Measuring sustainable agriculture on a national scale

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Abstract

The ratification of Sustainable Development Goals (SDGs) by all member countries of the United Nations demonstrates the determination of the international community in moving towards a sustainable future. To enable and encourage accountability, independent and transparent measurements of national sustainability efforts are essential. Among all sectors, agriculture is fundamental to all three pillars of sustainability, namely environment, society, and economy. However, the definition of a sustainable agriculture and the feasibility of measuring it remain elusive, in part because it encompasses both biophysical and socio-economic components that are still poorly integrated. Therefore, we have been developing a Sustainable Agriculture Matrix (SAM) on a national scale in order to measure country-level performance in agriculture. First proposed by Swaminathan for agricultural research and policy in 1990s, SAM is a collection of indicators measuring sustainable agriculture from environmental, social, and economic dimensions (Table 1). Specifically, from an Environment perspective, sustainable agriculture reduces unsustainable use of water resources for agricultural production, further loss of biodiversity from converting native habits to agriculture, production of forms of pollution that affect local and regional water and air quality, and emissions of greenhouse gases, and it maintains or improves 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 capacity, providing farmers access to market and credits, reducing farmers' risks. From a Social perspective, sustainable agriculture improves farmers' wellbeing, respects farmers' rights, promotes equitable opportunities, and benefits the whole society with enhanced system resilience and improved health and nutrition. Translating the illustrative concepts into measurable indicators will not only provide an independent and transparent measurement of national performance in the sustainability of agriculture production, which is at the center of Water-Energy-Food nexus, but also provide timely information to help guide evolving national policies regarding agriculture, trade, environment, and national security.

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INTRODUCTION

Agriculture is fundamental to society because it provides food and energy to support people's livelihood, and is a source of income and employment for the rural community. However, the pursuit of higher agricultural productivity to feed the growing and increasingly affluence world population has been accompanied by exacerbating environmental and social problems. Agriculture is the major driver of deforestation, contributes to about 90% of nitrogen and phosphorus inputs to the earth system, accounts for 13% greenhouse gas emissions (Russell 2014) , and is responsible for 70% of fresh water consumption (OECD 2019). Besides those acute environmental problems, many of the world rural communities are suffering from social problems such as poverty, aging population, and lack of opportunities, even though the agricultural sector became increasingly productive. Moving forward, agriculture is still facing the challenge of increasing productivity to meet the growing societal demands, but this challenge is unprecedented given the impacts of climate change and aggravating environmental degradation. Consequently, it is critical for countries and the world to develop an agriculture sector that is not only productive, but also sustainable and resilient.

Sustainable agriculture has been explicitly included as one of the Sustainable Development Goals (SDGs), which were ratified by all member countries of the United Nations (UN) in 2015, but the definition of sustainable agriculture has been very diverse in literature (Hayati 2017). Depending on the stakeholder priorities, and the spatial and temporal scales that the definition will be applied to, the definitions of sustainable agriculture have very different foci: while some consider sustainable agriculture as a set of management strategies (Hayati 2017), others define sustainable agriculture as an ideology or a set of specific goals (Hayati 2017; FAO 2018a; Swaminathan 1990). But there has been increasing consensus on defining sustainable agriculture based on its impact on the three pillars of sustainability, namely environment, economic, and social (Hayati 2017). Consequently, focusing on the agriculture sustainability on a national scale, this paper considers sustainable agriculture provides economic profitability and social welfare without sacrificing environmental quality (Figure 1).

To make countries' commitment towards sustainable agriculture accountable and to inform policy making, independent and transparent assessments are essential, but few quantitative assessments are available to date. Since the ratification of SDGs, an Inter-Agency and Expert Group has been assembled by United Nations (UN) to develop indicators to measure the performances of countries, and the indicator that emerged in the final list for measuring sustainable agriculture was the "SDG2.4.1: *Proportion of agricultural area under productive and sustainable agricultural practices*." This indicator has recently been upgraded to Tier II, where clear definition and methodologies have been established; but the data for this indicator remain scarce (Campbell et al. 2019); the methodologies, building on farm surveys, may suffer from the lack of consistency in defining and measuring sustainability among regions. In addition to UN's efforts, many efforts have been made by academia to develop matrices or indicators to assess the sustainability of the food system on national to global scales (Springmann et al. 2018; Béné et al. 2019; Chaudhary, Gustafson, and Mathys 2018) and sustainable agricultural intensification on a farm scale (Musumba et al. 2017). But few 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, and analyzing the synergies and tradeoffs among those impacts.

Consequently, we develop a **Sustainable Agriculture Matrix** (SAM), a set of indicators, to measure a country's agriculture sustainability from environment, social, and economic dimensions. Specifically, SAM is designed to assess progress or lack thereof due to the impacts of national or international efforts. The terminology of Sustainable Agriculture Matrix first appeared as an illustrative concept for agricultural research and policy in 1990 (Swaminathan 1990), and it highlighted the multi-dimensional nature of sustainable agriculture and urged moving from a one-dimensional policy-making framework towards coordinated thinking and actions among different dimensions of sustainable agriculture. To develop the illustrative concept of SAM to measurable indicators, we coordinated a highly interdisciplinary team of scientists to identify key aspects of sustainable agriculture for assessment within each dimension, establish the rationales for a range of socioeconomic and biophysical indicators and their sustainability thresholds, and develop a list of indicators by synthesizing existing data from multiple sources and disciplines. Using this initial list of indicators, we provide the first of its kind assessment for the agriculture sustainability of most countries around the world, analyzed synergies and tradeoffs among indicators under the existing agricultural production systems, and discussed the policy implications of this assessment.

RESULTS

SAM Indicators and thresholds

Recognizing that the agricultural sector is deeply interconnected with other parts of society, we focus the SAM assessment of environmental and economic dimensions on the direct impacts of agricultural production on the environment and economic profitability; while the social dimension concerns both the direct impacts on farmers and rural community and the broader impacts on the society, such as health and nutrition (Figure 1). Specifically, from an ***Environment*** perspective, sustainable agriculture reduces unsustainable use of water resources for agricultural production, further loss of biodiversity from converting native habits to agriculture, production of forms of pollution that affect local and regional water and air quality, and emissions of greenhouse gases, and it maintains or improves 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 capacity, providing farmers access to market and credits, reducing farmers' risks. From a ***Social*** perspective, sustainable agriculture improves farmers' wellbeing, respects farmers' rights, promotes equitable opportunities, and benefits the whole society with enhanced system resilience and improved health and nutrition.

Through multiple rounds of iteration among coauthors and other experts on sustainable agriculture, a final list of 17 indicators have been selected or developed as the first edition of SAM (see the Experimental Procedures section for the methods of indicator selection and Table 1 for the final list; details about each indicator are described in Supplementary Information Section 1). To enable cross-comparison among indicators and to identify priorities for improvement, we defined the "red" and "green" thresholds: the "red" threshold indicates a high risk of environmental, economic, or social destruction; while the "green" thresholds indicates an acceptable sustainability target. The score for each indicator is designed in the way that higher values indicate more sustainable. It is worthwhile to note that, even though developed independently, the SAM framework on a national scale shares lots of similarities with the assessment framework on farm-scale developed by FAO (FAO 2018b).

More specifically, the ***environmental dimension*** includes six indicators (Table 1), measuring the impacts of agricultural production on major environmental concerns on national to global scales. Those environmental concerns, except soil erosion, correspond to the planetary boundaries that are heavily influenced by agricultural activities, including freshwater use (measured by Sustainability of irrigation water consumption), human disturbance to nitrogen (N) and phosphorus (P) cycles (measured by N surplus and P surplus), land system change and biodiversity loss (measured by deforestation due to agricultural activities), and climate change (measured by greenhouse gas emission from agriculture activities) (Springmann et al. 2018, Rockstrom et al. 2009, Steffen et al. 2015). Consequently, the definition of these indicators and their thresholds align with the planetary boundary literatures with some modifications to adapt to country-level assessment and inter-country comparison (e.g., the use of N surplus in Zhang et al., (2015)).
Even though not included in the planetary boundary framework, the soil erosion indicator (SER) provide an initial country-scale assessment of soil health, one major aspect of agricultural impacts on the environment. While this indicator does not reflect all concerns of soil health, it is the only

indicator with data available on a global scale by country and for multiple years.
Admittedly, agriculture production has other environmental impacts that are not measured by those six indicators (e.g., the pollution caused by pesticide use), but 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 for farmers and agricultural business considering both agricultural production costs and benefits.. From the cost perspective, the economic dimension measures farmers' access to financing options (A2F) and agricultural supports from the government which potentially help them to lower the costs and increase their innovative capacities (AEXP). From the benefit perspective, the economic dimension evaluates farmers' labor productivity (AGDP), famers' ability to sell their products to markets (TROP) and the potential risks they face (PVOL).
In contrast to environmental indicators, there have not been have widely acknowledged physical limits for economic indicators, 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 each indicator (with higher values indicating greater sustainability, see SI for details) as the green and red thresholds (Hartzmark and Sussman 2018; Chen 2019; Ghosh and Wolf 1998; Roulin 2007; Stanojevic, Laoutaris, and Rodriguez 2010). This approach assumes that the indicator values beyond the 75th percentile indicate sustainable, while the values below the 25th percentile are not sustainable. Among the five economic indicators only A2F determines the thresholds according to its definition, where economies with deep access to financing options for farmers are considered safely sustainable, while those with limited or absent multilateral or government financing programs are hazardously unsustainable (EIU 2018).

The ***Social dimension*** includes six indicators (Table 1), measuring agriculture's direct impacts on farmers' livelihood and broad impacts on the entire society. The direct impacts include farmers' wellbeing (measured by Rural Poverty Ratio, RPV), farmers' right (represented by Land Right index from Land Mark, LRS) and equality (represented by gender equality, GGG). While these indicators cannot comprehensively cover all aspects of wellbeing, right, and equality, they are the indicators represent the important aspects of farmers' livelihood and are with sufficient data.
The impacts of agricultural production on health and nutrition are profound, but often convoluted with culture, dietary choice, and other socioeconomic and physiological factors. Multiple indicators have been considered for this important aspect of agriculture sustainability. UDN is selected for this version of SAM since it provides an effective measure of the first condition for achieving food and nutrition security, that of adequate calorie availability and consumption; but admittedly, it is limited in measuring the health and nutrition status (see Supplement Information for detailed rational for selecting the UDN indicator). More data and indicator development is needed to improve the assessment of agricultural impacts on health and nutrition.
Agriculture is fundamental for the food system resilience, which measures the ability that the food system adapt to external disruptions and provide stable food to its citizens. The food system resilience has been measured from three perspectives: socio-economic access to food in terms of income of the poorest quantile relative to food prices, biophysical capacity to intensify or expand food production, and the magnitude and diversity of current domestic food production (Seekell et al. 2017). Since the second perspective has been covered in the SAM environmental dimension, we therefore include their first and third perspectives as the food system resilience indicators under

the social dimension.
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 (See Supplementary Information). For indicators of which the thresholds are difficult to identify, such as crop production diversity (RSH), we applied the 25th-75th percentile approach, the same as what we use for economic indicators, to define the red and green thresholds.

Tracking the progress

The first edition of SAM indicators provides an initial assessment of a country's agricultural sustainability from multiple dimensions and enable tracking the 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) and climate (e.g., temperate and tropical climate; Figure 2). These countries are the ones with the highest agricultural land area within each of the income and climate groups. The evaluations for all 218 countries are available in Supplementary Information.

A country's performance in the economic dimension of SAM is generally consistent with its income level (e.g., measured by per capita GDP) and most economic indicators show improvement as income grows. Greater shares of high-income countries have achieved the sustainable targets (the "green zone") for the economic dimension comparing to the other income groups; while the share of countries fall 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 coincide with this pattern. Considering individual indicators in the economic dimensions, countries with higher income levels tends to have more productive and profitable agriculture for farmers (higher AGDP), more agricultural support (AEXP), and more access to credit and market (A2F and TROP). But crop rice volatility (PVOL) does not display a strong income correlations.

The performance of most social indicators is in sync with the economic development, but no country has achieved the sustainable targets for the social dimension even in the High income group (Figure 3). Countries with higher income levels tend to perform better in increasing its low-income households' food affordability (RSE), gradually eliminating rural poverty (RPV), better gender equality (GGG), and declining the percentage of their undernourished population (UDN). However, even the high-income countries, like Australia and the United States, have not eradicate the undernourishment problem, and some high-income countries are at high risks of UDN. China, Ethiopia, and Nepal have made great progress in eliminating undernourishment in past decades, but their current nutrition status is still alarming. Globally, the inequality between genders (GGG) is still a major issue for agriculture sustainability despite countries' income levels; and it appears to be more acute in countries with low to middle income. As female plays an important role in agricultural labor force and households nutrition access, improving GGG will likely to help these countries to eliminate rural poverty and malnutrition. Agricultural LRS in different groups of countries are contingent on their histories of land rights revolutions, and does not have obvious relationship with the income level.

The performance of environmental indicators declines with economic development, but the shares of countries that fall in the red zone are similar in the High- and the Upper Middle- income groups, consistent with the Environmental Kuznets Curve (EKC) hypothesis. Despite the income level or the climate condition, all countries have one or more adverse environmental concerns caused by agricultural production, and such concerns vary among countries due to the abundance of their natural resources and agricultural practices. Environmental concerns are especially acute in fast-developing middle income countries. For example, all environmental indicators for China and India have moved to the red zone except LCC. Even countries in the Low income group, such as Ethiopia and Nepal, have been experiencing increasing environmental risks such as high greenhouse gas emissions and degrading soil health. In contrast, some countries in the High income group, such as Australia and the United States, have demonstrated improving trend in some environmental indicators, such as N and P pollutions, and soil erosion; but continuous improvement is needed. For example, 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.

The states of agriculture sustainability

An overview of the agriculture sustainability around the world suggests that not a single country achieves sustainability thresholds for all indicators or in all three dimensions, namely environment, economic and social (Figure 4). Each country has at least one dimension and multiple indicators that need further improvement. The SAM report card 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., China, India, and Japan) face great challenges from their environmental dimensions. Lower-middle-income and low-income countries located in South Asia, Middle-East and Sub-Saharan Africa need to eliminate their rural poverty, improve food affordability and nutrition provision status in low-income households.

Tradeoffs and synergies among SAM indicators

Given the complex nature of agriculture 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, and consequently, some of the performance indicators may improve and some may decline. Therefore, understanding the tradeoffs and synergies among indicators are critical for policy makers to craft strategies towards sustainability (Pradhan et al. 2017; Nerini et al. 2018). Based on the historical records of the SAM indicators, we investigated the tradeoffs and synergies among indicators considering a significantly positive (or negative) correlation between a pair of indicators indicate synergy (or tradeoff) ((Pradhan et al. 2017); Figure 5).

The tradeoffs and synergies analysis of the SAM indicators demonstrates complex relationships among different sustainability concerns of the agriculture system, and those relationships are not necessarily consistent among countries. As shown in Figure 5, none of the indicator pairs show 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 efficiency of their agricultural system. While the tradeoffs and synergies relationships warrants investigation for each country case, several general patterns could be observed across countries.

1) Within each of the environmental, socio, and economic dimensions, indicators do not necessarily show synergies among each other, suggesting the improvement in one indicator does not necessarily guarantee the improvement in the other even they both 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); however, land cover change (LCC) has insignificant relationships with most other indicators in the environmental dimension, and soil erosion (SER) shows similar amount of countries for tradeoff or synergy relationships with the rest of the environmental indicators.

2) Both synergies and trade-offs exist between indicators from environmental and economic dimensions and such relationships are influenced by income levels. The trade-off between AGDP and SUIS, Nsur, Psur, LCC and GHG dominate middle-income and low-income groups and becomes strongest in the upper middle-income group. Some high-income countries have synergetic environmental performance with their economic developments, verifying the positive roles of economic development has brought to environmental condition improvements. In particular, soil quality display the most synergetic correlations with AGDP compared to other environmental indicators especially in high income and upper-middle-income groups. Stronger synergies in the high-income group and dominant trade-offs in middle and lower income groups are also observed for other economic indicators, such as AEXP and TROP. The eight example countries help to validate the pattern. The relationship between environmental and social dimensions follow a similar pattern: dominant trade-offs in middle and low income groups and more synergetic relations in high-income countries.

3) Not all social indicators increase with the improvement in economic indicators. It is alarming that a fraction of countries have even shown degrading trends in malnutrition and rural poverty even with increasing AGDP and agricultural supports (trade-offs). The relationships between gender equality, resilience, and the economic performances of SAM are mostly insignificant. Therefore, one should not assume the social performances of agricultural production improve with the economic performances automatically.

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Table 1 A summary of indicators included in the SAM.

Major Theme to assess	Indicators	Data sources	Green Threshold	Red Threshold	Units
Environmental Dimension					
Water availability	Sustainability of irrigation water consumption (SUSI)	Rosa et al. (2018) and Rosa et al. (2019)	1	2	km^3 total annual irrigation water/km^3 sustainable annual water use
Pollution	Nitrogen surplus (Nsur)	Zhang et al. (2015)	52	69	kg N/ha/yr
	Phosphorus surplus (Psur)	Zou et al. (in prepare)	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. (2018)	0	0.0053	ha deforested/ha cropland area/yr
Climate change	Total GHG emission from agriculture activities per harvested area including pastureland (GHG)	FAOSTAT	0.86	1.08	ton CO_2eq/ha
Soil fertility and soil health	Soil Erosion (SER)	Borrellie et al. (2013)	1	5	ton/ha
Economic Dimension					
Agricultural labor productivity	Agricultural GDP per agricultural worker (AGDP)	Derived from World Bank (WDI)	7946	460	2011 US$ PPP
Agricultural support	Government agricultural expenditure per agricultural worker (AEXP)	Agricultural expenditure data, IFPRI and FAO; agricultural worker，derived from WDI	2405	25	2011 US$ PPP
Market access	Total agricultural export values as a percentage of agricultural GDP (TROP)	Trade data, UN Comtrade; Agricultural GDP, WDI	71	17	%
Credit availability	Access to finance for farmers (A2F)	EIU	100	25	Score
Farmer's risks	Crop price volatility (PVOL)	Derived from FAOSTAT	0.10	0.23	-
Social Dimension					
Farmers' wellbeing	Rural poverty ratio (RPV)	World Bank	2	13	%
Rights and equality	Global gender gap report score (GGG)	World Economic Forum	0.8	0.7	Score
	Land rights (LRS)	Land Mark	3	2	Score
Health and nutrition	Prevalence of undernourishment (UDN)	FAOSTAT	0	7.5	%
Resilience	Crop production diversity (H index)	Calculated following Seekell et al. (2017)	48	22	Counts
	Food affordability (RSE)	Seekell et al. (2017)	100	30	%

Figure

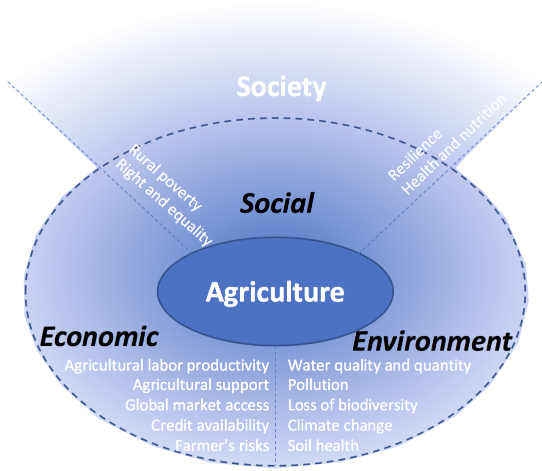

Figure 1 Framework of the SAM. Agriculture is the foundation of the society, therefore has broad impacts on the society as a whole. The dashed circle indicates the boundary of direct and indirect impacts of agriculture

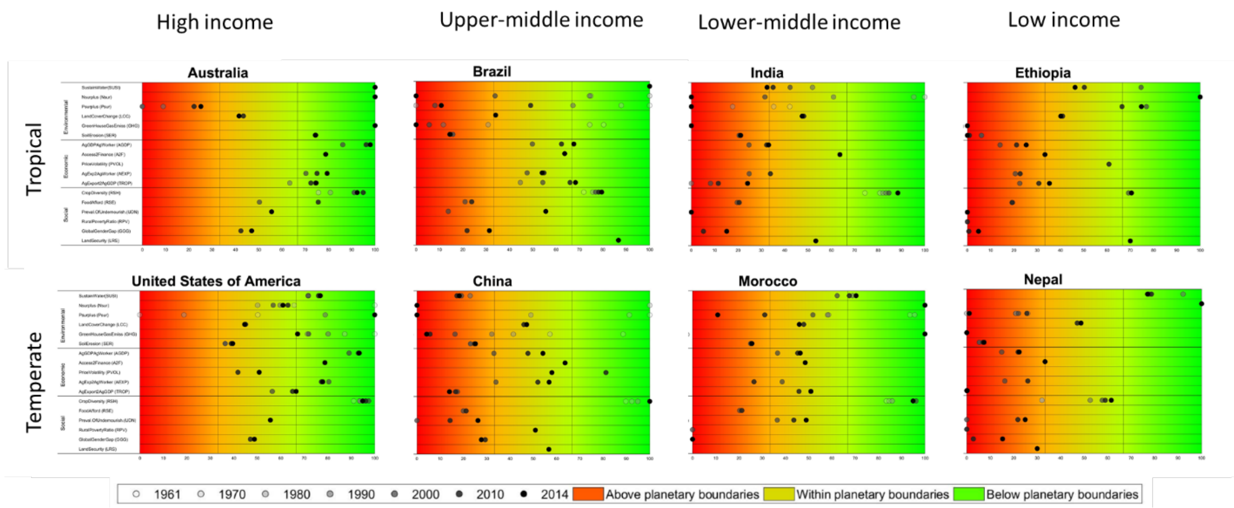

Figure 2 The trajectory of a country's performance in sustainable agriculture. Each row records the performance of a SAM indicator. The position of the circle is determined by the score of an indicator for a given country in a given year. Scores lower than 33.33 represented by red gradient backgrounds indicate performance blow the red threshold and at high risks. Scores between 33.33 and 66.67 represented by yellow gradient imply sustainability performance within red and green thresholds and at increasing risks. Scores above 66.67 represented by green gradient mean sustainability performance above the green thresholds and within safe operating zones.

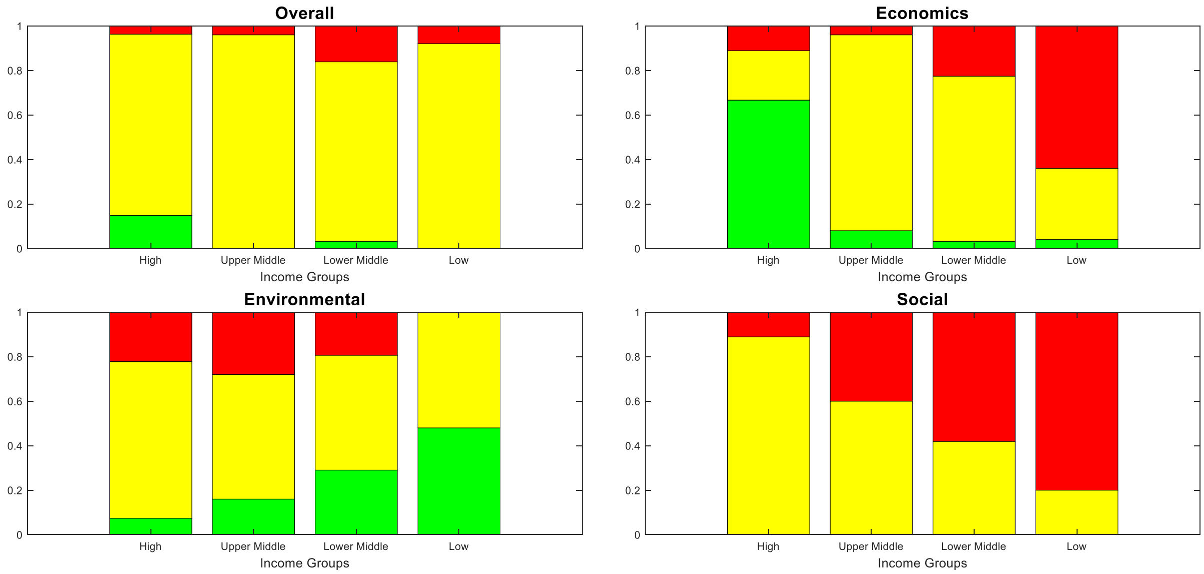

Figure 3 Dimensional percentage of countries in sustainability performance category by income group. From the upper left to the lower right, the four panels display the overall, economic, environmental, and social dimensions. Each panel display four groups of countries in each bar: high-income, upper-middle-income, lower-middle-income, and low-income countries. The green, yellow, and red patches in each bar denote the percentage of countries in each zone: "safe operating zones" (overall score > 66.67), "zone of uncertainty: the increasing risk of impacts", "dangerous level: high risk of serious impacts" (overall score < 33.33), respectively.

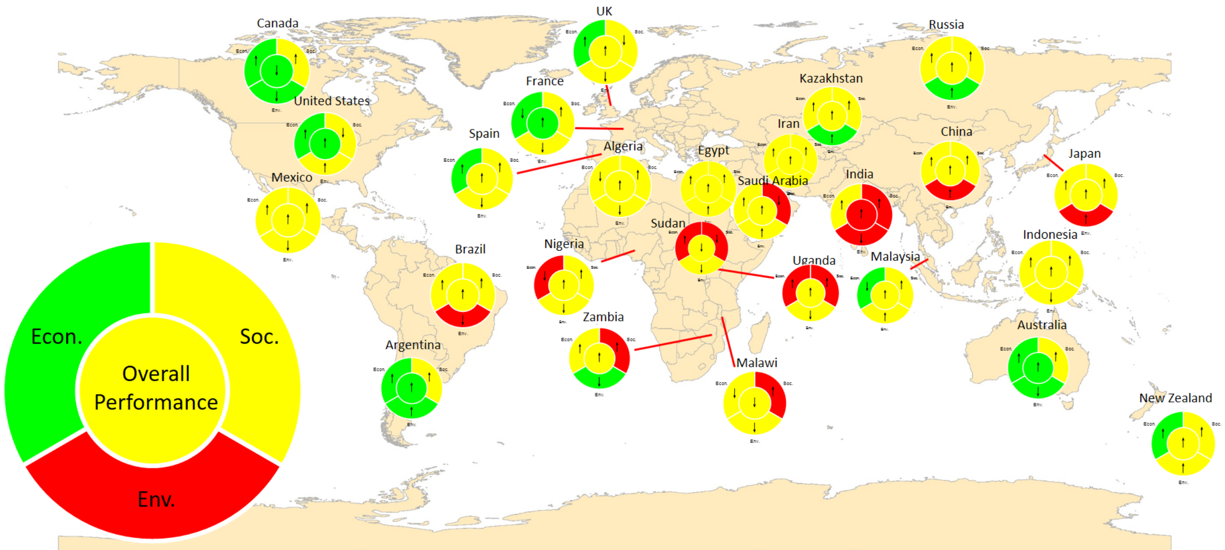

Figure 4 The SAM report card of agricultural sustainability for selected countries around the world. Each country is assessed with a dashboard panel, including the dimensional (i.e. environment, social, and economic dimensions of sustainability; outer ring) and overall (center of the panel) evaluation of agriculture sustainability. The arrows in each panel denotes the trends between year 2010-2014. The traffic color scheme is selected to indicate the urgency for taking action: the red color indicates the average dimensional/national performance is below the red threshold (average score < 33.33), and the sustainability is at a "dangerous level: high risk of serious impacts." The yellow color denotes the dimensional /national performance is between the red and green thresholds (33.33 < average score < 66.67), and the sustainability is at a "zone of uncertainty: the increasing risk of impacts." The green color shows dimensional/national performance above the green thresholds (average score > 66.67) representing "safe operating zones." Due to the lack of availability of the data in social dimensions, sustainability performance of the social dimension is biased towards indicators that have more data available.

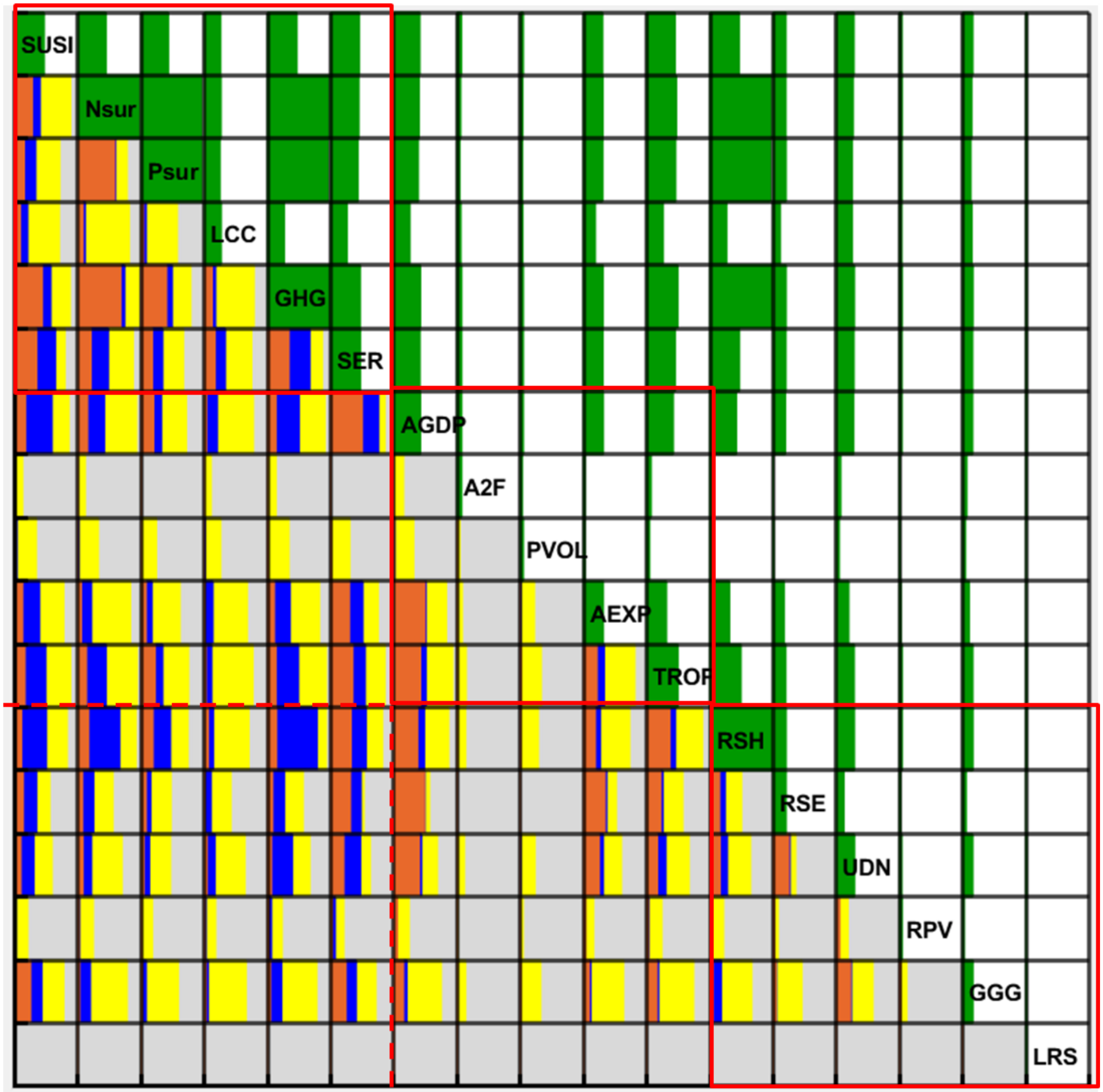

Figure 5 An overview of synergies and trade-offs between SAM indicators based on their performance scores (0-100, higher score indicates more sustainable). The abbreviations of the indicators are on the diagonal of the panel, and the green area of those boxes indicate the data availability for each indicator. In the lower left section of the panel, the colored bars present the synergies (orange; significantly positive Spearman's correlation between indicators, p-value < 0.05), trade-offs (blue; significantly negative Spearman's correlation between indicators, p-value < 0.05), unclassified (light yellow; the correlation coefficient is either zero or insignificant); the remaining area in the box indicates no-data (light grey). The green color bars in the upper right side of the panel represent the availability of data for each pair of indicators.

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