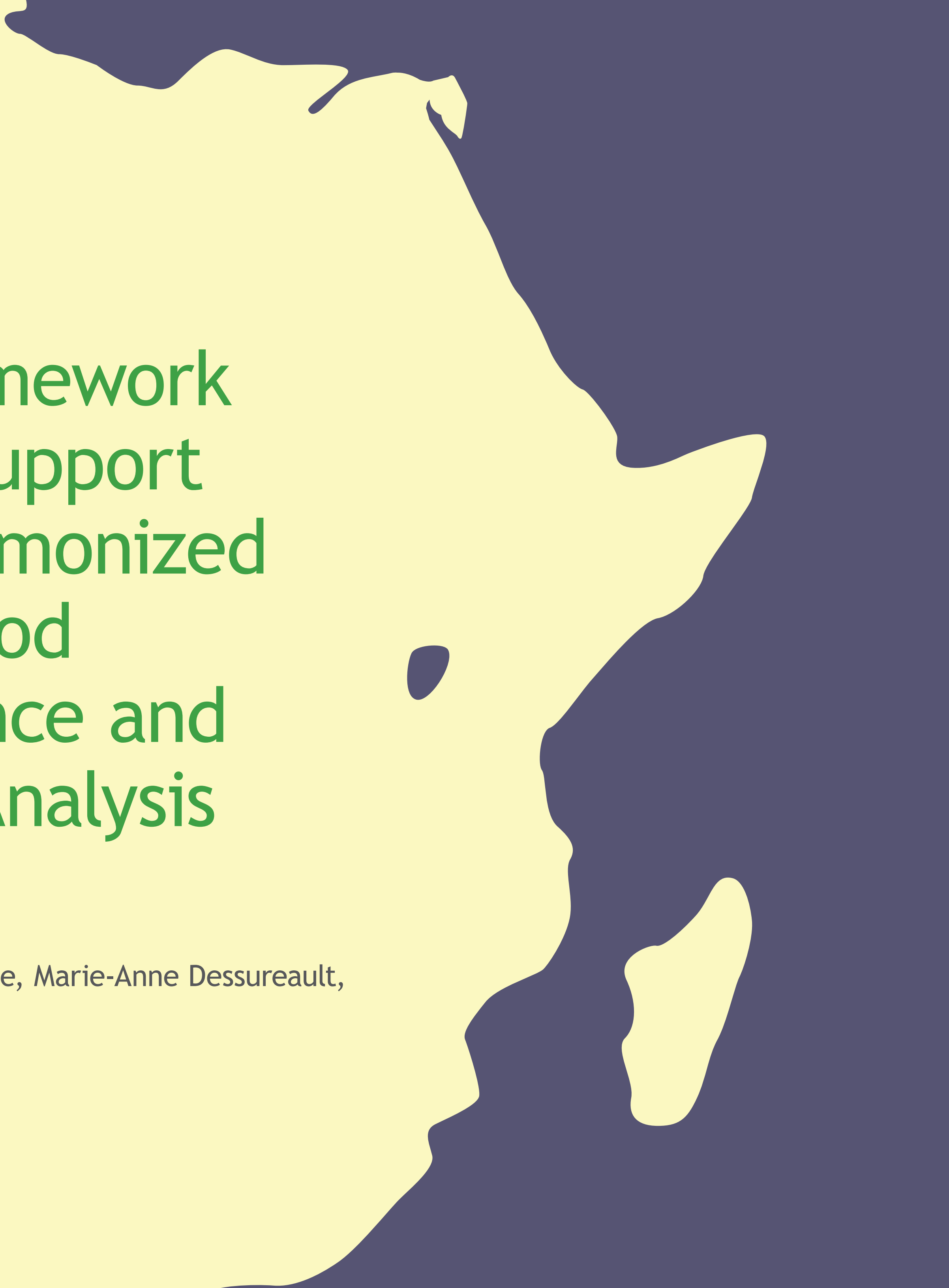

CHAPTER 7

A Forensic Framework and Decision Support System for Harmonized and Holistic Food System Resilience and Sustainability Analysis

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Introduction

Background

Today, many innovative food system transformation programs are taking place in several parts of the world, including developing, and low-income countries as well as those in Africa south of the Sahara (Benfica et al. 2023). Notably, in Africa, food systems are at a crossroads, facing several endogenous and exogenous shocks and stressors. Approximately 282 million people in Africa are undernourished, with a prevalence of 22.8 percent as measured by the prevalence of undernourishment, a Sustainable Development Goal (SDG) indicator (FAO et al. 2017; Agyemang and Kwofie 2021). Furthermore, continuous floods and droughts in many parts of the continent have reduced food security and calorie intake, respectively, by 5–20 percent and 1.4 percent below 2019 levels (Balgah et al. 2023). By 2050, climate change is anticipated to slow the fight against hunger, with an estimated 78 million people in Africa projected to experience chronic hunger in addition to the current numbers (Hasegawa et al. 2018). The individual and combined effects of external shocks and stressors on the African food system, including climate change, soil degradation, price fluctuations, political conflict, and widespread fragility, have created a complex risk environment that threatens food security and the overall well-being of many Africans. Against the above background, there is a consensus within the scientific and policy advocacy community that the African food system is flawed.

For these reasons, building a resilient and sustainable food system while striving to achieve the SDGs by 2030, the Paris Agreement goals by 2050, and the Agenda 2063 goals is critical to ensuring sustainable and inclusive development on the continent. On the one hand, a resilient food system, as defined by Fan and colleagues (2021), can eradicate weaknesses and address future uncertainty, including disruptive shocks. Food system resilience offers a valuable lens for investigating human health and well-being and how the supporting food systems they depend on can absorb and recover from various shocks and stressors, including unintended events such as the COVID-19 pandemic (Upton et al. 2021) and the war in Ukraine. In terms of a food system's recovery from shocks, emphasis has been placed on employing transformative strategies that result in improved functioning postshock rather than a return to the status quo. Upton and colleagues (2021) developed a framework to measure the resilience of rural households in Malawi, Zambia, Madagascar, and Kenya with respect to the COVID-19 pandemic and policy responses. The study demonstrated that severe illness and mortality from COVID-19 in most households substantially increased food insecurity compared to indirect stressors such as market dynamics. Mkhize, Mthembu, and Napier (2023) employed income sources, employment status, household food budget, agricultural production, and anthropometrics as indicators for measuring local food access and acceptability in relation to land use in Umlazi Township in Durban, South Africa. From the study, more than 67 percent of informal dwellers were unemployed, while households were restricted to a monthly food budget of less than US$115 (2,000 South African rand).[1] Additionally, more than 73 percent of the inhabitants in the target community had little or no access to land for cultivation, further exacerbating food security issues within the community.

On the other hand, a sustainable food system, as defined by the Food and Agricultural Organization (FAO), delivers safe and nutritious foods so that the capacity of future generations across economic, environmental, and social dimensions is not compromised (Emadi and Rahmanian 2020). Parallel to studies measuring the resilience of food systems, Jacobi and others (2020) developed a framework that captured five dimensions—namely, food security, right to food, environmental performance, poverty and inequality, and social-ecological resilience—to measure food sustainability in six different food systems in Kenya and Bolivia. In the study, agro-industrial food systems scored the lowest in environmental performance and security, while their resilience scores were medium to high. Similarly, the right to food, poverty, and inequality had the lowest scores across the case study food systems. In light of the above and several other existing studies, conceptual and theoretical advances have been made to support policymakers and stakeholders in defining indicators and metrics highlighting the complex dynamics between the different components of the African food systems. However, the unintended consequences of proliferation in resilience and sustainability indicators hinder efforts to generate evidence and empirical measures that are practically consistent, comparable, and able to steer decisions toward a sustainable African food system. Additionally, no commonly agreed-upon domains and indicators for measuring food systems' resilience and sustainability exist. Also, the above studies and a proliferation of literature on interventions on the continent have often evaluated food system resilience and

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[1] All dollar amounts are in US dollars.

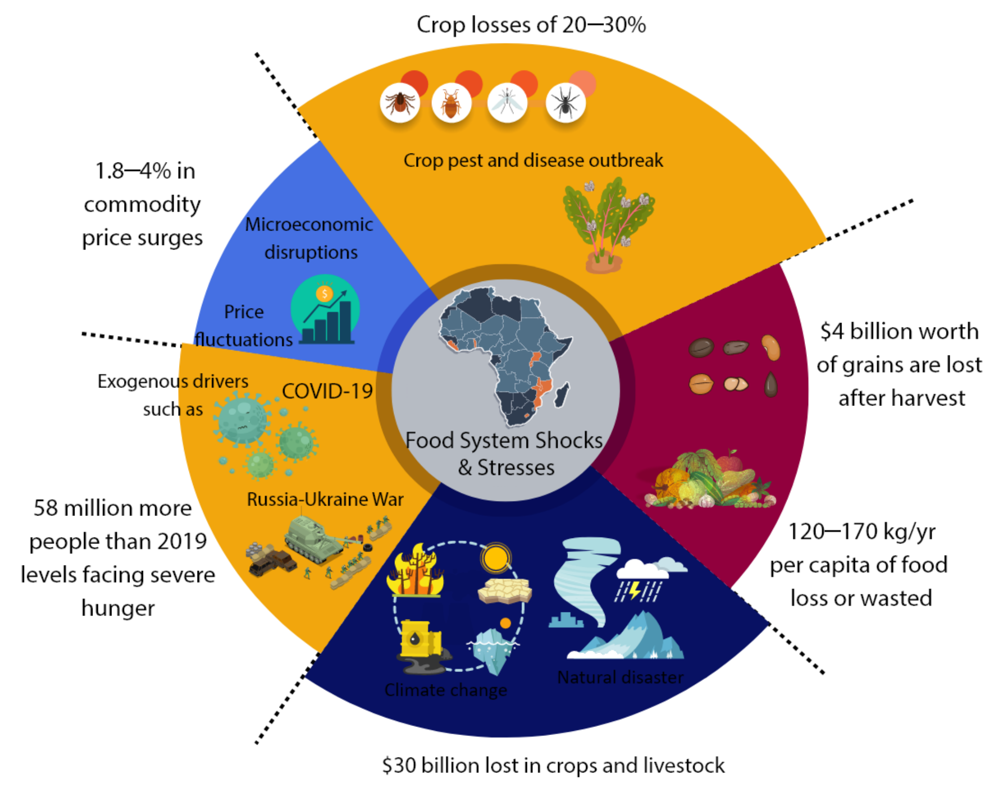
sustainability separately, neglecting their causal relationship, even though a resilient food system may contribute to sustainability (and vice versa), and strategies aiming to enhance resilience can promote sustainability (and vice versa).

Based on this premise, this chapter proposes a forensic framework that provides an opportunity to curtail weaknesses and build the capacity of food system actors while dealing with uncertainties, shocks, and external stressors. Furthermore, the proposed forensic framework incorporates multiple components and outcomes across multiple scales and levels, including social, economic, health, and environment, through harmonized sustainability and resilience dimensions and indicators. It also provides a quantitative approach to support decision-makers in objectively designing actions that systematically steer food systems toward sustainability and resilience. In the long term, this chapter sets a foundation for a holistic, harmonized, integrated food system resilience and sustainability assessment through a novel decision support system, Food System Rapid Overview Assessment using Scenarios (FS-ROAS), that helps stakeholders assess food systems and design appropriate interventions. Finally, a case study of the African continental and subregional food systems is examined, considering three harmonized dimensions—food and nutrition, socioeconomic, and environmental—to illustrate how the elements of the proposed forensic framework can be applied to a harmonized resilience and sustainability analysis. In anticipation of revisions to the 2014 Malabo Declaration on Africa Agriculture and the 2015–2025 Comprehensive African Agriculture Development Programme (CAADP), the proposed decision support system, FS-ROAS, presents an opportunity for heads of state and governments of the African Union to explore potential consequences of their recommitment to sustainable development in Africa.

Shocks and Stressors Affecting Food Systems in Africa

According to Ansah and colleagues (2019), the term *shocks and stressors* may be defined as events that may disrupt the normal functioning of a socioeconomic agent or activity, subsequently trickling down to tamper with household food security. These shocks could be categorized as covariate, which often threaten a broader population, or idiosyncratic, which affect an individual or household level (Lin 2011; Bullock et al. 2017). However, the manifestations of these shocks or perturbations within the African food system vary at different spatiotemporal scales. Figure 7.1 presents examples of stressors and shocks derailing the resilience and sustainability of the African food systems. At the production level, extreme weather conditions (droughts and floods), climate change, pest and disease outbreaks, and low technology adoption have exposed the fragilities of the African food system. For example, between 2008 and 2018, approximately $30 billion was lost in Africa

FIGURE 7.1—EXOGENOUS DRIVERS, SHOCKS, AND STRESSORS INFLUENCING THE AFRICAN FOOD SYSTEM



Source: Adapted from Baudron et al. (2019), Nordhagen et al. (2021), and Loboguerrero et al. (2019).
Note: Dollar amounts are in US dollars.

south of the Sahara and North Africa in crops and livestock due to these shocks and stressors. This led to a disaster-induced production loss of 559 calories per capita per day, equivalent to a 20 percent daily loss in the recommended dietary allowances for both men and women on the continent (FAO 2018). Furthermore, climate extremes impact approximately 16 million people annually (FAO and ECA 2018). At the distribution and retail level, price spikes, currency fluctuations, microeconomic disruptions, declining competitiveness in export markets, and wars influenced price inflation.

According to the International Monetary Fund, these shocks bring about a 1.8–4.0 percent price surge in agricultural commodities beyond generalized price increases (Okou et al. 2022). At the household level, shocks and stressors affect income and access to food, land, and livestock assets, and essential services such as water, health care, and electricity. The systemic shocks discussed above, along with unprecedented events such as the COVID-19 pandemic, the Ebola outbreak, and the war between Ukraine and Russia, have driven millions in Africa into deeper poverty, loss of livelihoods, and diminishing food purchasing power.

Why Are Analytical Approaches Based on Harmonized Indicators Needed?

In a review commissioned by the United Nations Development Programme, Winderl (2014) reported 18 indicators for measuring disaster resilience across households and subnational, national, and global scales. In another scoping review by Barrett and colleagues (2021), between 2008 and 2020, more than 9,558 published studies discussed food system resilience. However, the study also reported that the concept and development of resilience were inconsistently theorized and reliant on methods that have not been adequately reconciled to identify which metrics and tools best address a desired question within a defined food system. A study by Schipper and Langston (2015) also reported parallel findings when investigating 17 indicator frameworks for evaluating vulnerabilities and adaptation practices. In the context of sustainability, several indicators have been reported that can be adopted to measure the performance of food systems. In this regard, Béné and others (2019) employed a rigorous protocol to report on a subset of 27 indicators aggregated into four dimensions. Chaudhary, Gustafson, and Mathys (2018) reported on 25 sustainability indicators across seven domains: nutrition, environment, food affordability and availability, sociocultural well-being, resilience, food safety, and waste. However, despite much recent attention being given to the sustainability and resilience of food systems, most studies on the subject remain conceptual and general. In addition, generated evidence and data to support policy actions are frequently weak, fragmented, and arbitrary.

Moreover, no commonly agreed-upon set of indicators against which to measure food system dimensions exists for evaluating a defined food system. Furthermore, most studies have evaluated either the resilience or the sustainability of a defined food system, ignoring the causality between these two pillars. A resilient food system may contribute to a sustainable one, although sustainability is a function of more than just resilience (Roosevelt, Raile, and Anderson 2023). Thus, the outcomes of a resilient food system are inherently linked to a sustainable food system, and vice versa. Both sustainability and resilience are crucial for addressing the challenges faced by food systems, including environmental degradation, climate change, economic instability, and population growth. Sustainable food systems are likely more resilient because they depend less on nonrenewable resources, have lower environmental impacts, and support local economies and social equity. Conversely, more resilient food systems are likely to be more sustainable in the long term because they are better equipped to adapt to shocks and stresses and to maintain their functionality in the face of change (Tendall 2015). Therefore, efforts to promote sustainability and resilience are often intertwined and involve measures such as promoting agroecological farming practices, diversifying agricultural production, supporting local food economies, and strengthening social safety nets. By viewing resilience and sustainability as complementary, policymakers and stakeholders can make more informed decisions, weighing both immediate adaptive needs and long-term sustainability goals. Hence, a harmonization effort to capture the inherent similarity between food system resilience and sustainability indicators in harmony with the SDGs could permit comparability of different local food systems to help design resilience and sustainable adaptation programs that improve human health while operating within a safe planetary space. Since food systems differ in size and structure from one African country to another and between rural and urban areas, harmonized indicators must account for local food system resilience and sustainability drivers. Hence, this framework supports the need to strive for a resilient food system while working toward sustainability in the long term.

Forensic Framework Development and Harmonization

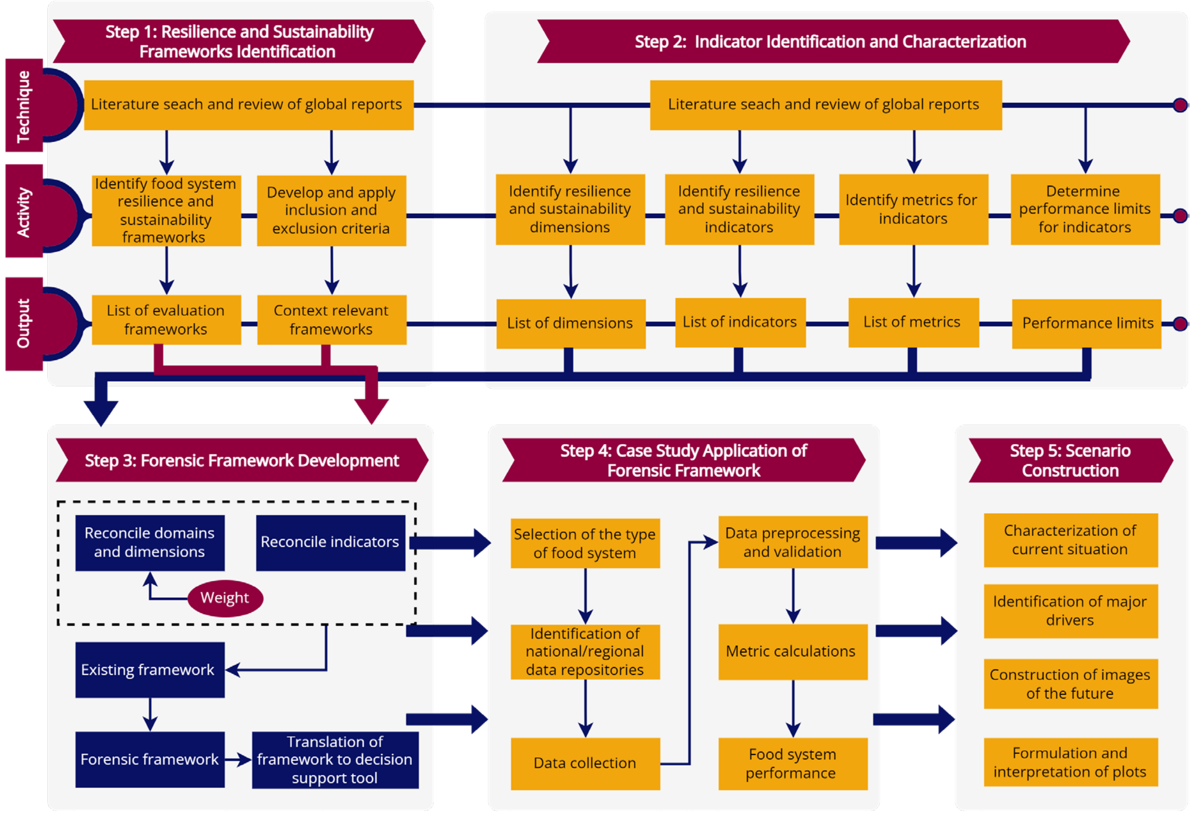
Theoretical Method and Approach

Figure 7.2 presents the methodological approach to developing a harmonized resilience and sustainability forensic framework. The approach consists of five main steps: (1) identification of resilience and sustainability frameworks, (2) identification and characterization of indicators, (3) development of the forensic framework and decision support system, (4) application to a case study, and (5) design of sustainable strategies through scenario construction. In component one of the methodological framework, a literature search strategy using keywords such as "food system resilience framework," "food system sustainability framework," and "sustainability and resilience framework" on search engines such as Google Scholar, Web of Science, and Science Direct were used to identify frameworks employed to quantify food system resilience and sustainability.

Additionally, conceptual and implementation studies that have discussed the resilience and sustainability of food systems were considered during the literature scoping. Moreover, existing studies and literature reviews by Arthur and colleagues (2022) and Béné (2020) also provided a useful reference point to a broad array of frameworks adopted to conceptualize the resilience and sustainability capacity of food systems. The next component within step 1 focused on subjecting the identified frameworks to three-stage inclusion and exclusion criteria, including (1) an alignment with the SDGs, (2) the capacity to capture food system outcomes, and (3) external shocks. These frameworks are the foundation of the proposed forensic framework.

Step 2 of the methodological approach applied a similar literature search approach to identify food system resilience and sustainability and resilience dimensions, domains, indicators, metrics for quantifying each indicator, and a reference performance limit. Keywords applied in the literature search included "sustainability indicators," "resilience indicators," "food system indicators," and "resilience and sustainability indicators." Indicators under the FAO's custodianship (SDG 2, 5, and 12) were also included. Similar to the activities in step 1, the identified indicators were subjected to three-level criteria, which revealed the identified indicator's relevance, quality, and interpretability. Additionally, the usefulness of an indicator in supporting policy design, planning, and decision-making was considered. Finally, data requirements, measuring tools, and reference performance limits outlined in SDGs 2, 5, and 12 were identified. Throughout this document,

FIGURE 7.2—METHODOLOGICAL FRAMEWORK



Source: Based on the work of Agyemang et al. (2022) and Jacobi et al. (2018).

candidate dimensions, domains, or indicators come from this pool of identified domains, dimensions, and indicators determined from the literature.

In step 3, the work of Constas, d'Errico, and Pietrelli (2022) served as the foundation for designing harmonized dimensions. The dimensions and domains identified from step 1 were aggregated into four food system dimensions in alignment with SDGs 2, 5, and 12. The four dimensions, (1) food security and nutrition, (2) socioeconomics, (3) politics and governance, and (4) environment (clean and healthy planet), reflected universal goals and food system outcomes desired by all. Similarly, the identified indicators were further aggregated into four food system dimensions. Due to the relative abundance of dimensions and indicators as applied in the literature, an evaluation process using a five-point Likert scale was applied to translate indicators and dimensions to the four food system dimensions through a stakeholder survey.[2] Each stakeholder was asked to rate the relative closeness or overlap of an identified domain/dimension from the literature in relation to the four aggregated resilience and sustainability dimensions. The survey results were translated into aggregate weights of importance through a weighted fuzzy-entropy technique (Parkash et al. 2008; Chen and Li 2010). Then, a forensic framework was constructed, combining a series of outputs from the steps above and the harmonized indicators. This time, building on the works by Agyemang and Kwofie (2021), Agyemang (2022), and Hebinck and colleagues (2021), a forensic framework was developed. For any forensic investigation, some indicators may be more valuable than others; hence, the framework allows stakeholders to select a candidate set of indicators from a preliminary list based on a set of criteria, including the availability of data for the selected indicator.

In step 4 of the methodological framework, we employ the forensic framework to assess resilience and sustainability in the African food system, drawing upon secondary data from (FAOSTAT 2020). Finally, we designed resilience and sustainability strategies in step 5 and explored the ramifications of the selected indicators through scenario design and machine learning (ML) modeling. The end-to-end ML pipeline to investigate plausible future scenarios is explicitly presented in the works of Agyemang and colleagues (2023) and Meroni and colleagues (2021).

Resilience and Sustainability: Definition of Terms

The term *resilience* has been applied in various contexts, such as ecology, engineering, agriculture, and economics, to understand whether systems could become more robust to external perturbations or shocks. Adger (2000, 349) and Carpenter and colleagues (2001; 767) describe resilience as the "ability of social groups (groups or communities) to cope with external stressors and disturbance as a result of external social, political and environmental change." Similarly, Folke and colleagues (2010, 2), Walker and colleagues (2006, 2–3), and Perrings (2006, 417) defined resilience as the "capacity to continue to develop in the face of change, incremental and abrupt, expected and surprising." It follows that a resilient food system can withstand, adapt to, and recover from shocks and stressors, ensuring that it continues to provide sufficient, healthy, and sustainable food for all. This includes dealing with potential disruptions like economic instability, climate change, conflict, and pandemics (Zurek et al. 2022). In the same harmony with the above definition, Tendall and colleagues (2015, 18) also defined food system resilience as "the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances."

According to the FAO, a sustainable food system can be defined as "a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (Nguyen 2018, 4). This definition is synonymous with the one proposed by the ERA-Net SUSFOOD program. In this, the term *sustainability in food system* refers to a "food system that supports food security, makes optimal use of natural and human resources and respects biodiversity and ecosystems for present and future generations, and which is culturally acceptable and accessible, environmentally sound and economically fair and viable, and provides consumers with nutritionally adequate, safe, healthy and affordable food" (Rokka 2018, 4).

The above definition of resilience and sustainability recognizes the importance of different dimensions and the time relevance of achieving such goals within the food system. Thus, we can define these concepts as being complementary to each other. In this study, the two concepts will be harmonized to simultaneously provide an opportunity to measure a given food system's performance (sustainability)

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[2] Stakeholders surveyed were from international and academic institutions and nongovernmental organizations.

and provide a means to design solutions to address present challenges over future periods (resilience), bearing in mind inherent trade-offs.

Resilience and Sustainability: Harmonized Dimensions and Indicators

Table 7.1 summarizes a candidate food system's resilience and sustainability dimensions identified from the literature, aggregated weighted scores, and harmonized dimensions. Each candidate dimension was translated to a food system scale of relevance, that is, household, district, regional, national, global, urban, and all scales. The aggregated weighted scores were obtained by translating the survey results through a weighted fuzzy entropy method. For each candidate domain harmonized to the four dimensions, the sum of weights is 1. In Table 7.1, the orange-shaded region refers to the highest weight, while the gray-shaded regions reflect the lowest weight attributed to the harmonized domains. The aggregated weighted scores show the relative closeness of the candidate dimension to the harmonized dimension. The highest weight, of 0.62 (62 percent), was reported for the aggregation of the air dimension to environmental sustainability dimensions. Fuzzy entropy weight between (0.3–0.61), (0.29–0.45), (0.33–0.53), and (0.29–0.62) were estimated for the closeness of candidate dimensions to, respectively, the food security and nutrition, socioeconomic, politics and governance, and

TABLE 7.1—RESILIENCE DOMAIN AGGREGATION, RESPECTIVE RATINGS, AND FOOD SYSTEM SCALE OF IMPORTANCE

TABLE 7.1—RESILIENCE DOMAIN AGGREGATION, RESPECTIVE RATINGS, AND FOOD SYSTEM SCALE OF IMPORTANCE

Sustainability domains from the literature	Aggregated sustainability dimension				
	Food security and nutrition	Socioeconomics	Politics and governance	Environment	Food system scale
Food security	0.37	0.30	0.18	0.14	All
Food nutrient adequacy	0.49	0.17	0.21	0.13	All
Affordability and availability	0.36	0.30	0.17	0.18	All
Food safety	0.41	0.31	0.20	0.08	All
Nutrition	0.37	0.18	0.27	0.17	All
Food waste and use	0.31	0.19	0.23	0.28	All
Food utilization	0.32	0.23	0.33	0.12	All
Diet quality	0.61	0.21	0.08	0.10	All
Food environment	0.34	0.20	0.26	0.20	All
Right to food	0.42	0.27	0.18	0.14	All
Income, poverty, and inequality	0.16	0.45	0.21	0.17	H
Socio-ecological performance	0.22	0.23	0.25	0.30	All
Sociocultural wellbeing	0.19	0.36	0.30	0.15	All
Human capital	0.10	0.45	0.22	0.22	H
Threatening conditions to income and access to food	0.46	0.33	0.15	0.06	All
Social safety nets	0.10	0.45	0.28	0.16	
Access to basic service	0.26	0.28	0.30	0.17	H, D
Stability	0.18	0.29	0.24	0.29	H, D,Re
Natural capital	0.13	0.16	0.27	0.44	All
Agricultural and non-agricultural assets	0.34	0.23	0.26	0.18	
Employability	0.06	0.35	0.33	0.26	H
Structural factors	0.08	0.27	0.53	0.12	H
Agency-related features	0.38	0.24	0.21	0.18	All
Policies affecting the food environment	0.33	0.20	0.33	0.14	All
Strategic planning	0.16	0.20	0.52	0.12	All
Effective implementing	0.30	0.18	0.34	0.18	All
Accountability	0.23	0.17	0.37	0.24	All
Environmental performance	0.14	0.23	0.13	0.49	All
Ecosystem stability	0.13	0.07	0.25	0.55	All
Resilience	0.38	0.15	0.15	0.33	All
Waste and loss reduction	0.20	0.19	0.27	0.34	All
Air	0.06	0.10	0.22	0.62	All
Water	0.35	0.18	0.11	0.37	All

Source: Domain and dimensions were sourced from Chaudhary et al. (2018), Béné et al. (2019a), Jacobi et al. (2020), Seekell et al. (2017).

Note: The food system scales adopted include household (H), district (D), regional (Re), national (N), global (G), rural (R), urban (U), and all scales (All). The orange-shaded region refers to the highest weight, while the gray-shaded regions reflect the lowest weight attributed to the harmonized domains.

environmental dimensions of sustainability. The weights demonstrate the extent to which the stakeholders surveyed considered the identified dimension to be associated with the aggregated domains. The weight of least importance, of 0.06, was estimated for the translation of employability and air to the aggregated food security and nutrition dimension. Although employability and air play a critical role in the food value chain, their weighted scores demonstrate that they could be best represented under socioeconomic and environmental dimensions. The harmonization of the resilience and sustainability dimensions helps to counter the potential negative effects associated with the proliferation of dimensions associated with food system analysis.

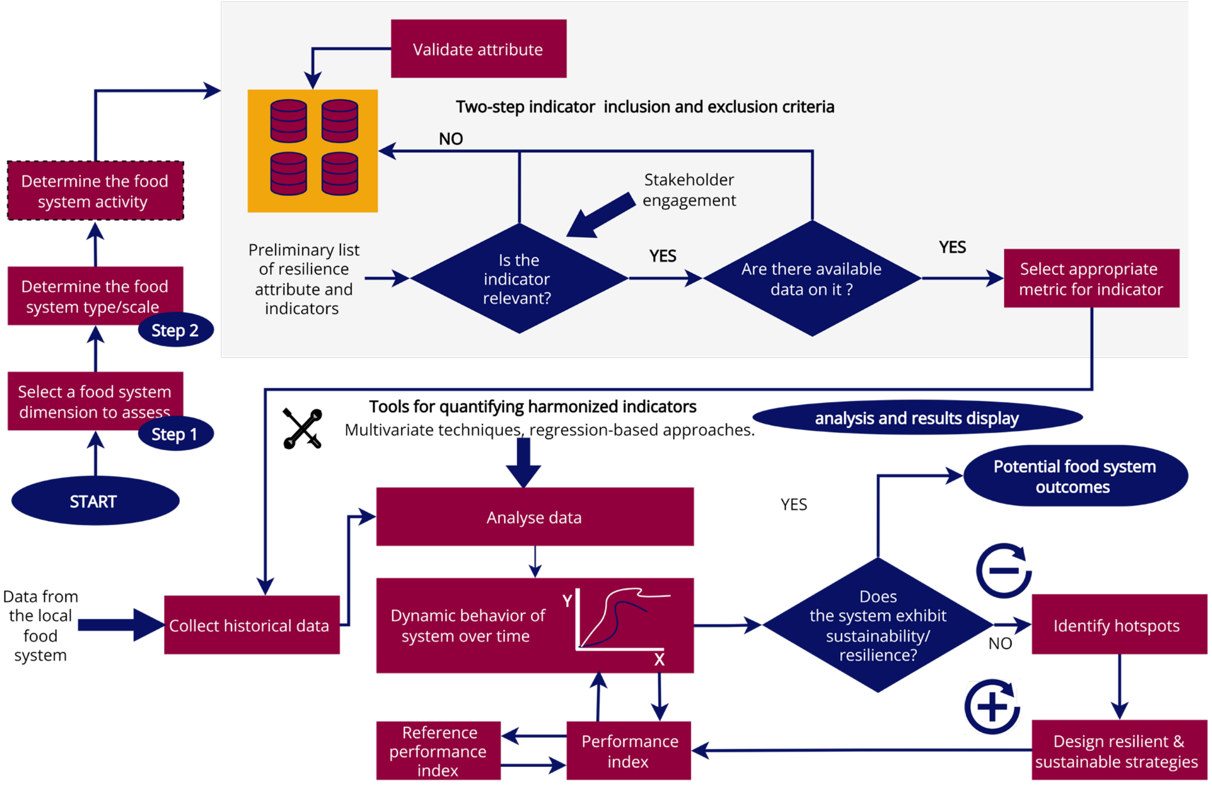
Differentiating between the regional, country, and local levels when analyzing food system resilience and sustainability is crucial due to the variability in context, scale, and interconnectedness of food systems. Each level has its unique challenges, resources, and opportunities. The local level might grapple with issues related to local farming practices, while at a national level, policies and infrastructural developments play a more significant role (Ingram 2011). The scale determines the nature of challenges and solutions. Regional challenges might encompass transboundary water issues affecting agriculture, while local challenges might involve soil quality or local market dynamics (Ericksen 2008). A change at the local level might ripple up to influence national and regional systems. Understanding each level helps in mapping these interconnected dynamics. Different stakeholders operate predominantly at different levels. Engaging with them requires an understanding of the level they influence most prominently.

Table A7.1 maps the indicators to the harmonized resilience and sustainability dimensions. It also demonstrates the different scales of applying the indicators. For example, indicators such as greenhouse gas emissions from the food system per capita (production-based) were mapped to all scales of assessment for the environmental dimension. This implies that at the regional, national, and local scales of food system assessment, the indicator can be adopted to measure the resilience and sustainability of a food system. However, indicators such as income diversity and land or growing space owned were mapped to socioeconomic and environmental dimensions. These indicators are applicable at the household scale of assessment. It is important to highlight that there is an inexhaustible list of indicators that could be added to Table A7.1; however, data constraints will be critical in adopting these indicators for food system analysis.

Forensic Framework for Resilience and Sustainability

This section presents the novel forensic framework for resilience and sustainability (f-RESUS). The overarching goal of the f-RESUS framework is to accommodate

FIGURE 7.3—FORENSIC FRAMEWORK FOR FOOD SYSTEM ASSESSMENT



Source: Based on the work of Agyemang et al. (2022) and Jacobi et al. (2018).

variations across different resilience and sustainability frameworks and dimensions in assessing the performance of a food system. Figure 7.3 presents the implementation framework for executing the forensic assessment. This framework can guide the development of an interactive decision support tool, allowing users to implement the assessment through a series of steps. The first step involves selecting a harmonized dimension of interest for analysis. The decision-maker can select from the four harmonized sustainability dimensions: food security and nutrition, socioeconomics, politics and governance, and environment. The choice of a dimension and scale of analysis will consequently populate a preliminary list of indicators subjected to inclusion and exclusion criteria to obtain candidate indicators for the analysis. The most critical criterion is the availability of secondary data on the selected indicator. When data are unavailable, the system automatically requests the decision-maker to enter the necessary or relevant data.

In step 2, the decision-maker can select the level of food system of interest: regional, national, district or local, rural, urban, or household. It is important to highlight that the choice of food system scale for the assessment may require specific indicators that might not be considered for others. The decision-maker can then visualize the sustainability of the defined system, redesign strategies, and explore the impact of the proposed strategies. The dynamics of these explorations were achieved by employing ML models. The results of the f-RESUS framework were further translated into a novel decision support tool leveraging the best-performing ML model.

ML Models

We used a multivariate model of the following form: $y = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n + e_{,i}$, where β_0 is the y-intercept, the y-value when all explanatory variables are set to 0. β_1 to β_i are the coefficients for variables x_1 to x_i; by design, y increases or decreases with a one-unit change in that variable, assuming that all other variables are held constant (Maulud and Abdulazeez 2020). In the current study context, the variables y refer to the indicators presented in Table 7.2, while x_i to x_n are the characteristics and drivers that influence a food system. The ML models adopted in this paper include the linear regression model, ridge regression model, LASSO (least absolute shrinkage and selection operator) regression, random forest model, elastic net regression model, and support vector regression model. Details of these models' specifications, data preprocessing, and statistical validation approach adopted in this study are presented extensively in the work of Agyemang and colleagues (2023). All experiments applying the ML algorithms and end-to-end pipeline framework were implemented using Python programming and the scikit-learn library.

Application: Case Study and Adaptability (the African Food System)

To illustrate how the f-RESUS may be applied to assess a food system dynamically, we examine the African food system considering three harmonized resilience and sustainability dimensions: the food security and nutrition, socioeconomic, and environmental dimensions. Under the food security and nutrition dimension, four outcome indicators were selected to prove the concepts presented above. Likewise, one outcome indicator (surface temperature change and emissions from agricultural land) was selected from the environmental sustainability perspective. The food price index and import quantity index were selected under the socioeconomic dimension.

Study Areas and Dataset Description

All datasets used in the study are from FAOSTAT (FAO 2020). The dataset ranged from 2000 to 2020 and was segregated into three African and subregional food system levels: production, supply, and loss/waste along the value chain. Each node of the food value chain described above contributes data on the following agricultural produce: cereals, starchy roots, pulses, vegetables, fruits, meat, eggs, milk, and fish. In addition, key food system drivers include food price inflation (weighted average), percentage of government expenditure, agriculture credit, development flows to agriculture from donors, and employment in agriculture. The food balance dataset adopted in this study shows the sources of supply and their utilization for each food item—thus, each primary commodity—and a number of processed commodities potentially available for human consumption in terms of caloric value (kcal/capita/day). This implicitly reflects the contributions of key food system actors such as producers, transporters, aggregators, processors, and retailers. A detailed description of these actors is beyond the scope of this chapter. To ensure collinearity in communication, the production (in 1,000 metric tons), supply (in kcal/capita/day), loss/waste (in 1,000 tons), value chain, and additional drivers mentioned in the previous paragraph will be referred to as "food system driving forces" throughout the rest of this paper. Overall, there were 735 data points. About 2.3 percent of the data points had to be imputed through five techniques: *k*-nearest neighbor, mean, median, iterative, and expectation-maximization methods. A total of 13.7 percent of the data points reflected food security and nutrition indicators.

Indicator Description

Table 7.2 presents the selected indicators for the corresponding harmonized dimensions, their descriptions, and their current performance limits. The current performance limit will serve as a reference to investigate the impact of designing resilient and sustainable strategies to address the challenges within the food security and nutrition, environmental, and socioeconomic dimensions of sustainability.

Dynamic Modeling Through the ML Pipeline

This section discusses the application of ML models to assess and predict the unintended consequences of adopting different strategies within the African food system using the eight indicators highlighted in Table 7.2.

TABLE 7.2—SELECTED INDICATORS FOR THE EVALUATION OF THE FOOD SECURITY/NUTRITION, ENVIRONMENTAL, AND SOCIOECONOMIC DIMENSIONS OF THE SUSTAINABILITY OF THE AFRICAN FOOD SYSTEM

Indicator name	Description	Current performance
Food security/nutrition		
Number of undernourished people (million)	The number whose habitual food consumption is insufficient to provide the dietary energy levels required to maintain a normally active and healthy life	254.7 million (in 2020)
Number of obese adults (18 years and older) (million)	The number of people with a body mass index of over 30	81.5 million (in 2016)
Number of women of reproductive age (15–49 years) affected by anemia (million)	Relative proportion of females in a given population that are affected by anemia	122.7 million (in 2019)
Minimum dietary energy intake (kcal/capita/day)	Measured per capita dietary energy intake that falls below the minimum level required	1,740 kcal/cap/day (in 2022)
Environmental		
Temperature change on land (meteorological year)	Mean surface temperature change due to agricultural production across a meteorological year	1.008°C
Emissions from agricultural land	The greenhouse gas emissions generated from the agrifood systems. It is computed following the Tier 1 methods of the IPCC guidelines	2,794,333.052 tons of CO2 (equiv.)
Socioeconomic		
Food price inflation	Change in price of a basket of food commodity	10.76% (2020)
Import quantity index	The physical quantity of agricultural products imported for domestic consumption or processing for a given reference year	133 (2020)

Sources: FAOSTAT (2020) and WHO (2023).
Note: IPCC = Intergovernmental Panel on Climate Change

Correlation Between Food System Drivers and Sustainability Indicators

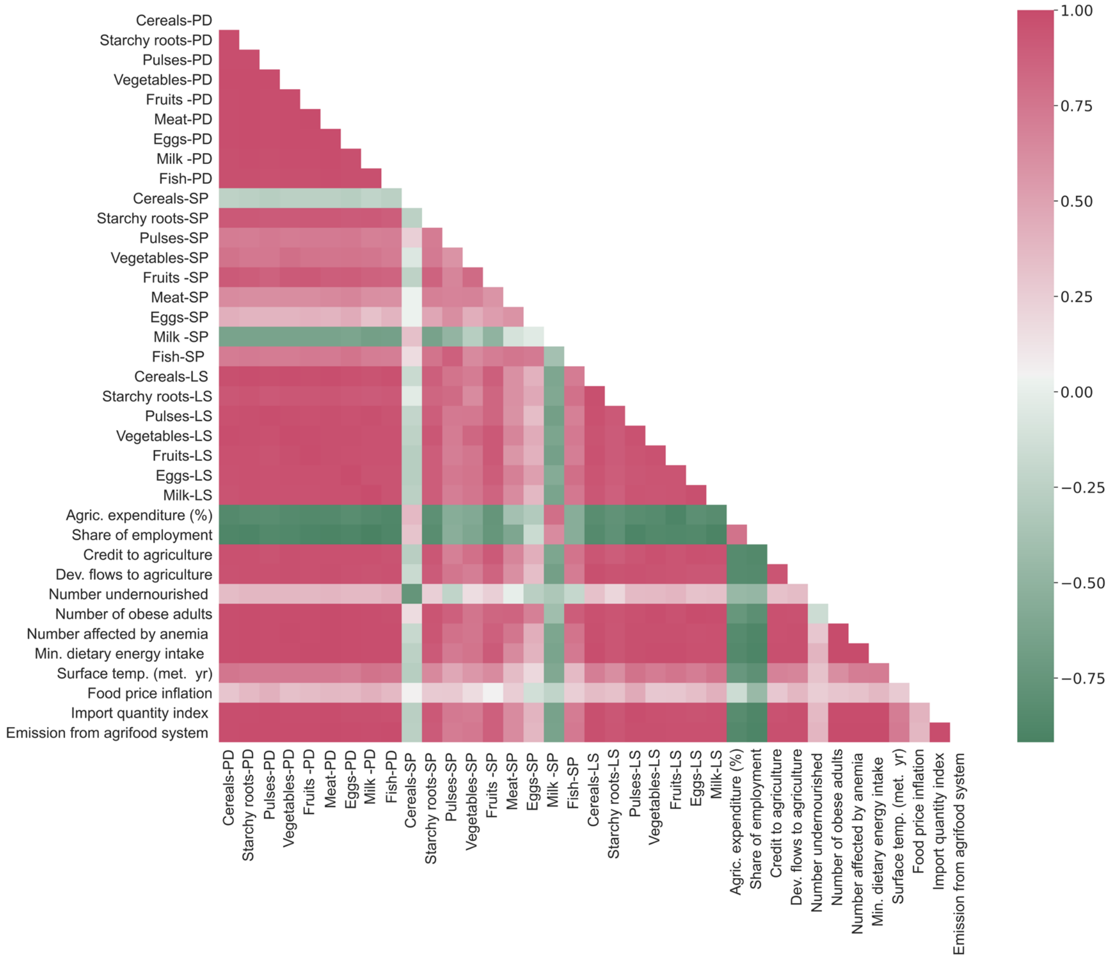
Figure 7.4 presents the correlation (Spearman) between the food system drivers and the selected indicators in Table 7.2. From Figure 7.4, it is evident that there is a strong positive correlation between the selected indicators and the driving forces of the food system on the continent. From the food supply perspective, we observe a strong positive correction with the sustainability indicators except for the cereals and milk supply. However, a weak negative correlation of between 0.19 and 0.76 is observed between cereal supply and five selected indicators (number undernourished, number affected by anemia, minimum dietary intake, surface temperature change, and import quantity index). On the contrary, a weak positive correlation of 0.17 and 0.05 is observed between cereal supply and, respectively, the number of obese adults (million) and food price inflation.

Additionally, a negative correlation in the range of 0.33 to 0.62 exists between milk supply and the selected indicators. The results suggest that the risk of the supply of cereals and milk contributing to the selected eight indicators is low. The results corroborate the work of Babio and colleagues (2022), who reported an inverse association between the consumption of dairy products and obesity prevalence risk through a meta-analytical study. Similarly, the share of employment was inversely correlated with all selected indicators and driving forces (except milk and cereal supply), demonstrating a weak to strong relationship, with a Spearman coefficient of 0.38 (number of undernourished) to

1.00 (number of obese and number affected by anemia). Likewise, agricultural expenditure demonstrated a similar relationship with food price inflation, with a negative correlation of 0.16. Therefore, due to the negative correlation, a threshold value of more than 0.50 inverse correlation was set to exclude food system driving forces with such an association from further analysis.

The results in this section suggest that food system drivers such as milk supply, agricultural expenditure by the government, and share of employment may not exert a direct causation on the selected indicators but do describe an observable pattern between them. Furthermore, the agricultural share of government expenditure and share of employment in agriculture can have independent consequences, which may be causally linked to the selected indicators' capacity to describe the resilience and sustainability of the African food system. However, the large share of the African population employed in agriculture (54 percent) does not necessarily lead to food security and nutrition. For example, a study by Adeyanju and others (2023) sampled 400, 429, and 606 young farmers in (respectively) Kenya, Nigeria, and Uganda, and reported low dietary diversity across the three countries despite their being food producers.

FIGURE 7.4—CORRELATION BETWEEN THE VALUE CHAIN DATASET AND SELECTED INDICATORS



Source: Authors, based on data from FAOSTAT (2020) and WHO (2023).

Note: LS = loss; PD = production; SP = supply.

Policy and Strategies to Achieve SDG Targets

This section uses the best model (see the work of Agyemang and others 2023) to explore future strategies within the African food system and their potential consequences through short-term scenario designs. We designed scenarios around critical issues that trigger actions to shape the future of the African food system. Five critical drivers—namely, agricultural production, food supply, food loss, agricultural credit, and development flows—are considered in the scenario designs. The 2030 timeline was selected because it marks the reference point to achieve SDGs. In this study, a designed scenario is regarded as sustainable and resilient if it yields reductions in the indicators and limits the trade-offs between them compared to the reference year of assessment. In each constructed scenario, the projections at the endpoint of 2030 will be compared to the base year 2020.

Business-As-Usual Scenario

In the business-as-usual (BAU) scenario, no efforts are made to address the current challenges; however, due to the rise in population and the demand to feed a projected 1.7 billion people on the continent by 2030, food production and supply will grow at an annual rate of 2.6 percent from 2020 to 2030 (Baquedano 2021). There are no changes in government expenditure share toward agriculture and consistent fluctuations in food price inflation. Again, little or no efforts are made to address persistent food loss along the value chain. Thus, food loss is further increased by a similar percentage along the value chain. Additionally, financial support from donors is delayed, with as low as a 1.5 percent increase in 2030 above the 2020 levels.

Stable Scenario 1: Increased Agricultural Production

In this scenario, we explore an increase in agricultural production by 15 percent above the projected levels by 2030, with a 25 percent reduction in food loss and waste due to the adoption of artisanal technologies to address postharvest losses. New agricultural ventures and employment opportunities are created due to increased credit for agriculture through financial institutions, approximately 9–12 percent above 2020 levels. There is an increase in development flows for agriculture through funds from external donors.

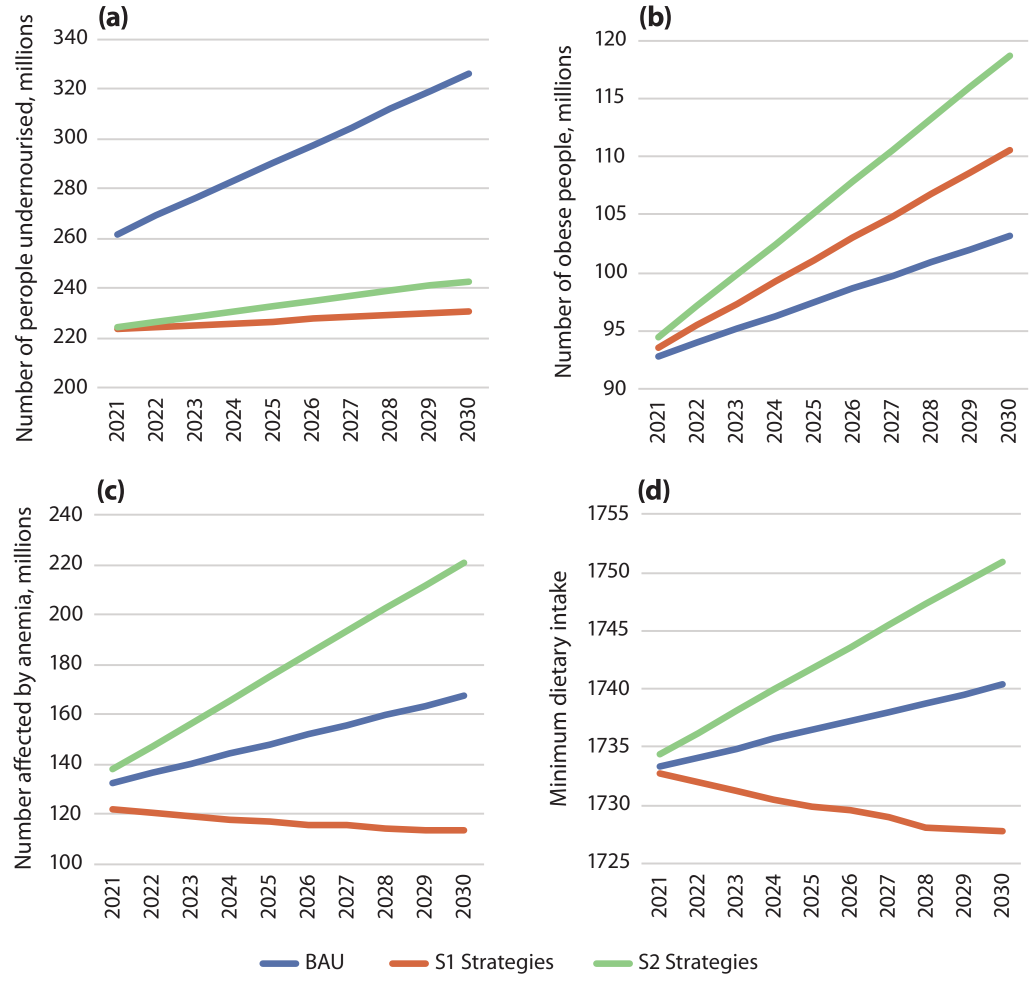
Stable Scenario 2: Increased Agricultural Credit

In this scenario, we explore a 15–18 percent increase in agricultural credit from financial institutions on the continent. This, along with government support, increases agricultural production. International donor agencies also increase their commitment to support the African food system (19–20 percent above 2020 levels at the end of 2030). Agricultural credit and government funds are redirected toward providing subsidies and technologies, increasing the production and supply of nutritious and healthy foods by an estimated 12 percent above the BAU scenario. Little effort is made to reduce food waste, with a potential reduction of 10–15 percent below the reference year level.

Interpretation and Logical Flow of Constructed Scenarios at the Continental Level

We can observe varying outcomes on the selected food security and nutrition indicators from the snapshots of the logical implications of the scenarios constructed in the sections below (Figure 7.5). From the first scenario, we

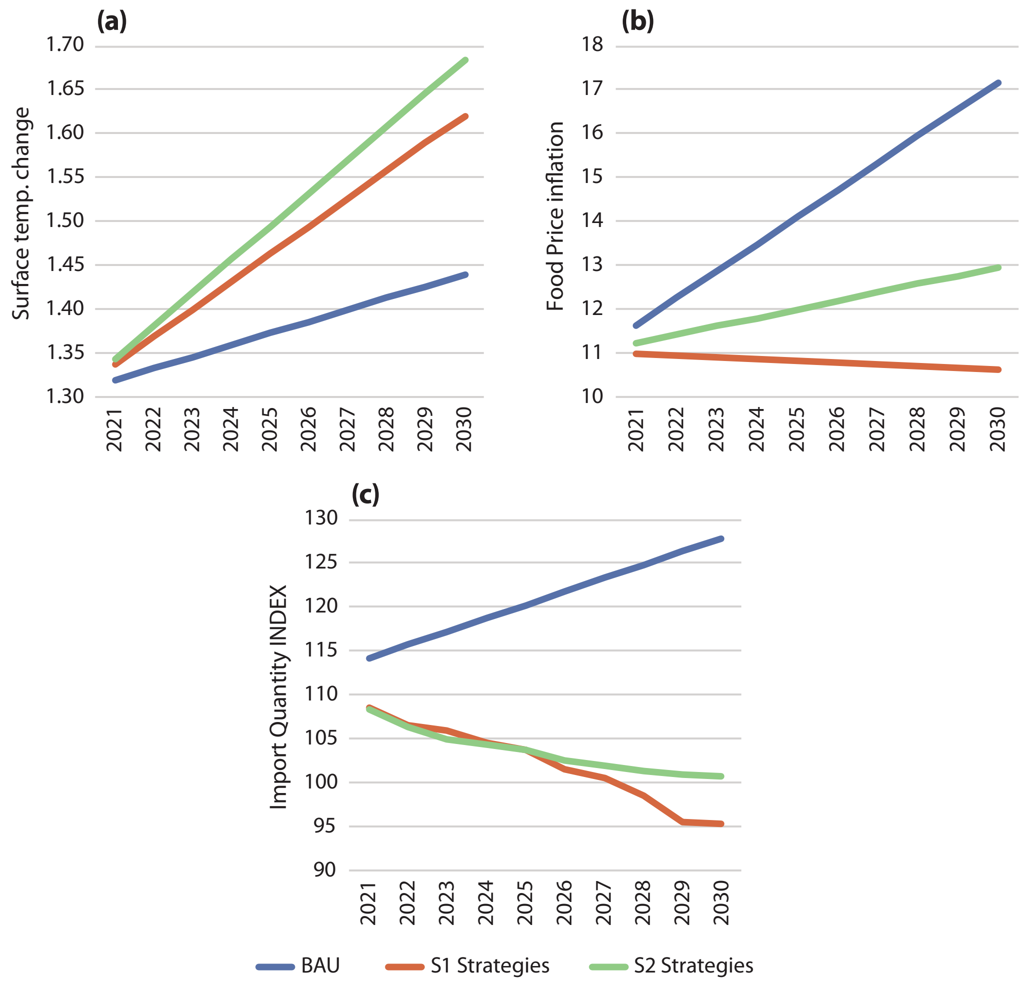
FIGURE 7.5—SNAPSHOT OF THE LOGICAL IMPLICATIONS OF THE CONSTRUCTED SCENARIOS AGAINST THE BUSINESS-AS-USUAL CASE



Source: Obtained from the application of ML models for forecasting.
Note: BAU = Business-as-usual; S1 = scenario 1; S2 = scenario 2.

can observe a profound shift in the number of undernourished people (230.8 million). A projected 23 million fewer people are undernourished, representing a 9.4 percent decrease when compared to the reference year 2020, when 254.7 million people were undernourished. In the second scenario, 83.2 million fewer people become undernourished compared to the BAU scenario. However, compared to the reference year 2020, there are a projected 11.7 million fewer people who become undernourished. Additionally, between 2021 and 2030, we observe a steady trend in absolute numbers for the projected number of people undernourished in scenarios 1 and 2. On the other hand, the BAU scenario shows a steeper increase to 326.18 million people who become undernourished, 71.5 million more than in the reference year, 2020.

FIGURE 7.6—SNAPSHOTS OF THE UNFOLDING FUTURES FROM THE CONSTRUCTED SCENARIOS



Source: Obtained from the application of ML models for forecasting.
Note: BAU = business-as-usual; S1 = scenario 1; S2 = scenario 2.

Interestingly, scenarios 1 and 2, respectively, result in a projected 7.3 and 15.5 million more obese people than the BAU scenario. This increase in the projected number of obese people represents 28.9 to 37.2 million more people projected to be obese compared to 2016 (81.5 million, as of the time of the study). Additionally, Figure 7.5(c) shows that scenarios 1 and 2 will result, respectively, in a projected 113.5 and 221.2 million people who will remain anemic. This represents a 7.5 percent reduction (scenario 1) and an 80.2 percent increase (scenario 2) compared to the 122.7 million people anemic in 2019. We observe a steady increase in minimum dietary intake to meet the reference daily calorie intake for an average adult. Despite the increase in supply, we observe an estimated decrease of 7.2 kcal/capita/day (scenario 1) and an increase of 15.9 kcal/capita/day (scenario 2) in dietary energy intake when comparing the scenarios against the reference year, 2020 (1,740 kcal/capita/day).

Moving on to observe projected changes in environmental and socioeconomic drivers, Figure 7.6 presents the logical unfolding of the future concerning temperature change on land, import quantity index, and food price inflation. In all scenarios, a rise in temperature is observed in the range of 1.43°C to 1.68°C, representing an 18.4–33.4 percent change from the reference year, 2020. In the food price index, there is a marginal decrease in scenario 1 (10.64) but an increase in scenario 2, to 13.0 at the end of 2030. However, in the BAU scenario, there is a dramatic increase, to 17.2, representing a 59.6 percent increase from the reference year, 2020.

Additionally, regarding the quantity of imports of foods, due to the projected increase in production, we observed reductions in the range of 12.3 to 17.4, representing 10.8 to 15.6 percent less than the reference year. The results presented in this section suggest that inherent and inevitable trade-offs must coexist to achieve sustainable and resilient food systems. As has been described above, there are instances where we observe projected reductions and increases, suggesting that depending on the indicator of interest to a decision-maker, a constructed food system scenario can be described as resilient and sustainable or otherwise.

Logical Flow of Increased Agricultural Production Scenarios at the Subregional Level

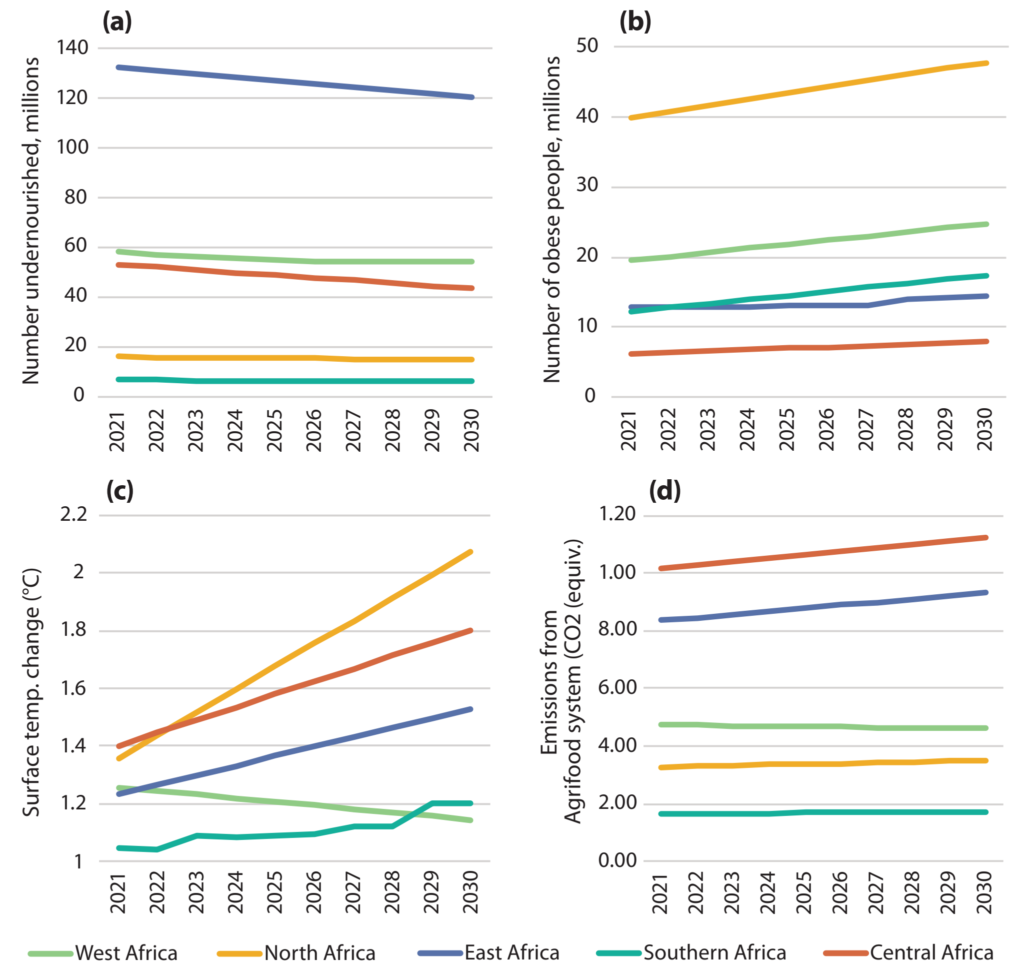
The analysis at the continent level extended to investigate the ramifications of the modeled scenarios at the subregional level. In this context, we explored the implication of the increased agricultural production scenario at five subregional levels: West, North, East, Central, and Southern Africa. Figure 7.7 presents the logical implications on four selected indicators. Across the different regions, it can be observed that the number of undernourished people decreases between 2.8 and 17.5 percent. The most significant reduction is observed in Central Africa (43.4 million), where an estimated 7.5 million people are projected to shift from being undernourished compared to the baseline year (51 million in 2020). However, the number of obese people increases between 23.9 percent and 35.8 percent across all regions compared to the baseline year, 2020. This time, Central Africa (1.9 million people) has the lowest number of people projected to be obese, as against West Africa, which has a projected 8.9 million people projected to be obese by 2030.

Within the environmental dimension, it can be observed that surface temperature change due to agriculture increases for all regions except West Africa, where it decreases from 1.22°C in 2020 to 1.14°C by 2030. The most significant increase is observed in North and Southern Africa, where surface temperature change increases by 36.2 percent and 40.5 percent above the baseline year levels of 1.32°C and 0.71°C, respectively. Similar observations are made when we consider emissions from agrifood systems. In this, emissions in the form of CO$_2$ (equivalent) increased between 5.5 and 11.5 percent for all regions except West Africa, where it was reduced by 4.1 percent below the baseline year.

Logical Flow of Increased Agricultural Credit Scenarios at the Subregional Level

Figure 7.8 presents the logical implications of the increased agricultural credit scenario at different regional levels. The plot narrative of this scenario suggests opposing yet similar trends when compared to the scenario of increased

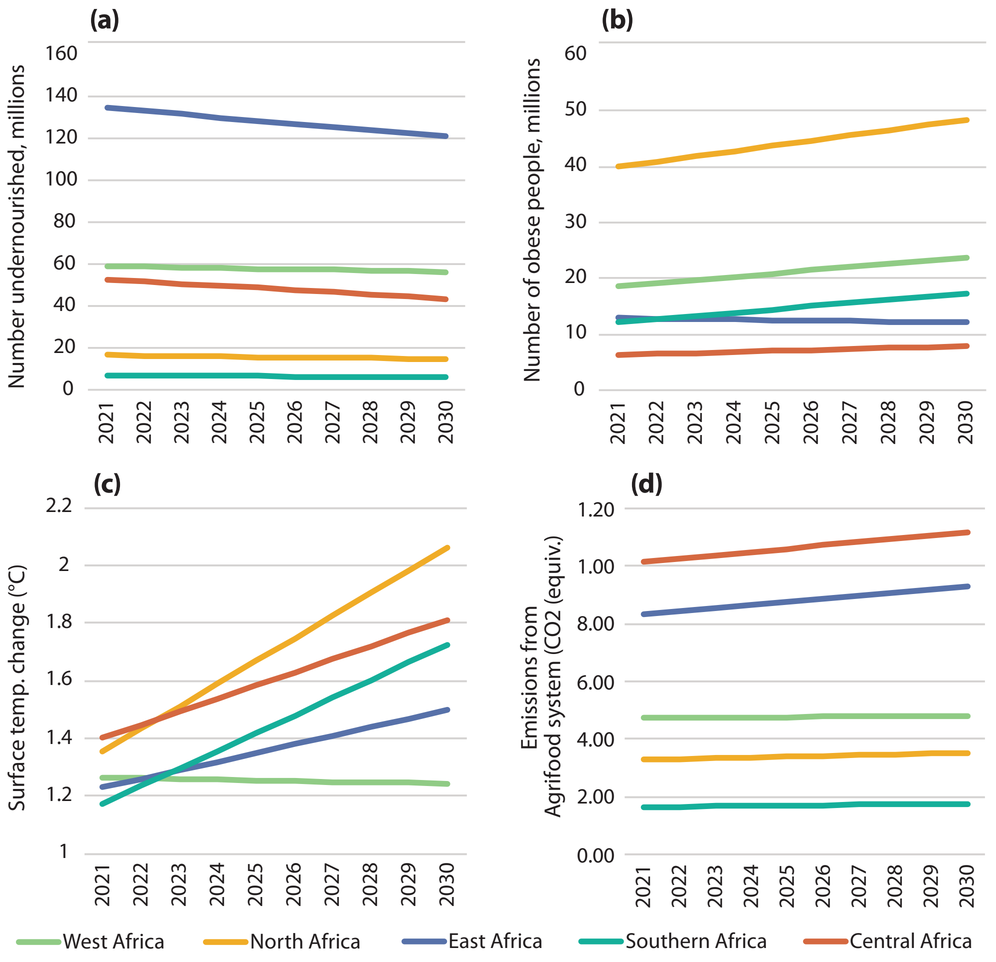
FIGURE 7.7—LOGICAL FLOW OF EVENTS ACROSS THE DIFFERENT SUBREGIONS ON THE AFRICAN CONTINENT



Source: Obtained from the application of ML models for forecasting.

agricultural production. For example, in West Africa, 600,000 more people become undernourished, while the North, East, and Southern Africa regions are projected to experience a 2.7–4.4 percent decrease in the number of people who become undernourished. In all regions, there is a projected small (0.1–1.7 percent) or no (Central Africa) change in minimum dietary energy intake in 2030 compared to 2020. Contrary to the scenario of increased agricultural production, in the possible future of this scenario, we observe an increase in surface temperature change across all regions, of between 2.3 percent (West Africa) and 58.7 percent (Southern Africa).

FIGURE 7.8—LOGICAL FLOW OF IMPLICATIONS ACROSS SUBREGIONS UNDER THE SCENARIO OF INCREASED AGRICULTURAL CREDIT



Source: Obtained from the application of ML models for forecasting.
Note: BAU = business-as-usual; S1 = scenario 1; S2 = scenario 2.

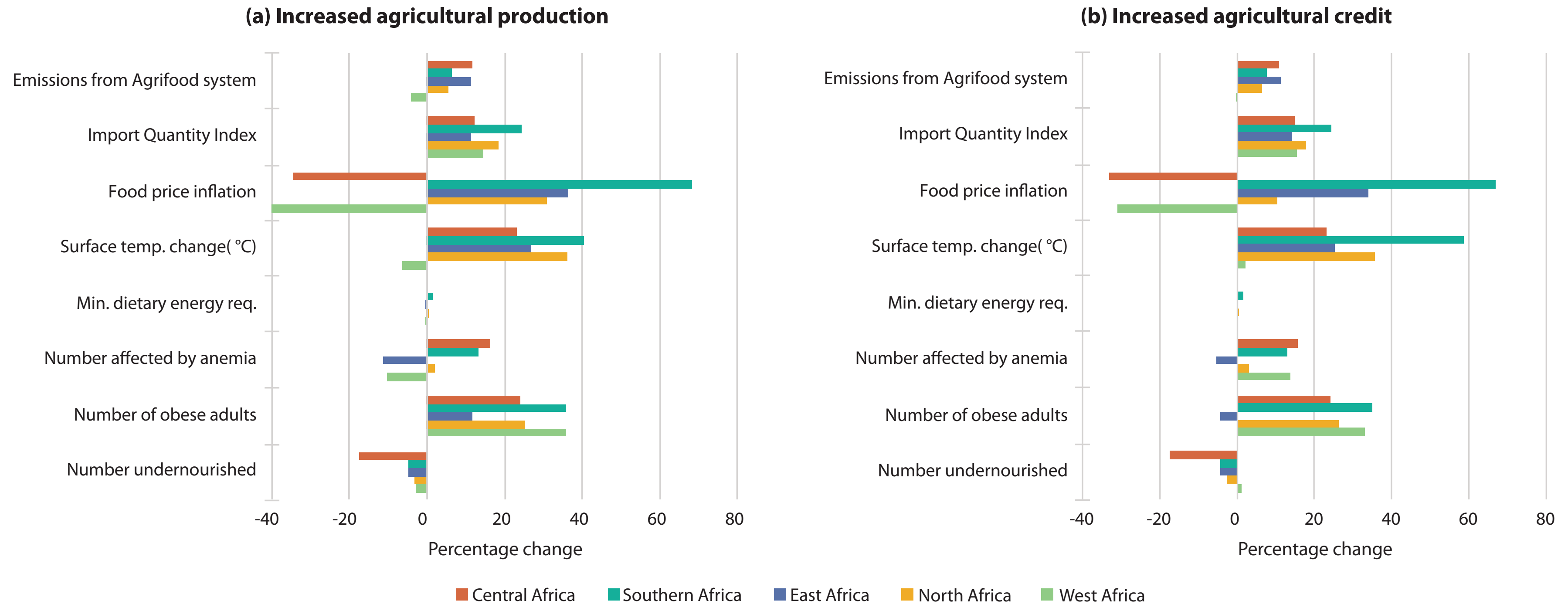
Overall, the constructed scenarios have illustrated the possible outlook within the African food system in the future by providing an opportunity to compare different outcomes. Inferring from the different outcomes, it is inevitable that inherent trade-offs must be accounted for if the African food system is to be repurposed to address its pressing sustainability issues through the revision of the Malabo 2015 agenda.

Figure 7.9 provides a much more straightforward way to evaluate the effects of the different scenarios across the selected indicators using two snapshots: one at the baseline year of 2020 and the other at the endline year of 2030. In both stylized scenarios, the findings suggest little to no change in the minimum dietary energy intake at continent and subregion levels. Interestingly, regions such as West Africa and Central Africa are projected to experience significant reductions in food price inflation—estimated to be 30.9–40.2 percent and 33.3–34.5 percent, respectively, when the baseline year, 2020, is compared to 2030. Across different regions, we observe significant variations; however, the two snapshots for both scenarios suggest a significant change for some indicators, while others will not change significantly in the future.

Translation of Models into a Decision Support System

Scenarios can be powerful tools for exploring the implications of different decisions. Pairing scenarios with relevant food system drivers and sustainability indicators provides an opportunity to predict the future of Africa's food system. This section proposes developing a novel decision support system using the ML algorithms presented in this study to enable stakeholders and policymakers to explore scenarios for a resilient and sustainable African food system. In addition to the ML algorithms, the proposed decision support system was built on the f-RESUS,

FIGURE 7.9—SNAPSHOT OF THE EFFECT OF THE STYLIZED SCENARIOS BETWEEN BASELINE (2020) AND ENDLINE (2030) REFERENCE YEARS



Source: Obtained by finding the difference between the baseline year and the forecasted endline year.

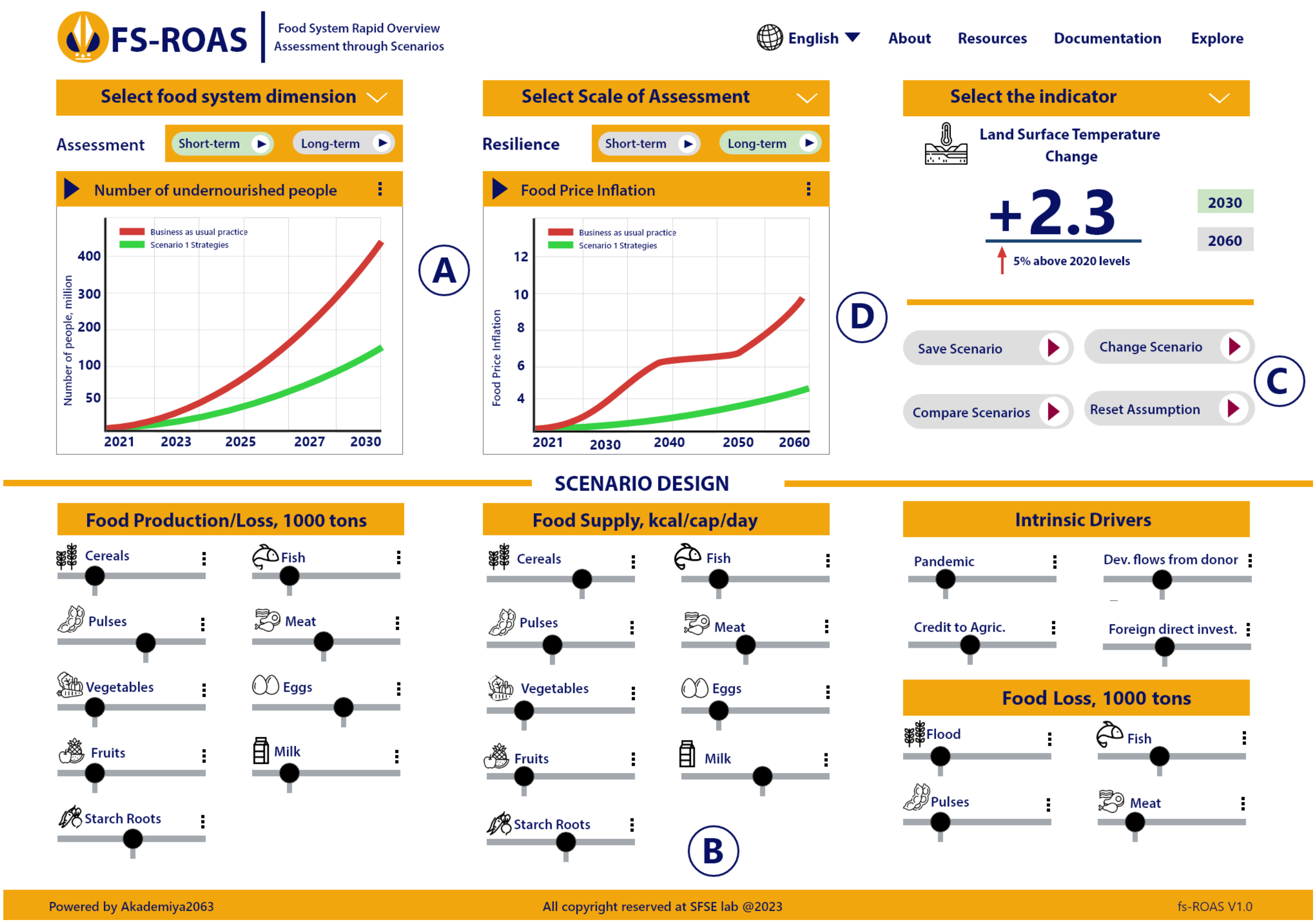
Note: A negative change connotes a reduction to levels more desirable, while a positive change refers to an exacerbation of challenges related to indicators to undesirable levels.

presented above; it provides the logical framework for designing and adapting the proposed decision support system.

The proposed decision support system, FS-ROAS, provides an opportunity to analyze food system transformation with harmonized sustainability and resilience indicators across four dimensions. Figure 7.10 presents the dashboard for the FS-ROAS decision support system.

FS-ROAS is characterized by specific modules that support assessing and designing mitigation strategies and comparing different strategies (marked A to D). The Reset Assumption button enables users to revert to the baseline scenario described earlier in the chapter. Likewise, the Change Scenario button enables a user to construct plausible scenarios, while the Save Scenario button supports storing the outcomes of an explored scenario. The Comparison Scenario button enables a comparison of possible outcomes for two or more constructed stylized scenarios against the BAU scenario. Depending on data availability, the proposed assessment and construction of stylized scenarios to address the multiple challenges of the food system can be translated to regional, national, and local food systems. Thus, conducting a similar analysis for specific regions and countries is possible.

FIGURE 7.10—DASHBOARD FOR THE F-ROAS DECISION SUPPORT SYSTEM



Source: Authors and based on the work of Agyemang et al. (2022). All icons used were obtained from flaticon.com and freepick.com.

Study Limitations/Shortcomings

The use of ML models in operational settings poses practical difficulties related to the setup of the modeling framework. ML workflows often consist of model and feature selection, hyperparameters, and model testing in a way that is relevant to an application. This makes it data-intensive—but there was not a large dataset available for the present study. A dataset of size 735, which can be described as data-poor, was applied in this study, generating many conflicts between the training and testing phases. Additionally, using a data-poor system may lead to information leakages between the training and test datasets.

Future Research in this Area

Future studies will investigate incorporating data that capture other food drivers within the food systems, thus increasing the size of the dataset used in training and forecasting. Further research will also explore the calibration, practical significance, and testing of ML models, such as neural network regression techniques, to increase the robustness of the predictions. More studies will focus on developing the proposed FS-ROAS decision support system and testing it with stakeholders and policymakers within the African food system.

Implications of the Study on the Malabo Declaration on African Agriculture and CAADP

Drawing insights from the present study and learning from previous practices that have shaped the current African and subregional food system is critical to the decision-making process among African heads of state. Strengthening African food systems to increase resilience and sustainability involves a wide range of strategies aimed at tackling the complexities and interconnectedness of agricultural, socioeconomic, and environmental factors. Some commitments within the Malabo Declaration on CAADP in 2014 suggested (1) recommitment to enhance investment finance in agriculture, (2) commitment to ending hunger by 2025, (3) commitment to enhancing the resilience of livelihoods and production systems to climate variability and other shocks, and (4) reaffirming commitment to end hunger by 2025 through strengthening development policies. However, the lessons from the stylized scenarios, which leveraged ML models that employed data from previous food system elements since 2000, suggest that multiple trade-offs must coexist to achieve a sustainable food system in Africa. In other words, if policymakers are to recommit to similar policy mitigation strategies, then there must be an opportunity to explore what possible endpoints can be achieved during the revisions of the Malabo Declaration on African Agriculture and CAADP.

As demonstrated through the stylized scenarios of increased agriculture production and increased agriculture credit, a recommitment to declarations in harmony with these scenarios could result in an estimated 11.75 to 23.81 million fewer people who become undernourished by 2030. Additionally, 9.2 million fewer people are projected to be anemic, while import quantities are projected to be reduced by between 12.2 and 18.5 percent compared to the baseline year, 2020. However, policymakers must bear in mind potential unintended consequences, such as the projected increase in obese people (28.9–37.1 million more people), the increase in surface temperature change to 1.62°C–1.68°C, and increased emissions from agrifood systems (3.7–7.6 percent higher than 2020 levels).

The proposed decision support systems provide an opportunity to explore stylized scenarios such as agricultural production diversification, climate-smart agriculture promotion, education and training, and policy and institutional reforms. Exploring such scenarios could give policymakers a broader perspective and opportunity to envision snapshots of the future of Africa's food system when revising and recommitting to the Malabo Declaration on African Agriculture and CAADP.

Concluding Remarks and Recommendations

This chapter set out to develop a forensic framework incorporating multiple components and outcomes across multiple scales and levels, including social, economic, health, and environment, through harmonized sustainability and resilience dimensions and indicators. In harmonizing candidate dimensions, a fuzzy entropy weight within the ranges of 0.31–0.61, 0.29–0.45, 0.33–0.53, and 0.29–0.62, respectively, was estimated for their closeness to the food security and nutrition, socioeconomic, politics and governance, and environmental dimensions of sustainability. The aggregated weighted scores demonstrated the relative closeness of the candidate dimensions to the aggregated dimensions and the extent to which the stakeholders surveyed considered the candidate dimensions to be associated with the harmonized dimensions. Also, we have highlighted how the outputs of the framework and the underlying ML models can be further translated into a decision support system, FS-ROAS. The FS-ROAS allows the prediction of the main characteristics of future African food systems against BAU conditions. Additionally, ML models provide an opportunity to capture interactions between different segregated components and the drivers of the African food system. The preliminary findings from the scenarios indicate that significant trade-offs between different food system outcomes must be accounted for to achieve a sustainable African food system. In the scenarios, there is the potential to increase the minimum dietary intake by 15.9 kcal/capita/day and reduce the number of people affected by undernourishment by 83.2 million. However, in achieving these targets, there is also the potential to increase the level of obesity by between 28.9 million and 37.2 million more people. While the potential for health benefits is rather grand, there are anticipated sustainability benefits and detriments that will coexist to achieve a sustainable food system within the short and long time frames.