Tracking global agricultural sustainability at the national scale

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SUMMARY

Agriculture is fundamental to all three pillars of sustainability, namely the environment, society, and the economy. However, the definition of sustainable agriculture and the feasibility of measuring it remain elusive. Independent and transparent measurements of national sustainability are essential to enable and encourage accountability and to contribute to evidence-based decision-making. Therefore, we developed a Sustainable Agriculture Matrix (SAM) to evaluate sustainability performance in agriculture and to investigate the trade-offs and synergies among performance indicators based on historical data for countries around the world. Results suggest that no country is free of concerns over agricultural sustainability, and the priority areas for improvement vary among countries. As their economies grow, most countries experience increasing environmental pressures from agricultural production, but some, mostly high-income countries, have shown promising signs of synergetic improvement in both socioeconomic (e.g., labor productivity) and environmental performances (e.g., soil erosion). While it is important to continue to improve indicator and data availability, it is also imperative to use existing indicators to inform policies and actions towards sustainable agriculture.

KEYWORDS

Sustainable agriculture, Indicators, Sustainable Development Goals, Environment, Agricultural policy

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 tradeoffs. To address multiple dimensions of agriculture's impacts, the concept of a Sustainable Agriculture Matrix was first introduced by Swaminathan[1]. It highlighted the multi-dimensional nature of sustainability and urged moving from a one-dimensional policy-making framework, such as increasing yields, towards coordinated thinking and actions among the social, economic, and environmental dimensions of sustainable agriculture.

Agriculture causes deforestation and biodiversity loss, contributes to about 90% of reactive nitrogen and phosphorus inputs from human activities to the Earth's biogeochemical cycles[2], accounts for 24% of anthropogenic greenhouse gas emissions[3], and is responsible for 90% of freshwater consumption globally[4]. Besides these acute environmental problems, many rural communities are suffering from social problems such as poverty, malnutrition, an aging population, and declining employment opportunities, even though the agricultural sector as a whole has become increasingly productive and hunger as significantly reduced worldwide[5]. Moving forward, agriculture is still facing the challenge of increasing productivity to meet growing societal demands for food, fiber, and energy. This challenge is further complicated by its potential impacts on diets and nutrition, climate change, and environmental degradation. Consequently, it is critical for countries and the world to develop an agricultural sector that is not only productive, but also nutritionally adequate, respectful to ecosystems and biodiversity, and resilient.

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. However, definitions of sustainable agriculture vary considerably[6]. Some 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)[1,6,7]. Nevertheless, there is a growing consensus on defining sustainable agriculture based on its impacts on the three pillars of sustainability, namely the environmental, economic, and social pillars[6]. Quantitative indicators are needed to examine the interactions between economic viability, social welfare, and environmental health within the context of sustainability for each pillar.

Independent and transparent assessments are essential to keep countries accountable for their commitment towards sustainable agriculture and to inform policy making, but few quantitative assessments are available to date. Since the ratification of the SDGs, an Inter-Agency and Expert Group has been established by the United Nations (UN) to develop the SDG indicators framework. 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 of the United Nations (FAO) 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. In addition to the UN's efforts, many in academia have developed models and indicators to assess the sustainability of food systems from national to global scales[8–10] and sustainable agricultural intensification on a farm scale[11]. 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 tradeoffs among these impacts. Some recent calls for monitoring agriculture worldwide have not yet resulted in actual datasets that enable trend assessments (e.g., Sachs et al.[12]). The lack of consistent quantification of agricultural sustainability across multiple dimensions hinders us from identifying undesirable tradeoffs of agricultural interventions and developing win-win solutions across multiple sustainability targets.

Consequently, inspired by Swaminathan's conceptual framework of a **Sustainable Agriculture Matrix** (SAM), we have developed a set of quantitative indicators to measure the sustainability of a country's agriculture across its environmental, social, and economic dimensions. Specifically, SAM is designed to assess a country's progress or lack thereof towards agricultural sustainability. To transform the illustrative concept of SAM to measurable indicators, we identify key aspects of sustainable agriculture for assessment within each dimension (environmental, economic and social), develop a list of indicators by synthesizing existing data from multiple sources and disciplines, and establish the rationales for a range of socioeconomic and biophysical indicators and their sustainability thresholds. Using our list of indicators, we provide an assessment, which is the first of its kind, for the agricultural sustainability of countries around the world at a national scale. We also analyze the synergies and tradeoffs among indicators within countries over time and discuss the policy implications of this assessment.

RESULTS

SAM indicators and thresholds

Recognizing that agriculture is deeply interconnected with other sectors (e.g., industry), we focus the SAM assessment on the direct impacts of agricultural production on the environment and economy, and broader impacts on the whole society (Figure 1). Specifically, from an ***Environmental*** perspective, sustainable agriculture avoids inefficient use of water resources, further loss of biodiversity from converting natural habitat to agricultural land, production of chemical elements that negatively affects local and regional water and air quality, emissions of greenhouse gases that disturb 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, and improving farmers' ability to manage risk. 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.

The 17 indicators selected for the SAM met most of the following criteria: relevance to one of the dimensions, conceptual or practical linkages to measurable aspects of sustainability, availability of data for the majority of countries and for more than three points in time, and uniqueness of information relative to other proposed indicators (Table 1; see the Experimental Procedures section for details on the methods of indicator selection; details about each indicator are described in Supplemental Information S.4 – S.6). As noted below, current data limitations did not permit inclusion of indicators covering some important topics and some indicators are not specifically developed only for agriculture. This set of 17 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.

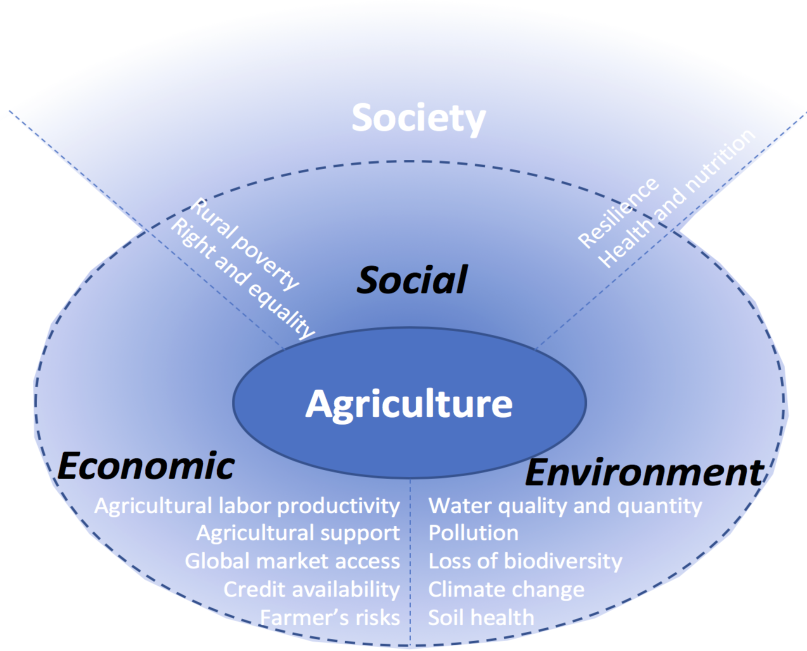

Figure 1. The scope of Sustainable Agriculture Matrix (SAM) assessment. The dashed circle indicates the boundary of direct and indirect impacts of agriculture. SAM assessment focus on agriculture's direct impacts on the environment and economics, as well as the direct and broader impacts on the society.

Table 1. A summary of the indicators included in the Sustainable Agriculture Matrix.

Major aspect	Indicators	Data sources	Green Threshold	Red Threshold	Units
Environmental Dimension					
Water availability	Sustainability of irrigation water consumption (SUSI)	Rosa et al.[14] and Rosa et al.[15]	1	2	km^3 total annual irrigation water/km^3 sustainable annual water use
Pollution	Nitrogen surplus (Nsur)	Zhang et al.[18]	52	69	kg N/ha/yr
	Phosphorus surplus (Psur)	Zou et al.[39]	3.5	6.9	kg P/ha/yr
Land use and loss of biodiversity	Land cover change due to agricultural activities (Lost forested area) (LCC)	Global Forest watch, Curtis et al.[40]	0	0.0053	ha deforested/ha cropland area/yr
Climate change	Total GHG emission from agriculture activities per harvested area including pastureland (GHG)	FAO[41]	0.86	1.08	ton CO_2eq/ha
Soil health	Soil Erosion (SER)	Borrellie et al.[42]	1	5	ton/ha
Economic Dimension					
Agricultural labor productivity	Agricultural GDP per agricultural worker (AGDP)	Derived from World Bank (WDI)[43]	7946	460	2011 US$ PPP
Agricultural support	Government agricultural expenditure per agricultural worker (AEXP)	Agricultural expenditure data, IFPRI[44] and FAO[41]; agricultural worker , derived from WDI [9]	2405	25	2011 US$ PPP
Market access	Total agricultural export values as a percentage of agricultural GDP (TROP)	Trade data, UN Comtrade[45]; Agricultural GDP, World Bank WDI[43]	71	17	%
Credit availability	Access to finance for farmers (A2F)	EIU [24]	100	25	Score
Farmer's risks	Crop price volatility (PVOL)	Derived from FAO[41]	0.10	0.23	-
Social Dimension					
Farmers' wellbeing	Rural poverty ratio (RPV)	World Bank[43]	2	13	%
Equality	Global gender gap report score (GGG)	World Economic Forum[46]	0.8	0.7	Score
Farmers' rights	Land rights (LRS)	LandMark[47]	3	2	Score
Health and nutrition	Prevalence of undernourishment (UDN)	FAO[41]	0	7.5	%
Resilience	Crop production diversity (H index)	Calculated following Seekell et al.[26]	48	22	Counts
	Food affordability (RSE)	Seekell et al.[26]	100	30	%

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: "red" thresholds indicate high risks of undesirable environmental, economic, or social impacts; while "green" thresholds suggest an acceptable sustainability target. Between those thresholds is a "yellow" zone, where outcomes may be approaching a sustainable or unsustainable level. The score for each indicator is designed so that higher values indicate more sustainable outcomes. The SAM framework on a national scale shares several similarities and key differences with the assessment framework at farm-scale developed by FAO[13] (Figure. S1).

More specifically, the ***environmental dimension*** includes six indicators (Table 1), measuring the impacts of agricultural production on major environmental concerns. Those environmental concerns, with the exception of soil erosion, correspond to proposed planetary boundaries that are heavily influenced by agricultural activities, including freshwater use (measured by sustainability of irrigation water consumption; SUSI)[14,15], human disturbance to nitrogen (N) and phosphorus (P) cycles (measured by N surplus and P surplus: Nsur and Psur), land system change and biodiversity loss (measured by deforestation due to agricultural activities: LCC), and climate change (measured by greenhouse gas emissions from agriculture activities: GHG)[8,16,17]. Consequently, the definition of these indicators and their thresholds align with the planetary boundary literature with some modifications to permit country-level assessments and cross-country comparisons (e.g., the use of N surplus in Zhang et al.[18]).

Although not included in the planetary boundary framework, the soil erosion indicator (SER) 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 a 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 five 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 (measured by the access to financing indicator; A2F) and price support from the government (measured by the government expenditures on agriculture as a percentage of agricultural GDP; AEXP), which potentially help farmers and agribusinesses lower their costs and increase their innovative capacities. From a benefit perspective, the economic dimension evaluates farmers' labor productivity (measured by agricultural GDP per agricultural worker; AGDP), farmers' openness to trade (measured by agricultural export revenues out of agricultural GDP, a modified version of trade openness index; TROP) and their exposure to crop price volatility (measured by weighted average coefficient of variation of crop prices; PVOL).

In contrast to the environmental indicators, the limits for most of the economic indicators are not widely acknowledged, and consequently it is difficult to define thresholds consistently across countries. As an alternative, we identified the 75th and 25th percentile of existing values for four of the economic indicators across all countries in all years (with higher values indicating greater sustainability, see SI for details) as the green and red thresholds[19–23]. In this approach the indicator values beyond the 75th percentile indicate likely sustainable practices, while the values below the 25th percentile are likely unsustainable. Among the five economic indicators only A2F determines the thresholds according to its definition, where countries with easy access to financing options for farmers are considered sustainable, while those with limited or absent multilateral or government financing programs are especially unsustainable[24].

The ***Social dimension*** includes six indicators (Table 1), measuring agriculture's direct impacts on farmers' livelihood and broader societal impacts. These include farmers' wellbeing (measured by Rural Poverty Ratio: RPV), farmers' rights (represented by Land Right Security index from Land Mark: LRS) and equality (represented by Global Gender Gap: GGG). 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[25]. Although multiple indicators exist for health and nutrition, we report prevalence of undernourishment (UDN), because it provides an effective measure of the first condition for achieving food security: that of adequate calorie availability and consumption. However, UDN is limited in measuring overall health and nutrition status (see Supplemental Information S.4.14 for additional rationale for selecting the UDN indicator).

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. 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: RSE), 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; RSH)[26].

Similarly 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 (See Supplemental Information). Where the thresholds are difficult to identify, such as crop production diversity (RSH), we employed 25^{th}-75^{th} percentile as benchmarks as done for economic indicators, to define the red and green thresholds. The thresholds for socioeconomic and environmental indicators help to provide an initial outline of the “safe and just space” for agriculture production[27].

Tracking progress

Here we assess countries’ agricultural sustainability from the three dimensions and track their performance over time. The SAM evaluation for a selection of eight countries is presented as examples from different income groups (i.e., high-, upper-middle-, lower-middle and low-income countries, based on thresholds of gross national income per person)[28] (Figure 2). We pick two countries with high total agricultural GDP (average of 2010–2014) within each income group, which covered all continents except for Antarctica. The evaluations of SAM indicators for all 213 countries or regions we studied are available in Supplemental Figures.

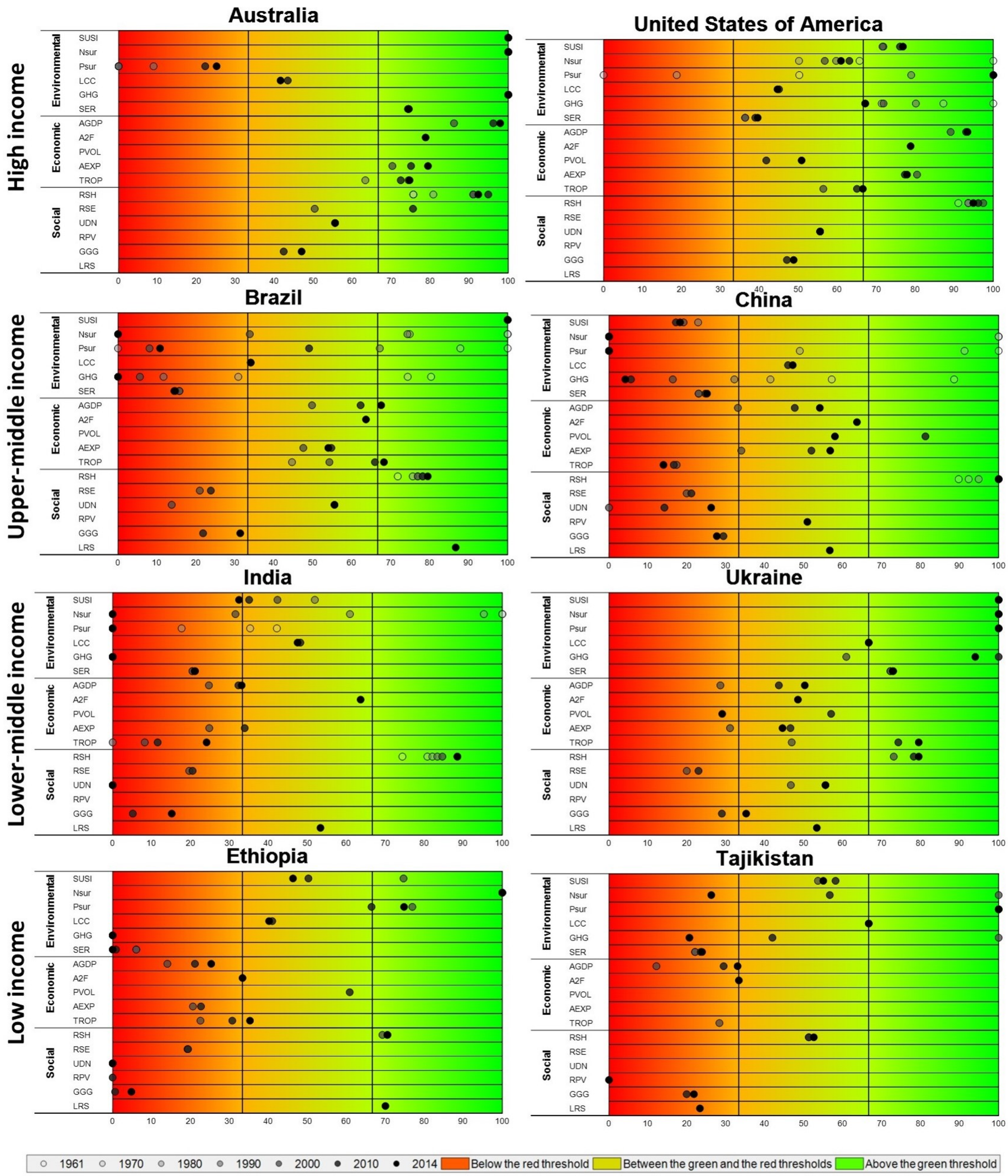

Figure 2. The trajectory of performance in sustainable agriculture for two representative countries in each of our income classes: high-income, upper-middle-income, lower-middle-income, and low-income countries. Each row records the performance of a SAM indicator. The position of the circle is determined by the score of an indicator for a given country in a given year. Indicators are converted to 0-100 scale with 33 and 67 corresponding to the red and green thresholds (See score calculation subsection under the section of experimental procedures). The gray scale dots indicate the year for which the indicator score applies, allowing visualization from 1961 (light gray) to 2014 (dark gray).

A country's performance in the economic dimension of SAM is generally positively related with its income level (e.g., measured by per capita GDP): most economic indicators show improvement as income grows. Unsurprisingly, a larger fraction of high-income countries has achieved the sustainable targets (the "green zone") for the economic dimension compared to 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 eight example countries from different income groups follow this pattern. Considering individual indicators in the economic dimension, countries with higher income levels tend to have agriculture of higher labor productivity, greater profitability (higher AGDP), more agricultural support (AEXP), and better access to credit and markets (A2F and TROP). Crop price volatility (PVOL), however, affects farmers' income stability regardless of countries' income level (Supplemental Information Figure S20).

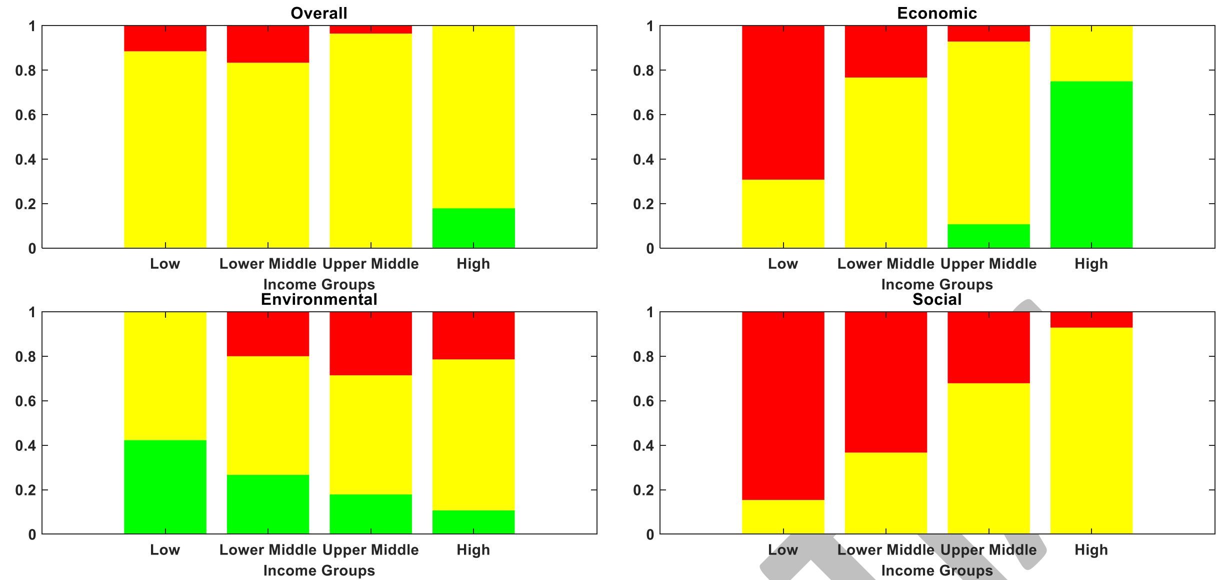

Figure 3 Dimensional fractions of all countries in sustainability performance category by income group. From the upper left to the lower right, the four panels display the overall, economic, environmental, and social dimensions. Each panel displays four groups of countries in each bar: high-income, upper-middle-income, lower-middle-income, and low-income countries [28]. The green, yellow, and red patches in each bar denote the percentage of countries in each zone: “safe operating zones” (overall score > 67), “zone of uncertainty: the increasing risk of impacts”, “dangerous level: high risk of serious impacts” (overall score < 33), respectively. Please see Figure S2 for each indicator’s performance by income group.

The performance of most social indicators corresponds to their stage of economic development. But no country, including those in the high-income group, has achieved the sustainable targets for all indicators in the social dimension (Figure 3). Countries with higher incomes tend to perform better regarding low-income households’ food affordability (RSE), gradually eliminating rural poverty (RPV), better gender equality (GGG), and decreasing the percentage of the population that is undernourished (UDN). However, even high-income countries, such as Australia and the United States, have not eradicated undernourishment, which may be further aggravated due to unexpected social events such as the COVID-19 pandemic. Ethiopia has made great progress in eliminating undernourishment in past decades (Figure 2), but the country’s UDN is still higher than the red threshold. Globally, gender inequality (GGG) is still a major issue for sustainability, although it appears to be more acute in low- to middle-income countries. The land right index (LRS) is contingent on each country's historical protection of community land rights policies.

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 (Figure 3). Adverse environmental impacts vary among countries due to the differences in their natural resources and agricultural practices. Environmental concerns are especially acute in rapidly developing middle-income countries. For example, all environmental indicators for China and India have moved to the red zone during the period of 1961-2014, except land cover change (the LCC indicator, Figure 2). Even countries in the low-income group, such as Ethiopia and Nepal, 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 improving trends for some environmental indicators, such as N and P pollution, and soil erosion. However, the P pollution indicator is still in the red zone for Australia and several indicators including N pollution 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 counted for the importing country. In other words, countries, especially those in the high-income group, can potentially improve their environmental performance by adjusting the domestic production portfolio towards more environmental-friendly and profitable products, or by importing more agricultural or food products[29,30].

Sustainability state of agriculture

An overview of the sustainability of agriculture around the world suggests that no country has achieved sustainability thresholds for all indicators or in all three dimensions (environmental, economic and social, Figure 4). Each country has at least one dimension and multiple indicators that require further improvement. The SAM report card in Figure 4 highlights the priority area for a country to improve its agricultural sustainability. For example, middle-income countries (e.g., Brazil, China, and India) and densely-populated countries (e.g., South Korea and Japan) face great environmental challenges. Many high-income countries with relatively small agricultural land area or relatively homogeneous climate face challenges of crop production diversity (e.g., Iceland and UK), and most high-income countries must urgently lower their GHG emissions from the agricultural sector (e.g., Finland, France, UK, and Greece). Lower-middle-income and low-income countries located in South Asia, 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 (Figure S3).

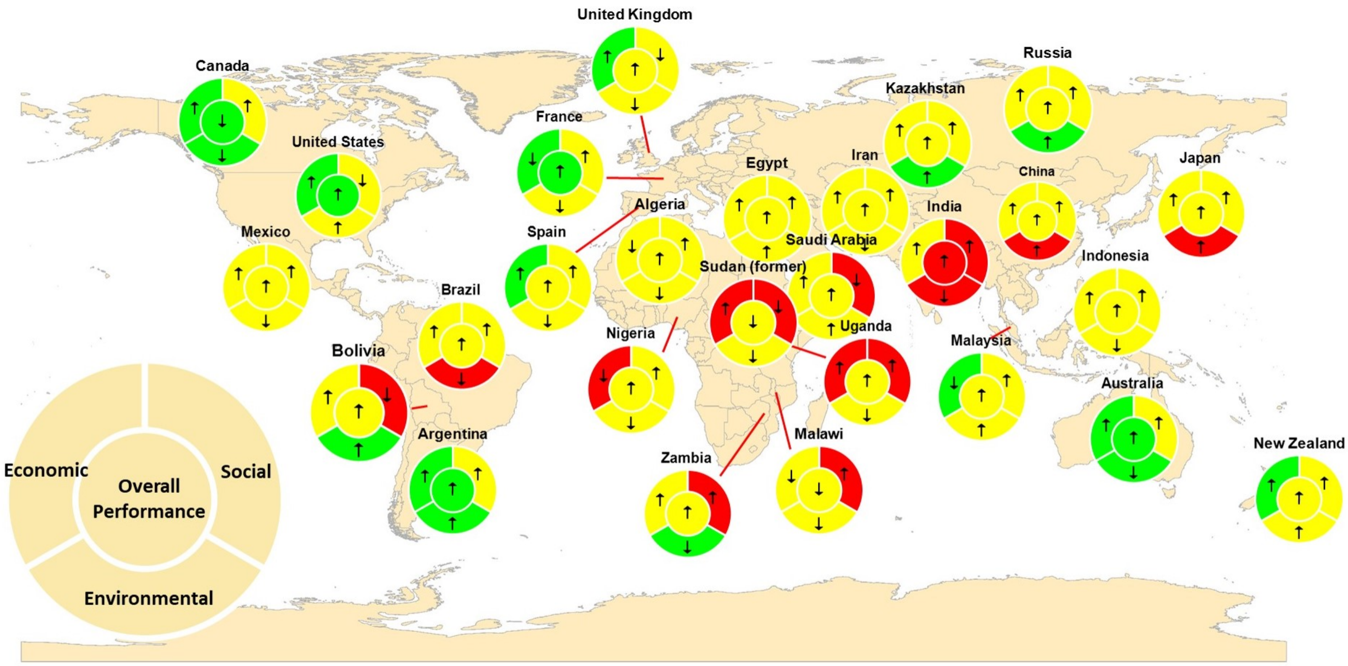

Figure 4. The SAM report card of agricultural sustainability for selected countries around the world. Each country is assessed with a dashboard panel, including the dimensional (i.e., environment, social, and economic dimensions of sustainability; outer ring) and overall performance (center of the panel) evaluation of agricultural sustainability. The arrows in each panel denotes the trends between year 2010-2014. We apply the same traffic color scheme as in Figure 3. Please see Supplemental Information for each indicator's sustainability performance in each dashboard panel for each country.

Tradeoffs and synergies among SAM indicators

Given the complex nature of agricultural systems and the multi-dimensional concerns of sustainability, one change in agriculture (e.g., implementing a new technology or a new policy), may lead to multiple impacts across the three sustainability dimensions, and consequently, some of the performance indicators may improve and others may decline. Therefore, understanding the tradeoffs and synergies among indicators is critical for policy makers to craft strategies towards sustainability[31,32]. Based on the historical records of the SAM indicators, we investigated the tradeoffs and synergies among indicators in each country (Figure 5), where statistically significantly (Spearman correlation $p < 0.01$) positive (or negative) correlations between a pair of indicators' time series indicates a synergy (or tradeoff)[31]. While these statistical relationships between indicators do not imply direct causal linkages, they provide an indication of the tradeoffs and synergies in a multi-target system with complex dynamics, and they can help to identify tradeoffs that are not yet well recognized.

The tradeoff and synergy analysis of the SAM indicators indicates complex relationships among the different sustainability concerns, and those relationships are not necessarily consistent among countries. As shown in Figure 5, none of the indicator pairs shows only tradeoffs 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 background, and different compositions and efficiencies of their agricultural system. While the tradeoff and synergy relationships warrant investigation for each country case, the following three general patterns by income groups can be observed across countries (Figure 5).

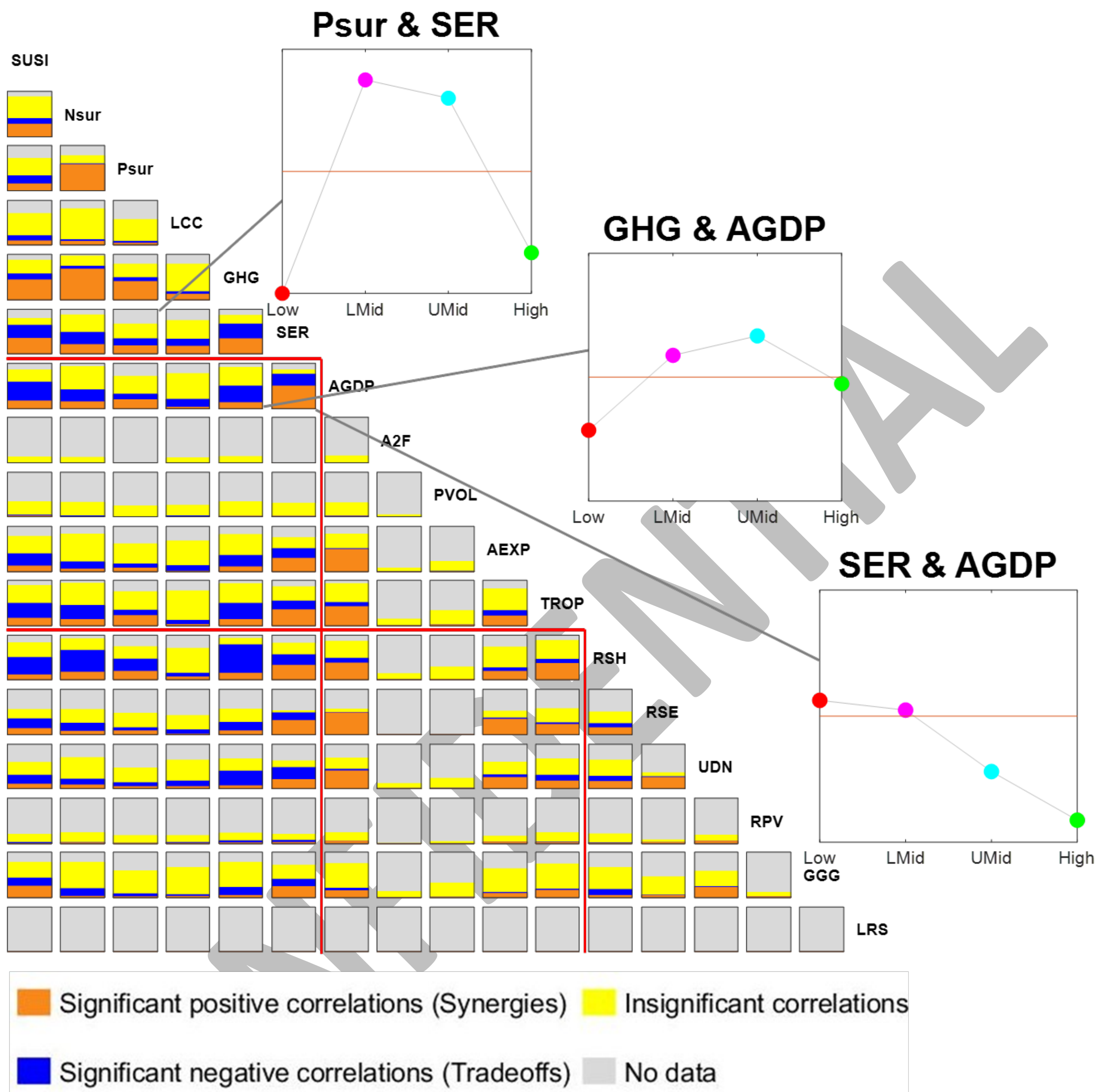

Figure 5. An overview of synergies and trade-offs between SAM indicators based on their performance scores. The abbreviations of the indicators are on the diagonal of the panel. The definition of the acronyms is in Table 1. In the main panel, the height of each colored bar is determined by the fraction of countries are in synergy (orange; significantly positive Spearman's correlation between indicators, p-value < 0.05), trade-off (blue; significantly negative Spearman's correlation between indicators, p-value < 0.05), or insignificant relationship (yellow; the correlation coefficient is either zero or insignificant); the remaining area in the box indicates no-data (light grey). The three small panels present the percentage of significant tradeoff relationships out of total significant synergetic and trade-off relationships in each of the income groups, namely low-income (Low), lower-middle-income (LMid), upper-middle-income (UMid), and high-income (High). The orange line is the 50% trade-off line, above which the dots indicate trade-off dominant relationships and below which the dots represent synergetic dominant relationships.

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 (Nsur), P surplus (Psur), and greenhouse gas emissions (GHG), suggesting these environmental impacts tend to worsen (or improve) concurrently in most countries. Land cover change (LCC), on the other hand, does not have significant relationships with most other indicators in the environmental dimension. Soil erosion (SER) shows either tradeoff 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 tradeoff relationships involving SER compared to low- and high-income countries, suggesting some middle-income countries have started to see reduced soil erosion while other environmental indicators continue to worsen (e.g., the panel for Psur & SER in Figure 5; see Figure S4 for relationships between SER and other indicators).

2) Trade-offs dominate the relationships between most environmental and socio-economic indicators, and such relationships are correlated with economic development levels (Figure 5 and Figure S4). The high-income group has the highest fraction of countries showing synergetic relationships between AGDP and all environmental indicators (except LCC) compared to other income groups, indicating that more high-income countries have managed to increase their agricultural productivity with less pollution and resource depletion. Similar patterns were observed in the relationships between other socioeconomic indicators and environmental indicators.

Compared to other environmental indicators, soil erosion (SER) shows a more synergetic relationship with AGDP (e.g., in Figure 5, the fractions of countries showing tradeoffs in the panel for SER & AGDP are lower than in the panel for GHG & AGDP), as well as most other socioeconomic indicators, and the fraction of synergetic 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. The eight example countries help to illustrate this pattern (Figure 2).

3) Not all social indicators increase along with economic indicators. Surprisingly, increases in agricultural expenditure (AEXP) and trade openness (TROP) are not accompanied with undernourishment (UDN) reduction in many countries (Figure 5); a few countries even show a positive correlation between UDN and AGDP over the study period (2000 – 2016). This lack of synergies may indicate a combination of factors including cheaper agricultural imports increasing undernutrition by depressing the income of rural households who may not have access to them[33] as well as the result of domestic policies that favor the expansion of export crops at the expense of smallholder farmers[34]. 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 tradeoffs and synergies.

DISCUSSION

An indicator system to inform actions

The Sustainable Agriculture Matrix provides the first of its kind quantitative assessment of agricultural sustainability for countries around the world, providing timely inputs for tracking countries' progress towards their SDGs commitment 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 from their own 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 to environmental models, 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 assessment of sustainable agriculture by SAM over time also provides the opportunity to better understand the tradeoffs 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"[35]. The tradeoff and synergy analysis based on SAM assessment demonstrates the major tradeoffs between economic (including agricultural productivity) and environmental dimensions of sustainability, especially for low- and middle-income countries and for most environmental indicators. It is among the first to provide a quantitative view of the tradeoffs and synergies among multi-dimensions of agricultural sustainability for countries around the world at the country scale.

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 overtime, and it is theoretically feasible for nearly all countries to move above the 25th percentile when current performance is compared to 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 complimentary 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 requires all indicators moving toward their respective sustainability targets. Consequently, it demands collaboration across government agencies and stakeholders. During the development of SAM, we have 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.

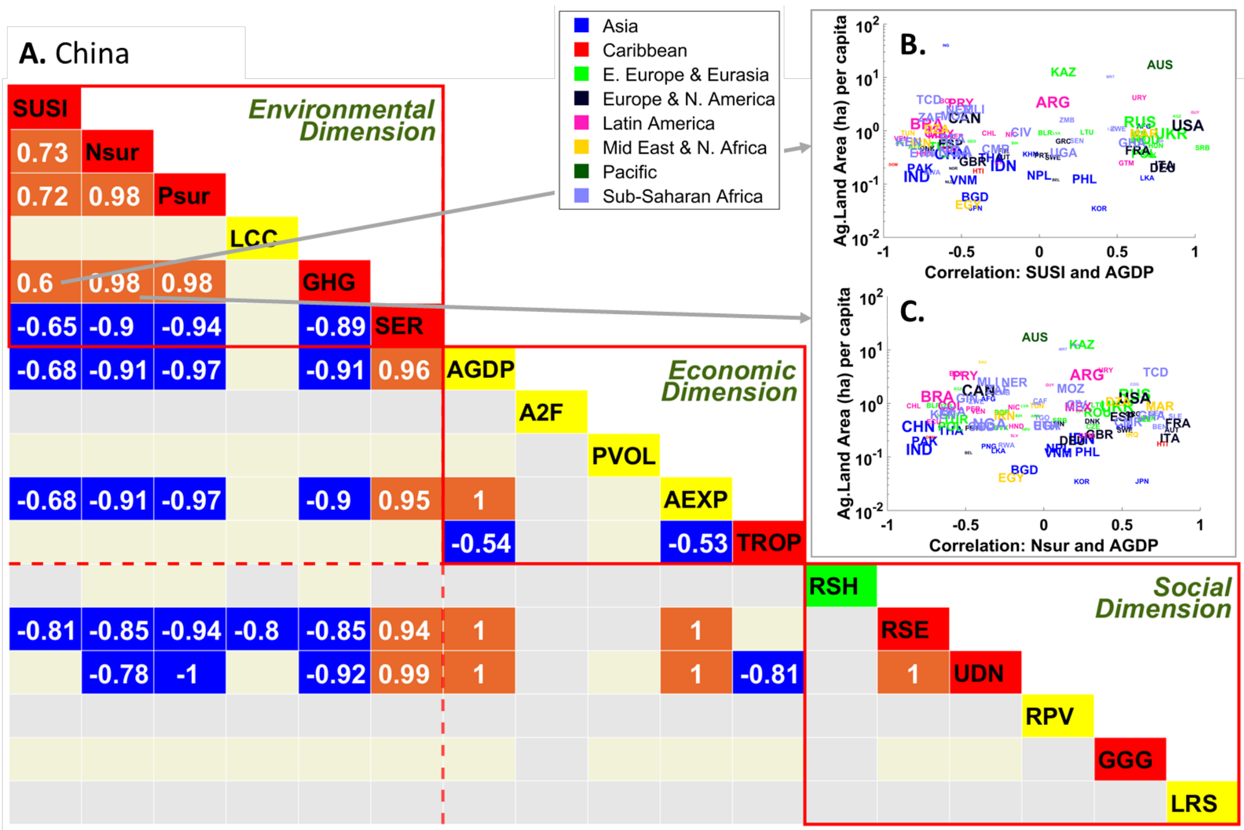

Figure 6 An example of using SAM indicators to explore differences in trade-offs and synergies within and among countries. Panel A. shows the performance of each indicator and their interactions in China. The background colors of the boxes in the diagonal are determined by the indicator performance for the most recent years (2010-2014) using the traffic light color scheme as in Figure 2. The red color indicates high urgency for taking actions. The colors of remaining boxes indicate the synergies (orange, significantly positive) and tradeoffs (blue, significantly negative) between indicators. Light yellow denotes insignificant relationships, and grey 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. Panel B shows the correlation between AGDP and SUSI and panel C shows the correlation between AGDP and Nsur for all countries. Countries (noted with three letter abbreviation based on ISO code) on the right suggest synergetic relationships while countries on the left suggest tradeoff 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.

3) The tradeoffs among indicators highlight necessary changes needed in the current agricultural system, in order to enable synergies for each country. For example, the dominating tradeoff relationships between environmental and economic dimensions in China suggests that current intensification approaches relying on intensive input use (e.g., irrigation water and mineral fertilizer) need to be transformed towards resource-efficient approaches. This change could help to relax the tradeoffs between those environmental indicators and agricultural productivity (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 tradeoffs between agricultural GDP per agricultural worker and the environmental indicators of N surplus and irrigation water use, France and the USA show synergies for these relationships (Figure 6B,C). While China and France have similar agricultural land use pressure (measured here by the agricultural land area per capita shown on the Y axis of Figure 6B,C), France managed to improve agricultural GDP per agricultural worker and reduce N pollution and unsustainable irrigation water use through adopting more resource-efficient technologies and implementing regulations on N use (positive correlations shown on the X axis of Figure 6B,C, while China shows negative correlations).

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 a global coverage. In order to arrive at the first set of SAM indicators, compromises had to be made to accommodate this lack of data. For example, the Land rights indicator (LRS) only has data for one year, but it is included in SAM because it provides measurement for one critical aspect of sustainable agriculture, and few other indicators provide both spatial and temporal coverage better than LRS. 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 (e.g., Nsur, Psur, GHG, and RSH) include data since 1961, some (e.g., SUSI, LCC, SER, AGDP, and TROP) have data since the 1990s, 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[12].

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[36], 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[37]. 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 in the Supplemental Information.

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 to 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; 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 regional heterogeneity in available resource (e.g., the SUSI 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

Overall, we have developed a first-of-its-kind indicator system to systematically assess country-level performances in sustainable agriculture across environmental, social, and economic dimensions, and multiple critical indicators within each dimension. The broad spatial and temporal coverage of the assessment enables a comprehensive view of the state of agricultural sustainability around the world, and an understanding of the tradeoffs and synergies among multiple sustainability targets. So far, no single country has achieved the sustainability target for all indicators, and the priorities for improvement differ among countries. Tradeoffs between economic and environmental performances in agricultural production are prevalent for many countries, indicating that systemic changes would be needed for countries to transition towards decoupling economic growth from environmental degradation. Examples of country-level synergistic, win-win-win relationships among environmental, economic, and social dimensions of agriculture need to be further investigated and communicated as possible lessons that could be adapted to other national contexts. While continuous improvement in indicator design and data availability is necessary, the broad application of SAM promises better informed and coordinated actions toward sustainable agriculture.

EXPERIMENTAL PROCEDURES

The development of SAM indicators

Based on the major three dimensions of sustainable agriculture, we identified a range of indicators that have already been defined and quantified (Table S1). We then selected or developed indicators for each key aspect based on the following criteria:

1) Each indicator assesses the impacts of agriculture on one major aspect of sustainability and its relationship with sustainability is generally monotonic.
2) The indicator should be mainly considered as the "performance" (or the impacts) of agriculture sector, instead of the "driver" for sustainable agriculture.
3) The indicator should have a clear and transparent definition.
4) 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[38].
5) While correlations among indicators can be informative, preferred indicators are not so highly correlated that two indicators appear to provide redundant information about the same conditions within each of the three dimensions

6) Each major dimension (Table 1) should have at least one indicator.

Data availability, the fourth principle, is one of the major constraints for selecting and developing indicators. 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. However, we had to compromise on this principle for selecting indicators for "rights and equality" and "soil health", because indicators that provide reasonable measurement of these major aspects have very limited data coverage for countries and years. In this case, we compromised on the data availability principle to make sure each major aspect has at least one indicator for assessment (the sixth principle).

Score Calculation

The SAM framework and the score transformations follow the rule of higher values indicating more sustainable agriculture. Before score calculations, we systematically transform all the raw values to make sure the values from low to high reflect the gradients of agricultural sustainability improvements. Logarithmic transformation is employed for some of the indicators to improve the assumption of normality, linearity, and homogeneity of variances (see Supplemental Information S.7 for more details about the raw value transformations).

With transformed raw values, two score calculation methods are used in this analysis: normalization method and threshold transformation method. In the normalization method, we establish upper and lower bounds using 95th and 5th percentiles and all variables are normalized to a scale of 0-100:

$$\text{Normalization Score} = \frac{x - min\ (x)}{max(x)\ - min\ (x)} \times 100$$

In the threshold transformation method, we map lower and upper thresholds as score 33.33 and 66.67 and other values are linearly transformed into scores ranging from 0-100 (scores lower than 0 and higher than 100 are bounded at 0 and 100, respectively).

$$Threshold\ transformation\ Score = \frac{33.33 * (Raw - Lower)}{Upper - Lower} + 33.33$$

$$or\ \frac{33.33\ (Raw - Upper)}{Upper - Lower} + 66.66$$

Supplemental Information S.8 provides additional details of score transformations.

In SAM analyses, we employ normalization scores to analyze the trade-offs and synergies of pairwise indicators and use the threshold transformation scores to track each country's agricultural sustainability performance with respect to the green and red thresholds.

Data and Code Availability

All datasets analyzed in this study are publicly available as referenced within the article or in the supplementary information.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation CNS-1739823 and by the National Socio-Environmental Synthesis Center (SESYNC) under funding received from the National Science Foundation DBI-1639145. The authors acknowledge all participants of Sustainable Agriculture Matrix workshops sponsored by SESYNC.

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 three-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 proved the final version of the draft.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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