Multidimensional Framework for Achieving Sustainable and Resilient Food Systems in Nigeria

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Abstract

Africa faces the grand challenge of feeding a growing, more affluent population in the coming decades while reducing the environmental burden of agriculture. Approaches that integrate food security and environmental goals offer promise for achieving a more sustainable and resilient food system for the continent and for adapting to a changing climate. Here we outline a multidimensional framework to be applied to the case of staple crop production in Nigeria with the

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eventual intended purpose being to inform sustainable and resilient food security pathways for the country. This chapter begins by presenting a broad overview of global food security challenges and distant and local drivers of food production decision-making, with the focus of then turning toward the food security and sustainability issues facing sub-Saharan Africa and Nigeria. The chapter then introduces a novel international collaboration focusing on food security and sustainability in Nigeria – the Assessing Climate Resilient and Nutritious Crops (CRENUT) project – the primary aim of which is to link stakeholder involvement, technical expertise, and multiple types of information to achieve policy-relevant research outputs that can enhance science-based agricultural decision-making in Nigeria. This project will follow a set of five key steps to move from basic scientific discovery to its application through agricultural policy: (1) in-depth understanding of stakeholder priorities and goals; (2) an assessment of data needs, data availability, and options for data generation; (3) analysis to develop strategies to align multiple goals and to fully understand the potential co-benefits or trade-offs associated with a particular agricultural policy; (4) identification of policy mechanisms by which the desired food security and sustainability outcomes can be achieved; and (5) the transfer of this collective knowledge to inform science-based decision-making related to agriculture and food security. In doing so, this chapter present a universal approach that can be used to identify a host of desirable policy pathways which, if pursued, can promote the sustainable development of Nigeria's agricultural sector and can realize co-benefits for nutrition, rural livelihoods, and climate change adaptation.

Keywords
Sustainability · Climate change · Food security · Water resources · Greenhouse gas emissions · Rural livelihoods · Agricultural policy · Food prices · Diets · Nutrition

Introduction: Achieving Sustainable Food Security in a Changing Climate: A Global Challenge

Global food supply has nearly tripled over the past half-century (FAO 2017) driven by demands resulting from demographic growth and improvements in income (Alexandratos and Bruinsma 2012; Tilman et al. 2011). Since World War II, global population has more than doubled from 3.1 billion (1961) to 7.6 billion people (2017), with South and East Asia experiencing the most substantial increases (UN-DESA 2015). Rising incomes have also meant that households can afford richer diets with higher calorie and protein intake per capita (Tilman et al. 2011). This general improvement in household economic status has meant that 216 million people in developing countries were able to escape undernourishment between 1991 and 2015 alone (FAO/IFAD/WFP 2015). Yet substantial nutritional deficiencies persist in many parts of the developing world with roughly one in nine people receiving inadequate protein and calories and still more lacking access to important micronutrients (FAO/IFAD/UNICEF/WFP/WHO 2017). Food security challenges related to ensuring nutritious food supply and equitable food access continue to disproportionately affect nations in the developing world, while habits of over-consumption have become commonplace elsewhere (Alexandratos and Bruinsma 2012).

Rising incomes and associated shifts in diets have also led to a growing percentage of agricultural production not being used for direct human consumption. Due in large part to the usage of energy-rich oil cakes as feed, 51% of the world's crop calories are currently devoted to animal production (Davis and D'Odorico 2015; FAO 2017). The growth in demand for animal products – combined with a shift toward a more crop-dependent livestock sector – has substantially increased competition for crop use between direct human consumption and feed to support livestock (Thornton 2010). Due in large part to the efficient feed conversion ratios of monogastrics as well as the inherent variability in rangeland biomass production (Steinfeld et al. 2006), the world's livestock systems have been transitioning from an extensive, beef-dominated system toward a focus on concentrated, feed-reliant pig and chicken production (Davis and D'Odorico 2015).

In addition to demographic and dietary changes, there has also been a rapid increase in demand for crop-based biofuels since the start of the century (OECD/FAO 2017; D'Odorico et al. 2018). This has led to the growing diversion of crop supply – and the agricultural resources required to support it (Rulli et al. 2016) – toward the production of bioethanol and biodiesel. The increasing proportions of crop supply used for feed or biofuel has also been accompanied by substantial food waste. Currently, one-quarter of food production is lost or wasted at various steps along the food supply chain – from losses during production and storage to uneaten food on a person's plate – with distinct regional patterns (Gustavsson et al. 2011). The production of this lost and wasted food is supported by large environmental footprints (Kummu et al. 2012; West et al., 2014). This ultimately means that a large fraction of the natural resources dedicated to food supply in the places of production is not efficiently exploited while also made unavailable for natural systems and other uses.

The recent boom in global population was made possible by massive increases in crop production over the past 50 years, with global crop supply more than tripling and animal production increasing by 2.5-fold during this time (FAO 2017). For certain, the wide diffusion of high-yielding crop varieties has led to much of the tripling in food supply and avoided substantial cropland expansion. At the same time, these changes have rendered global food production highly dependent on external inputs of fertilizer, pesticide, and irrigation. Hence, the use of these crops to feed billions more people and to prevent the massive conversion of natural systems has come with important trade-offs, promoting cultivation practices with extensive environmental consequences (e.g., water resource depletion, overapplication of fertilizers, use of marginal or sloped lands) where policies and subsidies inadvertently allowed (Pingali 2016). As a result, the global food system has become one of the most extensive ways by which humanity has modified natural systems. Croplands and rangelands now cover 34% of the planet's ice-free surface (Ramankutty et al. 2008). More than half of accessible runoff is withdrawn for human use (Postel et al. 1996), with the vast majority of consumptive water use devoted to agriculture (Hoekstra and Mekonnen 2012). Fertilizer production has more than doubled the amount of reactive nitrogen in the environment (Schlesinger 2009), while greenhouse gas emissions from food production (e.g., ruminant digestion, fertilizer denitrification) and land-use change contribute 19–29% of humanity's greenhouse gas emissions (Vermeulen et al. 2012). Shifts in diets toward animal-based products have enhanced the environmental impact of food production, as the livestock sector contributes disproportionately to the environmental burden of food production (Kastner et al. 2012; Mekonnen and Hoekstra 2012; Herrero et al. 2013; Eshel et al. 2014; West et al. 2014; Davis et al. 2015a). Trends within animal production toward more feed-reliant systems have also led to important environmental trade-offs, where improvements in land-use efficiency and GHG emissions per unit of animal production have been offset by the mounting water and nitrogen requirements of feed production (Davis et al. 2015a).

In addition to these mounting environmental impacts, the nutritional quality of global cereal production has also declined steadily with time, as nutrient-rich cereals have been supplanted by high-yielding rice, wheat, and maize varieties (DeFries et al. 2015). This has been in part driven by the increasing prevalence of large farms which generally produce a less nutritionally diverse set of crops (Herrero et al. 2017) and has resulted in dwindling amounts of key nutrients such as protein, iron, and zinc being produced per ton of cereal crop (DeFries et al. 2015). In addition, climate change is already impacting crop yields in key agricultural regions (Lobell et al. 2011). Enhancements of atmospheric CO_2 concentrations are also expected to exacerbate these declines by adversely affecting crop nutrient content in plant tissue, especially in C3 crops (e.g., rice, wheat) (Myers et al. 2014). Though food supply remains largely nutritionally adequate at the global scale, the persisting challenges of food access and widespread malnourishment and nutrient deficiencies amplify these trends in nutritional quality.

Massive levels of production, pressures on crop supply for multiple uses, and expansive environmental burden all characterize the current state of the global food system. This system has also become increasingly globalized, with 23% of food calories currently traded internationally and three out of four countries reliant on food imports to meet domestic demand (D'Odorico et al. 2014; Davis et al. 2014a). The steady rise in connectedness has ultimately been fueled by rising incomes, both directly and indirectly. For example, increasing demand for animal products – and the feed required to support their production – has meant that countries with emerging economies and a rising middle class (e.g., China) have had to depend more heavily on feed imports in order to support domestic animal production (Davis et al. 2015a). International food trade can act as either a buffer or a source of vulnerability for nations relying on food imports. On one hand, trade can allow countries to maintain populations above what locally available water resources would support (e.g., Suweis et al. 2013) and can act as a stabilizer when local production conditions are dependent on variable weather conditions, including precipitation patterns. On the other hand, this can leave importing countries more exposed to economic or environmental shocks that occur beyond their borders and beyond their direct control (e.g., D'Odorico et al. 2010; Puma et al. 2015; Suweis et al. 2015). The growing reliance on international food trade has also had differential effects on natural systems within importing and exporting countries. Because exporting countries can typically produce food with relatively high resource-use efficiencies, international food trade has led to important resource savings globally (Chapagain et al. 2006). However, for individual trade connections, a country may decide that the economic benefits of producing a particular crop may outweigh the environmental costs. The increasing importance of international food trade makes this kind of unsustainable production decision more likely, as trade has served to separate consumer choices from the environmental impacts of production (DeFries et al. 2010; Lenzen et al. 2012; Dalin et al. 2017) and allowed many high-income countries to displace environmental pressure into the developing world (Weinzettel et al. 2013).

Many countries have begun actively addressing their potential vulnerabilities within the global food system through various food security mechanisms, such as food self-sufficiency policies for key staple crops, fertilizer and irrigation subsidies, strategic reserves, and trade agreements. One such phenomenon that has recently received attention is the global land rush (Deininger 2013; Dell'Angelo et al. 2017). Since the start of the century, countries lacking in investment capital or access to agricultural technologies began encouraging direct investments in their agricultural lands in an effort to enhance local agricultural productivity, to support rural development and job creation, and to promote technology transfers. In response to the flexibility of these policies as well as to the growing perception of unreliable food trade linkages (e.g., 2008 food crisis), investors from import-dependent countries began acquiring large tracts of agricultural land in the developing world in an effort to expand the land and water resources under their control and to thereby enhance their capacity for absorbing shocks within the global food system (Davis et al. 2015b). While the initial intent of these land deals may have been noble, there is a growing body of scientific and anecdotal evidence showing that the development and food security goals of these investments are often not achieved (e.g., De Schutter 2011; von Braun and Meinzen-Dick 2009) and instead frequently bring substantial social and environmental consequences (see, e.g., Davis et al. 2015c; D'Odorico et al. 2017).

These realized and potential impacts are especially concerning for rural livelihoods, food security, and access to agricultural resources in the countries where the investments take place (including in Nigeria). One estimate found that the incomes of more than 12 million people could be lost globally if communities living within the boundaries of newly leased lands were displaced by large-scale land acquisitions (Davis et al. 2014b). Other studies have shown that such deals can place substantial additional pressure on the freshwater resources on which smallholder farmers traditionally depend (Rulli and D'Odorico 2013; Rulli et al. 2013) and can break cycles of local food production and consumption by facilitating exports (Rulli and D'Odorico 2014). For Nigeria and other developing countries, identifying mechanisms that support yield enhancements, technology transfers, and secure land tenure for these critical stakeholders is therefore essential for advancing global and local food security, promoting poverty alleviation, enhancing food system resilience, and ensuring the sustainable and equitable use of available (and often limited) natural resources.

As a result of these complex and interacting phenomena, the enhanced crop demands for food, feed, and biofuel – both locally and internationally – have increased the pressure on land and water resources. At the same time, global food production must increase substantially in the coming decades to meet the demands of a growing, more affluent world population. There is also universal recognition that strategies for achieving this additional food supply must enhance the nutritional quality of production while also avoiding additional environmental degradation and reducing the vulnerability of agriculture to climate change impacts (Lobell et al. 2008; Challinor et al. 2014; DeFries et al. 2015). In many agriculturally important regions, yield trends of major crops are already experiencing effects related to climate change (Lobell et al. 2011; Ray et al. 2015) and air pollution (e.g., Van Dingenen et al. 2009) and are expected to be further impacted if appropriate mitigation and adaptation strategies are not promptly adopted (Wheeler and von Braun 2013). For developing countries in particular, these potential declines in crop productivity combined with persistent undernourishment and steady demographic growth present formidable food security and sustainability challenges. It is thus essential for these nations to identify solutions that take into account multiple food security, environmental, and economic dimensions (e.g., MacDonald et al. 2015; Davis et al. 2017a). Sustainability and food security policies in countries with agriculture-based economies must determine whether additional natural resources are and will be adequately available to enhance production, especially in low-yielding areas (e.g., Davis et al. 2017b), and, if so, how to avoid their injudicious use (e.g., Pradhan et al. 2015). In this way developing nations can ensure that increases in production occur in places where and when natural resources can support it (see e.g., Hoekstra et al. 2012; Brauman et al. 2016; Mekonnen and Hoekstra 2016; Davis et al. 2017a). Only by accounting for the local economic, social, and environmental aspects of crop production can nations ensure that their food security goals are achieved sustainably and equitably (Pingali 2012; Garnett et al. 2013).

Local–Global Linkages, Drivers, and Impacts across the Global Food System

Global demands for food and feed are largely defined by population, dietary preferences, resource availability, and markets. Through their influence on the price that a farmer can ultimately obtain, all of these factors largely determine local choices regarding crops and management, thus linking global demands to local resource use. This local dimension may be further impacted by the local land tenure policy and property structure. With smallholder agriculture contributing about 70% of the world's food production (Samburg et al. 2016), how all of these local and global factors may benefit or impact rural livelihoods has important implications for the sustainable development of developing nations. Indeed, the inverse relationship between field size and yield (e.g., Chand et al. 2011; Larson et al. 2012) – after controlling for inputs – points to the central role that smallholder agriculture can play in ensuring future food security in the face of increasing climatic variability. By growing a greater variety of crop species, smallholders also help to retain resilience and diversity within croplands and agricultural systems. However, the fact that the majority of cultivated areas are rainfed also means that these farmers must cope with high and ever-increasing interannual variability in precipitation as well as more frequent extreme climate events and their negative effects on yield stability. To help minimize the exposure of these farmers to crop stress and potential failure, governments will need to help in expanding their adaptive capacity through improved access to irrigation, drought-resistant crop varieties, crop insurance, and alternative income sources. For irrigation expansion in particular, this will need to be implemented selectively so as to avoid the expansion of water-stressed areas. Overall, how governments and farmers choose to utilize these coping strategies will have significant implications for the local balance of water availability and demand and for the long-term sustainability of food systems.

The ongoing emergence of water scarcity – and stress on other agriculturally important resources – provides strong evidence that growing global demands are not well matched with sustainable food production sources (Fig. 1). In addition, the potential impacts of climate change on natural resource availability and the expected increases in natural resource demand from population growth will have important consequences for the magnitude and distribution of resource use and scarcity in the coming decades (Veldkamp et al. 2016). Exporting countries do not reap the food security benefits of a portion of their croplands but undergo the environmental costs (Suweis et al. 2013). Hence, they may need to reevaluate whether the economic benefits of doing so outweigh the impacts. The extent to which food production in both export- and import-dependent nations can cope with these challenges will therefore likely propagate to other parts of the world via food trade linkages. As such, how countries choose to meet domestic food demand – on the spectrum from complete food self-sufficiency to total import reliance – and how they respond to global market influences will determine the balance between their internal and external environmental footprints of consumption and their dependence on distant natural resources. For a resource-scarce country, this reliance on distant resources may prevent unsustainable resource use that might have occurred had the country produced the good domestically. However, food trade linkages can also expose that same country to economic or environmental shocks that occur beyond their control (e.g., Puma et al. 2015; Suweis et al. 2015). Based on the expected frequency and intensity of both remote and local shocks as well as the economic and environmental trade-offs they may be willing to accept, countries in sub-Saharan African and other developing regions will therefore need to decide how they focus resources – either on the improvement of local yields and their stability or on diversifying their trade linkages – in order to minimize their exposure to risk from climate change and variability.

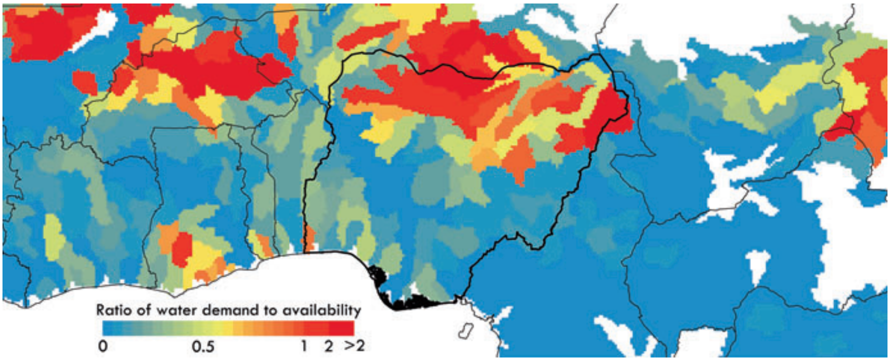

Fig. 1 Annual average water stress across croplands of West Africa. Water stress is calculated as the ratio of human consumptive water demand for crop production to annual renewable water availability (as defined in Brauman et al. (2016)). Water-stressed areas are defined as those areas where this ratio is greater than or equal to 1, i.e., where consumptive water demand exceeds renewable water availability. In these places, unsustainable water use is likely to occur, leading to the depletion of groundwater resources and/or of environmental flows. (Data on water stress came from Davis et al. (2017a). Nigeria is outlined with a bold black border)

While pressure on natural resources is a direct result of food production choices, these crop selections are ultimately dictated by global and local dietary preferences, economic mechanisms, and infrastructure that link the farmer to the consumer. The teleconnections of production and consumption decisions are essential to remember when developing solutions aimed at ensuring food system sustainability, rural livelihood development, and responsible resource use within agroecosystems. A radical shift in perspective is required in order to determine whether, where, and how food production should occur in the face of growing demand and a changing climate and to integrate food security goals with other sustainability objectives. All sustainable solutions for enhancing food security must begin by assessing whether sufficient resources are locally available – particularly in low-yielding areas (e.g., Davis et al. 2017b) – and to what extent these places can reliably support additional crop production. Only in this way can decision-makers ensure that increases in food production occur in places where and when natural resources can regularly support it (e.g., Wackernagel et al. 2002; Brauman et al. 2016), in order to avoid the local emergence of more severe stressed conditions. For many rainfed agricultural systems, this means not only accounting for the average amounts of food production and resource demand but also their potentially high interannual variability and their inherent trade-offs. By developing a baseline knowledge on resource availability and demand and how they are locally affected by management strategies, planners and policy-makers can make science-based decisions about which social, economic, and environmental outcomes and trade-offs will be acceptable to them and the people they represent.

The Challenges of Climate-Smart Agriculture in Nigeria and Sub-Saharan Africa

Achieving sustainable and climate-smart agricultural systems, addressing widespread undernourishment and nutrient deficiencies, and reducing dependence on food imports are a formidable set of challenges for sub-Saharan Africa. The region's population is expected to more than double by the year 2050, with major crop demand predicted to triple (van Ittersum et al. 2016). Further, much of the population of sub-Saharan Africa continues to rely heavily on staple crops (rice, maize, sorghum, millet, cassava, yams, and wheat) to meet nutrient requirements and – despite efforts at economic growth and human development – continues to experience substantial undernutrition. With the largest population on the continent (190 million people) and an expected population doubling before mid-century (410 million people by 2050), how and to what extent Nigeria will be able to sustainably meet future domestic food demand will have serious implications for global and regional food security in the coming decades. Compounding this demographic pressure, Nigeria already faces challenges related to food security and malnutrition (25% of the population is severely food insecure (FAO/IFAD/UNICEF/WFP/WHO 2017)), employment and poverty (the unemployment rate has tripled within this decade (NBS 2018)), and infrastructure (Foster and Pushnak 2011). In addition, a large portion of the Nigerian population relies directly on agriculture as their main source of income, a livelihood that leaves them especially vulnerable to climate variability and climate change. There is therefore a need not only to increase the production of and access to nutritious foods but also to buffer against anticipated climate impacts, minimize water use and greenhouse gas emissions, and promote sustainable and diverse rural livelihoods. While the country's large yield gaps and substantial potential for increased irrigation offer much promise for meeting its future food demand locally (van Ittersum et al. 2016), assessments of the nutrition quality, water use, emissions, climate resilience, and economic value of each staple crop in Nigeria are still missing but of great importance. Such work will provide an invaluable information base for the long-term sustainability of Nigeria's agricultural system and serve as an important next step in advancing the country's food and nutrition policies (MBNP 2016).

Indeed, recent work has shown that – in many areas of the world (including Nigeria) – the current distribution of crops still produces marked trade-offs between nutrition, water use, and economic value (Davis et al. 2017a). Other studies (e.g., DeFries et al. 2016) have also incorporated climate sensitivity into these considerations, showing that it is possible to make crop selections that realize co-benefits in terms of nutritional value, land-use efficiency, and climate resilience relative to current cropping patterns and practices. In Nigeria (and across sub-Saharan Africa), farmers that adopt appropriate crop diversification strategies will be able to better protect themselves from the adverse effects of climate change (i.e., climate change crucially affects farmers' crop choice decisions). This tactic of diversifying crop portfolios has already proven effective for mitigating the effects of climate variability experienced by farmers in developing countries (Barrett and Carter 2013; Mitter et al. 2015). Importantly, the extent to which this strategy can be adopted depends strongly on a household's capacity to perceive risk and to absorb shocks (e.g., price volatility, low rainfall) (Dercon and Christiaensen, 2011; Stuart et al. 2014). However, the potential advantages of selecting crops and cropping systems that better align outcomes in terms of nutrition, rural livelihoods, climate resilience, and environmental stewardship remain unclear for Nigeria.

The importance of agricultural transformation for economic growth, rural development, and poverty reduction is well documented (Babu et al. 2018), and this sector has been a priority in Nigeria's recent efforts to advance the country's economic transformation agenda. With the introduction of the Agricultural Transformation Agenda in 2011, Nigeria has made major strides toward defining and executing its policy objectives in the food and agricultural sector. Building on this progress, the new Nigerian government launched the Agriculture Promotion Policy in 2016. While these policies have improved the organizational and implementation strategies of the agricultural policy process (Babu et al. 2014), transformation of the sector remains both a challenging task and a critical lever for achieving sustainable development in the country. It is therefore essential to understand whether the current priorities of Nigerian agricultural policy also align with sustainable development objectives of the country (Babu and Blom 2014; Babu et al. 2014, 2018; FMARD 2016) and how and where agricultural strategies and crop choices can be improved to realize multiple economic, social, environmental, and food security benefits. To do this requires an assessment of the state of agricultural and sustainability information available in the country as well as the formulation of a multidimensional approach that can determine the various synergies and trade-offs associated with a particular policy pathway.

Toward Science-Based Agricultural Decision-Making: Steps for Achieving Policy-Relevant Research Outputs

The pathway in moving from basic scientific discovery to its application through agricultural policy involves multiple key steps, each of which can alone be difficult to achieve. This section provides a brief overview of the information, stakeholder involvement, and technical expertise required to achieve policy-relevant research outputs that can promote science-based agricultural decision-making. The five steps identified here are (1) in-depth understanding of stakeholder priorities and goals; (2) an assessment of data needs, data availability, and options for data generation; (3) analysis to develop strategies to align multiple goals and to fully understand the potential co-benefits or trade-offs associated with a particular agricultural policy; (4) identification of policy mechanisms by which the desired food security and sustainability outcomes can be achieved; and (5) the transfer of this collective knowledge to inform science-based decision-making related to agriculture and food security (Fig. 2). To complete this progression requires the involvement of and feedback from a diverse set of stakeholders and experts, as linking sustainable agricultural solutions with policy is a deeply cross-disciplinary challenge.

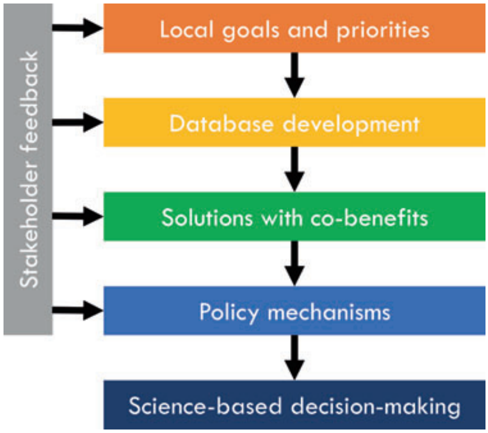

Fig. 2 Steps for informing sustainable agricultural decision-making

Understanding Stakeholder Priorities and Goals

Nigeria and the region of West Africa face well-known barriers to sustainability including pressing needs for enhancements of rural development, food security, environmental stewardship, and climate change adaptation. However, understanding how the country is choosing to address the various facets of sustainability in relation to agriculture – and which aspects they are prioritizing – demands close interaction with local experts, policy experts, and other stakeholders. These key persons can be intimately involved in informing all of the steps leading from scientific research to policy options, and these interactions between investigators and various stakeholders can serve as critical checks regarding the feasibility of particular strategies that could in principle help to move toward a sustainable agriculture system but lack real-world applicability or practicality. In addition, these collaborations can enhance the collective pool of expertise areas and resources available to a group of researchers, qualities which are essential in attempting to address inherently cross-disciplinary issues at the nexus of sustainability, agriculture, food security, and climate change. Input from local experts can also help to highlight linkages, trade-offs, or limitations that may not be apparent to investigators. For instance, if a researcher finds that a particular crop is drought-resistant and nutritious and has a low water footprint, they may recommend that this crop replace what is currently being cultivated in a particular area. However, it may be the case that the soil composition is unsuitable for the cultivation of any other crops, and any policy aimed at replacing the existing crop in these places would be doomed to fail. Access to the wealth of knowledge on these nuances of agriculture, food security, and agricultural policy therefore can only be achieved through sustained engagement with stakeholders, the relationships with whom require considerable effort to foster. Only in this way can academic researchers ensure that their work and insights reach those in a position to effect long-term sustainable changes within agriculture.

Data Availability and Data Generation

A formidable challenge facing agriculture and food security in Nigeria is a dearth of basic data availability and a lack of regular data collection. Depending on the specific institution or agency responsible for curating and updating particular information, these data issues may be manifested in a variety of ways. It may be the case that the data – though perhaps important for addressing certain key knowledge gaps – are simply not collected as there was never a program in place for their acquisition. Alternatively, the structure and financial support may be in place to support data collection – as with the case of Nigeria's agricultural census – but data collection simply does not occur. Even when the data are collected, the sampling methodology, data structure and representativeness, and other associated documentations can lack transparency and leave potential users unable to accurately assess the reliability of the information or to perform independent validation. This is not to say that the data collection schemes put in place are inadequate or deficient, simply that the supporting data description can make it difficult for independent investigators to fully understand the limitations of the data and are therefore often prevented from using it. It is also often the case that government data are either not publicly available, are not digitized or centrally stored, or face other bureaucratic or organizational challenges at the institutions in which they are housed. While many of these issues are beyond the control of the various bodies responsible for the management, oversight, and advancement of agriculture in Nigeria, they are ubiquitous – to a greater or lesser extent – across these agencies. Ultimately, these challenges significantly hinder the ability of the nation's experts and representatives to make informed recommendations and decisions related to agriculture, food security, rural livelihoods, and options for climate change adaptation of the sector.

In particular, there is little information on the environmental impacts of crop production in Nigeria. Yet this information is essential for informing food security and sustainability efforts and for examining the multidimensional outcomes of policy pathways for climate change adaptation in the country. To this end, the authors have established the Assessing Climate Resilient and Nutritious Crops (CRENUT) project with two main objectives. The first objective is to combine agricultural census data, crop water models, climate datasets and projections, remote sensing techniques, and economic information to quantify the greenhouse gas emissions, water use, nutritional quality, climate resilience, input costs, and prices of the staple crops grown throughout Nigeria. Information on the total energy use of the agricultural sector, the number and types of irrigation pumps, irrigation use by crop, shares of surface and groundwater use, groundwater depth, fertilizer application, and machinery will be combined to estimate crop-specific energy requirements and, as an extension thereof, greenhouse gas footprints (Rao et al. in review). Gridded crop-specific water footprints will be calculated as the crop water demand (i.e., the water required to prevent crop water stress) using a process-based crop water model. Crop water demand will be disaggregated between the crop water demand met by precipitation (green) and irrigation (blue) and will be calculated under current and future climate conditions (Chiarelli et al. 2016; Olayide et al.

2016; Davis et al. 2017a). Data on the nutrient content of staple crops (e.g., calories, protein, iron, vitamin A, etc.) will come from Nigeria's national nutrient composition report (Oguntoya and Akinyele 1995). These values will then be used to convert tons of production into nutritional supply to better target specific macro- and micronutrient outcomes. The climate sensitivity of each staple crop will be assessed based on the historical variation of each crop's yields in relation to interannual variability in rainfall and temperature using a mixed-effects modeling approach following DeFries et al. (2016). Model coefficients will be calculated separately for individual crops based on the geographic distribution of their cultivation and analyzed at the scale of agroecological zones. Output coefficients for precipitation and temperature will then be used as proxies for climate sensitivity. Input costs will be assessed utilizing available production cost data combined with much of the information used in the quantification of crop-specific greenhouse gas emissions. Lastly, information on consumer price and producer price will come from the FAO (2017).

Identifying Strategies for Aligning Multiple Sustainability Goals

The second objective of the CRENUT project is to assess the potential benefits and shortcomings of alternative, high-nutrient staple crops in Nigeria agricultural production. The above analyses will provide essential information to enable comparisons across the multiple aspects of nutrition, economic and cultural value, climate resilience, emissions, and water use (Fig. 3). These data be used to compare the climate resilience of different staple crops and assess where and to what extent particular staple crops can potentially contribute to Nigeria's nutrition security, income security, emissions reductions, and water sustainability under climate change. It will also be possible to consider scenarios in which each dimension is prioritized and examine the effect of such a choice on the other dimensions. For instance, by maximizing nutrient supply, it will be possible to determine its effect on economic value, overall climate resilience, and water use. The suite of possible outcomes will be examined for both current and future climatic conditions to understand whether incentives for alternative crops would be economically, socially, and environmentally meaningful in the long-term for Nigeria. In a more policy-relevant vein, this combined information will allow for an informed examination of the nutritional, economic, environmental, and climatic implications of a variety of possible food security and sustainability policy pathways and will thus allow decision-makers to determine whether the resultant co-benefits or trade-offs represent acceptable outcomes and, if so, to then explore policy levers for the achievement of those changes. It may be the case that specific policy mechanisms (e.g., government agricultural support programs) may already provide the necessary levers for achieving a particular outcome and that a modification of the specific included crops or subsidies may be all that is needed. Pursuing existing policy avenues can also help to ensure that a desired change is more rapidly enacted and that the necessary budgetary allocations are already in place. Overall, the planned data generation component of the CRENUT project will not only provide valuable agricultural

Fig. 3 Example comparison of crop dimensions for India. For each dimension, values are reported relative to the highest value in that category among the crops considered. For crop prices, for instance, rice had the highest price per ton; the per ton price for each crop was then divided by that of rice. Centered on the year 2006, data on price, climate sensitivity, calories, protein, and iron are from DeFries et al. (2016). Zinc data are from the USDA (2018). Irrigation water requirement data are from Mekonnen and Hoekstra (2010) for all of India. All data were originally reported on a per weight basis – except for climate sensitivity (unitless). A high value for climate sensitivity indicates greater vulnerability to rainfall and temperature variability. A high value for water indicates a high irrigation water requirement. The same multidimensional approach can be applied to Nigeria

information that is lacking for Africa's most populous country but can also (more importantly) be used to inform science-based agricultural decision-making in Nigeria and to identify optimum pathways for enhancing food security and sustainability within the country.

Policy Mechanisms for Implementation

A deep understanding of agricultural policy is essential for developing realistic and readily implementable solutions to the sustainable development of Nigeria's agricultural sector. It is possible to develop a multitude of hypothetical scenarios for enhancing food system sustainability within the country, but if a clear pathway to their realization does not exist, then their real-world applicability comes into question. Close engagement with local experts and stakeholders is therefore vital for eliminating glaring erroneous assumptions and for identifying feasible scenarios that account for multiple considerations related to agricultural policy, nutrition, environmental impacts, rural livelihoods, cultural preference, climate resilience, food prices, and input costs. The multidimensional approach introduced here offers promise for determining if and how trade-offs may occur, but it is ultimately the responsibility of policy-makers to decide whether such trade-offs would be acceptable to the people that they represent.

Science-Policy Interface and Science-Based Decision-Making

All of the previous steps are ultimately aimed at providing a collection of evidence that can be used to inform sustainable and resilient agricultural decision-making. By quantifying the various characteristics of the production of a variety of staple crops and by examining feasible scenarios of potential future crop production patterns, this can provide policy-makers with a spectrum of outcomes and allow them to readily examine the synergies and trade-offs associated with a particular future trajectory or policy pathway (Fig. 3). As such, this approach attempts to address a major challenge with which decision-makers must frequently contend – formulating sustainability policies with incomplete or imperfect information. In examining these multiple dimensions related to nutrition, livelihoods, environmental stewardship, and climate resilience together, policy-makers can then make more informed determinations as to whether any potential trade-offs would be acceptable for them and the people that they represent and ideally identify strategies that achieve a host of desirable outcomes simultaneously.

Feedback from and interactions with stakeholders is an essential component for all of the steps outlined here. This feedback is vital for better understanding local goals and priorities, for identifying dimensions or outcomes that are of greatest importance, for determining the data availability and needs to assess those outcomes comprehensively, and for developing solutions and strategies that conform to the nuances of local policy, culture, and society. In general, feedback between the first three steps – all of which occur before a policy change is instituted – can occur relative rapidly. By comparison, the feedback from monitoring and evaluation of an enacted policy change aimed at sustainability and climate change adaptation occurs on much slower iterations and within the limited scope and responsiveness allowable under that particular policy. This information is critical in determining if an intervention is not only having the intended outcomes but also avoiding any unintended consequences or negative externalities.

The ability of Nigeria to make informed science-based decisions related to agriculture and food security depends on a host of factors that extend beyond sustainability science alone (e.g., governance, research funding). Nonetheless such decisions cannot take into account considerations of sustainability unless sufficient information is available on which to base those decisions. The aim of the CRENUT project will be to fill important information gaps related to agriculture and the environment and to support decision-making related to food security, agriculture, and sustainability at all levels of government. Based on this knowledge, it will then be possible for the country to examine the long-term viability of the Nigerian Agricultural Policy and other guiding food security policies, to determine whether current practices will allow Nigeria to meet longer term sustainability goals (e.g., Sustainability Development Goals; Paris Accord), and to identify additional or alternative strategies that can enhance climate resilience and food system sustainability.

Sustainable Pathways for Meeting Future Food Demand in the Face of Climate Change

There is wide agreement that humanity's rate of resource use exceeds what can be sustainably generated and absorbed by Earth's systems (Wackernagel et al. 2002; Rockström et al. 2009; Galli et al. 2014; Hoekstra and Wiedmann 2014; Steffen et al. 2015). It is also clear that a continuation of current agricultural practices will enhance the vulnerability of the global food system to economic and environmental shocks (Suweis et al. 2015). A radical transformation of food systems across the planet is therefore required in order to increase nutritious food production while minimizing its environmental impacts and facing uncertainties related to demand and climate impacts (FAO 2009; Tilman et al. 2011; Alexandratos and Bruinsma 2012; Rosenzweig et al. 2014; DeFries et al. 2015). In addition, there is a growing need for agricultural solutions that better accommodate future uncertainties in natural variability in agricultural systems. Large crop yield gaps still exist in Nigeria and across sub-Saharan Africa (Mueller et al. 2012; van Ittersum et al. 2016) and offer farmers and the country the potential to substantially increase crop production, the local supply of food, and its stability. In addition, many places with the potential to transition to double-cropping systems have yet to do so (Ray and Foley 2013). By enhancing crop yields in those places where water resources can sustainably support it, Nigeria can improve its ability to cope during future climatic stress and can increase the strategic food reserves at its disposal. Doing so can also prevent additional agricultural expansion, the consequences of which would be profound and undesirable for the functioning of natural systems (Foley et al. 2011; Tilman et al. 2011). On the one hand, this agricultural intensification offers great promise for increasing the food self-sufficiency of regions of Nigeria that are subject to substantial interannual variability in rainfall (van Ittersum et al. 2016; FAO 2017). On the other hand, these remaining yield gaps raise questions about how best to promote the diffusion of high-yielding crop varieties and agricultural technologies – given that these agricultural advancements have yet to reach many places even 50 years on from the start of the Green Revolution (Pingali 2012) – and whether the primary focus of agroecosystems in northern Nigeria (where rainfall is inherently highly variable) should be to maximize yields or stabilize them. How the nation deals with these regional trade-offs between system redundancy and efficiency will be central in determining its long-term sustainability in the coming decades (e.g., Suweis et al. 2015).

Other recent work has shown the potential to maintain or reduce current levels of resource use while increasing crop production – thereby eliminating large inefficiencies in production systems. One such study demonstrated the possibility of using different irrigation and soil management strategies to close the crop yield gap by half without increasing cropland area or irrigation use (Jägermeyr et al. 2016). Other work showed that by redistributing crops based on their suitability, it is possible to increase food production while also realizing substantial water savings (Davis et al. 2017a, c). Still further work is needed to better understand how economic and environmental factors influence farmers' planting decisions and how the sum of individual farmer decisions ultimately dictates food availability, large-scale resource demand, and the overall climate resilience of the agricultural sector. These and other pursuits point to the need to integrate considerations of food, livelihoods, and the environment in developing more effective strategies for achieving sustainable food systems – ones that enhance the incomes and nutritional status of rural communities and that have a greater capacity to accommodate substantial interannual variability in precipitation. In identifying these food security strategies, Nigerian decision-makers will need to determine how best to effectively distribute the nation's risk to climatic variability and uncertainty in order to ensure that no single economic or environmental shock overwhelms its ability to buffer against it. Building resilience into all steps of these food supply chains – through the adoption of location-specific solutions and local knowledge – will be essential for achieving the long-term sustainability of agricultural systems in Nigeria.

More generally, the dilemma between increasing food supply and the environmental burden of production is a feature of historical agricultural approaches, and a large body of literature focuses on identifying strategies for its resolution (e.g., Godfray et al. 2010; Foley et al. 2011; Tilman et al. 2011). These potential solutions include enhancing crop yields on current croplands, improving resource-use efficiency, reducing food waste, and shifting to less resource-intensive diets – all of which can offer multiple benefits for the environment and for human health. Indeed, recent work has shown that employing a suite of these solutions can achieve food security and environmental co-benefits in the coming decades (Tilman and Clark 2014; Davis et al. 2016; Jagermeyr et al. 2016). Other work has shown that – by better aligning food security and environmental goals – it is possible to substantially reduce resource demand while also producing more food (e.g., Mueller et al. 2014; Davis et al. 2017a). While all of this research is a cause for optimism, the major challenge that remains in actualizing food system sustainability is in adapting these solutions to specific locations in ways that incorporate local priorities, that engender local buy-in, and that allow sufficient flexibility in adapting to climate change.

One key to addressing these challenges in Nigeria is to better understand the "wedges" – be they policy-based, cultural, infrastructural, or economic – that have produced discrepancies between current patterns of food production and those that optimize outcomes along the dimensions of nutrition, environmental sustainability, climate resilience, and livelihoods (e.g., Wada et al. 2014, NatGeo). Identifying and prioritizing certain "wedges" for intervention will require interdisciplinary approaches that link a global perspective – which accounts for the sometimes distant drivers of environmental change in Nigeria – with direct stakeholder engagement. In addition, understanding how local and distant policy and consumption decisions influence specific production choices – and acknowledging the growing role of international food trade in redistributing food (Wood et al. 2018) and its impacts of production – will be essential for effectively addressing sustainability challenges within food systems. Nigeria can complement these efforts through awareness initiatives and educational programs that inform the public of the environmental consequences of their dietary choices, including through the use of footprint tools (e.g., Leach et al. 2012), sustainability food labels (e.g., Leach et al. 2016), and guidelines for healthy eating (e.g., Tilman and Clark 2014), among other strategies. It is clear that any solution aimed at achieving sustainable food systems must be tailored to a specific place, taking into account nutritional, cultural, political, economic, and environmental factors. The approaches that will offer the most promise for achieving sustainable and climate-smart food systems will be those that best identify and minimize potential trade-offs and that seek ways to realize multiple co-benefits.

Conclusion

This chapter has provided a brief overview of the food security and sustainability challenges facing Nigeria and much of sub-Saharan Africa. Following from this, this chapter has outlined a five-step approach by which Nigeria (and other data-limited countries) may begin to address sustainability challenges related to agriculture and food security: (1) in-depth understanding of stakeholder priorities and goals; (2) an assessment of data needs, data availability, and options for data generation; (3) analysis to develop strategies to align multiple goals and to fully understand the potential co-benefits or trade-offs associated with a particular agricultural policy; (4) identification of policy mechanisms by which the desired food security and sustainability outcomes can be achieved; and (5) the transfer of this collective knowledge to inform science-based decision-making related to agriculture and food security. A nation can examine the co-benefits and trade-offs of a particular policy decision only if the information on dimensions of interest is available. The newly established CRENUT project introduced here will attempt to address these critical knowledge needs of the country by combining local expertise and technical capacity with in-depth and frequent input from government officials, decision-makers, and a variety of other stakeholders. These collaborations offer promise for best identifying the priorities of local communities and for aligning research objectives with national food security and sustainability goals. In doing so, this chapter has presented a universal approach that can readily incorporate the economic, nutritional, and environmental dimensions of greatest interest to a country. This approach can then be used to identify a host of desirable policy pathways which, if pursued, can promote the sustainable development of Nigeria's agricultural sector and can realize co-benefits for nutrition, rural livelihoods, and climate change adaptation.

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