 542), for example, is 16% of the total number of farmers who produce certified organic vegetables "grown in the open" (n = 3,300) and 23% of the total number of farmers who produce certified organic "berries and other fruits" (n = 2,325). Unlike our sample, which represents farmers who potentially grow both fruits and vegetables, the USDA data are separated by crop type (and the two categories listed here are not exhaustive categories of all types of fruits and vegetables), and the same farmer can be counted in multiple crop type categories for the total farm numbers by crop type. While imperfect, these USDA data provide approximate comparisons for our sample size.

Census data for each farm size category would be useful, but such data are only available for all farms with organic sales, which includes pastureland/rangeland and other non-horticultural crop farms. Size comparisons with such coarse data would be confounded by the significantly larger mean farm size of organic pastureland/rangeland, as well as field crop and hay farmers. In the USDA 2019 Organic Survey, mean farm sizes differ substantially among farms with pastureland/rangeland (112 ha), field crops and hay (102 ha), all vegetables grown in the open (28 ha), and berries and other fruits (9 ha). Although farm size comparisons between our survey and the Census are limited by data aggregation, we did observe similar farm size distribution: >50% were small-scale, <10% were large-scale, and the remaining were medium-scale farmers. In other words, our sample sizes for small (0.4–39 ha, n = 394), medium (40–404 ha, n = 109), and large (≥405 ha, n = 39) farms appear to broadly reflect the national distribution of organic farms that is skewed, in terms of farm number, towards small-scale farmers. (This farm size distribution also holds for conventional farms in the US.)

To ensure that we minimized sampling bias and obtained a sufficient sample of respondents who represented small- to large-scale farmers across a range of conventionalization, we used a highly diverse and purposeful survey outreach approach. This strategy included posting survey invitations on farmer listservs; publishing invitations through various social media platforms, on farming-focused websites, and in electronic agricultural newsletters; promoting the survey through trade magazine interviews; contacting farmers directly with email addresses obtained from extension educators, grower associations, non-governmental organizations, and public databases; and through referral (snowball) sampling.

While some of these outreach efforts reached organic farmers of all sizes (e.g., USDA Organic Integrity Database), others were more specific. For example, obtaining farmer email addresses from farmers' market managers across the country provided access primarily to small-scale organic farmers since large-scale organic farmers typically sell their produce through wholesale markets. To reach large-scale farmers, for example, we promoted our survey through extension educators at land-grant universities who often work with medium- and large-scale farmers (though specific "small farms" programs are an exception); crop consultants, who tend to do contract or salaried work for larger farms; farm bureau contacts, some of whom serve on state boards with large-scale farmers; and grower-shipper associations, which cater to large, vertically integrated farms.

Data collection

For the interview-based pilot study, only researchers JL and RBK were present with the participants. The number of interviews conducted (10–12 in both California and New York) was based partially on an assessment of data saturation. Notes were taken by hand during the interviews and all interviews were audio recorded if the participant provided consent. Audio files were transcribed and qualitatively coded to identify themes, specific questions, or particular wording that could be added to or refined in the survey tool. We evaluated our interview notes and transcripts to identify whether new topics related to farm size, the use of agroecological practices, or other attributes of conventionalization emerged. We iteratively revised our interview guide as we completed additional interviews, incorporating and testing out new questions and prompts. Eventually, we observed that relevant new topics or questions began to emerge less frequently, indicating that we were approaching saturation as it related to farmer-informed questionnaire development.

JL and RBK were not explicitly blinded to the experimental condition of farm size. In order to interview farmers from a range of farm sizes in each state, the researchers knew the approximate farm size prior to each interview. In terms of agroecological practice use or degree of conventionalization, the researchers did not have any specific prior knowledge of the farmers. The researchers used the same interview guide across all farmer interviews to reduce the occurrence of observer bias or confirmation bias.

These interviews provided valuable insight, informing our survey revisions. After modifying our survey based on the farmer interviews, the survey was tested by a range of small- to large-scale farmers from multiple US states. Feedback from this stage of the survey development was then integrated into a final set of revisions.

The national survey was created with the Qualtrics online survey platform. As such, it was an electronic survey that was accessible with a computer, tablet, or smartphone. As numerous question types were used in the survey (multiple choice, text entry, rank order, matrices, and Likert scales), data were continuous, categorical (both ordinal and nominal), and qualitative. Responses (data) obtained through the Qualtrics platform were exported to a comma-separated values (CSV) file and then imported into R for data cleaning and analysis.

Timing

The survey was opened on February 13, 2018, and closed on November 15, 2018. The survey was not closed at all during this time frame, but activity (i.e., engagement with the survey) corresponded to periods of greater outreach and survey distribution.

Data exclusions

All exclusion criteria were pre-established. For the analyses in our study, we required respondents to satisfy the following criteria: (1) farm in the United States, (2) manage farms at least 0.4 ha in size (to align with USDA Census thresholds, Fig.1), (3) manage some or all of their cropland organically, (4) grow some fruits or vegetables (not necessarily exclusively), and (5) indicate whether they use or do not use at least one of the eight agroecological practices of interest. A total of 1,264 total respondents started the survey, and 542 respondents were retained for the statistical analyses. The exact numbers of respondents excluded from the statistical analyses were as follows:

(1) Excluded 180 who did not indicate the country in which they farm (most of whom completed less than 10% of the survey) and 2 who were not farming in the US.
(2) Excluded 58 who did not indicate the size of their farm and 35 who managed farms less than 0.4 ha in size.
(3) Excluded 164 who did not indicate how they manage their crops (organically, conventionally, or both) and 97 who did not manage any of their land organically.
(4) Excluded 22 who did not indicate the type of crops they managed on their farm and 147 who did not manage any fruits or vegetables on their farm (e.g., some were exclusively small grain farmers).
(5) Excluded 17 who did not indicate whether they do or do not use any of the eight agroecological practices.

Non-participation

Due to the approach taken to advertise and distribute the survey (described above), we cannot calculate a response rate for the survey. For example, if an extension educator agreed to advertise the survey at a grower meeting, it was not possible to know how many farmers were present at the meeting, nor how many actually completed the survey after learning about it at the meeting. Similarly, we cannot know how many farmers saw our survey advertisements on social media, farmer websites, electronic newsletters, or many other types of outreach.

Out of a total of 1,264 responses, 12 respondents made 0% progress on the survey, indicating that they did not complete a single question. However, as respondents were allowed to skip any question in the survey, simply advancing the survey without answering any questions would increase the progression score according to Qualtrics. Also, survey sections were randomized to avoid any bias that might emerge due to survey question order. For these reasons, we cannot determine drop-off rates for the respondents.

Randomization

Participants were not grouped during data collection (i.e., when taking the survey). In the analysis stage, participants were grouped by farm size: 0.4-39 ha, 40-404 ha, or ≥405 ha. These size categories correspond to several combined groups used in the USDA 2017 Census of Agriculture, as described in our Methods. Using these groups allowed us to contextualize our research with a 30-year trend of cropland consolidation in the United States, which was relevant given the focus on farm size in our study.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☐	☒	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics

See "Research sample" above.

Recruitment

Participant recruitment was carried out as described in the "Sampling strategy" above. As the survey was entirely electronic (i.e., no paper versions were made available), self-selection bias, as it relates to internet access, was possible. Though high-speed internet is available to over 70% of the rural population in the United States, some farmers might not have encountered any online survey outreach. While some of our outreach involved organizations that print materials for their members and some of our contacts encouraged farmer participation in-person (e.g., at grower meetings), accessing the electronic survey would have been more challenging for farmers without good internet access at home. The effect of this self-selection bias would have been to suppress the response rate.

Though the survey introduction (the first screen of the electronic survey) describes the questionnaire in general terms, certain words might have contributed to self-selection bias. For example, the mention of "sustainably" producing crops, even though it was noted as context for the survey and not as selection criteria, might have attracted farmers who thought that they used particularly sustainable management practices, or it might have deterred those who thought their practices were less sustainable than some of their peers. Similarly, some farmers might not have completed the survey when they realized that they were not using many of the agroecological management practices that we were inquiring about. Though we did not call the practices agroecological in the survey, a farmer might have interpreted the use of these practices as the "desired" or "better" response—simply because we were asking about them—and decided to stop taking the survey rather than indicate that they did not use many, or perhaps any, of the practices. The result of such self-selection bias, if it occurred, would be to increase the predicted probability of using a given agroecological practice or suppress the response rate.

Ethics oversight

The Cornell Institutional Review Board for Human Participants approved our study (Protocol ID #1612006859).

Note that full information on the approval of the study protocol must also be provided in the manuscript.