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Un-yielding: Evidence for the agriculture transformation we need

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Abstract

There has been a seismic shift in the center of gravity of scientific writing and thinking about agriculture over the past decades, from a prevailing focus on maximizing yields toward a goal of balancing trade-offs and ensuring the delivery of multiple ecosystem services. Maximizing crop yields often results in a system where most benefits accrue to very few (in the form of profits), alongside irreparable environmental harm to agricultural ecosystems, landscapes, and people. Here, we present evidence that an *un-yielding*, which we define as de-emphasizing the importance of yields alone, is necessary to achieve the goal of a more Food secure, Agrobiodiverse, Regenerative, Equitable and just (FARE) agriculture. Focusing on yields places the emphasis on one particular outcome of agriculture, which is only an intermediate means to the true endpoint of human well-being. Using yields as a placeholder for this outcome ignores the many other benefits of agriculture that people also care about, like health, livelihoods, and a sense of place. Shifting the emphasis to these multiple benefits rather than merely yields, and to their equitable delivery to all people, we find clear scientific evidence of win-wins for people and nature through four strategies that foster FARE agriculture: reduced disturbance, systems reintegration, diversity, and justice (in the form of securing rights to land and other resources). Through a broad review of the current state of agriculture, desired futures, and the possible pathways to reach them, we argue that while trade-offs between some ecosystem services in agriculture are unavoidable, the same need not be true of the end benefits we desire from them.

KEYWORDS
agroecology, ecosystem services, justice, sustainability, telecoupling

THE PROBLEM: THE CURRENT STATE OF AGRICULTURE

The problems posed by agriculture are not new; we have been cataloging the threats posed to nature and its benefits to people for decades if not millennia,[1] and with increasing alarm in recent years as our perilous trajectory has become more evident.[2] The mounting evidence that something is wrong has tempered Green Revolution-era enthusiasm for maximizing yields at all costs.[3] Habitat loss due to agricultural expansion is one of the primary drivers of biodiversity loss.[4] Irrigation limits water available for use by other ecosystems and species.[5] Fertilizer use leads to runoff and eutrophication of freshwater and estuaries, with resulting problems for fisheries, drinking water, and recreation.[6] Human health and wildlife are threatened by a variety of pesticides and other agricultural chemicals.[7] Such localized impacts can scale up to pose global threats, and assessments of planetary boundaries have shown that agriculture exceeds its allocations of the boundaries defined for land, water, biodiversity, nutrient loading, and climate change.[8-10] The global food system alone could prevent the achievement of the 1.5°C climate target if it continues on its present trajectory, even if all other fossil fuel uses were eliminated.[11] It has also been estimated that 57% of global water use is unsustainable, the vast majority of which is directed toward the production of just five staple crops.[12] Predicted changes in population and per capita consumption by 2050 are expected to exacerbate environmental impacts of the global food system by 50–90%.[13,14]

These trade-offs between agricultural production and the variety of environmental and social problems it causes are complicated by the fact that benefits and costs often do not co-occur.[15] Instead the benefits and costs of agricultural systems move across space and time, connecting distant locations, also known as telecoupling, through trade, nontrade movement of ecosystem services (such as river flow or animal migration), and movement of people. Of particular interest is the role of agricultural trade in moving not only agricultural products, but also virtual resources, around the world. A systematic review of 350 global studies shows that factors embedded in our modern agricultural production, such as land, water, and eutrophying pollutants, are hidden costs primarily borne by regions of lower population density, the benefits of which flow to more populous regions.[16] Such "virtual" flows of these hidden costs are especially well documented for water; about a quarter of the water resources used in agriculture are virtually traded as water embodied in agricultural goods, including 11% of nonrenewable groundwater use[17] and 15% of unsustainable irrigation.[18] These trends are expected to double and triple, respectively, by the end of the century.[19] Embedded land-use change is also well studied, although predicting and attributing a change in land use to a change in demand for a product is difficult, due to the many complex and interacting processes determining land-use dynamics.[20] In rare cases, such as the 16-fold increase in soybean production in Brazil for Chinese markets,[21] linkages between markets can be specifically spatially allocated to land-use change in importing or exporting countries, or both. However, there are also counterexamples where trade can lead to increased environmental impacts at sites of consumption. For example, at least one meta-analysis documented increased application of synthetic fertilizers as a result of increased soy imports; domestic soy crops in the importing country were replaced with more input-heavy cereal grains.[22] Due to the many complexities and counterintuitive consequences of trade, the impacts of embedded land-use change remain uncertain.

Implicit in the virtual flows that link, or telecouple, distant locations are the economic inequalities between countries. Wealthier countries continue to increase their own consumption while not facing the consequences of the increased production required to sustain it. Production of export commodities affects local benefits that cannot be imported like agricultural products can; many regulating and cultural services such as mitigating flood risk or recreating in a clean lake are strictly place-based. But retaining cultural or regulating services in some places may come at the cost of degrading them in others if agricultural production is merely displaced. Wealthier cities are able to import their provisioning services such as agricultural production from low-income countries while retaining more regulating services in their surrounding rural landscapes; meanwhile, the low-income countries whose rural areas are devoted to food production for export consequently provide much lower levels of regulating and cultural services to their nearby cities.[23] This can be thought of as an "agrifood debt" between regions, in terms of "natural resources consumed, the environmental impacts produced, and the social wellbeing attained by populations that play different roles within the globalized agrifood system."[24] In general, the dramatic overconsumption of food, land, and other resources by a proportionally very small slice of global society, alongside the continued scarcity experienced by billions, produces trade-offs between equality, sufficiency, accumulation, and sustainability that have been well documented.[25–27] Equity in telecoupling must be confronted to fully tackle the global sustainability challenge presented by agriculture, in order to rectify or avoid one place's solution merely becoming another place's problem.

Equity within countries must also be considered when addressing the sustainability of agricultural production. Indeed, much of the history of the field of agroecology has been establishing how justice and sustainability cannot be achieved without each other.[28-31] Factors that can contribute to the environmental sustainability of agriculture often also support its financial sustainability, contributing to social justice through, for example, access to clean water, increased gender equality, and education.[25,27,32] The burdens of unsustainable production, on the other hand, and the resulting environmental degradation and long-term erosion of socioeconomic well-being, fall disproportionately on the poor[33] (not only less wealthy countries of the world as described above, but less wealthy and otherwise more vulnerable populations within countries). Yet, environmental sustainability efforts can be hindered by and often risk exacerbating inequity, if they lack an intentional focus on equity. For example, low adoption rates of sustainable management practices among smallholders have been attributed to inegalitarian land tenure systems, denial of rights to natural resources and public goods and services, monopolistic power in local formal and informal markets, direct private and State coercive violence, pressure moving smallholders onto more marginal lands more prone to degradation, and limited access to agricultural inputs to maintain productivity.[34-36] In ethical terms, it makes little sense to exclude justice and equity from sustainability considerations, as "sustainability without justice is simply sustained injustice."[37] Legacies of inequities faced by smallholders, including historical discrimination, land insecurity, and poverty traps, need to be addressed as part of any rational attempt to craft solutions to sustainability challenges.[38,39]

In sum, confronting the problems with our current agricultural systems requires considering trade-offs across spatial and temporal scales and among all actors potentially impacted, particularly the most marginalized producers (Figure 1). But to assess these trade-offs, we need to be clear about the desired end benefits and who in particular is gaining or losing, and when—similar to Redclift's classic questions of sustainability of *what*, based on *whose* judgment?[40] When considering

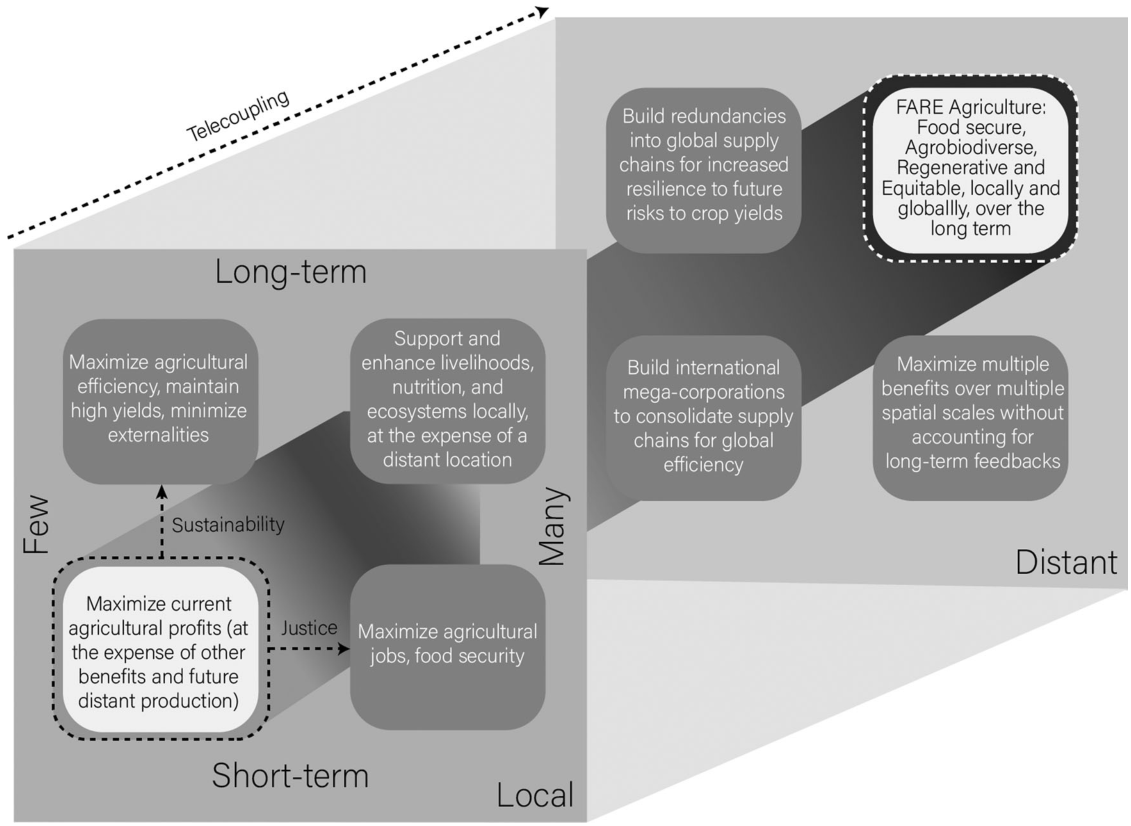

FIGURE 1 The current problem of agriculture: prioritizing localized short-term benefits to few at the expense of long-term benefits shared by many. The shaded line between the dashed boxes shows the pathway from the current system ("maximize current profits") to an ideal system ("FARE agriculture"). Attention to environmental sustainability (moving from the bottom/"short-term" boxes to the top/"long-term" boxes), justice (moving from the left-side/"few" boxes to the right-side/"many" boxes), or telecoupling (moving from the front/"local" panel to the back/"distant" panel) will improve in any individual dimension, but FARE (Food secure, Agrobiodiverse, Regenerative, Equitable) agriculture requires progress on all three fronts.

a change in agricultural production, do we care more about changes in profits or livelihoods, GDP or employment, food security, or nutrition? Each of these suggests different ideas by different actors of what constitutes efficient production; what may seem like economies of scale promoted through simplification toward monocultures threaten the livelihoods and way of life for small farmers, as well as the diet quality and nutritional health of the general population.[39] As Daly[41] has pointed out, injustice can classically be considered as "efficient" allocation, despite the strong moral objections most people share to placing the wealth of the few over the well-being of the many (Figure 1, horizontal axis).[42] Short-term profit maximization may seem to outweigh environmental harms because the latter can take years to fully manifest, by which point the damage may be irreversible, and may even undermine the long-term viability of the production system itself [43,44] (Figure 1, vertical axis). Locally sustainable decisions may simply displace commodity demand to distant locations where people lack the power to put safeguards in place to avoid or reduce unsustainable production and its impacts (Figure 1, diagonal axis).

Agricultural intensification and simplification will likely continue, as temporal lags and spatial disconnects buffer the most sociopolitically privileged from experiencing or acknowledging the consequences of this production strategy.[24,45] While the cause and consequences of many of the undesirable trade-offs in our agricultural systems are understood, vigorous and unresolved debates continue on the crucial question: how can society break free from these trajectories? Through these lenses of environmental sustainability and social justice, we next review the key interventions in agricultural systems needed to transition to a more desirable future: one that is Food secure, Agrobiodiverse, Regenerative, and Equitable and just (FARE, Figure 1).

CONCEPTUAL PATHWAYS TOWARD A MORE DESIRABLE FUTURE FOR AGRICULTURE

It has long been recognized that we produce enough calories to feed the current global population; malnutrition is overwhelmingly a problem of distribution and access[46,47] and is compounded by, and further impacts, the provision of other human rights.[32] Now, we have good evidence that we can meet future demand as well, by changing diets and efficiencies of delivery.[9,48] However, the benefits and challenges posed by agriculture have always gone beyond the provision of food, a single ecosystem service. Indeed, agriculture is implicated in nearly every goal for sustainable development,[49] just as it is implicated in our unfortunate progress toward most planetary boundaries.[8] The past decade has seen a convergence of global issues brought to international policy forums, via documents such as the Declaration on the Rights of Peasants and Other People Working in Rural Areas, the Nyéléni Declaration of the International Forum for Agroecology, the Sustainable Development Goals, the Paris Climate Agreement, and negotiation of new targets for the Convention on Biological Diversity. All emphasize the role that more multifunctional, and indeed multibenefit, agriculture can and must play in addressing not only food security but also climate, biodiversity, and other human development goals.

Successful transition to a multibenefit, or FARE, form of agriculture requires synergistic intervention upon both the production and consumption ends of the system, across scales. Shifting toward regenerative production practices and healthy diets while reducing food waste and loss has been proposed as the triple-bottom-line necessary to feed a population of 10 billion within planetary boundaries by 2050.[8,9,13,48] While we recognize the importance of addressing the complexities of demand, nutrition and distribution gaps, and waste to meeting these food system challenges, we focus here on shifts proposed in the production system, and their implications for environmental sustainability and social justice.

Environmental sustainability

Commonly cited sustainability targets for the agricultural production system include closing yield gaps (the gap between current and maximum biophysically attainable yields) by 75%, redistributing nitrogen and phosphorus fertilizer use globally (reducing fertilizers where they are overapplied, increasing where underapplied), improving efficiency in fertilizer and water use, adopting land management practices to transform agriculture from a carbon source to sink, and shifting production priorities away from meat, dairy, and feedstocks.[9,50] Juxtaposed against these more top-down interventions, concepts from landscape ecology guide the design of agricultural systems from the bottom-up. Rather than emphasizing production efficiencies, these interventions focus on the capacity for production systems to maintain or enhance biodiversity and ecosystem services, by maintaining habitat compositional and configurational heterogeneity, ensuring landscape connectivity and resource continuity, integrating native vegetation into and around farm fields, reducing field sizes, modifying and reducing chemical use, managing timing of disturbance events, and increasing perenniality.[51]

The first set of strategies, focused on closing yield-gaps and other efficiency measures, often coincide with "land sparing" strategies for sustainability, which promote intensification in some places to free up land for nature in other places.[52] These are often pitted against the second set of strategies, focused on supporting multifunctional landscapes or "land sharing" approaches, which typically aim for lower-intensity agriculture with fewer trade-offs.[53] However, this stylized dichotomy may not be a useful one when what we truly seek is a FARE agriculture that improves the well-being of people around the world now and in the future.[54,55] In fact, it has been well documented that intensification can backfire, reducing not just biodiversity but the ecosystem services that support continued productivity in agriculture,[56] and extensive review has shown intensified agriculture commonly results in lose-lose outcomes among multiple aspects of human well-being.[33] Intensification does not even necessarily "spare" land, due to rebound effects; higher production values associated with intensification may stimulate further agricultural expansion when demand is elastic (such as it often is for luxury goods), when there are few institutional or physical barriers to land-use change, or when significant inequality or concentration of wealth exists.[20,57]

Social justice

Justice is featured in frameworks for agricultural transformation in multiple ways: as a key strategy for achieving other goals, and as a goal in and of itself. For example, equity is cited as a key principle for achieving a resilient food system that is capable of not only sustaining itself but also capable of adapting and transforming as needed.[58] Adaptive capacity can be built by promoting food sovereignty through regionalized food distribution networks and by encouraging participation from all actors in the food system (i.e., sociopolitical equity between countries and within countries).[59] Addressing equity and justice as a strategy for achieving sustainability goals means securing smallholder well-being, through measures such as the revitalization of abandoned farmlands and agricultural extension services, diversification of production and income, redistributive land reform, and strengthening local institutions in the face of economic globalization.[60,61]

There are many proposed mechanisms that seek to tackle the sustainability crisis through re-examining and redesigning the economics, and the inherent inequities of the economics, driving the crisis.[140] A significant portion of agriculture's positive and negative externalities are not reflected in agricultural products' prices, and indeed may even exceed their current market value.[62-64] This suggests there may be a role for supply management[65] and higher farm gate prices, which have mixed effects but are likely to reduce global poverty in the economic long run.[66] Other mechanisms include replacing traditional subsidies for agricultural inputs with green payments, especially to small farmers, and providing additional economic pathways out of poverty that are not restricted to agriculture, such as through payments for ecosystem services programs (although the evidence base on the effectiveness of such programs, particularly their effects on equity and justice, is still limited).[67-69] The success of comprehensive reform attempts, such as the Green New Deal, will hinge on whether they can avoid pitting sustainability against the viability of rural communities, which Patel and Goodman[70] argue was a lesson learned from the original New Deal; that "better living through farming can't happen without canny political alliance-building, stitching together a bloc that addresses hunger, poverty, malnutrition, and inequities in wealth and wages, both in the countryside and city." And so yet again, justice and sustainability are intimately tied, not just in terms of each's effects on the other's realization, but in the processes to build broader societal buy-in and ultimately the sociopolitical power to create needed system-level changes.[71-73]

In order to bring these conceptual FARE ideals into reality, it is necessary to consider how to operationalize them. To do so, we examine how specific interventions have been shown to improve sustainability and justice in agricultural systems. Thus, the remainder of this review will move beyond principles into practice, reviewing the broad evidence base that the field of agroecology has built over the past decades to inform how to manage a diverse set of benefits from agricultural systems, specifically examining the potential ecosystem service outcomes (including social justice-oriented outcomes) in agricultural landscapes under different management strategies.

OPERATIONALIZING PATHWAYS FOR FARE AGRICULTURE

A vast body of literature has accumulated on operationalizing sustainability and/or justice in agricultural systems, so rather than review the primary literature, we assemble the evidence from systematic reviews and meta-analyses (Table 1). Syntheses evaluating synergies and trade-offs between ecosystem services in agricultural systems draw on decades of field-level research evaluating the outcomes of different agricultural and environmental management strategies. Emerging from this review of reviews is clear evidence of how reduced disturbance, systems integration, increase in crop and landscape-level diversity, and the securing of substantive aspects of socioenvironmental justice can operationalize pathways for sustainable, just agricultural systems, while reducing trade-offs and securing win-wins between diverse ecosystem services and human well-being outcomes. We consider the intertwined roles of sustainability and justice in determining the success of these strategies and show how FARE agriculture can be realized (Figure 2).

Reduce disturbance

Sustainable production is the goal of many different approaches and bodies of thought, including agroecology, conservation agriculture, ecological intensification, permaculture, biodynamic agriculture, and organic agriculture. One of their common aims is to reduce the disturbance caused by agricultural management in order to allow the return of natural biological processes above and below ground. Techniques include reduction or avoidance of tillage of the soil, maintenance of ground cover and/or crop residues, and integrated pest and nutrient management in lieu of chemical pesticides and fertilizers. Across a variety of cropping systems, these lower-disturbance production techniques have been demonstrated to deliver win-wins for multiple ecosystem services, increasing water use efficiency, carbon sequestration and climate regulation, nutrient cycling, erosion control, environmental pollution control, weed control, insect and pathogen control, and soil biodiversity, many of which in turn support more resilient future crop production.[74,75] While organic agriculture in isolation has been associated with 25% lower yields on average,[76] this effect diminishes or disappears entirely when implemented in concert with diversification practices.[77] Practices aimed at improving cropland and grazing land management, increasing soil organic carbon content, and reducing soil erosion showed evidence of synergies and no significant trade-offs between human well-being (defined by the Sustainable Development Goals) and a variety of ecosystem services (defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services framework of Nature's Contributions to People).[78]

Improve systems integration

Another strategy that shows great potential for win-wins among ecosystem services is the reintegration of production systems that have historically been integrated (such as crop and livestock production[79]) but have become spatially and managerially disconnected in recent decades due to specialization. A broad review of integrated crop-livestock systems (ICLS) shows improvements in an array of ecosystem services, including crop and livestock yields, as well as carbon fixation, emissions reduction, nutrient retention and cycling, soil biodiversity, and weed control, along with increased self-sufficiency and resilience to market and climate shocks.[80] A meta-analysis of 66 studies across three continents found that annual cash crops in ICLS had similar yields to crops in comparable unintegrated systems and even higher yields in loamy soils.[81] Similarly, reviews of permaculture show that integrating chickens into orchards and fish into rice fields improves pest regulation and nutrient cycling, and enhances livelihoods through the production of multiple food sources on the same land.[82] Meta-analyses of community forestry and protected areas demonstrate similar results with greater rigor due to a larger evidence base; allowing multiple uses and respecting local stewardship leads to better ecological and social outcomes.[83-85] The socioecological integration highlighted by these examples provides grounds for further study appropriately assessing both social and ecological outcomes of agricultural systems.[86,87]

Maintain and enhance diversity

The maintenance of diversity at different scales in agricultural systems may have the greatest evidence base for creating win-wins between provisioning and other ecosystem services. One of the most comprehensive syntheses (a meta-meta-analysis of 98 individual meta-analyses comprising >5000 original studies) documented that diversification practices at landscape and local scales enhance yields while at the same time increasing pollination, pest control, water regulation, nutrient cycling, soil fertility, carbon sequestration, and climate regulation.[88] In fact, diversification may even mitigate some of the negative impacts of intensification; the few examples where intensification enhanced ecosystem services beyond short-term crop production are those that also implemented landscape restoration or diversification of agronomic practices.[33] Diversification can be implemented at the field

TABLE 1 Meta-analyses and other literature syntheses relevant to operationalizing FARE agricultural systems, grouped into four categories or strategies: (1) reduced disturbance, (2) systems integration, (3) maintaining diversity, and (4) tenure security or broader justice considerations

Reference	Strategy evaluated	Description (review type, sample size, and findings)
Ghosh et al.[74]	Reduced disturbance	Review of effects of conservation agriculture on 12 ecosystem services, finding positive impacts on: crop/food production (5—51% increase), carbon sequestration (11—26% increase), soil moisture, waste decomposition, erosion control, pest and disease management, nutrient cycling, primary production, and seed dispersal.
McElwee et al.[78]	Reduced disturbance	Quantitative review (with a focus on meta-analyses) of impacts of 40 practices on 17 human well-being outcomes and 18 categories of ecosystem services (1440 possible combinations), finding that crop/grazing/livestock management and agroforestry show win-wins for social and ecological outcomes.
Oldekop et al.[83]	Reduced disturbance; systems integration; maintaining diversity; justice	Meta-analysis examining the effects of protected area management on ecological and socioeconomic impacts, based on 165 protected areas within 171 studies, finding that allowing sustainable resource use (including subsistence farming) improved social and ecological outcomes.
Seufert et al.[76]	Reduced disturbance	Meta-analysis of 66 studies (316 observations) on the impact of organic on crop yields in 34 species, showing that yield differences are highly contextual, ranging from 8% to 43% lower organic yields in developed versus developing countries, similarly variable over other factors (25% lower on average).
Ponisio et al.[77]	Reduced disturbance; maintaining diversity	Meta-analysis of 115 studies (1071 observations) on the impact of organic on crop yields in 54 species, finding that organic yields are only 19% lower than conventional yields on average, and that two diversification practices, crop rotations and multicropping, reduce this yield gap to 8–9%.
Stavi et al.[75]	Reduced disturbance	Quantitative review of the impacts of four practices on nine ecosystem services, including yields, finding that the overall environmental score is the largest for conservation systems (72%), intermediate for integrated systems (69%), and smallest for conventional systems (52%), while crop yield productivity score is the largest for integrated systems (83%), intermediate for conventional systems (66%), and smallest for conservation systems (58%).
Anderson et al.[31]	Systems integration; justice	Book-length qualitative review of the dynamics of a FARE agroecological transition/transformation, finding that transformation to agricultural systems producing gains for both human well-being and nature is most likely when enabling conditions are present across multiple "domains" (e.g., systems integration): appropriate rights to access to nature; systems of knowledge and culture; systems of economic exchange; social networks; sociopolitical equity; and discourse. It is also proposed that holistic approaches will best be able to address trade-offs when territorial (i.e., local and regional) governance approaches are strengthened.
Garrett et al.[80]	Systems integration	Review across five representative countries on the impacts of crop-livestock integration on five ecosystem services and two human well-being outcomes, showing improvements in crop and livestock yields, carbon fixation, emissions reduction, nutrient retention and cycling, soil biodiversity, and weed control, along with increased self-sufficiency and resilience to market and climate shocks for integrated crop-livestock systems.
Hajjar et al.[84]	Systems integration; tenure security	Systematic review based on the data of 643 community forestry management cases in 51 countries, collated from 267 peer-reviewed studies, finding that simultaneous positive outcomes across environmental, income, and tenure/access rights dimensions were rare, but that certain biomes (tropical/subtropical montane forests), governance conditions (low initial national human development and governance quality scores), and strong pre-existing de facto local tenure rights made double- and triple-positive outcomes more likely.
Krebs and Bach[82]	Systems integration	Qualitative review of 214 papers on 12 principles of permaculture, with demonstrated improvement in environmental and social outcomes for cropping systems integrated with livestock, poultry, fish, and/or perennials.
Peterson et al.[81]	Systems integration	Meta-analysis of 66 studies (across three continents, 12 crops, and four livestock species) on the impacts of crop-livestock integration on yields, finding 5% higher yields in integrated than unintegrated systems on loamy soils, and no difference between the two in clay and sandy soils.

(Continues)

TABLE 1 (Continued)

Reference	Strategy evaluated	Description (review type, sample size, and findings)
Barral et al.[93]	Maintaining diversity	Meta-analysis of 54 studies in 20 countries across five supporting and regulating ecosystem services, showing that restoration of native habitats in agricultural landscapes increases biodiversity (68%), supporting services including maintenance of soil quality (42%), and regulating services including carbon sequestration, pollination, and pest control (by an average of 120%).
Garibaldi and Pérez-Méndez[92]	Maintaining diversity	Quantitative synthesis of agricultural and economic datasets from 44 countries over 15 years, finding that countries where crop diversity increased also supported more agricultural jobs and improved crop yields.
Garibaldi et al.[95]	Maintaining diversity	Review of >90 meta-analyses and quantitative reviews (many reviewing >100 studies each) of impacts of native habitat in working landscapes on 18 categories of ecosystem services, finding that maintaining 20% of agricultural landscapes in native habitat is necessary to improve soil biological activity and nutrient availability, enhance pollination for pollinator-dependent crops, slow the rapid evolution of pests and weeds, prevent floods and regulate climate, and can even increase overall economic efficiency.
Iverson et al.[89]	Maintaining diversity	Meta-analysis of 26 studies (301 observations) measuring the effects of polyculture on both yields and biological control, finding a 40% and 31% increase for yield and biocontrol, respectively, in polycultures over monocultures.
Rasmussen et al.[33]	Maintaining diversity	Quantitative review of 53 studies (60 cases) measuring both ecosystem services and human well-being, finding strong trade-offs or even lose-lose outcomes with agricultural intensification, but noting that the only win-win outcomes were seen when landscape restoration or crop diversification were included as strategies along with intensification.
Tamburini et al.[88]	Maintaining diversity	Meta-meta-analysis of 98 meta-analyses and second-order meta-analysis based on 5160 original studies (41,946 observations) measuring the effect of local or landscape diversity, finding win-wins between crop yields and pollination, pest control, water regulation, nutrient cycling, soil fertility, carbon sequestration, and climate regulation.
Weißhuhn et al.[90]	Maintaining diversity	Systematic review of 175 studies yielding 75 relevant studies on the effects of polyculture on seven ecosystem services (including yields), finding perennial polycultures enhance soil fertility, soil protection, climate regulation, pollination, pest and weed control, and landscape aesthetics compared to annual monocultures, and that economic impacts of slightly lower biomass production may be offset by production cost-savings.
Gladkikh et al.[107]	Tenure security	Systematic review of >4000 studies yielding 29 relevant studies for quantitative review on 11 cultural ecosystem services (social relations, mental health, cultural heritage, education, recreation, identity, sense of place, aesthetic, spirituality, perspective, and existence value) experienced by refugee communities in agricultural systems. Findings suggest that interactions with ecosystems ease the resettlement process and well-being, including mental health.
Higgins et al.[103]	Tenure security	Meta-analysis of 59 studies on the impacts of land tenure on numerous environmental and social outcomes, finding tenure security associated with positive impacts on environmentally friendly investments and female empowerment, but not (significantly) with productivity, access to credit, or income.
Jones et al.[101]	Tenure security	Systematic review of 854 studies yielding 78 studies for quantitative review on socioeconomic factors determining the participation in payments for ecosystem services programs, finding that strengthening land rights increased participation.
Katusiime and Schütt[102]	Tenure security	Qualitative review of 74 studies on the impacts of land tenure on the sustainability of management practices, finding increased tenure security to be associated with improvement in land management, consideration of long-term investments, and socioeconomic outcomes.
Lawry et al.[104]	Tenure security	Synthesis of findings from 20 quantitative studies and nine qualitative studies that passed methodological screening, showing that tenure boosted productivity (monetary value) by 35% on average (with strongest effects in Latin America and Asia), and boosted welfare (consumption or income) by an average of 14% (with low heterogeneity between results from Latin America, Asia, and sub-Saharan Africa).

(Continues)

TABLE 1 (Continued)

Reference	Strategy evaluated	Description (review type, sample size, and findings)
Prokopy et al.[105]	Tenure security	Systematic review of 1632 studies yielding 93 relevant studies for quantitative review of impacts of land tenure on the sustainability of management practices in the United States; did not find a clear signal of land tenure but suggested that "farmers' perceived stability and/or anticipated longevity of a lease arrangement, rather than simply whether the land is rented or not, may be needed to more effectively understand how ownership or tenancy may influence levels of adoption."
FAO and FILAC[85]	Justice (recognition, procedural justice, distributive justice, and tenure security)	Systematic qualitative review of over 300 studies published over the last two decades on forest governance by indigenous and tribal peoples in Latin America and the Caribbean, finding that indigenous land governance was predominantly associated with decreased deforestation.

Note: These four categories were emergent from this review, not predetermined. Studies were identified through a search in Web of Science filtered for "reviews" as the document type, using the search terms "ecosystem servic*" and "agricultur*." Only reviews, meta-analyses, or other literature or data syntheses that measured ecological and/or socioeconomic impacts of agricultural management strategies were selected, with a preference for studies documenting both. This review was not comprehensive; studies were screened for the number of studies they included and those with the broadest evidence base were prioritized.

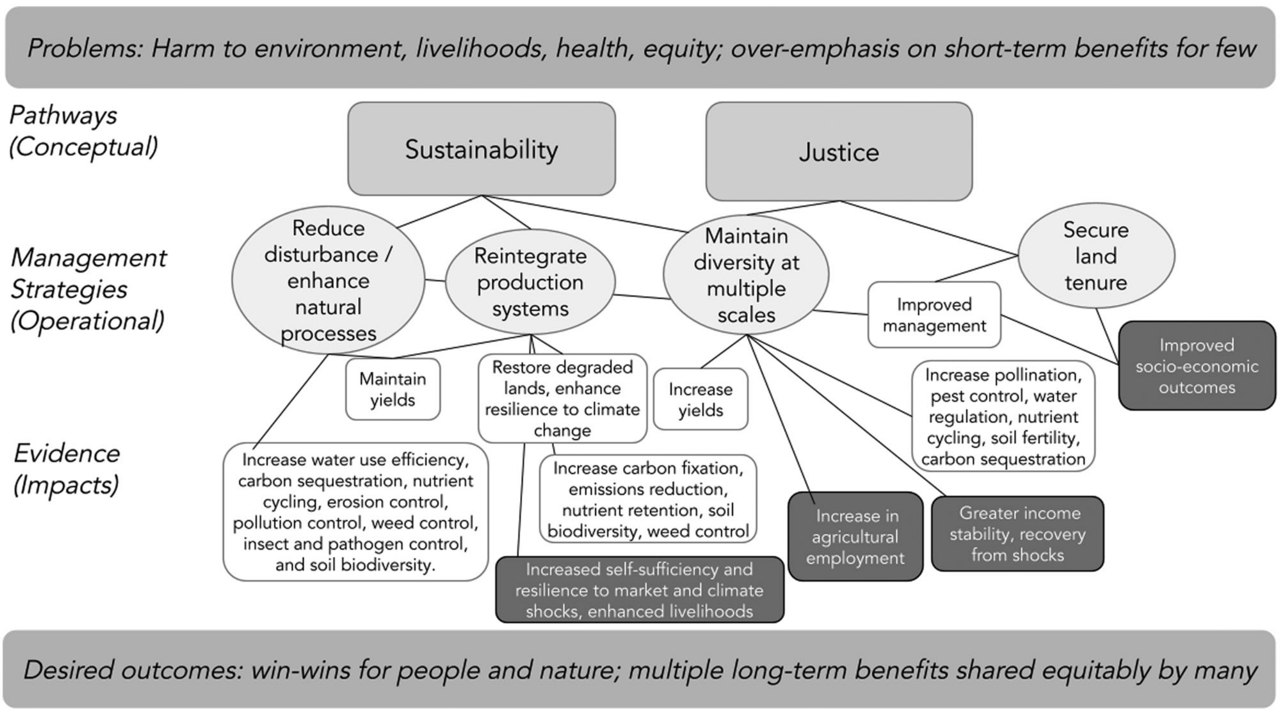

FIGURE 2 Evidence for operationalizing sustainability and justice pathways in agricultural systems.

scale, through intercropping or integrating native habitat elements into flowering strips or hedgerows, and at the landscape scale, in terms of increasing the number of different crops grown on neighboring farms or the amount of noncrop habitat nearby. The importance of linkages between elements of diversity across these scales is increasingly being recognized, as discussed below.

The first line of evidence for the benefits of diversification concerns crop diversity. Polycultures (multiple crops planted together) frequently produce win-win outcomes between crop yield and biocontrol, especially when plant–plant competition is reduced through careful selection of secondary crops.[89] Perennial polycultures enhance soil fertility, soil protection, climate regulation, pollination, pest and weed control, and landscape aesthetics compared to annual monocultures.[90] Diversity at the farm level has also been shown to improve stability in income, recovery from shocks, and food security.[39,91] At even larger scales, countries whose crop diversity has increased have also experienced growth in agricultural jobs, due to the accompanying diversification of inputs, services, and machinery requiring a greater number of agricultural employees to manage and operate.[92] In short, maximizing profits may favor simplification (particularly if social and ecological externalities are not accounted for) but if the goals for agricultural production systems include stability of livelihoods and job security, diversification is without question a sounder strategy.

A second line of evidence for the benefits of diversification concerns the integration of native habitat elements within and around farm fields. Restoration of native habitats in agricultural landscapes increases biodiversity (by an average of 68%), supporting services, such as maintenance of soil quality (by an average of 42%), and regulating services, such as carbon sequestration, pollination, and pest control (by an average of 120%), with no significant differences found between local (hedgerows or field margins) and landscape (large-scale conversion back to nature) interventions.[93] Native plants better support beneficial arthropod populations than non-natives, enhancing arthropod-mediated ecosystem services like pollination and pest control.[94] A target of 20% native habitats within agricultural landscapes has been proposed based on a broad review of the land area needed to support the provision of ecosystem services, such as soil erosion control, nutrient availability, pollination, pest and weed control, and flood mitigation—and it is thought that this target can be achieved with little or no trade-offs to crop productivity if implemented in line with natural heterogeneity in crop yields.[95]

A third consideration connecting these two lines of evidence is the scale of diversification. Many small changes at farm levels can aggregate up to a landscape-level effect, but collective action to achieve such aggregation can be difficult to catalyze. One of the main criticisms of Europe's agri-environmental schemes (incentivizing proenvironment behavior in farmers) is that they target single sites and are uncoordinated among neighboring landowners; it is thought that implementation of these schemes would need to expand from the local to the landscape and regional levels to be effective conservation strategies.[56] It has further been argued that these schemes should target local habitat restoration in simplified landscapes, where increasing diversity may play a more important role in delivering ecosystem services.[96] However, a minimum threshold of habitat may be necessary to achieve any benefit, and interventions may, therefore, be most successful in landscapes of moderate complexity.[94] For this reason, a "fractal perspective" is suggested; for example, the 20% target proposed for the integration of native habitat may be necessary or most beneficial if achieved at all spatial scales, from single fields to whole landscapes.[95]

Safeguard justice in tenure security

Injustice in agricultural production systems can manifest in a lack of access to resources and decision-making power, to markets and credit, to knowledge, and to governance, networks, and other political and social infrastructure.[31] Such inequalities in who has access to and benefits from resources for agriculture or is helped or harmed by externalities (distributive justice) can be further compounded by a lack of sociopolitical recognition or procedural justice in agricultural policy-making,[72] such as when smallholders are left out of the crafting of agricultural policies that favor larger commercial producers.[67] While there exists a rich literature on recognition and procedural justice in agroecology, especially in regards to improved socioeconomic outcomes associated with food sovereignty,[139] or the rights to have rights over food,[97,98] we focus here on the dimension of justice with the broadest evidence base in food and agriculture systems: distribution of resource access and tenure security.

Tenure security, determining rights to who can use the land or other resources, and for how long, is considered a necessary precondition of successful conservation intervention (in agricultural systems, or any system). It concerns more than just land; tenure security has been found increasingly important to define rights to carbon, water, or other ecosystem services in agricultural systems.[99] However, the majority of study has focused on land tenure security, the mechanisms for which include creating a transparent and easily accessible landholding registry, providing legal assistance, clarifying institutional responsibilities, simplifying overlapping tenure systems, resolving disputes, and improving monitoring and evaluation of tenure governance systems.[31,99] Payments for ecosystem services programs have found most successful participation when the programs strengthen tenure security, for example, by facilitating community control of pasture lands,[100] or by reducing risks faced by producers.[101]

Increasing land tenure security has been linked to an array of beneficial outcomes, with varying degrees of certainty, including environmental sustainability, production efficiency, productivity, income stability and equality, poverty alleviation, hunger reduction, improved soil quality, and decreased degradation.[31,61,102] A meta-analysis of 59 studies from Asia and the Pacific, Sub-Saharan Africa, and Latin America and the Caribbean found that land tenure security could be connected to positive effects on environmentally friendly investments and female empowerment, but failed to find strong support for links to productivity, access to credit, and income.[103] However, our understanding of "tenure" may need to be more nuanced to truly understand its influence. An earlier review[104] of many of the same studies included in the aforementioned meta-analysis[103] emphasized the importance of regional differences in the role of customary tenure arrangements. Similarly, authors reviewing 35 years of literature on the adoption of conservation agriculture in the United States, while failing to find a clear influence of land tenure, posited that the measurement of this variable may be oversimplified—often just a ratio of land rented to total land farmed, or a binary measure of whether farmers rented land or not, rather than the farmers' perceived or realized longer-term stability of a tenure arrangement.[105] These equivocal results align with previous findings on land reform,[106] which suggest that tenure security may only support FARE agricultural systems if it is redistributive of sociopolitical power and resources.

When considering tenure security, special attention should also be paid to marginalized groups, including the landless. Robinson et al.[99] called for tenure systems to "recognize basic human rights and safeguard against intracommunity discrimination toward women, pastoralists, indigenous groups, or other minorities," but in many cases, these groups lack secure rights to ownership. More beneficial outcomes are likely to be seen through restoring justice to these groups .[138] A recent report reviewing more than 300 studies of dynamics in Latin America found that indigenous land governance was predominantly associated with decreased deforestation, and thus that increased recognition and respect for indigenous and tribal peoples' collective tenure rights over land could contribute to mitigating climate change, conserving biodiversity, and managing forests sustainably.[85] Likewise, challenges faced by immigrants and refugees may be better addressed through increasing access to land. These groups are particularly vulnerable to disruptions in ecosystem services in agricultural systems, and access to nature has been shown to ease the resettlement process and overall well-being in many ways, including social relations, mental health, cultural heritage, education, recreation, identity, sense of place, aesthetic, spirituality, perspective, and existence value.[107]

Key takeaways and next steps for operationalizing FARE systems

The evidence is unyielding; our goals for agriculture require an "unyielding," dispelling the notion that yields should be the singular focus of agriculture.[108,109] The narrative that agricultural systems face inherent trade-offs between productivity and environmental sustainability and social justice is mainly relevant to intensified monoculture systems focused on maximizing yields. The four strategies that emerged from our review on the evidence to operationalize FARE agriculture exhibit win-wins between provisioning and regulating services and between ecosystem services and broader human well-being. Although these strategies have been presented separately, as that is how they have been evaluated in the scientific literature for the most part, synergies and dependencies between them are likely to occur. For example, crop diversification practices can eliminate yield penalties from lower disturbance agriculture (like organic).[77] One could imagine other potential synergies. Increasing equity in tenure security may support more diversified farming systems since different growers may increase the number of different crops grown. Reintegrating crop and livestock systems could assist in reducing disturbance as livestock moving through the crop remove pests or weeds. Certain strategies could also work on multiple fronts, such as integrating noncrop habitats into farm fields to simultaneously reduce disturbance and increase diversity. Further work is needed to explore the full potential of FARE agriculture when these strategies are applied together.

CLEARING THE PATH TO FARE AGRICULTURE

Given the evidence for win-wins among ecosystem services and the social benefits of more FARE agricultural systems, it is not surprising that there is already some encouraging progress toward positive transitions. Some 163 million farms (29% of the worldwide total) on more than 450 million hectares (9% of global agricultural land) are practicing some form of "sustainable management," including low-disturbance agriculture and integrating diversity into crop and pasture systems.[110] Every example of successfully scaling up such strategies has involved building social capital, in the form of establishing trust relations, a sense of reciprocity, common norms, and connectedness in groups.[110] However, adoption rates of the sustainability interventions reviewed above need to grow far beyond 9% of global agriculture to escape the dire consequences predicted for biodiversity, water, climate, and justice in our current agricultural system. How can full transformation take hold, enabling these strategies to reduce disturbance, integrate systems, diversify, and secure tenure where each is most needed, to achieve a more FARE agriculture that benefits everyone, locally and globally?

Many policies aim to incentivize such transformation. China's 2018 Rural Revitalisation Strategy targets the expansion of "multifunctional" agriculture, as a means of achieving more balanced development between urban and rural areas.[111] Over 160 cities worldwide have committed to the Milan Urban Food Policy Pact of 2015, to develop "sustainable food systems that are inclusive, resilient, safe and diverse, that provide healthy and affordable food to all people in a human rights-based framework."[31] Even relatively staid policies are shifting toward more FARE agriculture, such as Europe's Common Agricultural Policy (CAP), which now emphasizes farmers' roles as landscape managers to maintain biodiversity and landscape aesthetics, and considers agriculture as a key path for climate mitigation and green recovery from the current financial crisis.[111] Such policies also provide a note of caution, however. The greening measures in the CAP, as an example, exclude perennial crops such as vineyards because they were considered to already be sustainable, but this inadvertently penalizes them,[112] ignoring their biocultural values and thus threatening these refugia of diversity that have kept these systems resilient for so long.[113] A prime challenge going forward is translating the scientific evidence on ecosystem services in agricultural systems into policies that will support and not undermine the enhancement or continued provision of these services. This challenge must be addressed alongside an increased focus on integrating participatory and community-based methods and commitments to equity and justice into policy and science.[114–116]

In other words, the barriers to transformation to FARE agriculture are not all barriers of science or knowledge, but scientists can still play a role in their removal. Knowledge gaps are minor compared to other barriers—as our synthesis of the myriad reviews on this topic shows, how to transition is not really a knowledge problem. However, continuing to *innovate* in particular ways can help build confidence in the approaches and lower the remaining uncertainty in their viability. Inertia, born of discomfort with change or risk avoidance, is always a problem with any transition, and scientists improving the way we *communicate* existing knowledge can address this issue. Undoubtedly, the greatest barrier to transformation is a systemic problem of entrenched interests in the status quo that favor the few at the expense of the many—the only solution to which, some have argued, is to break the current system so it can be rebuilt. Addressing this goes well beyond the realm of research, and strategies likely involve a combination of measures addressing market demand, creating better incentive systems, and raising legal requirements.[117] However, even here research scientists have a role to play as science-based *advocates* for transformation.[116,118] Finally, a new way of doing science will likely be needed to answer the remaining challenges of scaling up and accounting for telecoupling, one that *integrates* science and governance in an adaptive learning cycle.

Innovate: Filling research gaps

Like the solutions to food system challenges themselves, solutions-oriented research must be interdisciplinary, cross-sectoral, and above all translational. Vandermeer et al.[119] proposed that the research agenda for "solving the global food crisis" lay at the intersection of four domains: (1) the ecology of agroecosystems; (2) equity in global and local food systems; (3) cultural dimensions of food and agriculture; and (4) human health. Within each of these domains, there exist remaining questions to explore, but the most profound advances can be found in their intersections. Chappell and Schneider[120] point out that research linking race and (anti)racism to agroecology and sovereignty is lacking. Rasmussen et al.[33] found a dearth of studies tracking win-wins between ecosystem services other than food and well-being beyond economic metrics, including health. Cultural ecosystem services are also missing from many agricultural ecosystem service assessments. We found no reviews quantifying the effect of different agroecological practices on cultural services, despite detailed conceptual mapping of the impacts of intensification and expansion of monoculture agriculture on the sense of place, rural lifestyle, recreation, aesthetics, heritage, traditional knowledge, and ensuing socioenvironmental conflicts.[121] The context-specificity inherent in the research approaches required to evaluate cultural services makes it difficult to compare or synthesize studies,[111] and experts agree that the concept of cultural services is still missing from practical implementation in agricultural policies.[122] Perhaps the most fundamental research gap is the disconnect between the scales at which we understand the challenge. Most of the problems are diagnosed at the global scale, while most of the solutions are tested at the local scale, and we lack evidence about how those local solutions can scale up to address these global problems. The challenges in bridging this particular gap extend beyond the science community (see *Integrate: A new science-governance paradigm*).

Communicate: Changing the dialogue and addressing concerns

Even with some research gaps remaining, the evidence is overwhelmingly in favor of FARE management of agricultural landscapes. Scientists need to make it clearer that the perception of trade-offs between ecosystem services in agriculture depends on the definition of the end benefits, especially for provisioning services. Emphasizing benefits like jobs, livelihoods, and nutrition, rather than the yield of one particular crop, is important. Furthermore, communication can be improved through understanding the feedback loop linking growers' attitudes toward nature, farming practices, and expected impacts, as well as the constraints and structures farmers act within, which are key steps in influencing behavior.[123,124] Scientists must also acknowledge the importance of relational values in changing behavior, such as farmer knowledge, identities, and attitudes toward certain practices and the way their landscapes contribute to their sense of place.[111] Cultural ecosystem services like a sense of place, as well as the aesthetic quality of the landscape and ability to maintain a rural lifestyle, may in fact be the primary motivation for many agricultural landholders[125] (rather than profit maximization, as often assumed). The modes of communication that scientists use may also need to change.[118] Duru et al.[126] found the use of knowledge bases integrating scientific and experiential knowledge and model-based games to be most effective in designing diversified farming systems and landscapes. Communicating about the evidence on specific pathways for operationalizing FARE agriculture could be improved through techniques for building and evaluating positive futures, finding and nurturing seeds of sustainability, and navigating the emerging pathways through adaptive science-policy cycles.[127]

Advocate: Science-backed champions for transformation

Chappell and Schneider[120] proposed a new three-legged stool for sustainable agriculture, based on agroecology, food sovereignty, and food justice. Food sovereignty recognizes indigenous and local knowledge, which can then be more equitably incorporated into improved agroecological practices. Food justice can expand participation in agrifood systems to include the needs of marginalized communities who are impacted by its operation. Coming from a different perspective but arriving at similar conclusions, Chapin[128] proposed a deeply transformational change toward Earth-stewardship, which entails a shift from accumulation of material wealth to a focus on sustaining inclusive wealth (from built, human, social, and natural capital) in a way that is equitably distributed across societies. These provide examples of how scientists can lean into rather than shy away from normative issues, such as what constitutes an ethical or moral future. Scientists can also play an important role in highlighting the evidence for means of achieving those desired ends. Identifying leverage points can help point to a variety of ways to intervene in a system that is not working.[129,130] Focusing on leverage points recognizes influential "deep" interventions that are more difficult to enact but likely to yield more transformational change, as well as the shallower interventions that can help ready the system for more difficult, deeper changes.[131]

Integrate: A new science-governance paradigm

Cutting across all of these areas is the need to understand how various strategies implemented at local scales around the world can scale up to meet global goals, or how a seemingly win-win strategy for one system may ripple through other systems with unintended consequences. If local trade-offs between provisioning and other services are minimized, can we avoid global trade-offs through embodied or hidden "virtual" costs in traded products? As noted above, telecoupling remains a key gap in an otherwise well-established evidence base on operationalizing sustainability in agricultural systems. A full accounting of telecoupling in agriculture, however, requires not just new science but a new science-governance paradigm. Three key advances laid out by Schröter et al.[132] describe the elements of such a paradigm: (1) improved understanding and analysis of telecoupled ecosystem service flows; (2) information translation for decision-makers at the science–policy interface; and (3) governance to address the sustainability of telecoupled ecosystem service flows. The first point cannot be addressed without the third, because while environmental models are rapidly improving in accuracy and resolution of the mapping of biological (wildlife migration) and biophysical (air and water) flows, tracking the material flows of traded goods and the biophysical flows embodied in them will require a radical shift in the transparency of our supply chains. Scientists are accustomed to observing the visible world, but adequately representing our telecoupled agricultural systems requires new forms of data generation to observe the often invisible or at least anonymized flows in our global economy. Therefore, in order to close this gap, the scientific process may need to be injected into policy rather than expected to merely support or inform it, with scientists engaging in new ways of democratizing science.[115,133,134] Tying an individual product to its location of production at a fine spatial resolution would unleash a revolution in ecosystem service telecoupling research. Could the necessary re-envisioning of the information systems used to track agricultural commodities be achieved through government regulation or private sector cooperation? Such science-governance process integration is not a new idea, although the methodologies, potentials, and risks continue to be explored.[135] Resilience theory has long emphasized the importance of allowing for experimentation and learning, and science can learn from policy "experiments" that can inform the next round of policies in an adaptive cycle.[31,136,137]

Agriculture is at the root of many significant environmental and social problems, threatening the achievement of many globally agreed-upon goals, but this means that agriculture is also integral to their solution. Ensuring that agricultural landscapes provide multiple benefits to people, sustainably and equitably, is the start of that solution. Here, we have examined meta-analyses and quantitative and qualitative reviews of empirical evidence on the role of agriculture in environmental and human well-being to identify practical pathways toward better agriculture. Ultimately, agriculture has the potential to provide many different benefits to people through multiple ecosystem services—including food, but also including places to recreate, beautiful aesthetics and a sense of place, carbon sequestration to combat climate change, flood control, water quality regulation, and much more. Prioritizing just one service, measured as agricultural yields, primarily for one dimension of its benefits, valued as profits, has created the illusion that trade-offs with these other key ecosystem services are inevitable. Our review shows that it does not have to be this way: focusing on the equitable delivery of benefits to many rather than on the financial well-being of a few can help reorient our agricultural production systems toward the prevalence of synergies rather than the inevitability of trade-offs.

AUTHOR CONTRIBUTIONS

The authors contributed equally to the conception and design of this review, and R.C.-K. and M.J.C. undertook the literature review. All authors participated in drafting the manuscript and revising its intellectual content and accept responsibility for the integrity of the evidence presented.

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COMPETING INTERESTS

The authors declare no competing interests in this work.

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