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Quantitative assessment of agricultural sustainability reveals divergent priorities among nations

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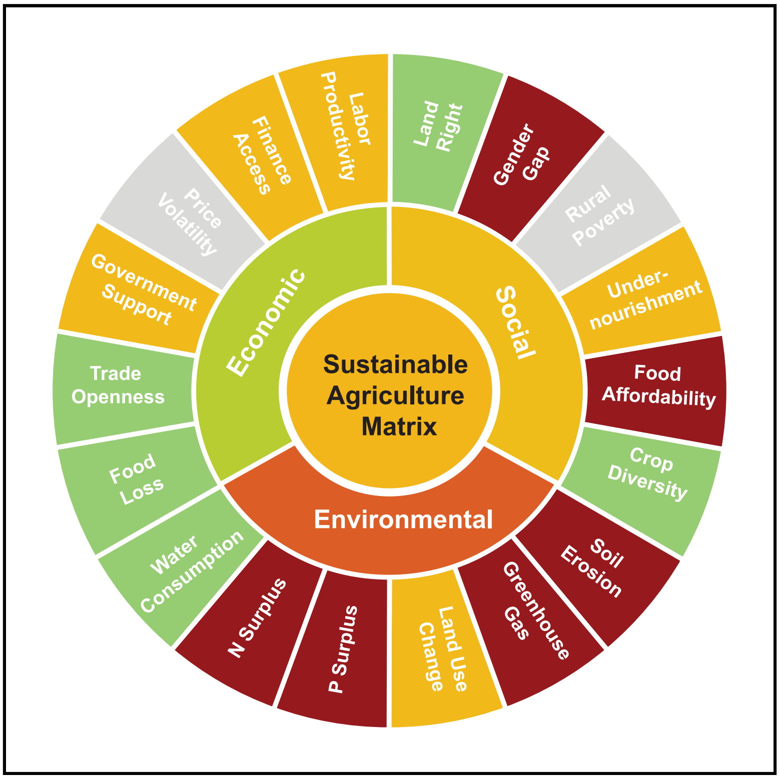

Highlights

- We offer a Sustainable Agriculture Matrix to track performance of countries worldwide
- Priority areas for improving agricultural sustainability depend on development stage
- Analysis of trade-offs and synergies among indicators can inform national policies

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In brief

Sustainable agriculture has been difficult to define or measure, due to its complex mixture of environmental, social, and economic concerns. We present and analyze a new set of country-level, multidisciplinary, and quantitative indicators of sustainable agriculture to show historical trends, identify needed areas of improvement, and investigate trade-offs and synergies among indicators. This Sustainable Agriculture Matrix will help inform national and international policies to advance sustainable development goals related to agriculture.

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Quantitative assessment of agricultural sustainability reveals divergent priorities among nations

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SCIENCE FOR SOCIETY The 2015 Sustainable Development Goals present pathways toward a sustainable future. The agriculture sector is fundamental to three pillars of sustainability: the environment, the economy, and society. However, the definition of sustainable agriculture and the feasibility of measuring it remain elusive. Independent and transparent measurements of countries' efforts to promote sustainable agriculture are essential to ensure accountability of commitments and study their effectiveness. Here we present the Sustainable Agriculture Matrix (SAM) based on historical data on environmental, social, and economic indicators of agriculture. Analyses of these data demonstrate where progress is being made, identify priorities for needed improvements, and reveal trade-offs and synergies among the indicators for each country. As further data become available, the SAM will be improved, but this version offers a unique start for quantifying trends and informing policies to advance agricultural sustainability.

SUMMARY

Agriculture is fundamental to all three pillars of sustainability, environment, society, and economy. However, the definition of sustainable agriculture and the capacities to measure it remain elusive. Independent and transparent measurements of national sustainability are needed to gauge progress, encourage accountability, and inform policy. Here, we developed a Sustainable Agriculture Matrix (SAM) to quantify national performance indicators in agriculture and to investigate the trade-offs and synergies based on historical data for most countries of the world. The results reveal priority areas for improvement by each country and show that

the trade-offs and synergies among indicators often differ. Exceptions to common economic-versus-environmental trade-offs, for example, offer opportunities to learn from countries with synergistic pathways for multiple sustainability indicators. These SAM indicators will improve as data become more available, but this version offers a useful starting point for evaluating progress, identifying priorities for improvement, and informing national policies and actions toward sustainable agriculture.

INTRODUCTION

Agriculture is fundamental to society as a reliable source of nourishment essential for human existence. Agriculture also provides income and employment for rural communities and people all along the food supply chain. However, the pursuit of higher agricultural productivity to nourish a growing and increasingly affluent world population has been accompanied by mounting environmental and social trade-offs. For example, agriculture is a major driver of deforestation and biodiversity loss;[1] contributes to about 90% of reactive nitrogen (N) and phosphorus (P) inputs, as well as most of the pesticide chemicals inputs,[2,3] from human activities to the Earth's biogeochemical cycles;[4] accounts for 21%–37% of anthropogenic greenhouse gas emissions;[5,6] and is responsible for 90% of freshwater consumption globally.[7] Besides these acute environmental problems, many agriculture-dominated rural communities are suffering from social problems such as poverty, malnutrition, and declining employment opportunities, even though the agricultural sector as a whole has become increasingly productive and hunger has significantly decreased worldwide.[8] Moving forward, agriculture is still facing the challenge of increasing productivity to meet growing societal demands for food, fiber, and energy.[9] This challenge is further complicated by its potential impacts on diets and nutrition, climate change, and environmental degradation.[4,10,11] Consequently, it is critical for countries and the world to develop a sustainable agriculture sector that is not only productive but also nutritionally adequate, compatible with ecosystem health and biodiversity, and resilient. As a result, sustainable agriculture has been explicitly included as one of the Sustainable Development Goals (SDGs; specifically as SDG 2.4.1), which were ratified by all member countries of the United Nations (UN) in 2015.

To promote accountability for nations' commitments toward sustainable agriculture and to inform policy making, consistent and transparent assessments are essential. However, definitions of sustainable agriculture vary considerably,[12] and few quantitative assessments on agricultural sustainability for world countries are available to date. Some scholars and practitioners consider sustainable agriculture as a set of management strategies, while others define sustainable agriculture as an ideology or a set of specific goals (Table S1).[12–14] Nevertheless, there is a growing consensus on framing sustainable agriculture based on its impacts on the three pillars of sustainability, namely the environmental, economic, and social pillars.[12] Several frameworks and indicators have been developed to quantitatively assess the sustainability of food systems from national to global scales (Note S2; Table S2)[10,15,16] and sustainable agricultural intensification on a farm scale.[17] Few, however, have focused on assessing the impacts of agricultural production on a diverse range of environmental, economic, and social dimensions of sustainability on a national scale, establishing thresholds or targets, and analyzing the synergies and trade-offs among these impacts. For example, sustainable agriculture indicators developed by the World Resources Institute (WRI)[18] assess the environmental impacts of agriculture production only (Figures S2 and S5); the Integrated Indicators for Sustainable Food Systems and Healthy Diets[19] and the Food Sustainability Index[20] evaluate the performance of the whole food system instead of focusing on impacts on the three pillars of agricultural sustainability. Many of these agriculture-related indicators have low data availability (Figures S2–S5).

Sustainable agriculture indicators are also developed as part of the SDG indicators framework by an Inter-Agency and Expert Group at the UN. The indicator that emerged in the final list for measuring sustainable agriculture was: "SDG2.4.1: *Proportion of agricultural area under productive and sustainable agricultural practices*." As the custodian agency for this indicator, the Food and Agriculture Organization (FAO) of the UN has led the methodological development of this indicator, which has now been recognized by the international community. The methodologies, building upon farm surveys, will require time and resources to implement, especially for detecting and comparing historical trends.

Despite the efforts of several organizations, the call for monitoring agriculture worldwide[21] has not yet resulted in actual datasets that enable trend assessments. The lack of consistent quantification of agricultural sustainability across multiple dimensions hinders the identification of undesirable trade-offs of agricultural interventions and the development of win-win solutions across multiple sustainability targets.

Here, we address the urgent need for a consistent and transparent assessment framework for sustainable agriculture by developing a Sustainable Agriculture Matrix (SAM), a set of quantitative indicators to measure the impacts of agricultural production on environmental, social, and economic dimensions of sustainability for 218 countries or regions in the world (see detailed methodology for the framework and indicator development in the section "experimental procedures"). First introduced by M.S. Swaminathan[14] as a conceptual framework, SAM highlights the multi-dimensional nature of sustainability, moving from a one-dimensional policy-making framework, such as increasing yields, toward coordinated thinking and actions among the social, economic, and environmental dimensions of sustainable agriculture. To transform Swaminathan's illustrative concept to measurable indicators, we identified key aspects of sustainable agriculture for assessment within each dimension (environmental, economic, and social) based on a broad survey of existing frameworks and indicators, developed a list of indicators by synthesizing existing data from multiple sources and disciplines (see the detailed process for indicator development in the experimental procedures), and established rationales for a range of quantitative socioeconomic and biophysical indicators and their

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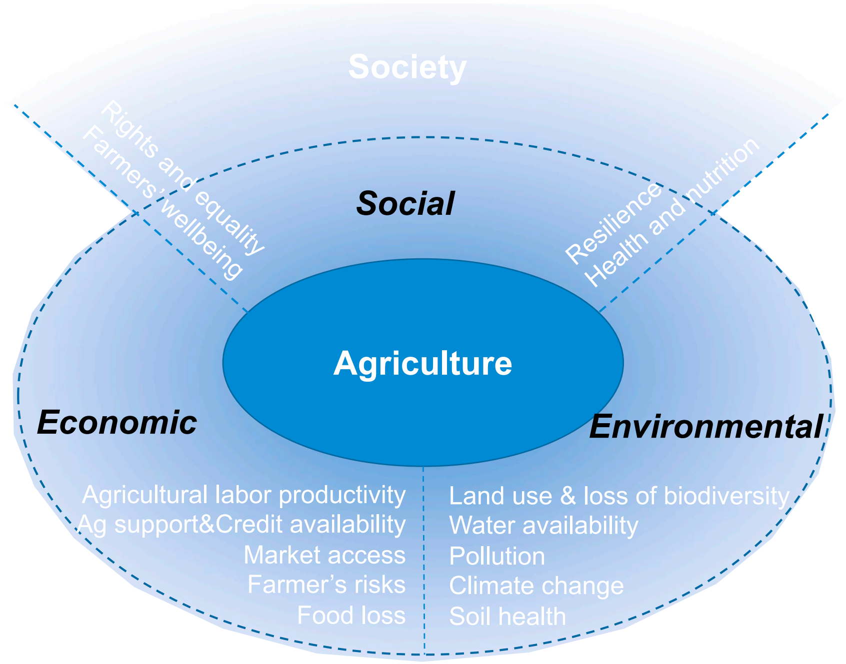

Figure 1. The scope of SAM assessment

The dashed circle indicates the boundary of direct and indirect impacts of agriculture. SAM assessment focuses on agriculture's direct impacts on the environment and economics, as well as the direct and broader impacts on society.

sustainability thresholds (see detailed discussion for each indicator in Notes S3–S5). The resulting matrix of indicators enable assessments of the agricultural sustainability of countries around the world at a national scale. Because we expect assessments and the policies for improvements to vary by country, our purpose is not to define universal pathways to sustainability but rather to provide data for each country to evaluate its own progress and policies appropriate for its needs. To that end, we also analyze the synergies and trade-offs among indicators within countries over time and discuss examples of lessons learned from the range of country-level histories.

RESULTS

SAM indicators and thresholds

Our first result is SAM itself, and we describe the scope of the SAM assessment and its indicators here since they are the result of the literature survey and the iterative process of indicator development (see the experimental procedures). The SAM assessment focuses on the direct impacts of agricultural production on the environment and economy, and broader impacts on the whole society (Figure 1), recognizing that agriculture is deeply interconnected with other sectors (e.g., industry). Specifically, from an environmental perspective, sustainable agriculture avoids inefficient use of water resources, further loss of biodiversity from converting natural habitat to agricultural land, injudicious use of chemical compounds that negatively affects local and regional water and air quality, emissions of greenhouse gases that disrupt the global climate, and losses in soil health and fertility. From an economic perspective, sustainable agriculture improves the economic viability of the agricultural sector by enhancing agricultural productivity and profitability, advancing agricultural innovation, providing farmers access to markets and credit, improving farmers' ability to manage risk, and reducing food losses along the supply chain. From a social perspective, sustainable agriculture improves farmers' wellbeing, respects farmers' rights, promotes equitable opportunities in rural communities, and benefits all of society with enhanced food supply system resilience and improved nutrition and health. These are the major aspects of agricultural sustainability assessed by SAM.

The state of agricultural sustainability can be captured by identifying indicators for each of the major aspects above, and, ideally, these indicators should (1) closely relate to and have a monotonic relationship with one of the major aspects of agricultural sustainability; (2) have available data for all countries and multiple years; (3) measure the performance rather than the drivers or practices; and (4) be simple and transparent. However, in practice, such indicators are rare; therefore, we established criteria for evaluating indicators accordingly and set principles to select indicators (see the experimental procedures for details on the methods of indicator selection).

After screening over 200 initially proposed indicators, 18 indicators were selected and developed for the SAM (Table 1; details about each indicator are described in Notes S3–S5). Overall, this set of SAM indicators on a national scale shares several similarities with the assessment framework at farm scale developed by FAO,[13] and is linked to most SDG targets (Figure S1). Admittedly, current data limitations did not permit the inclusion of indicators covering some important topics and some indicators are not specifically developed only for agriculture. This set of 18 indicators may be expanded or improved upon in the future, but, in our judgment, they collectively represent the best and most comprehensive quantitative matrix currently available.

To enable cross-comparison among indicators and to identify priorities for improvement in a country's performance, we defined red and green thresholds for each indicator, aligning with the framework of planetary and social boundaries for human activities.[36–39] Red thresholds indicate high risks of undesirable environmental, economic, or social impacts, while green thresholds suggest an acceptable sustainability target (see Notes S3–S5 for more details on threshold setting for each indicator). These thresholds for environmental and socioeconomic indicators in SAM help to provide an initial outline of the "safe and just space"[38] for agriculture production.

More specifically, the environmental dimension includes six indicators (Table 1), measuring the impacts of agricultural production on major environmental concerns. Those environmental

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Table 1. A summary of the indicators included in the SAM

Major aspect	Indicators	Data sources	Green threshold	Red threshold	Units
Environmental dimension					
Water availability	sustainability of irrigation water consumption (water consumption)	Rosa et al.[22,23]	1	2	km^3 total annual irrigation water/km^3 sustainable annual water consumption
Pollution	N surplus	Zhang et al.[24]	52	69	kg N/ha/year
	P surplus	Zou et al.[25]	3.5	6.9	kg P/ha/year
Land use and loss of biodiversity	the lost forested area due to agricultural activities (land-use change)	Global Forest Watch, Curtis et al.[26]	0	0.0053	ha deforested/ha cropland area/year
Climate change	total greenhouse gas emission from agriculture activities per harvested area (greenhouse gas)	FAO[27]	0.86	1.08	ton CO$_2$eq/ha
Soil health	soil erosion	Borrellie et al.[28]	1	5	ton/ha
Economic dimension					
Agricultural labor productivity	agricultural GDP per agricultural worker (labor productivity)	derived from World Bank (WDI)[29]	7,946	460	2011 US$ PPP
Credit availability	access to finance for farmers (finance access)	EIU[30]	100	25	score
Farmer's risks	crop price volatility (price volatility)	Derived from FAO[27]	0.10	0.23	–
Agricultural support	government agricultural expenditure per agricultural worker (government support)	agricultural expenditure data, IFPRI[31] and FAO[27]; agricultural worker, derived from WDI [9]	2,405	25	2011 US$ PPP
Market access	total agricultural export values as a percentage of agricultural GDP (trade openness)	trade data, UN Comtrade;[32] agricultural GDP, World Bank WDI[29]	71	17	%
Food loss	food loss percentage (food loss)	EIU[30]	2.2	6.6	%
Social dimension					
Resilience	crop production diversity H index (crop diversity)	calculated following Seekell et al.[33]	48	22	counts
	food affordability by low-income population (food affordability)	Seekell et al.[33]	100	30	%
Health and nutrition	prevalence of under-nourishment (under-nourishment)	FAO[27]	0	7.5	%
Farmers' wellbeing	rural poverty ratio (rural poverty)	World Bank[34]	2	13	%
Equality	global gender gap report score (gender gap)	World Economic Forum[34]	0.8	0.7	score
Farmers' rights	Land rights	LandMark[35]	3	2	score

The words in parenthesis in the Indicators column are the abbreviated names for the indicators. The rationales for determining the thresholds are detailed in Notes S3–S5. IFPRI, International Food Policy Research Institute; WDI, World Development Indicators; PPP, purchasing power parity.

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concerns, with the exception of soil erosion, correspond to proposed planetary boundaries that are heavily influenced by agricultural activities, including freshwater use (water consumption: sustainability of irrigation water consumption),[22,23] human disturbance to N and P cycles (N surplus and P surplus), land system change, biodiversity loss (land-use change: deforestation due to agricultural activities), and climate change (greenhouse gas: greenhouse gas emissions from agriculture activities).[10,36,37] Consequently, the definitions of these indicators and their thresholds align with the planetary boundary literature with some modifications to permit country-level assessments and cross-country comparisons (Notes S3–S5). Although not included in the planetary boundary framework, the soil erosion indicator provides an initial country-scale assessment of one aspect of soil health, for which there is growing interest but limited data on national scales. While this indicator does not reflect all concerns of soil health, it is the only indicator with at least basic estimates available with global coverage, by country and for multiple years. Admittedly, agricultural production has other environmental impacts that are not directly measured by those six indicators (e.g., the environmental damages caused by pesticide use and the biodiversity loss due to changes in crop mixes or to land-use change other than deforestation), and the assessment of those impacts in the SAM framework requires future efforts in developing the concept, data, and thresholds of new indicators on a national scale.

The economic dimension includes six indicators (Table 1), which measure the economic viability of farmers and agribusinesses considering both agricultural production costs and benefits. From a cost perspective, the economic dimension measures farmers' access to financing options (finance access: the access to financing index), price support from the government (government support: government expenditures on agriculture as a percentage of agricultural gross domestic product [GDP]), which potentially helps farmers and agribusinesses lower their costs and increase their innovative capacities and food losses along the supply chain (food loss: a measure of post-harvest and pre-consumer food loss as a ratio of the domestic supply). From a benefit perspective, the economic dimension evaluates farmers' labor productivity (labor productivity: agricultural GDP per agricultural worker), farmers' openness to trade (trade openness: agricultural export revenues out of agricultural GDP, a modified version of trade openness index), and their exposure to crop price volatility (price volatility: weighted average coefficient of variation of crop prices).

In contrast to the environmental indicators, the limits for most of the economic indicators are not widely acknowledged or established, and, consequently, consistent threshold definition can be difficult across countries. As a first approximation in addressing this, we identified the 75th and 25th percentile of existing values for five of the six economic indicators across all countries in all years (with higher values indicating greater sustainability, see Note S7 for details) as green and red thresholds.[40–44] In this approach, the indicator values beyond the 75th percentile indicate likely sustainable practices, while the values below the 25th percentile are likely unsustainable.

The social dimension includes six indicators (Table 1), measuring agriculture's direct impacts on farmers' livelihood and broader societal impacts. These include farmers' wellbeing (rural poverty: rural poverty ratio), farmers' rights (land rights: land right security index from LandMark), and equality (gender gap: global gender gap index). While there are many other aspects of wellbeing, rights, and equality, these indicators have sufficient data and capture important aspects of farmers' livelihoods.

The impacts of agricultural production on health and nutrition are profound and often depend on social norms, culture, access to information, and other socioeconomic and physiological factors.[45] Although multiple indicators exist for health and nutrition, we report the prevalence of under-nourishment, because it provides an effective measure of the first condition for achieving food security: that of adequate calorie availability and consumption. However, under-nourishment is limited in measuring overall health and nutrition status (see Note S5 for the additional rationale for selecting the under-nourishment indicator).

Sustainable agriculture is fundamental for the resilience of food systems; i.e., the ability of food systems to adapt to external disruptions and to provide a stable food supply. Here, food system resilience is measured using two indicators: socioeconomic resilience considering the food affordability by low-income households (i.e., lowest 20% income quantile divided by averaged food expenditures), and food production resilience considering the diversity of crop production (i.e., an H index for measuring the number of crop types that provide certain quantities of calories *per capita*).[33]

Similar to economic indicators, it is challenging to define the sustainability thresholds of social indicators. Thresholds for social indicators are primarily set based on literature and expert opinions (Note S5). Where the thresholds were difficult to identify, such as crop diversity, we employed 25th–75th percentile as benchmarks, as done for economic indicators, to define the red and green thresholds.[46]

The current state of agricultural sustainability

Our second result is the overview of the sustainability of agriculture around the world that SAM provides (Figure 2A). The assessment for 2010–2014 shows that all countries (except the US and Canada) have at least one indicator in red (indicating unsustainable and high risk), and no country has all indicators in green (indicating a safe and just space for human activities[38]), suggesting that all countries require further improvement in some aspects of agricultural sustainability. Globally, improvement is urgently needed in environmental and social dimensions. Four out of six indicators in the environmental dimension (i.e., N surplus, P surplus, greenhouse gas, soil erosion) indicate that over 50% world's population fall in countries that are in the red zone (Figure S38), while three indicators in the social dimension (i.e., food affordability, under-nourishment, gender gap) are red. In contrast, only one indicator in the economic dimension (i.e., trade openness) has over 50% of the global population in red zone countries; on the other hand, all indicators in the economic dimension have less than 20% of the world's population in countries that have achieved the green threshold.

For individual countries, the priority areas for improvement vary widely, as indicated by the SAM report card (Figure 2A). For example, middle-income countries (e.g., Brazil, China, and India) and densely populated countries (e.g., South Korea and Japan) have the most environmental indicators in red. Many high-income countries with relatively small agricultural land

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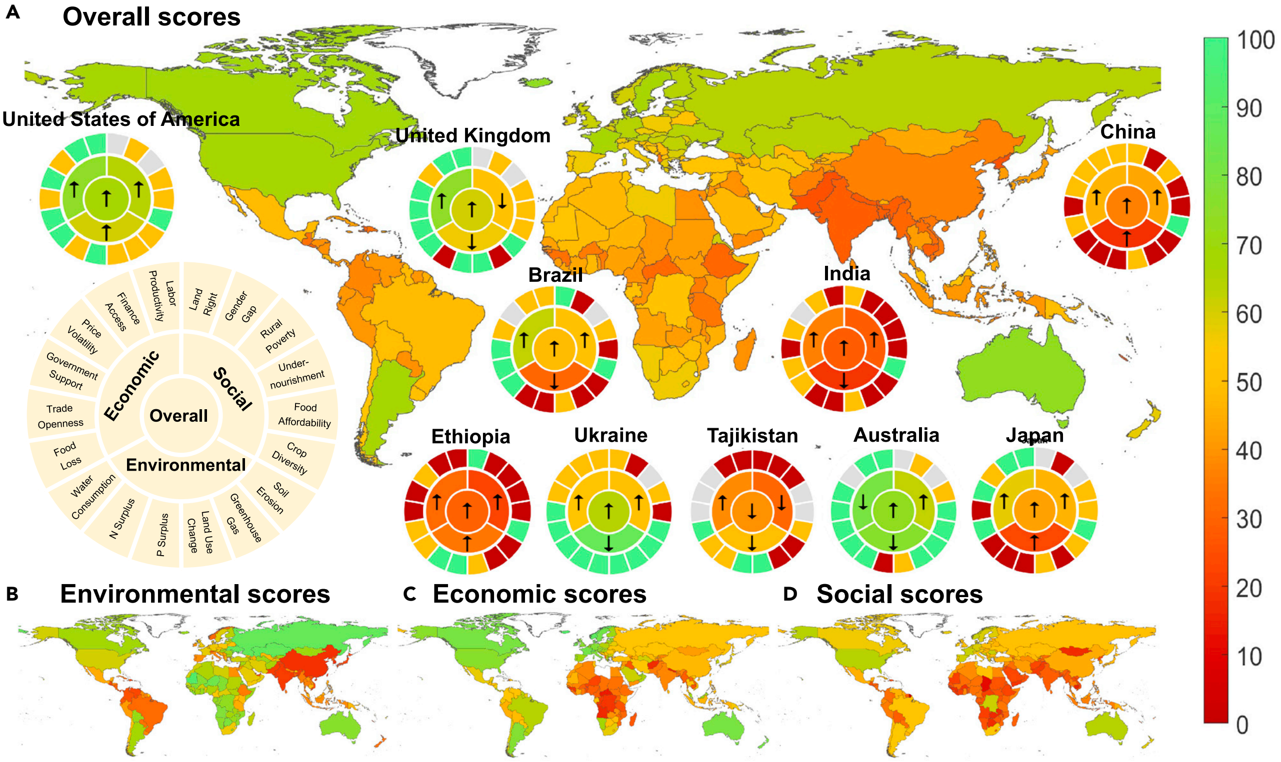

Figure 2. An overview of agricultural sustainability around the world

(A–D) The overall SAM score for each country and report cards for a selection of countries for the 2010–2014 period. For the report card (see legend at the lower left in A), the outer ring denotes the performance of each indicator according to the traffic-light color scheme that aligns with the planetary boundary literature: red indicates a "dangerous level: high risk of serious impacts," yellow color denotes a "zone of uncertainty: the increasing risk of impacts," green indicates a "safe operating space."[36–38] The middle and inner ring denotes the scores for each dimension and the overall score (see the experimental procedures for detailed design for the report card and score calculation). The arrows in each panel denote the trends between the year 2010 and 2014. The scores for environmental, economic, and social dimensions are mapped in (B), (C), and (D) respectively. Please see supplemental information for each indicator's sustainability performance distribution maps (Figure S44) and each country's report card (Figure S45).[38,46]

areas or relatively homogeneous climates face challenges of crop production diversity (e.g., Iceland and UK), and most high-income countries in Europe urgently need to lower their greenhouse gas emissions from the agricultural sector. Lower-middle-income and low-income countries located in South Asia, the Middle-East, and Sub-Saharan Africa exhibit pressing demand for eliminating rural poverty and improving food affordability and nutritional status, especially in low-income households (Figures S29, S44, and S45).

Summarizing the performance of SAM indicators onto the three dimensions, we found that a country's performance in the economic and social dimensions of SAM is generally positively related to its income level (e.g., measured by *per capita* GDP), while the performance in the environmental dimension is the worst in the upper-middle-income group (Figure 3). To summarize the highly diverse set of indicators, we converted the raw values of each indicator to a 0–100 scale (indicator score) based on the red and green thresholds, calculated dimensional scores, and overall performance scores based on these indicator scores (see the experimental procedures for detailed description). The result shows that a larger fraction of high-income countries have achieved the sustainable targets (the green zone) for the economic dimension compared with the other income groups, while the fraction of countries falling in the red zone increases from the upper-middle-income groups to the low-income groups (Figure 3). The social dimension follows a similar pattern, but no country has achieved the green zone despite income levels. The fraction of countries within each income group that falls in the green zone of the environmental dimension declines as income grows, and the fraction in the red zone is the highest in the upper-middle-income group, aligning with the environmental Kuznets curve theory[24] (i.e., environmental impacts first increase and then reduce with economic development).

Tracking progress overtime

In addition to providing an overview of agricultural performance with a range of indicators in all three dimensions of sustainability, SAM also tracks the performance of individual countries during the period of 1961–2016, which is our third result (Figure 4).

Overall, most countries have made significant improvement in their socioeconomic indicators but have shown varying level of deterioration in their environmental indicators (Figures 4 and S41). For instance, the eight example countries from different income groups have mostly observed significant improvement in four economic indicators (i.e., labor productivity, government support, finance access, and trade openness) and four social

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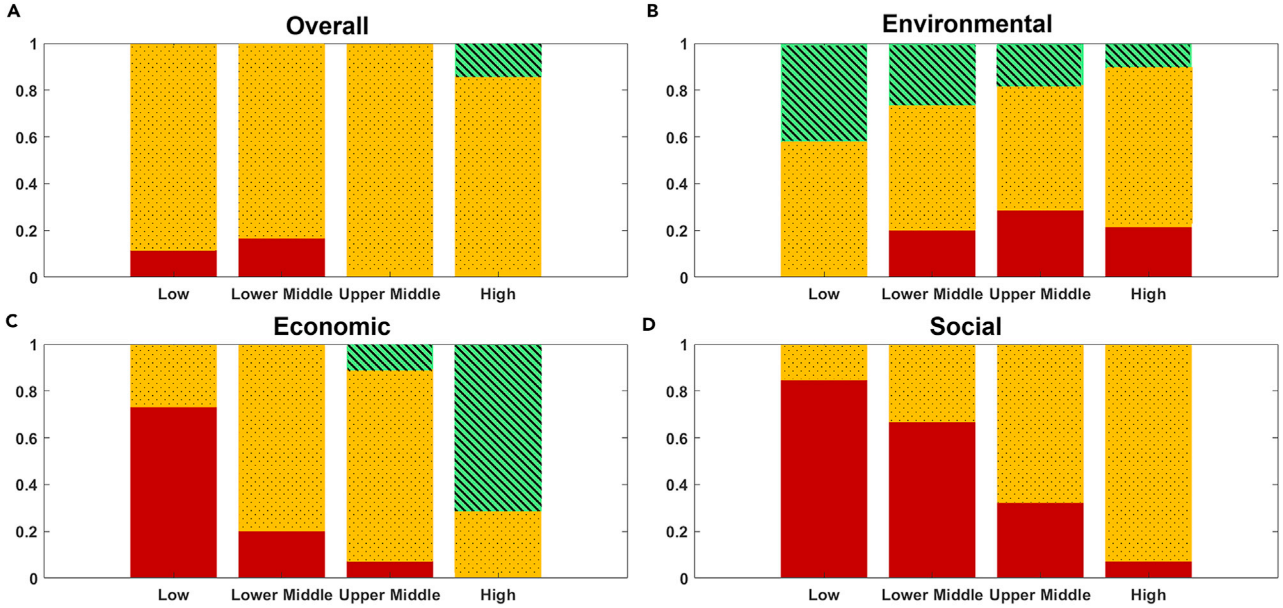

Figure 3. The performance of agricultural sustainability by income groups in 2010–2014 (average)

(A–D) The fractions of countries that are in the red, yellow, and green zones in each income group are displayed based on the overall scores (A) and the scores for each of the three dimensions (B–D). The score calculation is detailed in the experimental procedures. The scores lower than 33 or higher than 67 correspond to red and green zones, indicating the level of sustainability. The scores between 33 and 67 correspond to the yellow zone. Please see Figure S28 for each indicator's performance by income group. Please see the score calculation in the experimental procedures.

indicators (i.e., crop diversity, food affordability, under-nourishment, gender gap). For the remaining four indicators in the economic and social dimensions, all historical trends are not detectable or significant except three cases: significant deterioration in price volatility in China and food loss in India, and significant improvement in the rural poverty indicator in Ethiopia. Comparing socioeconomic indicators across income groups, it is observed that countries with higher incomes tend to perform better; however, even high-income countries, such as Australia and the United States, have not eradicated under-nourishment, which actually has deteriorated over the past decade and may be further aggravated due to sudden social crises such as the COVID-19 pandemic.[48] In contrast, Ethiopia has made great progress in eliminating under-nourishment in past decades, but the country's under-nourishment indicator is still in the red threshold (Figure 4).

The performance of environmental indicators varies among countries mainly due to the differences in their natural resources, agricultural practices, and development stages. Environmental concerns are especially acute in rapidly developing middle-income countries. For example, almost all environmental indicators for the three major developing countries (i.e., China, India, and Brazil) have been deteriorating, and most indicators have fallen into the red zone (Figure 4). Only some improvement has been observed for soil erosion in China and India, and for land-use change in Brazil; however, such improvement is not yet sufficient to move these countries to the green zone of these indicators. Even countries in the low-income group, such as Ethiopia and Tajikistan, have been experiencing increasing environmental risks such as higher greenhouse gas emissions and increased soil erosion. In contrast, some countries in the high-income group, such as Australia and the United States, have demonstrated significant improving trends for some environmental indicators, such as water consumption, P surplus, and soil erosion. However, the P surplus indicator is still in the red zone for Australia, and several indicators, such as N surplus and soil erosion, are still in the yellow zone for the United States. It should be noted that SAM focuses on the impacts of domestic agricultural production; therefore, the environmental impacts associated with agricultural products imported from other countries are not attributed to the importing country. In other words, countries, especially those in the high-income group, can potentially show a better apparent environmental performance by adjusting the domestic production portfolio toward more environmentally friendly and profitable products, or by importing more agricultural or food products, which may well be produced less sustainably.[49,50] For the historical trajectory extending back to 1961 for the same eight countries, see Figure S30. A similar assessment for all 218 countries or regions is available in Figure S46.

Trade-offs and synergies among SAM indicators

Our fourth main result focuses on revealing trade-offs and synergies among the SAM indictors and how they vary by country. Given the complex nature of agricultural systems and the multi-dimensional concerns of sustainability, one change in agriculture (e.g., implementing new technology or a new policy) may lead to multiple cascading impacts across the three sustainability dimensions, and, consequently, some of the performance indicators may improve and others may decline. Therefore, understanding the trade-offs and synergies among indicators is critical for policymakers to craft strategies toward sustainability.[51,52] Based on the historical records of the SAM indicators (Figure 4),

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Figure 4. The 1991–2016 trajectory of SAM indicators for a subset of countries

Within each of the four income groups (i.e., high-income, upper-middle-income, lower-middle-income, and low-income countries[47]), two countries (one in tropical and another in temperate climate zone) with the highest total agricultural GDP (average of 2010–2014) are displayed here. Each row records the performance of a SAM indicator with one column per year, and the color of each cell is determined by the score, as described in the experimental procedures. The blank cells indicate that data are not available for the corresponding indicator/year pairs.

we investigated the trade-offs and synergies among indicators in each country (Figure 5), where statistically significantly (Spearman correlation $p < 0.05$) positive (or negative) correlations between a pair of indicators' time series indicates a synergy (or trade-off).[51] While these statistical relationships between indicators do not imply direct causal linkages, they provide an indication of the trade-offs and synergies in a multi-target system with complex dynamics, and they can help to identify trade-offs that are not yet well recognized.

The trade-off and synergy analysis of the SAM indicators indicates complex relationships among the different sustainability concerns, and those relationships are not necessarily consistent

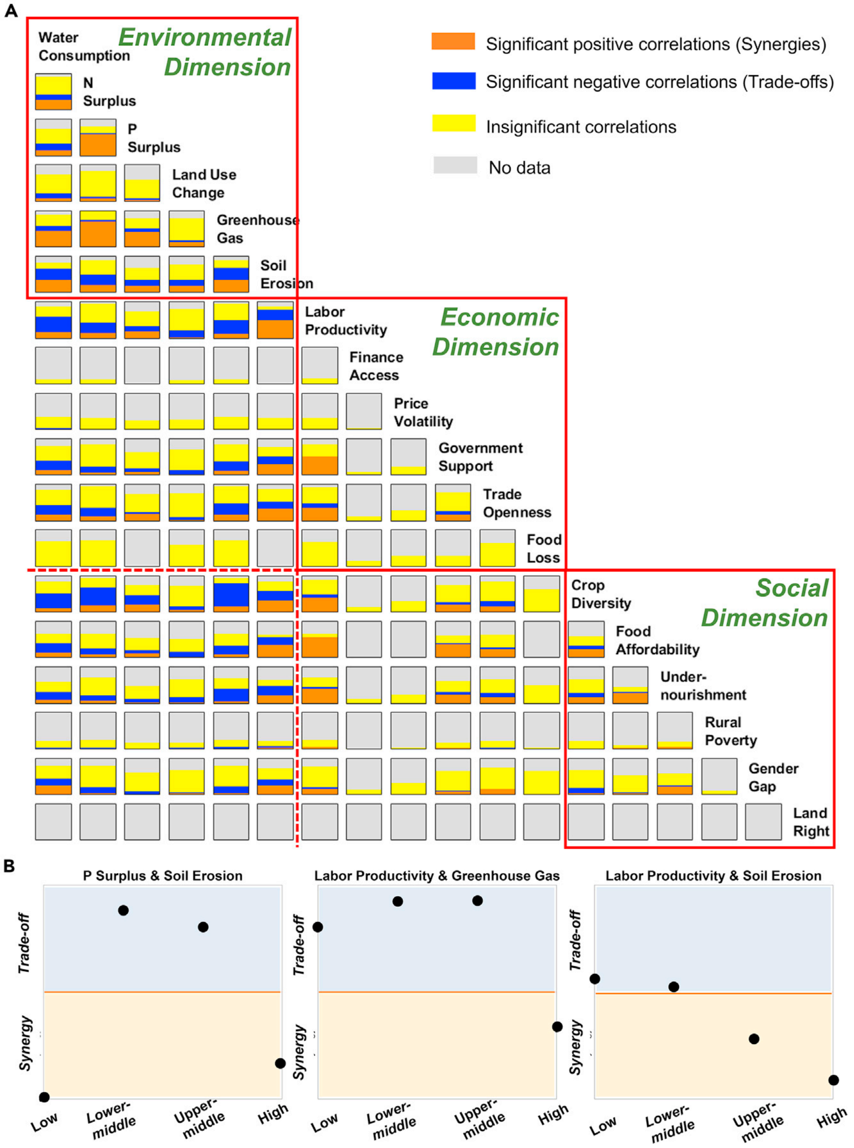

Figure 5. An overview of synergies and trade-offs between SAM indicators for 112 major agricultural production countries

(A) The short indicator names are on the diagonal of the figure, and each box at the lower-left part of the figure summarizes the relationships between a pair of indicators. In each box, the height of each colored bar is determined by the fraction of countries in synergy (orange: a significantly positive correlation between indicators, $p < 0.05$), trade-off (blue: significantly negative correlation), or insignificant relationship (yellow); the remaining area in the box indicates no data (light gray). See the experimental procedures for detailed methodologies.

(B) The three sub-figures present the percentage of significant trade-off relationships out of total significant synergetic and trade-off relationships in each of the four income groups.[47] The orange line is the 50% trade-off line, above which the dots indicate trade-off-dominant relationships and below which the dots represent synergistic-dominant relationships.

among countries. As shown in Figure 5, none of the indicator pairs shows only trade-offs or only synergies for all countries. The lack of consistent relationships among indicators could be partly attributed to country-specific characteristics, such as geographic locations and cultural backgrounds, and different compositions and efficiencies of their agricultural system. While the trade-off and synergy relationships warrant investigation for each country case, the following three general patterns by income groups can be observed across countries (Figure 5):

(1) Within each of the environmental, social, and economic dimensions, indicators often, but not always, show synergies among indicators within the same dimension. Improvement in one indicator may be linked to improvement in another, but this is not always the case, even if both indicators belong to the same dimension of the sustainability concerns. Taking the environmental dimension as an example, synergies dominate relationships among N surplus, P surplus, and greenhouse gas indicators, suggesting these environmental impacts tend to worsen (or improve) concurrently in most countries. Land-use change, on the other hand, does not have significant relationships with most other indicators in the environmental dimension. Soil erosion shows either trade-off or synergy relationships with the other environmental indicators. Such synergy and trade-off relationships also display strong patterns based on the level of economic development. Middle-income countries tend to have more cases of trade-off relationships involving soil erosion compared with low- and high-income countries, suggesting some middle-income countries have started to experience reduced soil erosion while other environmental indicators continue to worsen (e.g., the panel for P surplus and soil erosion in Figure 5; see Figure S31 for relationships between soil erosion and other indicators).

(2) Trade-offs dominate the relationships between most environmental and socioeconomic indicators, and such relationships are correlated with economic development levels (Figures 5 and S31). The high-income group has the highest fraction of countries showing synergetic relationships between the labor productivity indicator and all environmental indicators (except for land-use change) compared with other income groups, indicating that more high-income countries have managed to increase their agricultural labor productivity with less pollution and resource depletion. Similar patterns were observed in the relationships between other socioeconomic indicators and environmental indicators. Compared with other environmental indicators, soil erosion shows a more synergetic relationship with labor productivity (e.g., in Figure 5, the fractions of countries showing trade-offs in the panel for soil erosion and labor

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productivity are lower than in the panel for greenhouse gas and labor productivity), as well as most other socioeconomic indicators, and the fraction of synergistic relationships is higher in country groups with higher income, suggesting that a reduction in soil erosion often aligns with long-term socioeconomic sustainability of agriculture.

(3) Not all social indicators increase along with economic indicators. Surprisingly, increases in government support and trade openness are not accompanied by a reduction in under-nourished population in many countries (Figure 5); a few countries even show a trade-off relationship between under-nourishment and labor productivity indicators over the study period. This lack of synergies may indicate a combination of factors. For example, the population growth may outpace the increase in agricultural productivity; change in consumption pattern and uneven distribution of food among income groups may also delay or mute the influence of agricultural productivity increase on the reduction of under-nourished population; cheaper agricultural imports may increase undernutrition by depressing the income of rural households;[53] domestic policies may favor the expansion of export crops at the expense of the livelihood of smallholder farmers,[54] even the whole population. The relationships between gender equality, resilience, and the economic performances of SAM are mostly insignificant, suggesting that the social dimensions of agricultural production do not automatically improve with economic performance. These results suggest a need for more country-specific investigations of trade-offs and synergies and that pathways to sustainability may be context specific for many countries.

DISCUSSION

An indicator system to inform actions

The Sustainable Agriculture Matrix provides quantitative assessment of agricultural sustainability for countries around the world, providing timely inputs for tracking countries' progress toward their SDGs commitments for 2030. While the official indicator for sustainable agriculture (SDG 2.4.1) is still at the stage of data collection and capacity development, the assessment results by SAM can start to engage countries in understanding their performance in agricultural sustainability with a quantitative view and to motivate countries to compare with and learn from their peers and their historical trends. The SAM assessment is complementary to the SDG 2.4.1 indicator. SAM is developed independently from the intergovernmental processes, uses publicly available data from national statistics, can look retrospectively at trends leading up to the present, keeps data synthesis approaches transparent, and focuses on the impacts of agriculture using data collection and synthesis methods consistent across nations.

The SAM indicators may provide valuable information to assist decision-making on a national scale in several respects:

(1) The setting of the green and red thresholds, while imperfect, may help countries to identify priority areas for improving agricultural sustainability (e.g., those indicators that fall in the red and yellow zones in Figure 6A). It is important to note that those socioeconomic thresholds set by the percentile approach use available data from all countries and across all years; therefore, the thresholds change very little over time, and it is theoretically feasible for nearly all countries to move above the 25th percentile when current performance is compared with historical performance. Nevertheless, we recognize that some countries may be unable to meet the green thresholds due to differences in their natural resource endowments and socioeconomic conditions. As SAM indicators track a country's performance over time, they demonstrate the progress made in a country and are complementary to the cross-country comparisons.

(2) Displaying positive and negative impacts of agriculture together in a consistent manner provides a unique opportunity to engage in constructive conversations among different agencies and ministries within government and different stakeholders (e.g., farmers, manufacturers, traders, consumers). Achieving sustainable agriculture ideally requires that all indicators move toward their respective sustainability targets. Consequently, it demands collaboration across government agencies and stakeholders. During the development of SAM, we shared our progress with a broad group of stakeholders, including experts leading the development of SDG 2.4.1, through policy roundtables organized by the FAO's Liaison Office for North America and multiple international conferences, and used SAM as an opportunity to engage in open discussions and co-learning with various stakeholders. This co-development not only results in improved design and visualization of SAM indicators but also leads to transdisciplinary (involving natural scientists, social scientists, and key stakeholders) collaborations on analyzing and applying SAM to guide the pursuit of sustainable agriculture.

(3) The assessment of sustainable agriculture by SAM over time also provides the opportunity to understand better the trade-offs and synergies among normative goals represented by the indicators, which are of key concern for many international organizations and development agencies. For example, FAO recognized that one of the major challenges for achieving sustainable agriculture is to "acknowledge and explore the full range of potential tradeoffs and in some cases contradictions, between sustainability and productivity."[55] The trade-offs among indicators highlight necessary changes needed in the current agricultural system, in order to enable synergies for each country. For example, our analysis revealed that many countries had strong trade-offs between the under-nourishment indicator and economic indicators (e.g., government support and trade openness; Figure 5A), and the lack of synergies urges policymakers to reconsider agricultural policies favoring export products or the distribution of benefits from the export revenue. The dominating trade-off relationships between environmental and economic dimensions in China suggest that current intensification approaches relying on intensive input use (e.g., irrigation water and mineral fertilizer) need to be transformed toward resource-efficient approaches, and the government support for agricultural production needs to be re-designed (Figure 6A). To enable such transformations, lessons could be learned from the countries that have demonstrated synergies. For example, while China, Brazil, and India are among the countries with significant trade-offs between agricultural GDP per agricultural worker (the labor productivity indicator) and the environmental indicators of N surplus and water consumption, France and the USA show synergies for these relationships (Figures 6B and 6C). While China and France have similar agricultural land-use pressure (measured here by the agricultural land area *per capita* shown

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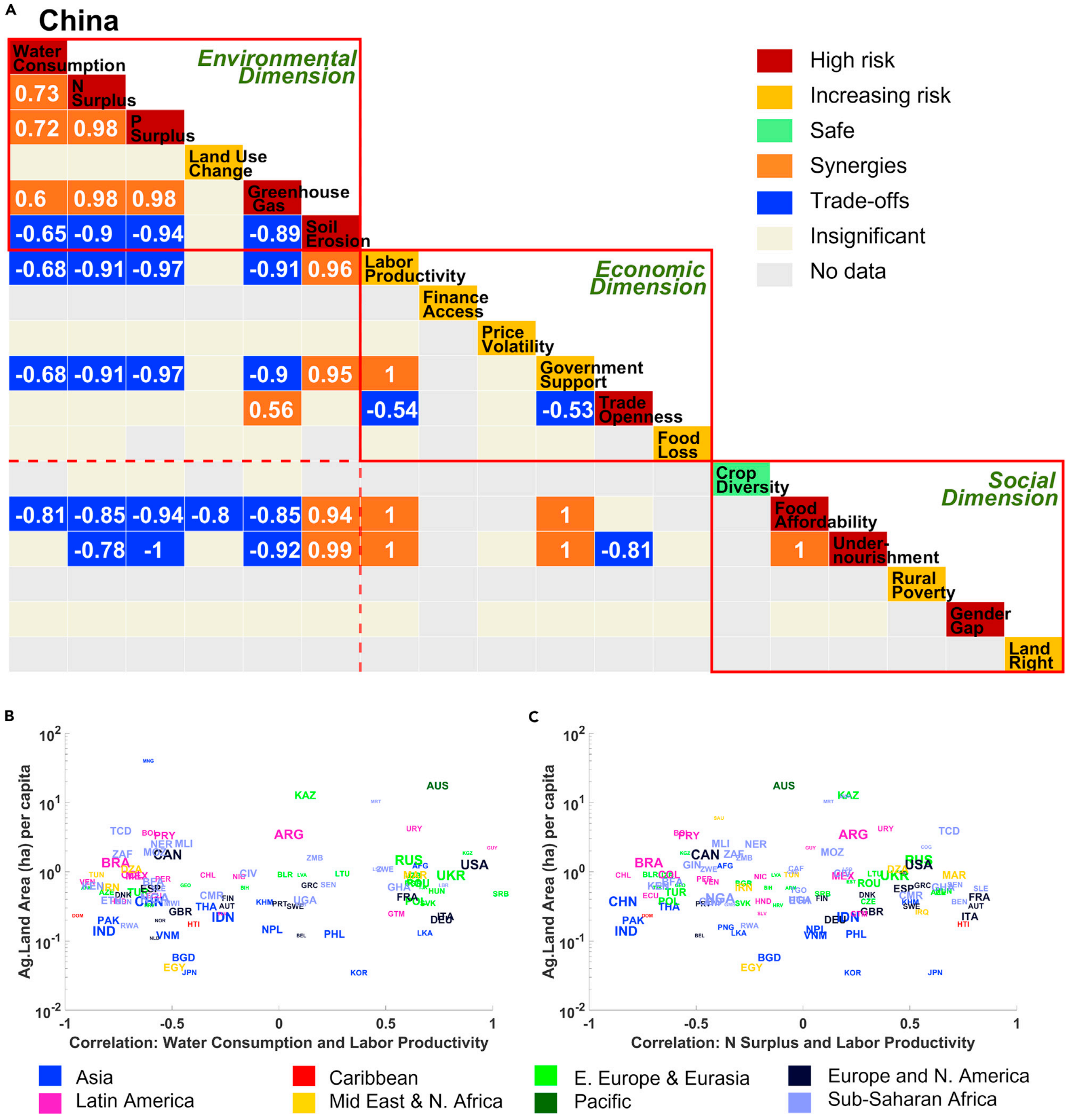

Figure 6. An example of using SAM indicators to explore differences in trade-offs and synergies within and among countries

(A) The performance of each indicator and their interactions in China (the assessments for all 218 countries are available in Figure S47). The background colors of the boxes in the diagonal are determined by the indicator performance for the most recent years (2010–2014) using the traffic-light color scheme as the outer ring of the report card (see the experimental procedures for detailed methods). The red color indicates high urgency for taking actions. The colors of the remaining boxes (not in the diagonal) indicate the synergies (orange, significantly positive) and trade-offs (blue, significantly negative) between indicators. Light yellow denotes insignificant relationships, and gray means not enough data for correlation. The number in a colored box is the Spearman's value for the correlation between the corresponding pair of indicators.

(B) The correlation between water consumption and labor productivity.

(C) The correlation between N surplus and labor productivity for all countries. Countries (noted with three-letter abbreviation based on ISO code) with positive correlations (on the right side of each graph) suggest synergistic relationships, while countries with negative correlations (on the left side of each graph) suggest trade-off relationships, and countries in the middle show no significant correlation. The y axis is determined by *per capita* agricultural land area, indicating the land-use pressure for each country.

on the y axes of Figures 6B and 6C), France managed to improve agricultural GDP per agricultural worker and reduce N pollution and unsustainable irrigation water use. Further investigations into the historical trajectories of these indicators and related policy (e.g., changes in agricultural subsidies, the adoption of the European Nitrate Directive in the 1990s) and technological changes in France and other countries with similar success, will help to identify effective policies and technologies, as well as their potential influences on other SAM indicators, and consequently inform strategies in China and other countries. Co-developing case studies with stakeholders will help to accelerate the identification and implementation of effective strategies.

The quest for indicators and data of good quality

The development of SAM indicators reveals the gap between the complex concept of sustainable agriculture and existing data and indicators at the country scale and with global coverage. In order to arrive at the first set of SAM indicators, compromises had to be made to accommodate data limitations. For example, the land rights indicator only has data for one year, but they are included in SAM because they provide a measurement for one critical aspect of sustainable agriculture, and no other pertinent indicator provides both spatial and temporal coverage better than land rights. While most indicators cover a broad range of countries, many fall short on temporal coverage, which limits tracking progress over time. So far, only a handful of indicators include data since 1961 (e.g., N surplus, P surplus, greenhouse gas, and crop diversity), some have data since the 1990s (e.g., water consumption, land-use change, soil erosion, labor productivity, and trade openness), while the rest have data from only the past several years. It is critical to make sure that the raw data for calculating SAM indicators are continuously collected and made available to the public.[21]

In addition to the lack of data for existing indicators, indicator development is needed for improving the measurement of some critical aspects of sustainable agriculture, such as soil health. While there has been much interest in developing indicators of soil health at the farm scale,[56] very few soil health indicators can be aggregated to the national scale. For example, soil organic matter is known to confer many beneficial soil health properties, such as improved water holding capacity and increased activity of beneficial organisms, but most measurements are at local plot scales and few countries are able to assess changes in soil organic matter at an aggregated national scale. The indicator for human health and nutrition should be improved to include all aspects of malnutrition, including the supply of protein and micronutrients, thus reflecting indicators of nutrition-sensitive agriculture.[57] Indicators for rights and equality need to be improved to measure other essential rights and equality issues (e.g., education, gender equality) specifically for farmers or community lands. The caveats of each indicator included in this SAM version are discussed further in Note S5.

Focusing on the national-scale assessment, the current SAM indicators have limitations in reflecting the heterogeneity of the sustainability performance of agriculture within a country. For example, the US corn/soybean belt has more total N surplus than other US regions due to its intensive crop production activities, and China's east coast regions are more developed and polluted compared with its western regions. Characterizing such heterogeneous performances is important for evaluating agricultural sustainability. Two potential directions could be explored: (1) implementing the SAM assessment framework on a subnational scale,[58] and (2) developing tailored national-scale statistics that could reflect the spatial heterogeneity within countries. As many SAM indicators are built on subnational statistics or consider the spatial heterogeneity in available resources (e.g., the water consumption indicator), it would be feasible to develop SAM following these two potential directions in order to better reflect the heterogeneity of the sustainability performance of agriculture within a country.

Conclusion

We have developed an indicator system, SAM, to systematically assess and visualize country-level performances in sustainable agriculture across environmental, social, and economic dimensions, track the spatial and temporal variation in progress toward sustainability objectives, and identify the trade-offs and synergies among multiple sustainability targets. As expected, no single country has achieved sustainability targets for all indicators, but SAM also reveals how the priorities for improvements in the sustainability of agriculture differ among countries. By highlighting priority areas for improving agricultural sustainability for each country, the SAM assessment may provide the necessary evidence base for policymakers and stakeholders seeking means of improving their agricultural sustainability. SAM also demonstrates the spatially and temporally varying interconnections among sustainability targets, reveals prevalent trade-offs between economic and environmental performances in agricultural production, and thus facilitates potential collaboration and coordination among policymakers who influence a wide range of topics, including food and agricultural policies, rural development, and environmental policies. Visualizations of assessments across countries also provide opportunities to identify effective policies and technologies that have enabled synergistic relationships among environmental, economic, and social dimensions of agriculture in some countries and that could consequently inform policies in other countries that are facing trade-off challenges. While continuous improvement in indicator design and data availability is necessary, the broad application of SAM offers an opportunity for better-informed and coordinated actions toward sustainable agriculture.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and results for resources and reagents should be directed to and will be fulfilled by the lead contact, Xin Zhang (xin.zhang@umces.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

All datasets analyzed in this study are publicly available as referenced within the article and in the supplemental information. A summary table of candidate indicators collected from existing literature is available at Dryad: https://doi.org/10.5061/dryad.6hdr7sr0c.

Raw values for each SAM indicator and corresponding scores are available at the same link. The codes for score calculation are available at https://github.com/yaoguolin/SustainableAgricultureMatrix.

The development of SAM indicators

The development of first-edition SAM indicators was an iterative process carried out by a transdisciplinary expert panel, involving natural scientists, economists, social scientists, and stakeholders. The SAM framework and indicators were developed through a series of workshops supported by the National Socio-Environmental Synthesis Center (SESYNC) over the years 2017–2021, following the steps below (Figure S42).

First, we reviewed the existing definitions and evaluations for sustainable agriculture (Notes S1 and S2). The review of existing literature suggested a growing consensus on defining sustainable agriculture according to its impacts on the environmental, economic, and social dimensions of sustainability.[12] Therefore, we defined the scope of the SAM framework to assess the impacts of agricultural production on these three dimensions of sustainability. Considering the interconnections between agriculture and other sectors, we further refined the scope to assess direct impacts of agricultural production on the environment and economy, and broader impacts on the whole society (Figure 1). Based on the review of existing indicator frameworks related to sustainable agriculture, we also identified a list of criteria used for evaluating and selecting indicators (Table S2) and applied these criteria in our indicator development process in later steps.

Second, under each of the environmental, economic, and social dimensions, we identified and discussed major aspects (e.g., water availability, pollution, labor productivity, market access, resilience, farmers' wellbeing) of agricultural impacts on sustainability based on literature reviews and experts' opinions.

Third, we identified and proposed relevant indicators and preliminarily matched them with the most relevant major aspects based on literature reviews of existing agricultural sustainability frameworks (e.g., Food Sustainability Index by Economist Intelligence Unit [EIU][20], Integrated Indicators for Sustainable Food Systems and Healthy Diets by EAT-SDSN-CGIAR [a joint effort from the EAT Initiative, UN Sustainable Development Solutions Network, and the Consultative Group for International Agricultural Research],[19] indicators of sustainable agriculture by the World Resource Institute [WRI],[18] FAOSTAT [Food and Agriculture Organization Corporate Statistical Database][27]) and experts' opinions.

Fourth, we evaluated these candidate indicators against the following criteria:

(1) Relevance to agriculture: to what degree the indicator is relevant to the impact of agricultural production in contrast to other human activities.
(2) Relevance to sustainability: to what degree the indicator is relevant to one dimension or a major aspect of sustainability.
(3) Performance or driver: whether the indicator is mainly considered as the performance (impacts) of the agriculture sector or the driver (the causes) for sustainable agriculture.
(4) KISS (keep it simple, stupid): to what extent the indicator has a simple and transparent definition. Indicators with simple and transparent definitions are preferred.
(5) Monotonic relationship: whether the indicator has a monotonic relationship with the major aspect of agricultural sustainability in general. For example, the amount of pesticide chemical use does not have monotonic relationship with the agricultural impacts on the environment, because not all pesticides are equally harmful for the environment and some may be used effectively with integrated pest management (IPM) systems, benefiting both the environment and agricultural productivity. This is one of the most important attributes in our list that is overlooked by many other frameworks. This attribute is important because the raw value of the indicator will be transformed to scores on a 0–100 scale, with higher values indicating greater sustainability, and then will be used for comparison among countries and tracking change over time.
(6) Data availability: to what extent are the data available across countries and years?

Fifth, based on the initial evaluation of the indicators, we selected indicators for SAM with the following principles:

(1) Each indicator assesses the impacts of agriculture on one major aspect of sustainability and its relationship with that specific aspect of sustainability must monotonic (i.e., criteria 1 and 2 were ranked as "high" and criterion 5 was evaluated as "yes").
(2) Each major aspect of agriculture sustainability should have at least one indicator, and the indicator should enable cross-country comparisons.
(3) The available data for the indicator should cover over 80 countries (covering the majority of agricultural production countries and global population) and preferably for more than 3 years.[59] The 3-year minimum requirement for data availability is preferred because the determination of a sustainable system requires at least 3–5 years of observations. The minimum indicator requirement of coverage of at least 80 countries is determined to ensure cross-country comparisons and experience sharing.
(4) Each of the major aspects is not over-presented and overwhelmed by many indicators with high correlation.[19]
(5) Performance indicators and indicators with simple and transparent definitions are preferred.

The following examples illustrate the process for selecting appropriate indicators for each of the major aspects of sustainable agriculture identified in step 2. For the health and nutrition major aspect, we initially proposed micronutrient deficiency, child stunting, and under-nourishment, but the first two of these potential indicators only measure a narrow aspect of a country's nutritional status (a violation of principle 5), so we decide to use only the third: prevalence of under-nourishment. After several rounds of iteration, there were still a few major aspects (e.g., rights, equality, and soil health) for which the best indicators had poor data coverage for countries and years. In order to make sure each major aspect has at least one indicator (principle 2), we compromised on the data availability principle (principle 3).

Sixth, a preliminary list of indicators was shared with experts within each of the environmental, economic, and social science expert groups, who discussed the pros and cons of the indicators (Notes S3–S5), defined the red and green thresholds, and discussed potential improvements. The green and red thresholds follow familiar traffic-light signals, are consistent with the planetary boundary concept proposed by Rockstrom et al.,[36] and are the boundaries that separate "safe operating space", "zone of uncertainty: increasing risk of impacts," and "dangerous level: high risk of serious impacts," respectively[37] (Figure S43A).

Seventh, we iteratively reviewed the major aspects and their indicators until the major agricultural impacts on sustainability had been accounted for, all principles for selecting SAM indicators were met to the best of our ability, and a consensus was reached among all experts who participated in the SAM development.

Design of report card and score calculation

Developed to measure environmental and socioeconomic performances of agriculture, SAM indicators have different units and values with different distributions and meanings for agricultural sustainability; therefore, it is very challenging to make comparisons among indicators using the raw values. To address this challenge, we designed a report card, as well as methodologies for score calculation, to provide an overview of agricultural sustainability for each country. The design of the report card (Figure 2) and scores focus on showing each indicator's relationship with the red and green thresholds for sustainability.

The report card includes three layers. The outer ring shows the performance of each indicator using a traffic-light color scheme (Figure S43A). The color of the indicator is determined by the relationship between the raw value of the indicator (e.g., the raw value of N surplus indicator is measured with a unit of kg N/ha/year) and the red and green thresholds determined for the indicator: if the value of the indicator falls between the red and green thresholds, the color of the indicator is yellow; if the value is outside of the range determined by the red and green thresholds, then the color of the indicator is determined by the color of the threshold that is closer to the indicator value; if no data are available, the indicator is shown in gray.

The score of each indicator is converted from the raw value of the indicator according to the following steps:

(1) Logarithmic transformations. To improve the consistency of value distribution among indicators, we first applied a logarithmic transformation to those indicators that did not have quasi-normal distributions.

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(2) Direction adjustments. In order to ensure the higher value of each indicator corresponds to more sustainable performance in that specific assessment theme, raw values of the indicator were multiplied by -1 for those indicators where higher raw values meant lower sustainability (e.g., higher N surplus values mean less sustainability, so they are multiplied by -1) (see details about the logarithmic transformation and direction adjustment for each indicator in Note S7 and Table S3).

(3) Score calculation. With adjusted raw values (Raw_{adj}) from the first and second steps, we performed a linear transformation considering that red and green thresholds correspond to the score 33 and 67 (i.e., one-third and two-thirds of the 0–100 score scale; Figure S43).

$$Score = \frac{33 * (Raw_{adj} - Red_{adj})}{Green_{adj} - Red_{adj}} + 33 \qquad \text{(Equation 1)}$$

Here, Red_{adj}, $Green_{adj}$ are the red and green thresholds adjusted following the same step 1 and 2 as the indicator; *Score* denotes the score value for each indicator after the linear transformation. This score design focuses on the relationships between the indicator values and the green and red thresholds. The design is inherently the same as the presentation of the planetary boundaries by Steffen et al.,[37] which scale the performance of each indicator with the upper and lower planetary boundaries. After the linear transformation, we set the score values that are lower than 0 or higher than 100 to 0 or 100, respectively.

The middle layer of the report card shows the aggregated score for each of the three dimensions, namely the environmental, economic, and social dimensions. The score for each dimension is the average score of all indicators with the dimension. The center of the report card is the overall score: the average of the scores for all three dimensions. This calculation method for the dimensional and the overall score has been used by indicator systems such as SDGs Index[60], Schmidt-Traub et al.,[61] and Xu et al.[62] While this aggregation method is imperfect, it provides a useful visual overview of the status of overall agricultural sustainability across countries. The values for each dimension and individual indicator are provided in Notes S3–S5 so that users may assign different weightings of indicators for their own aggregation purposes and preferences.

We performed a sensitivity analysis to test the potential fluctuations of each country's overall performance by randomly removing one to nine indicators. We found that, when removing up to three indicators from the aggregated score, one standard deviation of the score variation was smaller than 5 (for scores ranging from 0 to 100), confirming the robustness of the indicators of choice in SAM (see Figure S39).

Trade-offs and synergies analysis

We assessed the trade-offs and synergies among SAM indicators by examining their statistical relationships, using the adjusted raw values (Raw_{adj}) for each indicator after the logarithmic transformations and direction adjustments. To minimize the influence of potential outliers on the statistical analysis results, we bound the values for each indicator with the 5th and 95th percentiles of all available data for the indicator. Then, for each country and each pair of indicators, we applied Spearman's rank correlation analysis[63] to the historical records of SAM indicators. The Spearman analysis has been applied to examine trade-offs and synergies among indicators.[63] If a pair of indicators show a significant (i.e., Spearman correlation $p < 0.01$) positive correlation, it suggests a synergy between indicators, while a significantly negative correlation suggests trade-off.[28] This analysis was applied to 112 countries with high agricultural activities and influence (average harvested area >100,000 ha over 1961–2016; please see Note S11 for more details).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.08.015.

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AUTHOR CONTRIBUTIONS

X.Z. proposed the initial idea. X.Z. and E.A.D. obtained funding. X.Z., E.A.D., and K.P. led a 3-year project for developing SAM. All authors contributed to the conceptualization and development of SAM indicators, with C.D., E.A.D., and X.Z. leading the environmental dimension, A.M.K., D.R.K., G.Y., and M.M. leading the economic dimension, and K.P., F.G., P.D., and K.F.P. leading the social dimension. X.Z. and G.Y. led the collection of the data, designed the analyses, and wrote the initial draft. G.Y. led the data analyses and writings in economic and social dimensions. X.Z., S.V., and E.A.D. led the data analyses and writings in the environmental dimension. All authors reviewed, revised, and approved the final version of the draft.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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