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Chapter 4

Modeling Sustainable Nutrition Security

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Abstract. Sustainability considerations should be an integral component of food security assessments. Nourishing the expected global population of nine billion in the face of fast diminishing land and water resources and looming climate change has tremendous economic, environmental, and social implications. Furthermore, whereas much past work on food security had focused on feeding the world through more staple crop calories, the current emphasis is on nourishing the global population through the provision of a more nutrient-rich diet. Hence the focus on micronutrient deficiencies (so-called 'hidden hunger'), dietary diversity, and the nutrient density of the food supply – all critical components of overall nutritional status. To aid future assessments of 'sustainable nutrition security', we need a new methodology and some novel assessment metrics and tools. Seven metrics are proposed, each based on a combination of multiple indicators, for use in characterizing sustainable nutrition outcomes of food systems: (1) nutrient adequacy of foods and diets; (2) ecosystem stability; (3) food affordability and availability; (4) sociocultural wellbeing; (5) food safety; (6) resilience; and (7) waste and loss reduction. Each of the metrics comprises multiple indicators that are combined to derive an overall score (0-100). The metrics can be combined with simulation models and then deployed by decision-makers and investors to set meaningful goals, track progress, and evaluate the potential impact of targeted food system interventions. The goal is to improve food system sustainability and resilience and to improve human nutrition and health outcomes.

Keywords Food systems; nutrition security; modeling methodology; metrics; sustainability outcomes; dietary quality outcomes.

4.1 Introduction

The world's food systems are under escalating pressure to deliver nutritious and sustainably-produced food in the face of multiple threats, including human population growth, rapid urbanization, dwindling resources, and degraded ecosystems [1]. About 1 billion people lack sufficient food [2] and about 2 billion people suffer from a number of micronutrient deficiencies [3]. Paradoxically, more than 2 billion adults are overweight [4], of whom 500 million are obese [5]. These stark challenges to food systems and nutrition security cast an even more ominous shadow when they are considered in the context of intensifying extreme weather and climate change. The fifth assessment report from the United Nations Intergovernmental Panel on Climate Change (IPCC) highlighted the effects of changes in climate and water availability on crop yields, the resulting spikes and volatility in food prices and likely food shortages [6]. The US Third National Climate Assessment report detailed additional food security threats through effects on food processing, storage, transportation, and retailing [7]. To this

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was added a special report, prompted by recent extreme weather events, such as drought, wildfire, storms and flooding [8]. General public concern around food sustainability issues is growing.

Adapting food systems to global warming and water shortages is a daunting challenge. In currently dry regions, drought frequency will likely increase [6]. On-going climate change means that all areas are likely to suffer more frequent episodes of severe drought, with potentially devastating impacts on food security [9]. Although there is still much uncertainty in climate model predictions [10], a number of identified geographically-specific 'hotspots' are likely to be most affected [11]. The most vulnerable regions are those where water supply is highly variable, including both severe water scarcity [12, 13] and flooding risk [14]. Crop irrigation will become an ever more essential adaptation strategy [15]. However, there are many important food production regions where irrigation will not be viable in the long term, due to depletion of aquifers and reduced glacier- and snow-melt [16].

The overall net effect of climate on crop yields, commodity prices, and food availability is assessed through the use of so-called 'integrated models,' [17-19], capable of linking climate [20], crop [21], and economic [22] models. The science of integrated modeling, which has advanced rapidly in recent years, is now being increasingly used to assess alternative adaptation and mitigation scenarios and to test potential interventions in local, regional and global food systems. However, the underlying models being used in these assessments are often based on insufficient data. Further, model assumptions have not always been fully tested across different food systems that are critical to food and nutrition security. As a result, estimates can vary widely. Yield reductions due to climate change of more than 25% have been predicted for important grain crops [21]. These impacts on crop yields translate into effects on prices, land use conversion, and total food production. Net impacts on global food prices through year 2050 are estimated through the integrated models to range from negligible to price increases of more than 60% [22].

Agricultural innovations have played a role in adapting to climate change by boosting production, keeping food costs down, and thereby improving food security [23]. Sustainable intensification can help to close yield-gaps, defined as the difference between observed and theoretical crop yields. It can also contribute to climate mitigation, by significantly reducing the carbon footprint of food production. For instance, reducing global maize yield-gaps to the levels achieved in the US would produce an additional 335 MMT of maize grain [24]. Countries such as the US are also generally achieving higher levels of eco-efficiency, as measured by per-unit of production greenhouse gas emissions and the utilization of land, water, and energy [25]. These same countries are seeing their eco-efficiency levels increase more quickly than is the case in countries not pursuing a sustainable intensification strategy. During the first decade of the 21st century, high-intensification countries saw eco-efficiency increases in four major row crops: canola (26%), cotton (23%), maize (17%), and soybeans (18%). In stark contrast, low-intensification countries had no change in eco-efficiency during this same ten-year period [25].

The principal challenge to food systems is to integrate the 'productionist' supply side with the evolving food demand, made more complex by the nutrition transition. Our research center (CIMSANS, the Center for Integrated Modeling of Sustainable Agriculture and Nutrition Security) recently assembled a broad array of diverse private- and public-sector scientists with expertise across the different parts of the overall food system to discuss these issues: experts in agriculture, nutrition, sustainability, and modeling [26]. They described a vision to produce a comprehensive, globally integrated modeling methodology to describe how nutrients are produced, processed and consumed – in order to determine the fundamental role that food systems play in providing for 'sustainable nutrition security' (SNS). Several of these same researchers subsequently published a set of seven food system metrics for use in the assessment of SNS [27]. The primary purpose of this chapter is to describe these seven metrics and show how they may be used to assess SNS.

However, before proceeding further, it is important to distinguish between food security and nutrition security. Food security has been defined by the Food and Agriculture Organization (FAO) as the state or condition wherein:

All people, at all times, have physical, economic and social access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life [28].

Nutrition security is a much broader concept, as underscored by a recent Lancet series [29]. These two elements are brought together in the prevailing definition of food and nutrition security (FNS):

All people at all times have physical, social and economic access to food, which is safe and consumed in sufficient quantity and quality to meet their dietary needs and food preferences, and is supported by an environment of adequate sanitation, health services and care, allowing for a healthy and active life [30].

The concept of FNS has now been extended to sustainable nutrition security (SNS) by adding the traditional dimensions of sustainability: economic, environmental, and social. Evaluating and eventually enhancing SNS requires the establishment of science-based and decision-relevant metrics that make it possible to categorize and compare different assessment and intervention scenarios [31]. Rather than considering food production only, an overall 'food systems' approach includes the food consumption side and the various strategies involving the food value chain and consumer behavior that are also potential targets for modification [32, 33].

4.2 Metrics for Characterizing Sustainable Nutrition Security

An initial set of SNS metrics was developed as part of a consensus report by a number of nutrition, climate change, food system, and economic experts representing a range of public and private institutions [26]. The present metrics can help to assess progress toward the Sustainable Development Goals (SDGs). Composite metrics can be composed of multiple indicators using a variety of algorithms. Indicators can be defined as quantitative or qualitative factors that capture system changes following an intervention in a simple and reliable manner. Indicators, in turn, are derived from multiple variables, with data collected through modeling or direct field observations.

The metrics, and their component indicators, were further refined at the ILSI RF workshop by a broad set of stakeholders from government, academia, and industry [34]. The seven chosen metrics were: (1) nutrient adequacy of foods and diets; (2) ecosystem stability; (3) food affordability and availability; (4) sociocultural wellbeing; (5) resilience; (6) food safety; and (7) waste and loss reduction [27]. These metrics were selected due to their importance as measures of the overall food system and its impact on human health, as well as its influence on social, economic and environmental sustainability. A key guiding principle in the development of the metrics was to avoid needless creation of new metrics or indicators when suitable ones already existed in the literature or in the community of practice. Another guiding principle was that the metrics should be based upon open data. Accordingly, literature reviews were conducted for each of the seven metrics to identify valid and reliable open data related to each metric and to develop appropriate indicators. After thorough evaluation, descriptions of individual metrics were sent to a range of topical experts for further review. The metrics were then given a final review by a larger, broad group of stakeholders from academia, governmental agencies, and the private sector (see Acknowledgements).

Each of the metrics and indicators was scored from 0 to 100, with higher values desirable. Various systems have been proposed for weighting indicators. However, based on stakeholder feedback, it was decided to apply equal weighting to indicators. Developing a method for quantifying each indicator on a scale of 0-100 was a challenge. In certain cases, a third party had already published an indicator scaled in this manner. Those were directly used as indicators. In other cases, the indicator itself was defined as a percentage, readily convertible to a 0–100 scale. Other indicators had a finite range of possible values, and could be scaled by simply applying a constant multiplicative factor. More challenging, however, were indicators which did not have a bounded range of possible values, such as

Greenhouse Gas Emissions (GHGs) or Land Use. In these cases, a logarithmic equation was used to derive a 0-100 score [see 27]. The equation has a series of desirable characteristics. It has a score of 100 for the hypothetical case of no emissions/use, a score of 50 for median performance (e.g. during a specified baseline year), it asymptotically approaches a score of 0 as emissions/use increase, and it generates a normal distribution of scores if the underlying data are log-normally distributed (as is typically the case).

4.2.1 Nutrient adequacy of foods, diets and the food supply

A literature review and consultation with a series of nutrition experts resulted in the selection of the following five Food's Nutrient Adequacy indicators: Non-Staple Food Energy, Shannon Diversity, Modified Functional Attribute Diversity, Nutrient Density Score, and Population Share with Adequate Nutrients. One potentially relevant indicator has been developed – the Healthy Eating Index [35]; however, this indicator is specific to the United States, having been developed to measure compliance with that country's Dietary Guidelines. It is also worth noting that these particular indicators focus on the adequacy of national food system nutrient levels to meet dietary requirements for essential nutrients, and therefore do not specifically address over-consumption at unhealthful levels or other nonlinear effects. The first four of the chosen indicators refer to food availability for an average consumer in the country of interest, and the fifth refers to the percentage of the population with dietary intake of specified food nutrients above certain thresholds. As such, the last indicator requires the collection of actual dietary data at the individual level, as well as estimates of inter-individual variation in dietary intake. All five of these indicators have recently appeared in the literature, and there are data available at the country level [36-38].

4.2.2 Ecosystem stability

A food system cannot be considered sustainable unless its underlying resource base is sustained and it has neutral or positive impacts on important ecosystem services. These overall impacts are characterized using the Ecosystem Stability metric, with an indicator that quantifies the current status of ecosystems (Ecosystem Status) [39], together with a group of indicators based on the notion of eco-efficiency – with higher scores for food systems that have lower per capita environmental impacts.

Robust quantitative approaches for describing the environmental impact of agricultural production systems (pre-farm gate) have been developed [40, 41], but system boundaries for the analysis must be significantly expanded to include post-farm gate activities in order to quantify the overall impact of the food system on the environment. An example of such an approach using Life Cycle Assessment (LCA) modeling for a number of particular foods was recently reported by a multi-partner collaborative effort, the World Food LCA Database [42]. Based on current global data availability and previous LCA modeling work [25], four eco-efficiency indicators are specified: GHG Emissions, Net Freshwater Withdrawals, Non-Renewable Energy Use, and Land Use, all on a per capita basis. When applied at the national level, these indicators refer to all food system activities that take place within that country's borders, except for the GHG emissions and non-renewable energy use associated with movement (though not the production) of exported food, which are both allocated to the ultimate importing country.

All eco-efficiency metrics should be calculated using the accepted principles of LCA as specified in an appropriate International Organization for Standardization (ISO) standard, such as ISO 14040 [43]. As explained in the ISO standards, indirect effects and other forms of so-called 'consequential' LCA (comparing current realities to hypothetical counterfactuals) can be used if properly documented. However, for the sake of simplicity, the definitions and example calculations provided in this chapter use the more traditional form of LCA, known as 'attributional' LCA. This approach considers only the actual emissions and use of resources that can be attributed to current activities – rather than, for instance, comparing them to the water use that would occur in a re-forested farm field, or such factors as indirect land use change.

4.2.3 Food affordability and availability

Taste, cost, convenience, and cultural norms are the primary factors driving consumer food choices. Socioeconomic status and ease of access to foods also affect the type and nutrient quality of food purchases. These choices directly impact nutrition and sustainability outcomes, and the degree to which consumers have the capacity to make such choices is directly related to factors such as disposable income and food availability. At the national scale, additional measures of food access include the prevalence of poverty and the degree of income inequality. Four indicators are adopted: Food Affordability, Food Availability, Poverty Index, and Income Equality. The first three of these factors are reported annually as part of the Global Food Security Index (GFSI) [44]. The GFSI reporting system includes a spreadsheet providing country-level scores (0-100) for 109 countries for the years 2012-2015. This format is directly applicable to the methodology described herein and so no further adjustment is needed.

An additional economic metric that has been suggested by certain stakeholders is a measure of the economic health of the various players in the food system value chain. There are compelling arguments for doing so, as it is clear that these players, who are especially but not exclusively food producers, must remain financially viable if the overall food system is to remain sustainable. However, it was not possible to identify a suitable, widely accepted, globally applicable indicator for characterizing the economic health of this sector, so this has been left as a potential future enhancement of the metric methodology.

4.2.4 Sociocultural wellbeing

Sociocultural wellbeing is essential to sustainable development. Together with environmental and economic considerations, the subject of the two previous metrics, societal factors are widely considered to be the co-equal third 'pillar' of sustainability [45]. Indeed, based on the FAO definition, sustainable diets are those that are nutrient-rich, affordable and culturally acceptable. Taste and culture affect food choices and drive eating habits.

The Sustainability Consortium has used a broad multi-stakeholder process to conduct an extensive 'hot spot' analysis within food supply chains and has identified a number of potential societal issues within commercial supply chains for foods. The list was evaluated to determine which of these factors can be quantified using data currently available at the national scale. This analysis resulted in the selection of the following four 'Sociocultural Wellbeing' indicators: Gender Equity, Extent of Child Labor, Respect for Community Rights, and Animal Health & Welfare.

4.2.5 Resilience

Extreme events, including those related to climate change (droughts, floods, heatwaves), have begun to induce excessive volatility in global food prices [46], causing the United Kingdom, for example, to recently sponsor a special report on the resilience of the global food system [47]. This UK report investigated the immediate impacts and indirect effects (due to a variety of potentially unhelpful national responses) of a multiple breadbasket failure. Such shocks threaten food security and livelihoods in complex ways that challenge conventional approaches to providing humanitarian and development assistance.

Resilience has been defined by the US Agency for International Development (USAID) as the ability of people, households, communities, countries, and systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth. Resilience is also defined as the capacity that ensures adverse stressors and shocks do not have long-lasting adverse development consequences [48]. Resilience is difficult to measure, but there has been one comprehensive effort to quantify it at the national level, the ND-GAIN Index [49], one of the two indicators chosen to quantify overall resilience. The other is a measure of diversity in food production, which also helps build resilience by avoiding the potential for catastrophic consequences due to the loss of a single crop (such as Ireland's historic potato famine of the mid-19th century).

4.2.6 Food safety

Foods must obviously be free of biological and chemical hazards if they are to safely provide human nutrition. Some of these hazards, particularly harmful microorganisms, are expected to become an increasing concern under climate change, due to the more rapid growth possible with higher humidity and higher temperatures [50]. Potential hazards exist throughout supply chains, and there is extensive monitoring for foodborne disease, as summarized in the Global Burden of Foodborne Illnesses (GBFI) food safety report [51], which serves as one of the two 'Food Safety' indicators. The other indicator comes from the previously cited GFSI report, which contains an independent assessment of country-level efforts to ensure food safety [44].

4.2.7 Waste and loss reduction

The FAO estimates that approximately one-third (by weight) of all food produced for human consumption is lost or wasted each year [52]. Pre-consumer losses are relatively more important than post-consumer waste in lower-income countries, whereas post-consumer waste is greatest in higher-income countries. The environmental and economic costs associated with food waste and loss are immense. As noted previously, food systems generate a significant fraction of GHG emissions, are responsible for the majority of net freshwater withdrawals, and negatively impact biodiversity. Further, if decomposition occurs in predominantly anaerobic environments, much of the wasted food generates methane (CH_4), a powerful GHG that adds to the overall environmental burden of the world's food systems.

The proposed metric to quantify Waste and Loss Reduction is to simply express, as a percentage, the portion of the produced food that is not either lost (pre-consumer) or wasted (post-consumer). As noted above, about one-third of all produced food suffers one of these two fates, so the average value of this metric for all countries is a little less than 70. This includes the portion of produced food crops that are not harvested and left in the field. However, inedible or unused portions of food that are intentionally used for other purposes (such as energy generation or to restore soils) should not be counted as waste.

The new 'Food Loss and Waste Protocol' (FLW Protocol) has just been finalized by the World Resources Institute [53], a critical multi-stakeholder effort to develop the global accounting and reporting standard for quantifying food and associated inedible parts removed from the food supply chain. It is intended to enable a wide range of entities – countries, companies, and other organizations – to account for and report in a credible, practical, and internationally consistent manner how much food loss and waste is created and to identify where it occurs, enabling the targeting of efforts to reduce it. It is anticipated that this protocol will provide the most appropriate methodology to follow when attempting to quantify this metric in the future.

4.3 Use of the Metrics for SNS Assessment

Modeling the status of SNS is based on the incorporation of these seven metrics into a novel conceptual modeling framework. Public-private partnerships are being convened by CIMSANS to assemble the resources and expertise needed to implement the framework and conduct such assessments [26]. Through their interactions with each other and additional experts, the partnership members have already identified a number of additional integrated modeling improvements that would be desirable to include in the SNS assessment.

4.3.1 Conceptual framework

The conceptual framework for what is required in order to characterize SNS is presented schematically in figure 4.1.

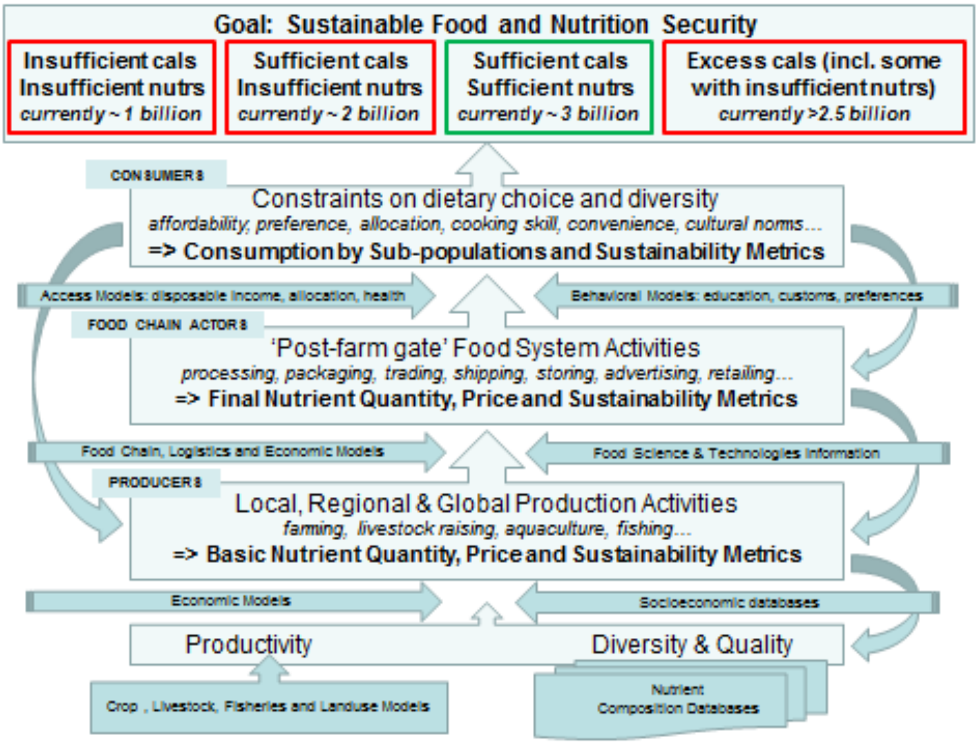

Figure 4.1 Schematic demonstrating the multiple types of information that must be assembled in order to characterize SNS. Abbreviations: cals, calories; nutrs, nutrients (adapted from [26] and used with permission).

Current integrated models primarily describe the 'PRODUCERS' box in this figure, whereas the new conceptual framework also captures two new broad categories of food system activities: (1) all of the processes that convert raw agricultural commodities into the types of foods available in the marketplace (labeled 'FOOD CHAIN ACTORS'); and (2) the complex set of factors that combine to determine which and how much of the available foods are actually consumed by individuals (labeled 'CONSUMERS').

The metrics defined in this chapter must be incorporated into an overall food system modeling framework as summarized schematically in Fig. 1. The aforementioned partnerships will collaborate with a wide range of other organizations on the development of such tools. Private-sector players in the food value chain have critical information that must be combined with this basic production information. Actual consumption and overall sustainability of the various food types containing these nutrients are then complex functions of consumer preferences (taste, education, culture, food preparation, and waste), and access (disposable income, allocation, and prices). For instance, fruits and vegetables contain certain components (e.g. phytochemicals and other bioactive compounds) that may be critical for good health, which may not be accounted for in nutrient composition databases.

4.3.2 Assessing national food system performance

As a first example use of the metrics, they were used to describe the current status of SNS among nine countries for which data were readily available [27]. Projections of future SNS status are of keen interest to many stakeholders, and these metrics are intended to eventually be coupled with the outputs of integrated models such as IMPACT [54]. This will make it possible, for instance, to quantify the effect of climate and water availability changes on future nutrition and sustainability outcomes. One example of this approach already underway involves the calculation of the ‘Food’s Nutrient Adequacy’ metrics from IMPACT model run results (GC Nelson et al., in preparation).

4.3.3 Selection of new food system practices

The metrics presented here are ideal for assessing the effectiveness of food system policies and practices intended to improve human nutrition and sustainability outcomes. Such developments are urgently needed in order to build resilience of the global food system to extreme weather under climate change [47]. For instance, greater adoption of Climate-Smart Agriculture (CSA) practices is one set of actions that are needed, including practices that mitigate emissions and build more resilient systems [55]. Modeled values for the seven metrics could be used to assess the relative merits of adopting particular food system policies and practices.

4.3.4 Setting targets and monitoring progress

The metrics can also be used to set targets and monitor progress on the adoption and impact of new food system practices specifically tailored to the needs of particular countries, especially those relevant to attaining the newly adopted SDGs. Food systems have been characterized as complex adaptive systems [56], which means that unintended consequences are possible. For instance, a recommendation to eat more fruits and vegetables may cause additional ground water depletion in drought-stricken areas and have impacts on social systems through increased requirements for immigrant labor. It is therefore essential that whatever metrics are utilized are intrinsically holistic and therefore capable of detecting such nuanced effects. The metrics presented here are specifically intended to do just that, making it possible for policy-makers and investors to set targets on particular areas of current interest (e.g., more nutritious diets), while at the same time having confidence that economic, environmental, and social measures of sustainability are being monitored and potentially improved as well.

4.4 Conclusions

Climate change, extreme weather, and dwindling natural resources represent major challenges for the world’s current food systems. Sustainable food systems need to meet accelerating global demand for food in a manner that will meet human nutrition and health needs and comply with environmental constraints. The food system metrics presented here make it possible – for the first time – to holistically and accurately measure food system performance across all relevant domains of interest. The key domains are nutrition, environment, economic, social, resilience, safety, and waste. This new metrics methodology permits a quantification of sustainable nutrition security (SNS) – a potentially useful tool for decision-makers for setting meaningful goals, prioritizing investments, and tracking progress on SDGs. The seven sustainability metrics can be applied to all countries, regardless of income level. Although the focus of this chapter has been on the application of the metrics at the national scale, some or all of the metrics would also have practical utility at smaller geographic scales, albeit with the requirement for collecting and reporting data of finer spatial resolution. It should also be noted that a lack of data for some countries on some of these indicators could represent a lack of policy monitoring and therefore highlight areas for action.

4.4 Summary: Key messages

- Sustainability considerations have largely been absent from most food security assessments conducted to date.

- A new methodology has been developed based on the concept of 'sustainable nutrition security.' This novel assessment methodology is intended to remedy both kinds of deficiencies in the previous work by defining seven metrics.
- These metrics are: (1) food's nutrient adequacy; (2) ecosystem stability; (3) food affordability and availability; (4) sociocultural wellbeing; (5) food safety; (6) resilience; and (7) waste and loss reduction.
- These food system metrics make it possible – for the first time – to holistically and accurately measure food system performance across all relevant domains of interest: nutrition, environment, economic, social, resilience, safety, and waste.
- This new methodology allows quantification of sustainable nutrition security (SNS), an approach which can now be deployed by decision-makers and investors to set meaningful goals, track progress on SDGs, and evaluate the potential impact of food system interventions intended to improve both human and planetary health.

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