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The new Malthusian challenge in the Sahel: prospects for improving food security in Niger

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Abstract
The world economy has largely overcome the Malthusian challenge, but there are regions such as the Sahel where this challenge remains formidable and food insecurity is exacerbated by multiple threats of climate change, low agricultural productivity, and high population growth. While the interactions among these forces governing long-term food security are widely discussed for policy making in the Sahel, analysis of the comparative magnitude of the forces in the resulting food security outcomes is largely absent. In this paper, we identify the relative contribution of these long-term drivers of food security outcomes in rural and urban Niger into 2050. We then consider three policy scenarios to address food security issues: accelerated investments in agricultural R&D (supply side), reduction of fertility rates (demand side), and market integration. We use a historically validated partial equilibrium model tailored to Nigerien agriculture, with data inputs gleaned from various sources, including household and farm surveys and grid-cell level production data. Our study finds that among growth in population, income, and agricultural productivity and climate change impacts on yields and labor productivity, population growth in Niger will remain the single largest driver of crop output growth and undernourishment in the country. Three-fourths of the increase in undernourished population is projected to be among the urban population. Climate change impacts on agricultural productivity will have differential impacts on undernourishment prevalence among rural and urban population, pushing an additional 2 million people into undernourishment by 2050. The relative impacts of climate change are larger among the rural population offsetting revenue gains from increased crop prices. We emphasize that feasible advancements in agricultural productivity are likely to be outpaced by rapid population growth and climate change setbacks unless simultaneous actions are taken on the demand side. On the supply side, interventions are required in transforming R&D spending into higher farm productivity. Greater integration into regional markets will also aide in mitigating undernourishment prevalence.

Keywords Food security · Population growth · Climate change impacts · Agricultural R&D · Partial equilibrium model · Niger

JEL Q54 · Q1 · J11

1 Introduction

At global scale, the Malthusian challenge in which exponential population growth is confronted with the prospect of linear agricultural output growth has been largely overcome with ongoing advancements in agricultural productivity, including the Green Revolution (Pingali, 2012; Otsuka & Muraoka, 2017), as well as declining fertility. Over the last half-century, world population doubled while food supply tripled, even as land under cultivation grew by only 12 percent (Pingali, 2012). As a result, despite soaring demands, over the course of the 20th century food prices (in inflation adjusted dollars) fell by an average of 1 percent annually (Fuglie & Wang, 2012) making food more accessible for the

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Table 1 Decadal growth rate (%) in population, income and agricultural TFP, output and input (Niger)

	1961–70	1971–80	1981–90	1991–00	2001–10
Population growth	2.8	2.8	2.8	3.5	3.7
Income growth (per capita GDP)	-0.8	-0.9	-2.7	-0.8	0.3
Agriculture					
Growth in total factor productivity	-2.1	-0.3	0.7	2.2	1.9
Growth in output	2.9	3.8	1.0	5.1	5.5
Growth in input	5.0	4.1	0.3	3.0	3.5
	Land extensification Labor intensification Droughts		Research in high yielding varieties	Dissemination & adoption	Slow-down in release of high yielding varieties

Empirical estimates of the agricultural TFP growth rate in Niger (and SSA in general) vary, but the consensus is that productivity declined in the first two decades of Niger's independence and started improving from the 1980s (Block, 2014; Fuglie, 2011)

Source: Agricultural output, input and TFP (author's calculation based on Fuglie (2018) using data from FAOSTAT), population (time series sourced from FAOSTAT which is based on UN World Population Prospects 2017 revision), real GDP (World Development Indicators), per capita real GDP (real GDP/population)

general population. Yet, the world is not on track to achieve Sustainable Development Goal 2 (SDG2) of Zero Hunger (FAO et al., 2020) and the Malthusian challenge remains a formidable one in the Sahel region of sub-Saharan Africa (SSA) where both caloric undernourishment and child undernutrition are rising (WHO, 2020). At the same time climate change impacts pose some of the biggest threats to food security in the region (IPCC, 2014).

Niger, which is situated in the Sahel, is a prime example of the new Malthusian challenge (Potts et al., 2011, 2013). Even though agricultural output growth has been considerable since the 1990s at around 5 percent per year (Table 1), it has not contributed to a commensurate reduction in poverty and food insecurity. Nigeriens suffer from a food insecurity situation that is categorized as serious level.[1] One of the primary reasons for this lack of success is the country's remarkably high rate of population growth. With an average of nearly 7.5 children per women, the total fertility rate in Niger is the highest globally (INS/Niger and ICF International, 2013). It is the only country in the world where population is projected to nearly triple by 2050 (UNDESA, 2019a). Landlocked and rainfed agriculture-dependent, Niger faces the challenge of feeding and employing the fastest growing (around 4 percent p.a.) and youngest population (50 percent aged < 15 years) in Africa (UNDESA, 2019a), with limited natural resources and human capital in an increasingly harsher climate. This is a perfect storm in the making.

The Sahel region has been identified as one of the most climate change vulnerable regions due to its high exposure to heat and low adaptive capacity (Niang et al., 2014). Moreover, fiscal resources are increasingly limited[2].With conflict and insecurity rising in the region, defense and security spending are crowding out funds for education, agriculture, and sexual and reproductive health which are crucial for long-term sustainability and resilience[3] (UNOWAS, 2018). Van Ittersum et al. (2016) estimate that even if Niger closes 80 percent of the yield gaps in cereal production by 2050, it will still not be able to maintain current level of cereal self-sufficiency without massive expansion into marginal cropland. Projected population growth from 23 million people today to around 65 million people in 30 years poses significant food security and sustainability challenges for Niger.

Against this backdrop, our paper answers three questions. First, which are the largest drivers of long run food insecurity in Niger? What are the likely *quantitative impacts* of key drivers of food security, including population growth, income growth, agricultural productivity, and climate change impacts, in determining Niger's food security outcomes in 2050? Towards this end, we focus on the following metrics: undernourishment prevalence, count and gap, as well as crop output growth. A second question is the following: How will rural and urban households be *differentially affected* by these developments? While most households in Niger are rural, as with much of Africa, rapid urbanization is underway (UNDESA, 2019b). Third, based on the answers to the first two questions, we ask what is the relative effectiveness of three widely discussed policy responses to this crisis: accelerated investments in

[1] Niger ranked 101 among 117 countries in global hunger Index (GHI) in 2019 with a score of 30.4. The cut off score for an alarming situation is 35. GHI scores are based on undernourishment, child wasting, stunting, and mortality levels.

[2] The public sector funding gap in the 10 Sahelian countries, on average, remain 32% of the required resources.

[3] Security related spending rose from 1.5 percent of GDP in 2011 to 5.2 percent in 2015.

agricultural research and dissemination (R&D) for productivity growth (supply-side intervention), reduction in population growth rate (demand side intervention), and tighter integration into regional markets (trade).

We look at the issue from the angle of “double exposure” (Brown et al., 2017), whereby people and processes are exposed to both economic and climate-related shocks and stressors. Given the paucity of data and the limited knowledge about economic parameters governing the food system in Niger, we employ a modified version of the relatively parsimonious global partial equilibrium model of crop supply and demand in the agriculture sector named the Simplified International Model of Crop Prices, Land Use and the Environment (SIMPLE) model (Fig. 3) (Hertel, 2011; Hertel & Baldos, 2016b). SIMPLE has been used to analyze adaptation to climate change (Baldos & Hertel, 2015; Lobell et al., 2013), the role of R&D and productivity growth in ensuring food security and environmental sustainability (Baldos & Hertel, 2014; Hertel et al., 2014) as well as the impacts of reducing food waste and post-harvest losses (Barrera & Hertel, 2020; Hertel & Baldos, 2016a). The modified model (SIMPLE-Niger) is tailored to Nigerien agriculture and is elaborated using data from Nigerien household and agricultural plot surveys to estimate rural income sources, undernourishment, caloric distribution of food, and input cost shares in crop production. Data from FAOSTAT and EarthStat are combined to produce agricultural production and land use data across five climatic zones in Niger. After validating the model against historical data, we project the economy forward to 2050 from the baseline year 2009, based on projected growth in population, income and total factor productivity (TFP), and anticipated climate change impacts on both crops and agricultural labor productivity. As we are looking at long-run trend impacts on food security, the climate change impacts in this paper refer to long-term trend impacts, as opposed to extreme events, which are also projected to increase in frequency and severity (Trisos et al., 2022). As the paper does not account for the immediate impacts of extreme events such as flood the climate change impacts on food security could be underestimated.

We make several contributions to the literature and policy discussion surrounding food security in the Sahel region. First and foremost, the paper informs policy discussion in a critical country in the region by providing comparative analysis of key drivers of food security outcomes. The importance of issues associated with population growth, economic growth, climate change effects, and agricultural productivity is well recognized at the national level.[4] However, their roles in food security outcomes are typically analyzed separately, instead of in combination. This makes it difficult to have a comparative view of significance and magnitude of their role in outcomes at national level for policy making, especially when development budgets are constrained. By supplying an integrated, quantitative analysis, we offer a framework to fill this gap and to inform policy initiatives such as 3N: “Nigeriens Nourishing Nigeriens,” and the Economic and Social Development Plan, implemented by the government of Niger.

To the best of our knowledge, no other paper has presented such a forward-looking evaluation of the Malthusian challenge in the Sahelian region. It is surprising how little attention Niger, in particular, has received in the literature until recently. Part of the reason is scarce, poorly documented, and often inaccessible data. In addition, there is a tendency in most forward-looking, macro-economic analyses to group all sub-Saharan African countries into a single aggregated region, missing out country level details and the data scrutiny that these studies deserve. Montaud et al. (2017) is one of the few exceptions. They offer a static, economy-wide analysis to study the changes in income, poverty levels, food insecurity ratio, food access index, and food availability index in Niger solely due to climate induced yield changes. However, they do not provide a prospective analysis of the outcomes based on the economic, climatic and demographic drivers analyzed in this paper. As we show here, climate change has significant, but relatively modest impacts as compared to the other drivers of food insecurity in Niger – even when new estimates of heat stress on human labor capacity are also included. In related work, Hertel et al. (2020) highlight the new Malthusian challenge facing the region, but the authors limit their policy analysis to R&D investments and trade in technology.

Importantly, we distinguish between the effects in rural i.e. primarily agricultural households, and urban households, recognizing the existing dualism in the Nigerien economy and the differences in vulnerability of rural versus urban households. There is a dearth of information on long-term food security of urban households in Niger and in general in West Africa (van Wesenbeeck, 2018) even though there is increasing urban agglomeration. A review of the literature reveals no analyses on how undernourishment will likely evolve in the long term in urban areas as a combined effect of the forces reflected in this paper.

Results from this study should be interpreted with consideration that the food security outcome indicators are not adequate reflections of diet quality, but of diet quantity only (Jones et al., 2013). In addition, although livestock is an

[4] In the 2017–21 Economic and Social Development Plan, Niger identified ensuring demographic transition, maintaining sustainable and inclusive economic growth, strengthening food and nutrition security, and adaptation of production systems to climate change among its eight major challenges. Specific targets had been set in each of the strategic axis addressing these challenges, such as reducing population growth to 3.06% by 2021, projecting GDP growth rate to an optimistic 6.2% from the current 5%.

important sector in Nigerien agriculture, we model only the crop sector in Niger at the regional level. The livestock sector is modeled as generating the derived demand for crop through livestock feed. Livestock and mixed crop-livestock systems will also be affected by climate change. However, to date there is limited empirical evidence or widely available simulation models on this topic (McCarl & Hertel, 2018; Thornton & Herrero, 2015), hence creating scope for future research area.

The paper proceeds with the following section describing the food security challenges and the driving forces in the context of Niger. In Section 3 we briefly present the SIMPLE-Niger model including the food security module. Section 4 covers data sources, data base construction, model, and experimental design. In Section 5 we discuss the key findings related to the role of different drivers and their impact on undernourishment outcomes in the next 30 years and based on these key findings present policy scenarios in Section 6. Section 7 concludes the paper along with gaps and recommendations for future research.

2 Historical context

Before looking forward to 2050, it is useful to look back in time in order to gain historical and contextual perspective. Since the 1960s, Niger experienced very rapid and steady population growth, yet income growth was slow and at times negative, while agricultural growth was primarily driven by agricultural land expansion. Even when compared to the rest of SSA, Niger stands out in terms of declines in TFP and in per capita income over the 1960–2006 period (Fig. 1). The main driver of crop output growth has been demand from population growth. This stands in marked contrast to much of the rest of the world, where agricultural TFP[5] was the dominant driver of output, and in contrast to China which experienced a phenomenal growth in income led crop demand even as population growth was suppressed. It is this combination of high population growth and low agricultural productivity that has resulted in the persistent Malthusian challenge in Niger. Coupled with an environment that is increasingly vulnerable to climate change, the challenge has become amplified.

[5] TFP reflects the technology and efficiency with which all inputs are transformed into outputs. Sources of crop output growth can be decomposed into agricultural land expansion (extensification) and/or growth in yield per hectare (intensification). Yield growth itself can come through input intensification (i.e., more capital, labor, and fertilizer per hectare of land) and/or TFP growth. Growth in TFP can occur from research on productivity, economic policy reforms, growth in human capital of labor forces including its skill level and health status, infrastructure development etc. (Fuglie & Rada, 2013).

Population growth Niger continues to have a remarkably high population growth rate–the highest in Africa (3.8 percent in 2017) - and one that has yet to show any signs of slowing down.[6] The total fertility rate is around 7.5 children per woman and this is below the desired fertility rate (INS/Niger & ICF International, 2013). The reasons behind the high fertility rates are complex.[7] Along with its neighboring countries, gender inequality is extreme in Niger, ranking 157 among 162 countries in the Gender Inequality Index[8] (UNDP, 2019). Unmet need for family planning among women is around 20 percent (UNDESA, 2020); however an estimated 65 percent of women also believe there is no need for family planning (UNDESA, 2017). Population growth is expected to have a large demand on food in Niger.

Income growth In general as per capita income grows, the budgetary share of food decreases (Clements & Chen, 1996) and consumer responses to income and prices decline (Muhammad et al., 2011; Theil & Finke, 1983). Rising income also results in dietary shifts as income and price elasticities decline faster for crops relative to livestock and processed food (Gerbens-Leenes et al., 2010)–meaning at early stages of economic development people add relatively more of these two food groups, whereas the growth in crop outputs is often driven by demands for livestock feed.

Population growth also far outpaced Niger's GDP growth (Table 1). As a result, per capita real GDP continued to decline until the early years of the new millennium, thereby depressing any income growth led food demand. With Niger's real per capita income at a very low base and only recently improving, the shift in diet composition is likely to be delayed, which means reliance on staple crops for dietary energy intake will remain high in the future.[9]

[6] The population growth rate in Niger is the fourth highest in the world. The average population growth rate in SSA is 2.7 percent per annum. The growth rate in Niger is increasing at an average of 0.07 percent points a year.

[7] High fertility rates in Niger are not only due to factors such as low child survival rates (replacement) or "supply side" economic factors such as unavailability of family planning services. It also stems from a deep desire to have large families, based on an accumulation of the mother's desire, family desire and social norms (Canning et al., 2015).

[8] Gender Inequality Index is a composite index of reproductive health, empowerment, and labor force participation.

[9] Nigeriens rely on carbohydrates primarily sourced from crops for seventy-two percent of their dietary energy calorie (DEC). Reliance on cheap sources of starch for meeting energy requirements, is typical of households in least developed countries. However, FAO et al. (2020) notes in its global study that while a nutrient adequate or healthy diet would be on average affordable in most countries in SSA, in Niger the costs would be two times and five times of average food expenditures respectively, the highest ratios globally.

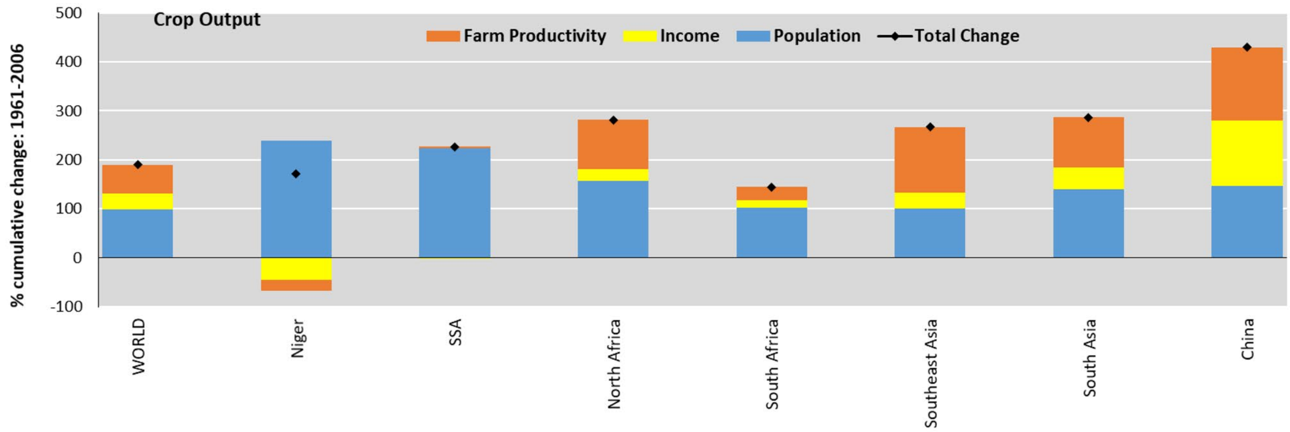


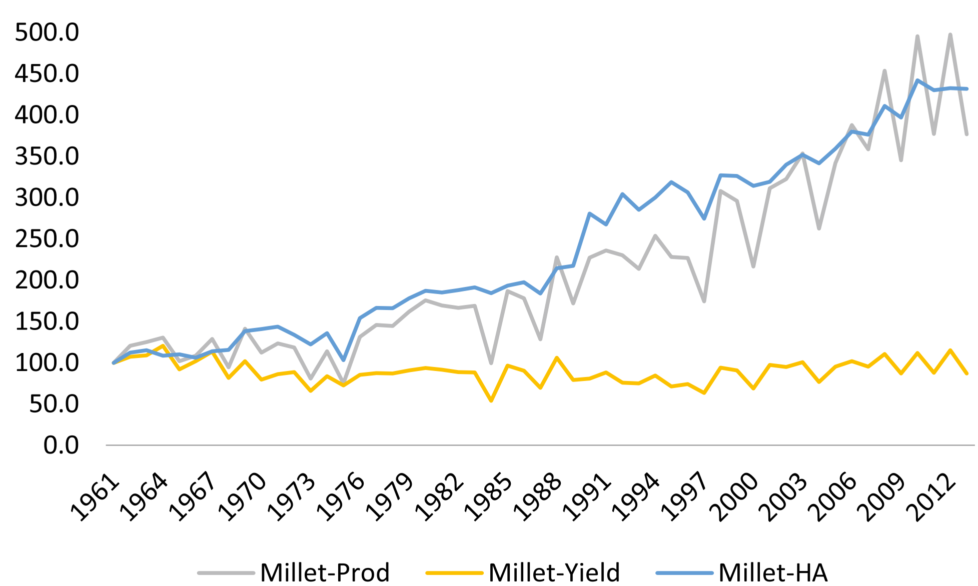
Fig. 1 Historical drivers of crop output growth in key regions and for Niger, 1961–2006. Black dots report the cumulative change based on the historical simulation. The blue, orange, and yellow parts of each bar report the relative contribution of each of the underlying drivers to the total change in output growth. The orange bar shows the contribution of agricultural TFP growth to this total, while the yellow and blue bars show the role of income and population, respectively, in driving total crop output. Source: Replicated from Hertel and Baldos (2016a) with Niger as an additional region

Agricultural TFP growth Since the 1990s, TFP growth has replaced cropland expansion and input intensification as the primary source of global agricultural growth (Fuglie & Wang, 2012). In other high population growth regions such as South Asia and Southeast Asia, TFP growth has been a key supply-side driver, leading to long run price declines, despite growing demand for food. However, Niger has relied largely on cropland expansion for its considerable agricultural output growth. A look at the historical trends in production output, harvested area and yields in millet, the main staple crop in Niger, illustrates this point (Fig. 2).

In the future, continuing conversion of land for cultivation is neither sustainable nor conducive to the environment. Based on FAOSTAT, the amount of agricultural land available for farming and grazing was cut in half in rural per capita terms during 1990–2015 (from 4.9 to 2.7 hectares/person) despite rural–urban migration. Even if agricultural land continues to expand at current rates, it would still be outpaced by rural population growth with crop land expected to fall to 0.6 hectares per rural inhabitant by 2050 (World Bank, 2021).

Although agricultural TFP growth in Niger has been low for reasons that include lack of investment in national agricultural research (Fuglie & Rada, 2013), poor dissemination of new technologies (Ndjeunga et al., 2015), slower adoption of new seed varieties even in comparison to other Sahelian countries (Alene et al., 2015; Ndjeunga et al., 2015), and generally harsher environmental conditions for agriculture; compared

Fig. 2 Historical trend in millet production (Prod), yield and harvested area (HA) in Niger from 1961 to 2012, base year 1961 = 100; Data source: FAOSTAT



to the past decades it improved significantly starting in the 1990s. Some of the contributors to the 2 percent per year growth in agriculture TFP (Table 1) has been adoption of new crop varieties released in earlier decade including those coming from CGIAR centers (Walker et al., 2016; Ndjeunga et al., 2015), local agroforestry (farmer-managed natural regenerations, Reij et al., 2009), and soil and water conservation technologies such as zai pits (Partey et al., 2018).

Climate change Niger is vulnerable to an increasingly harsher and unpredictable climate. It has a rainfed agriculture-based economy where farming employs 80 percent of the population and contribution of agriculture to GDP is 40 to 45 percent. Regional climate analyses suggest a concentration of rainfall into fewer, more extreme events over West Africa and the Sahel (Vizy & Cook, 2012), which can lead to occurrences of flood (Lebel & Ali, 2009) and disturbances in growing period rainfall. This presents significant challenges for farmers who suffer from increasingly unpredictable spatial and temporal variability in rainfall[10] (Asfaw et al., 2016, 2018). While projecting future rainfall variability in the Sahel is difficult, climate scientists are more certain about the projected temperature increase (Christensen et al., 2007; Ben Mohamed, 2011).[11] Niger is one of the five countries in Africa where temperature rose by at least 2°C over the 1961–2009 period (Abidoye & Odusola, 2015). Diffenbaugh and Giorgi (2012) identify the Sahel and tropical West Africa as one of the hotspots of climate change, and unprecedented climate extremes are projected to occur as early as 2040 in these regions (Mora et al., 2013). Schlenker and Lobell (2010) finds that by midcentury, the mean estimates of aggregate production changes in SSA are –22, –17, –17, and –18, and –8 percent for maize, sorghum, millet, groundnut, and cassava, respectively, which are some of the most common crops grown in Niger.

3 Modeling framework: SIMPLE-Niger

In this section we discuss the framework that we use to assess the Malthusian challenge confronting Niger, including data and methods used to support the long-term projections. SIMPLE is a framework for modeling regional and global crop supply and demand. It is designed to capture the major socio-economic forces at work in determining cropland use, crop output, crop prices and household nutritional attainment. The model has been historically validated globally (Baldos & Hertel, 2013), regionally (Hertel & Baldos, 2016a), and with respect to undernutrition (Baldos & Hertel, 2014).

For purposes of this study, we made several modifications to the original SIMPLE framework, dubbing it SIMPLE-Niger (Fig. 3). This partial equilibrium framework is designed to be parsimonious, making it well suited to the data scarce environment which we are confronted with in Niger. Placing the agriculture sector in a general equilibrium model would have required far more data and parameters, and makes model validation much more challenging. Testing the model's ability to replicate the past is important prior to projecting the future. SIMPLE-Niger was validated with respect to the growth rate of Niger's crop output over the 1991–2009 period (see Supplementary Appendix S1).

In the model framework[12] the disposition of crops includes direct consumption, livestock feed use and food processing,[13] as well as feedstocks for biofuels (exogenous in the model). Aggregate demand is driven by population, per capita income and commodity prices. ε_{INC} and ε_P are the price and income elasticities for each of the four consumption commodities i.e. changes in food quantity demanded w.r.t. to changes in price and income respectively. These vary with per capita income and therefore evolve over time.

On the supply side, there is one single crop sector. In the original SIMPLE model, crop production is modeled via a Constant Elasticity of Substitution (CES) production function employing land and non-land inputs. The elasticity of substitution between land and non-land inputs, σ_{CROP}, determines the potential for endogenous intensification of production. The supply elasticities of land and non-land inputs to the crop sector (ε_{LAND} and ε_{NLAND} respectively) are also region-specific. Intensification of non-land inputs allows for crop yield growth even in absence of technological change. Yield growth through intensification is distinct from agricultural TFP growth – as it reflects more intensive

[10] It is evident from the studies by Daouda et al. (1998) for the periods of 1950–1967 and 1968–1985, and by Sivakumar (1992) for 1969-1988 that isohyet lines (which are horizontal parallel lines on the map connecting points of similar rainfall range) moved southward from 1950 to 1980s, resulting in the most productive zones to shrink. The isohyets moved north again from 1988-1998 (Ben Mohamed et al., 2002). Although this looked promising whether the trend will continue is debated. It is evident, however, that even though rainfall may have increased the rainfall season has become shorter and there is more spatial and temporal variability with erratic and extreme rainfalls often leading to flooding in the Niger river.

[11] More discussion about uncertainties and yield impact estimation in Supplementary Appendix S4.

[12] A complete listing of model variables, equations, and source of data is available in the textbook authored by Hertel and Baldos (2016b).

[13] Livestock (and processed foods) are value-added products in the model, which are produced and consumed within each demand region using crop and non-crop inputs. The livestock sector generates derived demand for crop through livestock feed, in addition to non-crop inputs. Technological change and factor substitution in these sectors can alter the intensity of crop use in producing these products. It is assumed that only the livestock sector has the ability to increase feeding intensity (via input substitution or reduction of waste) as captured by the elasticity of substitution between feed and non-feed inputs and technical change.

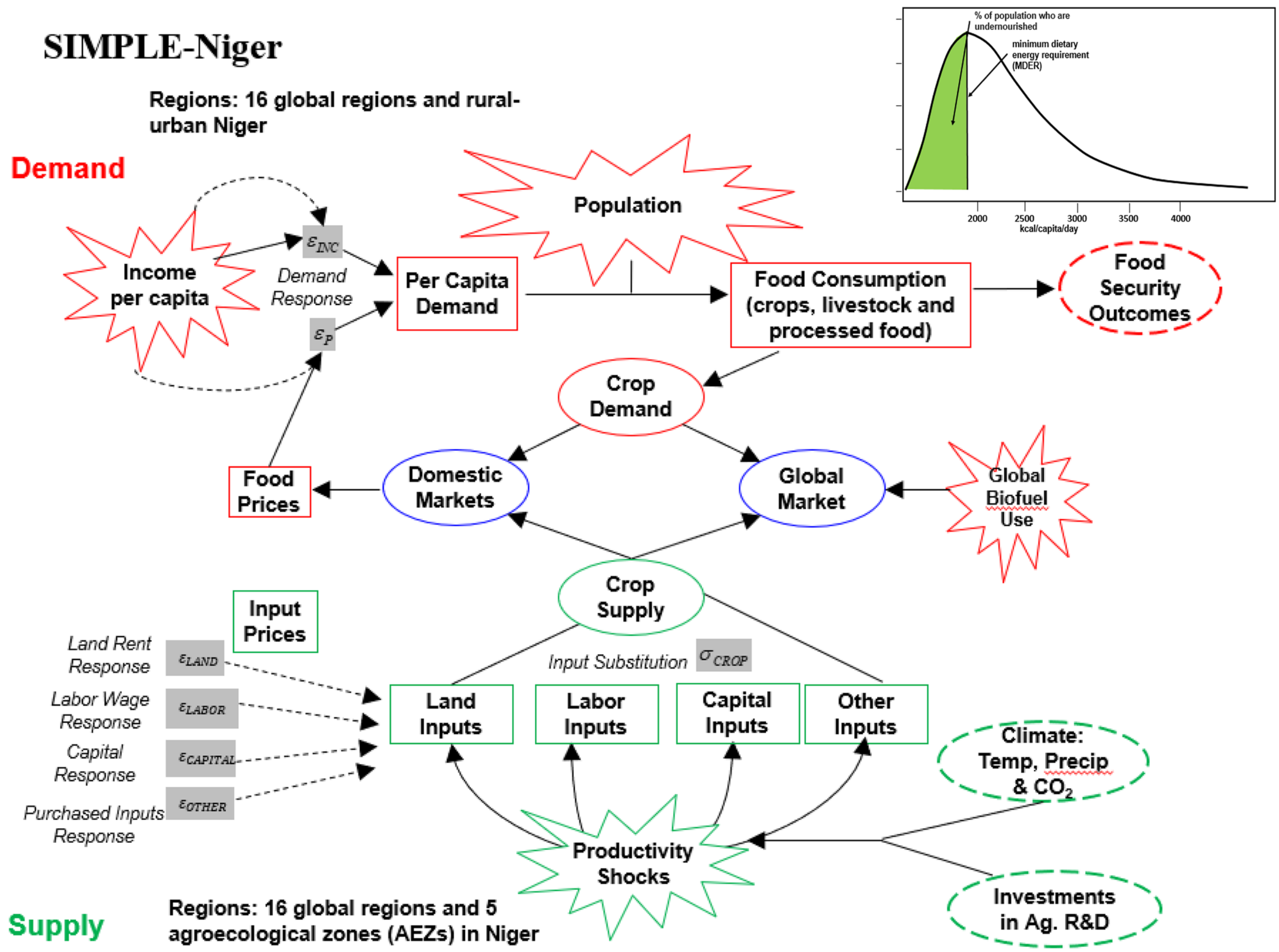


Fig. 3 Structure of SIMPLE-Niger model. The bottom panel (green) refers to regional crop production for the aggregate crop commodity. The upper panel (red) refers to regional crop demand. The spiked boxes represent variables that are exogenously implemented in the model

use of non-land inputs. TFP growth is exogenous in the model which could result from adoption of new technologies stemming from agricultural research, development, and dissemination as well as trade and climate change.

To capture the dynamics of labor employment and wage changes and to link crop income to rural household income there are three extensions made to the core model to form SIMPLE-Niger. These are i) disaggregating Niger's population into rural and urban households, ii) disaggregating the single composite non-land input in the model into labor, capital, and purchased inputs (Supplementary Appendix S3), and iii) modeling rural income as an endogenous variable: linking changes in crop prices directly to rural household income. On-farm income is endogenously determined via linkages to the economic returns to inputs i.e. land rents, labor wages, and prices of other inputs which are, in turn, linked to price of crops. Equation (1) is the main equation linking rural income to changes in crop prices. The percentage change in rural income is a share-weighted average of three rural income sources.

$$y = \alpha_{land} y_{land} + \alpha_{labor} y_{labor} + \alpha_{other} y_{other} \tag{1}$$

where, y is the % change in rural household income. y_{land} is the % change in income from value of crop land, which is linked to income from crop sales, and α_{land} is the share of household income derived from this source. y_{labor} is the % change in income from value of labor, which is linked to change in agricultural labor wages and the quantity of labor demanded, and α_{labor} is the share of household income derived from this source. y_{other} is the % change in non-crop income and α_{other} is the share of household income derived from this source. Any income that is not related to income from crop sales or agricultural wages, such as income from transfers, livestock and by products, non-agricultural wages, self-employment etc. is non-crop income.

Food security module We use the food security module introduced in Baldos and Hertel (2014) to model nutritional outcomes in Niger. Food security in this paper is measured by caloric consumption (caloric undernutrition) and

Table 2 SIMPLE-Niger model parameters and values

Elasticity	Description	Value	Note
ELAND	Price elasticity of land supply	0.5	For all agro-ecological zones in Niger, value is same as for SSA in Baldos and Hertel (2013)
EOTHER	Price elasticity of purchased inputs	1.34	Same as for price elasticity of non-land inputs in SSA in Baldos and Hertel (2013)
ELABOR	Price elasticity of labor inputs	1.34	Same as above
ECAPITAL	Price elasticity of capital inputs	1.34	Same as above
ECROP	Elasticity of substitution in production of crops	0.5	Assumption: ECROP is assumed to be half the value for SSA
ESUB	Elasticity of substitution between domestic and imported crops	6	Calibrated to fit the rate of price transmission of crops in Niger (~14%) and SSA (~19%)
ETRANS	Elasticity of transformation between domestic and imported crops	6	
SDEV_CAL (NRUR)	Standard deviation of log normal dist. of per capita caloric consumption	0.31	Estimated from ECVMA 2011 (household survey)
SDEV_CAL (NURB)	Standard deviation of log normal dist. of per capita caloric consumption	0.285	Estimated from ECVMA 2012

indicators for the shortfall in caloric consumption (calorie gap).[14] We concentrate on prevalence and incidence of undernourishment, as well as the undernutrition gap. The undernutrition index (prevalence of undernourishment) is defined as the fraction of population whose daily dietary energy intake is below minimum dietary energy requirement (MDER) (green area to the left of the MDER line in inset of Fig. 3). The undernutrition gap, which indicates the intensity of hunger, is the average dietary energy deficit that an undernourished person needs to close to satisfy the minimum requirement. The undernutrition gap is derived by integrating the caloric deficits of each malnourished person and dividing it by the malnutrition headcount.

The distribution of per capita caloric consumption is assumed to be log-normal which is consistent with the traditional assumption used by FAO regarding the dietary energy intake within a country (Neiken, 2003). Changes in per capita food consumption are converted into changes in average caloric consumption. Shifts in the log-normal distribution of caloric consumption results in changes in the undernutrition -index, -gap, and -headcount (Supplementary Appendix S2). The per capita caloric intake is linked to per capita income. For agricultural households in the model, this creates an endogenous link between changes in caloric intake, and changes in household income and purchasing power due to climate change induced production and crop price changes.

4 Data and experimental design

The baseline database for SIMPLE disaggregates the world economy into 16 regions, one of which is SSA. For our study, we disaggregated Niger from SSA, thereby making Niger the 17th region[15] in SIMPLE-Niger and placing it within the global and regional system. In the baseline database, the crop supply regions within Niger are disaggregated into five agro-ecological zones cutting across its administrative regions: Saharienne, Saharo-Saheliene, Saheliene, Sahelo-Soudaniene, and Soudaniene (map and zone descriptions in Supplementary Appendix S7).

On the demand side, baseline data on food consumption patterns and undernutrition are disaggregated by rural and urban households. The model parameters and values are provided in Table 2 and the data sources for building a Niger specific 2009 baseline are in Table 3. The baseline data for the other 16 regions[16] include income, population,

[14] These indicators are limited to the caloric volume aspect of food security and does not account for the quality of food consumption. This can be considered a limitation from nutritional point of view given the emphasis on diet quality and it underestimates Niger's food insecurity situation. Stunting among children under 5, vitamin and micronutrient deficiency, diet diversity index are complementary measures of undernutrition. However, incorporation of these measures in the study will require improved data.

[15] The 16 global regions are Eastern Europe, North Africa, South America, Australia & New Zealand, European Union, South Asia, Central America, South Africa, Southeast Asia, Canada, USA, China & Mongolia, Middle East, Japan & Korea, Central Asia, Sub Saharan Africa (*excludes Niger and South Africa*).

[16] For interested readers a complete listing of sources and construction of regional data of the original framework is listed in Supplementary Materials of Baldos and Hertel (2013) available at http://iopscience.iop.org/1748-9326/8/3/034024/media/erl472278suppdata.pdf. The details of Niger data construction process can be found in the Supplementary Appendix S3.

Table 3 Main data sources for constructing 2009 baseline for Niger

Cropland area and crop production quantity	Calculated from i. Sub-national level 2009 data (Ministry of Agriculture Niger and FAO CountrySTAT) ii. 2000 grid level data (EarthStat, http://www.earthstat.org/)
Cost shares of land, labor, capital, and other intermediate inputs in crop production	Calculated from iii. Plot-level production data: Niger Living Standard Measurement Survey- Integrated Survey of Agriculture 2011 (LSMS 2011/ECVMA) iv. Niger Social Accounting Matrix (SAM) provided by IFPRI
Share of crop use (direct consumption, processed food, livestock sector)	v. Calculated from Niger SAM
Food security module (undernourishment prevalence, standard deviation of caloric intake, minimum dietary energy requirement (MDER), share of food groups)	vi. Niger LSMS 2011/ECVMA
Income	vii. World Development Indicators (WDI) viii. Niger rural–urban income disaggregation: LSMS-ISA 2011/ECVMA, Niger SAM
Population	ix. United Nations Population Division
Agricultural employment	x. International Labor Organization (ILO)
Sources of rural household income	xi. LSMS-ISA 2011 data processed by FAO and published in DATAPORTRAIT

consumption expenditures, and crop production and their sources are as follows. GDP in constant 2000 USD and population are obtained from the World Development Indicators and the World Population Prospects, respectively. Consumption expenditure data and agricultural input cost share are calculated from the Global Trade Analysis Project (GTAP) V.6 database (2006), while data on cropland cover and production, utilization and prices of crops are sourced from FAOSTAT.

To create **the future baseline scenario**, the farm and food system is projected from 2009 to 2050. The exogenous shocks to the system to create the baseline projections for all 17 regions (Niger and the other 16 regions) are population, per capita income, agricultural productivity growth, and climate change induced long-term changes on crop yields and agricultural labor productivity. Population and income growth rates are based on the Shared Socioeconomic Pathways (SSP) database, which provide alternative trends in socio-economic projections (O'Neill et al., 2017). The SSPs are designed as a range of plausible baseline scenarios, excluding mitigation policies, and thus allowing researchers to look into mitigation and adaptation. The SSPs come with a database of future income and population growth, and associated narratives on adaptation and mitigation challenges.

Given the uncertainties in fertility rates, rural urban migration, and economic growth patterns, we made projections under three SSP scenarios–SSP2, SSP3 and SSP4[17] (Table 4) and focus the presentation of key results in this paper on SSP4 scenario,[18] which is the most plausible one for Niger. The GDP projections under SSP4, which assume a high population growth scenario and high challenges to adaptation, are closest to historical trends in Niger. In this scenario, low income and education and little access to effective institutions leave large portion of the population vulnerable to climate change (Riahi et al., 2017). Mitigation challenges are low and adaptation challenges are high with substantial proportion of populations at low levels of development- as it is in Niger (more on SSPs in Supplementary Appendix S6).

The urbanization shares are from the National Center for Atmospheric Research (NCAR) (Jiang & O'Neill, 2017) which are used in the SSP scenarios to project rural and urban population in 2050. These urbanization scenarios are based on UN estimates of urbanization, but modified by linking countries to reference countries which are correlated to have experienced similar urbanization patterns in the past. The SSP2, SSP3 and SSP4 assume medium, slow and rapid urbanization rates. For Niger the 2050 projections are 35, 24, and 50 percent respectively. The UN projects 28 percent of the population to be living in urban areas of Niger by 2050 (UNDESA, 2019b).

[17] SSP2 assumes "middle of the road" world where trends broadly follow their historical patterns (SSP2). SSP3 assumes a fragmented world of "resurgent nationalism". SSP1 and SSP5 represent relatively optimistic trends for human development with rapid economic growth. SSP1 "Sustainability" features low adaptation and mitigation challenges, while SSP5 assumes that growth will be driven by energy intensive, fossil fueled development (Riahi et al., 2017). The underlying income and population growth projections and the narratives are very unlikely scenarios for Niger and thus we did not consider them.

[18] Interested readers can find the results under all the scenarios in Supplementary Appendix.

Table 4 Annual growth rates of GDP, population and per capita GDP in Niger under different SSP scenarios for 2009–2050

		SSP 2	SSP 3	SSP 4
GDP	Niger	6.9	5.9	5.4
	Urban	8.5	6.8	7.6
	Rural	5.8	5.4	3.4
Population	Niger	3.1	3.6	3.6
	Urban	5.0	4.6	6.4
	Rural	2.5	3.3	2.3
Per capita GDP	Niger	3.7	2.2	1.8
	Urban	3.3	2.0	1.1
	Rural	3.3	2.0	1.1

Table 1 presents comparable historical growth rates in population and per capita GDP

The SSPs provide GDP growth projections at the national level but not by rural–urban areas. To project GDP growth rates in rural and urban areas, we assume Niger's current urban premium (the ratio between per capita income in urban area and in rural area), which is 2.17, remains constant in 2050 for all SSP scenarios.

Agricultural productivity growth is difficult to measure, let alone project several decades into the future. For crop productivity changes, following Hertel and Baldos (2016a), we assume that the historical patterns of productivity growth persist into the future (Fuglie, 2012; Ludena et al., 2007). Regional TFP growth rates for the crops and livestock sectors are based on adjusted historical estimates from Fuglie (2012) and projections from Ludena et al. (2007). Historical rates from Griffith et al. (2004) are used for the processed food sector, assuming these rates apply in the future and across all regions.

4.1 Climate change induced crop productivity changes

In consideration of climate change induced productivity changes, we consider both changes in yields and changes in labor productivity. Buzan and Huber (2020) finds with substantial warming (+4°C), local summer agricultural labor productivity losses become catastrophic, and parts of West Africa incur labor capacity losses of around 25 percent, one of the highest. Here, we adapt labor productivity changes from de Lima et al. (2021) based on heat stress impacts on agricultural labor for an increase in temperature by 2°C on labor capacity. This rise in temperature from the period 1986–2005 is increasingly likely to arise by mid-century (IPCC, 2021).

As for climate change impacts on yields there is consensus that the changing climate will have adverse effects on crop yields in Niger (Ben Mohamed, 2011; Sultan et al., 2013; Thomas & Rosegrant, 2015; Van Duivenbooden et al., 2002). The grid level yield projections for millet, sorghum, and groundnut are made by borrowing estimated coefficients of average temperature and precipitation on yields of these crops in sub-Saharan African countries which have low levels of fertilizer use from Schlenker and Lobell (2010). The yield projections for maize are drawn from Haqiqi et al. (2021) who extend Schlenker and Roberts (2009) to estimate crop yield response functions for irrigated and non-irrigated crops at the global level employing NASA NEX-GDDP (Global Daily Downscaled Projections) conducted under CMIP5 and RCP 8.5[19] for future climate change projections. The grid level yield projections for each of these crops are aggregated to the climate zones in Niger weighing them by cropland share. These changes are reported in Table 5 and are treated as productivity shocks in the crop sector's production function.

5 Key findings

5.1 Future drivers of projected crop output growth in Niger

As we look forward to 2050, two results stand out for crop output growth in Niger. First, population growth within Niger will likely remain the single largest driver of crop output growth in the next 30 years. Second, among drivers originating from the rest of the world (RoW), agricultural productivity in other regions will have the largest impact in Niger.

[19] Representative Concentration Pathway (RCP) 8.5 which is a greenhouse emission trajectory. The RCPs set pathways for GHG emissions and effectively the amount of warming to be observed. RCP 8.5 indicates an increase of around 2.5ºC by 2050 in Niger, reference period 1995–2014, sourced from the World Bank's Climate Change Portal (https://climateknowledgeportal.worldbank.org/country/niger/climate-data-projections).

Table 5 Reduction in crop yields (%) in Niger's climate zones by 2050 due to future changes in heat, RCP 8.5

Crops	Saharienne	Saharo-Sahelienne	Sahelienne	Sahelo-Soudanienne	Soudanienne
Groundnut	-16.3	-15.8	-15.7	-15.3	-14.6
Maize	-38.7	-35.4	-32.8	-28.6	-27.0
Millet	-18.0	-17.5	-17.3	-16.9	-16.1
Sorghum	-12.1	-11.8	-11.6	-11.3	-10.8
Weighted aggregate yield shock (%)	-15.86	-15.74	-15.71	-15.36	-14.89
Reduction in agricultural labor productivity (%)	-17.3	-10.6	-7.9	-8.2	-8.6

The climate zone and crop specific yield shocks are weighted by harvested area share to estimate an aggregate yield shock by each climate zone

Source: Groundnut, millet, and sorghum yield changes, and maize yield changes are based on Schlenker and Lobell (2010), and Schlenker and Roberts (2009) respectively and adapted from Haqiqi (2019) and Haqiqi et al. (2021); labor productivity changes are adapted from de Lima et al. (2021), estimation details in Supplementary Appendix S4 and S5

Table 6 shows a decomposition of drivers of crop output in Niger to 2050, broken down by origin of these drivers i.e. Niger and rest of the world (RoW). Population growth in Niger and associated increases in rural labor supply[20] are expected to explain nearly one-third of the crop output growth in Niger regardless of the SSP scenarios considered, followed by impacts of agricultural TFP growth and climate impacts within Niger. That projected Nigerien crop output is likely to continue to be driven by demand from the rapidly growing population is consistent with the rest of SSA where population will continue to play the largest role (Hertel & Baldos, 2016a; Hasegawa et al., 2015). However, unlike projections for the world and those for many other regions where income growth is projected to play an increasing role in crop output growth through changes in diet and increased demand, in Niger the role of income growth is still projected to be relatively minimal. Compared to these demographic effects, net climate change impacts have a smaller but substantial impact on crop output growth. In addition, if the improvements in productivity growth rates from the past decade continue at the rate of rest of SSA, agricultural productivity will expectedly have a larger contribution in crop output growth than in the past.

Growth in population, agricultural productivity, and income within Niger and RoW have differential impacts on crop output growth within Niger. From the results presented in Table 6, it is evident that the biggest RoW (negative) driver for Nigerien domestic crop output is the growth in agricultural productivity in other regions which depresses world prices for crops, thereby making imports cheaper. Relatively higher productivity growth outside of Niger means output growth within Niger will be smaller because it lowers the cost of competing imports from RoW. In contrast, growth in population and income in RoW drives more crop output in Niger as the world in general requires more crops, influencing Niger through the world markets.

5.2 Urban areas will suffer from increasing concentration of food insecurity

Table 7 shows that overall in Niger the prevalence of undernourishment (% of total population undernourished) is likely to be reduced under SSP4 (and under all considered SSP scenarios). This is due to future projected growth in income and agricultural productivity. However, with rapid population growth outpacing agricultural productivity growth, the total number of undernourished people is estimated to double under the most plausible scenario, SSP4. Invariably in all scenarios, it is in urban areas where most of the increase in undernourished people will occur. Under the SSP4 scenario by 2050 around 75 percent of the total projected undernourished population in Niger (4.5 million out of 6 million) will be in urban areas, up from 20 percent in 2009. This projected concentration of undernourished people in urban areas may seem unexpected; but the decomposition of drivers of changes and existing rural–urban situation provides insights.

Disaggregation of the undernourishment outcomes by rural–urban households casts a picture of improvements in rural areas, in no small part due to net sellers among rural households benefiting from an increase in food prices, increased demand for wage labor, and already existing lower prevalence of undernourishment in rural areas than in urban areas.[21] The changes in number of undernourished people in urban areas is primarily driven by urban population growth,

[20] The labor endowment effect refers to the shift in rural labor supply. This is tied to projected rural population growth in Niger.

[21] Niger currently has a relatively small urban base, but its concentration of undernourished population is higher in urban areas (20 percent vs. 15.4 percent in rural areas, LSMS 2011/ECVMA).

Table 6 Decomposition of change in crop output growth in Niger between 2009 and 2050 under three SSP scenarios

Crop Output Growth (%)	Total change, 2009–2050 (%)	Population Niger	Population RoW	Income Niger	Income RoW	Ag TFP Niger	Ag TFP RoW	Climate Impacts Niger	Climate Impacts RoW	Labor Endowment
SSP4	103	65	12	4	9	48	-55	-44	22	42
SSP3	137	60	15	8	8	50	-52	-45	21	72
SSP2	175	98	21	19	13	63	-89	-60	36	74

Source: Authors' simulation results

followed by agricultural productivity and lastly by growth in income (Table 7). Urban population growth occurs not just due to urban area expansion and natural population growth but also due to increasing rural–urban migration. 50 percent of the Nigerien population are projected to be living in urban areas by 2050 under the SSP4 scenario.

The relative magnitude of income growth compared to other drivers is smaller in urban areas than in rural areas. When income increases, diets are diversified and tend to shift towards livestock and processed food, and food consumption becomes less price and income sensitive (Muhammad et al., 2011). In rural Niger while per capita caloric consumption of crops is expected to rise, caloric intake from livestock and processed food is expected to rise faster due to growth in income coupled with larger income elasticities of demand for these products. In contrast, since the urban population is on average at an income level 2.17 times higher than the rural population, the diet shift due to income growth is comparatively less price and income sensitive. Thus, the effect due to income growth is much smaller in urban households compared to rural ones. Urban households tend to be adversely affected by food price hikes as they usually do not have agricultural incomes that might benefit from higher food prices, nor any agricultural production to buffer their food consumption.[22]

5.3 Food insecurity impacts of climate change are disproportionately larger for rural households

Although the impact of climate change on caloric intake in Niger is more modest than the impact of population growth, these effects are nevertheless substantial. An additional 2 million Nigeriens are predicted to be pushed into undernourishment by 2050 under the SSP4 scenario solely due to climate change induced changes on crop yields and labor productivity. A climate change induced productivity shock means there is a smaller quantity of crop produced for a given amount of inputs. With relatively price inelastic demand, the decrease in crop output due to reduced yield and labor productivity results in strong consumer price increases for food commodities. The crop price increase negatively affects the purchasing capacity of both rural and urban households, and the net effect on their food security outcomes due to climate change are projected to be negative, despite increases in farm revenue for rural households. As a result, all indicators of undernutrition outcomes i.e. count, index, and gap are negatively affected by climate change

[22] Urban households in Niger source only 4 percent of their dietary energy from own produced food (vs 32 percent by rural households). Consequently, they also have a larger share of purchased food in total food consumption in terms of monetary value (89 percent in urban vs 67 percent in rural).

Table 7 Projected changes in undernutrition outcomes from 2009 to 2050 in rural and urban Niger under SSP4 scenario, and decomposition of the change by food security drivers

				Decomposition of the difference				
	2009 Baseline (A)	2050 Baseline (B)	Difference (A)-(B)	Population	Income	Agriculture Productivity	Labor Endowment	Climate Change
Undernourished count (in millions)								
Niger	2.6	6.0	3.4					
Rural	2.0	1.6	0.5	1.80	-0.67	-1.68	-0.72	0.79
Urban	0.5	4.5	-3.9	7.34	-1.20	-2.96	-0.29	1.03
Undernutrition index (% of population)								
Niger	16.2	1.8	-14.4					
Rural	15.4	4.6	-10.8	0.09	-3.17	-7.84	-3.50	3.65
Urban	20	13	-7	13.76	-7.00	-17.43	-2.08	5.77
Undernutrition gap (kcal/cap/day)								
Rural	231.8	186	-45.7	-0.19	-13.37	-33.32	-14.48	15.64
Urban	237.8	209.3	-28.5	56.80	-28.78	-71.66	-8.56	23.74

The 2050 baseline includes impacts of climate change. The columns under "Decomposition of the difference" report the contribution of each of the underlying drivers to the total change

Source: 2009 baseline- Niger 2011 LSMS-ISA, 2050 baseline-model simulation

impacts on yields and labor productivity. At the national level, the undernourishment count and index increase between 50 to 90 percent due to climate change induced crop productivity changes. Negative climate impacts are not unexpected. What is noteworthy is the difference in the magnitude of the effect in rural and urban Niger.

The climate change induced changes have a greater relative effect on the food security outcomes in rural households than in urban households. We estimate the contribution of climate change induced productivity changes on undernourishment (percent change from 2050 baseline) in rural areas to be 1.7 times greater than in urban areas. Of the total change in undernourishment count in rural and urban households, climate change contributes to 14 percent and 8 percent of the change respectively (based on Table 7). This difference is primarily due to climate change induced increases in price of crops from which rural households obtain almost 80 percent of their caloric intake. The reduction in crop productivity due to climate change increases prices of crops, livestock and processed foods. These supply-side increases in food prices are faced by rural and urban households alike. However, the largest increase in price is in crop commodities and rural households obtain much larger share of caloric intake from crop commodities (80 percent) than their urban counterparts.

The strong reliance on crops for caloric intake outweighs any gains in agricultural income among rural households. The adverse productivity shock increases crop prices and impacts rural households in number of ways: i) price of market bought food increases (and this effect is felt by urban households as well), ii) as yields decrease, but sales prices increase, revenue may increase or decrease depending on the price elasticity of farm level demand and iii) income from farm labor wages changes as both labor productivity decreases and crop prices increase. Our simulations suggest that income from both crop sales and wage labor will increase in Niger in the wake of climate change. However, the increase in food prices outweighs the gains from increased agricultural revenue. These results are consistent with the empirical findings of Hill and Porter (2017) for Ethiopia which finds that despite realized poverty rates being similar, the vulnerability of rural households to drought and food price inflation were considerably higher than that of urban households. Recognizing these differential impacts and the impact channels is important for designing different rural and urban policy and program strategies to tackle the household food security impacts of climate change.

6 Policy scenarios

In 2012, Niger put in place a sustainable food security and agricultural development strategy named the 3 N Initiative ("Nigeriens Nourishing Nigeriens") in order to increase production from agropastoral and fishing activities and reduce the impact of droughts and other adverse weather events on the people of Niger and their livelihoods. The

Table 8 2050 scenarios: business as usual and three policy scenarios

Scenario	Description	Population	Income	Public R&D investment	Market Integration
2050 BAU	Business as usual	SSP4	SSP4	Historical growth rate 3.00% p.a	Trade elasticities in the model calibrated to 6
2050 R&D	Accelerated investment in research and development	Public R&D spending growth rate is doubled from historical growth rate of ~3% p.a. to 6% p.a			
2050 Pop	Reduced population growth	Population growth rate of 2.4% p.a. by 2050 instead of 3.6% p.a. as assumed in SSP4 scenario			
2050 More Int	Increased market integration	Trade elasticities are increased by 50% to 9			

Nigerien government is emphasizing demographic transition and enhanced food and nutrition security in its development plans. For long-term, sustainable development policy makers can use the results from the previous section to understand relative importance of population growth, income, agricultural productivity, and climate change on crop output growth in Niger and the differentials impacts on food security outcomes among urban and rural population. In this section we explore the implications of three possible policy responses for achieving Niger's food security goals. These three scenarios (Table 8) are i) accelerated investment in research and development (supply side) ii) demographic transition (demand side) and iii) market integration.

From the supply-side perspective, we analyze the potential impacts of increasing agricultural productivity growth through increased spending on agricultural R&D. In the second policy experiment, we assume population growth rate will reduce to an optimistic 2.4 percent annually (close to the optimistic scenario in the 2017–21 Economic and Social Development Plan) instead of 3.6 percent as assumed in 2050 baseline SSP4 scenario.

In the third policy scenario, we explore what increased integration with world markets would mean for household food security outcomes in Niger. The outcomes are not always obvious as net sellers and net buyers are impacted differently by market integration and the net impacts also depend on initial conditions in the country (Clapp, 2017; Swinnen & Squicciarini, 2012). This policy response can be overlaid on the previous two policy responses, as this governs the extent to which Nigerien markets interact with international agricultural markets. The level of influence of the RoW drivers also depends on the level of market integration. The scenario is implemented by increasing trade elasticities by 50 percent from baseline level to reflect more complete price transmission and thus increased market integration.

6.1 Accelerated investment in research and development

Agricultural R&D spending by national, private and international research centers contributes to building R&D capital stock or knowledge capital which eventually translates into TFP growth with a lag structure. Fuglie and Rada (2013) estimated econometrically that a 1 percent increase in national agricultural R&D stock in SSA raises TFP by 0.0394 percent, meaning if annual R&D spending is raised 1 percent and continued at this new level, then TFP will eventually increase by 0.0394 percent. It takes several years for the knowledge generated from research to be fully incorporated into higher farm productivity and output (Alston et al., 1995). Thus, investments in R&D materialize into TFP growth with a lag and TFP may continue to grow even without any growth in R&D spending due to the lag effects between R&D spending and R&D stock accumulation (Fuglie, 2018).

Public R&D spending alongside spending by Consultative Group for International Agricultural Research (CGIAR) are the primary sources of R&D that has contributed to TFP growth in SSA (Fuglie, 2018; Hertel et al., 2020). In this policy experiment, we examine the effect on undernourishment outcomes if the public R&D spending growth rate is doubled from historical growth rate of around 3 percent p.a. to 6 percent p.a. Private R&D spending, which is, almost nonexistent in Niger is excluded from these scenarios. We use the historical data on public, private, and international spending on agricultural R&D collected by Fuglie (2018) and follow the same approach in the paper to convert R&D spending into TFP growth (detailed in Supplementary Appendix S9). The R&D expenditure is converted into agricultural R&D knowledge capital stocks using a triangular lag structure spread out over 35 years. The R&D capital stocks are then converted to growth rates in agricultural TFP via the R&D TFP elasticities.

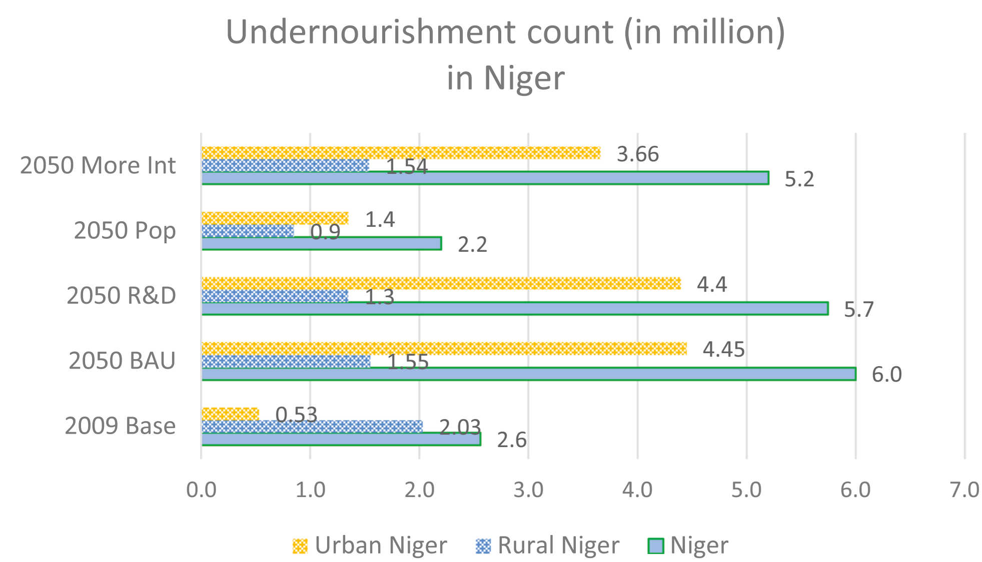


Fig. 4 Comparison of no. of people in Niger projected to be undernourished in 2050 under different scenarios, business as usual and baseline. 2009 base depicts baseline at 2009, 2050 BAU is baseline in 2050 where TFP growth rate is based on historical trends, 2050 R&D are projections for 2050 with public R&D spending growth twice of historical trends, 2050 Pop are projections for 2050 based on reducing population growth to 2.4%, and 2050 More Int refers to more market integration compared to all other cases. Source: 2009 baseline data from ECVMA 2011, 2050 results based on simulations

Following this approach, if annual spending growth in public R&D is doubled from 3 to 6 percent in Niger, it results in an accumulated total growth of 45 percent from 2006 to 2050 i.e. from an index value of 100 in 2006 to 145 in 2050. At 3 percent annual R&D spending growth the accumulated growth would be 20 percent over 2006–2050 period.

An accelerated level of public spending in R&D is expected to aide in improving household food security situation. However, an increase in public R&D spending growth rate from 3 to 6 percent in Niger results in a small improvement–a decrease of 0.25 million in undernourishment count compared to the 2050 baseline (2050 BAU in Fig. 4). These improvements are higher in rural households (a decrease of 13 percent from 2050 baseline) than in urban households (a decrease of 1 percent), where population growth instead of agricultural productivity is projected to be the main driver of food security.

One of the reasons for this moderate effect is the low rate at which R&D capital stock transforms into TFP growth in Niger. From a synthesis of over 40 econometric studies, Fuglie (2018) synthesized regional elasticities. For Niger we adopt the TFP elasticities as those of rest of SSA which are 0.13 and 0.04[23] for public R&D spending and CGIAR spending respectively. These values are lower than any other region except transition economies in Eastern Europe.

[23] Country specific elasticities are not available. It is possible that elasticities could be smaller or larger for Niger. R&D spillovers from neighboring countries could be better captured or perhaps the CGIAR is targeting relatively more attention in Niger (with an ICRISAT station in the country, for example). NGOs might also be contributing with development of small-scale irrigation methods (Walker et al., 2016), and zai pits and agroforestry innovations (Reij et al., 2009) that have been widely adopted.

The small R&D transformation elasticities tell us there is much scope for future improvements in TFP by improving the way national R&D systems operate, thereby boosting the elasticity of TFP with respect to knowledge capital. Moreover, it is worth mentioning that R&D spending is not the only source of TFP growth. Economic policy reforms and labor force schooling also have significant effect on agricultural TFP growth in SSA (Fuglie & Rada, 2013).

6.2 Reduced population growth scenario

In the 2017–21 Economic and Social Development Plan (ESDP), the government targeted a reduced population growth rate of 3.06 percent by 2021. In this scenario, we postulate a population growth rate of just 2.4 percent annually by 2050 (close to the most optimistic scenario in the 2017–21 ESDP) instead of 3.6 percent as assumed in 2050 baseline SSP4 scenario.

The reduced population growth rate scenario has a substantially larger positive outcome on household food security in Niger (Fig. 4). These results are not surprising as analysis of drivers of food security outcomes show outcomes were primarily driven by population growth. A limitation in the current analysis is that it is missing information on how much investment will be required for the reduction in population growth which can make the two policy scenarios (accelerated R&D and reduced population growth) comparable in monetary terms.

Making direct investments in family planning or sexual and reproductive health, which in turn contributes towards reducing fertility, is a deeply political and challenging issue which makes allocation of funds for these purposes difficult (Potts et al., 2011; Shiffman & Quissell, 2012). However, investing in formal education (Martin, 1995; Shapiro, 2012) and women's labor force participation (Bloom et al., 2009), which are less controversial, is also well known to reduce fertility rates while empoweOneof the reasonsring women to decide freely and responsibly the number, spacing and timing of their children. Lutz et al. (2004) showed in their work for a number of African countries that education can be a key determinant in reducing malnutrition and food security. Niger has made substantial progress in education for girls, but still lags behind other West African countries (World Bank, 2019). One of the reasons is its very high incidence of child marriage which has a negative correlation with educational attainment and is conducive towards early childbearing.

6.3 Market integration

Considering the number of people involved in agriculture, does a more integrated market enhance household food security in Niger? The answer is not obvious since producers and consumers are differentially affected by increased agricultural trade. In this experiment, we create a scenario of a Nigerien domestic market that is more integrated with the rest of the world.

The extent of market integration in the model is captured by the elasticities of substitution (ESUB) and transformation (ETRANS) between domestic and international goods and the initial shares of international goods in the consumption and production bundles. ESUB represents the change in the ratio of imports to domestic consumption in response to a change in the ratio of domestic to import prices.

ETRANS represents the change in the ratio of exports to domestic sales in response to a change in the ratio of export to domestic prices. When farmers are well integrated into the world market, a strong supply response to international prices is expected and the elasticity of price transformation is high. Price transmission is generally measured in terms of the transmission elasticity, defined as the percentage change in the price in one market given a one percent change in the price in another market (Minot, 2011).

Price transmission rates and the speed of adjustment of domestic markets to world prices are low for millet and sorghum which are mostly locally produced, and high for rice and maize which are mainly imported. Aker (2007, 2010) investigated Niger cereal market performance during food crises and found that Niger's millet market responds to supply rather than demand shocks, and neighboring country markets namely Benin and Nigeria have a significant effect on domestic markets in Niger. Cornia et al. (2016) found that there are important short-term but not long-term effects of international cereal prices on the Niger domestic millet price. Zakari et al. (2014) find a 10 percent change in prices of markets in Chad, Mali and Burkina Faso in the long run induce an adjustment of 2.98 per cent in Niger millet prices within one month – or a price transmission elasticity of about 30 percent. For sorghum, the transmission rates vary from 15 to 39 percent depending on the country.

The absolute value of the trade elasticities (ESUB and ETRANS) for Niger are set to 6. This value has been obtained by calibrating the model at the baseline (2009) to the price transmission levels in Niger attained from recent empirical work of Zakari et al. (2014). This is the value used for projections of food security in Niger in 2050 under SSP4 scenario and is intended to reflect a persistence of current levels of market integration (2050 BAU in Fig. 4). To explore the consequences of changes in market integration, we consider a market experiment under which trade elasticities are increased by 50 percent to 9 in order to reflect larger price transmission and thus increased market integration. This projection scenario is named *2050 More INT* in Fig. 4.

Comparison of the BAU/baseline integration and more integration scenarios in 2050 in Fig. 4 shows that, on average, a more integrated market is beneficial for household food security in Niger. The prevalence of undernourishment decreases both in rural and urban Niger compared to baseline scenario. In the rural areas, the consumer impacts of lower food commodity prices marginally dominate the rural income impacts of lower farm prices and the net result on rural food security is positive. This outcome is more evident in urban areas where households are more reliant on the market for their food purchases.

An important point to note on the grounds of environmental sustainability is that in a more integrated market scenario, as markets operate more efficiently and the share of imports increases, local crop output growth is accompanied by lesser agricultural land expansion (by around 47 percent from 2009 to 2050 in a more integrated scenario vs. 65 percent in current integration scenario). There is mounting evidence of land degradation, conflicts over land, and agricultural land pressure in Niger (Moussa et al., 2016). The land use, land use change, and forestry sector (LULUF) is the largest contributor to greenhouse gas (GHG) emissions in Niger (UNFCC, 2016), and agricultural land expansion at the expense of converting forests and grazing areas is a major driver of land use change (Gibbs et al., 2010; UNFCC, 2016). Tighter market integration contributes to more sustainable land use which would in turn lead to less GHG emissions.

Increasing the price transmission between domestic and international markets will require efforts in many fronts. Niger's formal non-tariff barriers to trade are high, but a wider range of informal non-tariff barriers constrain intra-regional trade (Lesser & Moisé-Leeman, 2009; Meagher, 2003). It ranks 148 out of 167 countries in the World Bank's Logistics

Performance Index (LPI)[24] indicating there is much scope for improvements in trade and transport related infrastructure specially temperature-controlled logistics for agricultural products, efficiency in customs procedure, and ease of arranging competitively priced shipments (Di Lorenzo & Fadika, 2022) bearing in mind a large share of the trade happens through informal cross-border trade (Lesser & Moisé-Leeman, 2009; Meagher, 2003; Zakari et al., 2014).

7 Conclusion, policy implications, and future research

We use a partial equilibrium model customized to Nigerien agriculture, and regional, national, grid cell, farm, and household level data to examine the relative magnitude of socio-economic and climate-related stressors on food security outcomes in rural and urban Niger in 2050. We then assess three policy scenarios: accelerated agricultural R&D, decreased population growth, and enhanced market integration. Our results demonstrate that population growth will remain the single largest driver of food security outcomes in Niger, as per capita income growth lags and advancements in agricultural productivity are likely to be outpaced by the growing population. We project that, even though prevalence of undernourishment is likely to be reduced by 2050 under all considered SSP scenarios, the total number of undernourished people will remain stagnant or increase, as is the case under SSP4 - the most plausible scenario. In addition, the impacts of climate change cannot be ignored. We estimate that an additional 2 million people (SSP4 scenario) in Niger will be pushed into undernourishment by 2050, solely due to adverse climate change induced changes on crop yields and agricultural labor productivity.

Our results also highlight the differential impacts of climate change and socio-economic conditions on rural and urban households. On one hand, around three-fourths of the total increase in number of undernourished people in Niger by 2050 are expected to reside in urban areas, driven primarily by the high rate of urban population growth. On the other hand, rural households are more exposed and vulnerable to climate change induced changes on labor and crop productivity, and the changes have a relatively larger impact on rural food security outcomes than on urban outcomes. Of the total change in undernourishment headcount to mid-century, climate change contributes to 14 percent and 8 percent of the changes in rural and urban areas respectively. One of the reasons for the larger impact on the rural households is higher reliance on crop-based products for caloric intake which outweighs any gains in agricultural revenue due to increased crop prices. These results highlight the need for paying attention to urban food security alongside rural food security and to recognize that the underlying drivers of the outcomes are different in both magnitude and mechanism for rural and urban households.

Our policy scenario assessments suggest that relying on increased R&D spending to close the food demand–supply gap will be insufficient. Interventions on the demand side (population growth scenario) have the potential for greater impacts on household food security in Niger than supply side intervention (investments in agricultural R&D). This is not surprising because food security outcomes are largely driven by population growth in Niger, and historically the rate at which R&D spending in the region has translated into farm productivity gains through technology adoption has been very low, with limited spillovers from other regions. The trade integration simulation shows the overall positive outcomes of more integrated regional markets for food security in Niger. Both rural and urban household undernourishment levels improve, and there are positive environmental outcomes due to moderated cropland expansion.

These policies are best considered as packages of reforms, as opposed to individual interventions. On the population growth front, despite the socio-economic and political challenges, Niger would benefit greatly by empowering women and educating both men and women, adopting a rights-based approach to population growth policies. Such an education and empowerment strategy will allow Niger to turn its young population into a strong human capital base which could provide a firm foundation for economic growth (Schultz, 2002; World Bank, 2019). In addition, policies to address population growth, such as reducing gender inequality patterns in education and empowerment, simultaneously contributes to agricultural productivity growth and food security by closing gender gaps in agricultural productivity (Diiro et al., 2018; Sraboni et al., 2014) and the gender gap in agricultural productivity is one of the highest in SSA (Backiny-Yetna & McGee, 2015).

On the agricultural R&D front, overall investment has remained low and enhanced research capacity will be necessary to maintain, and possibly accelerate, recent improvements in agricultural productivity growth. There is also potential for accelerated TFP growth through efficiency gains in the R&D and knowledge dissemination activities in Niger. This can be achieved through improved support for local researchers (Walker, 2015), enhanced extension services (Asfaw et al., 2016), private sector partnerships for technology dissemination (Fuglie, 2016), and input market access.

[24] https://lpi.worldbank.org/international/aggregated-ranking, accessed on 20 April 2022. The LPI is an index consisting of efficiency of clearing process by border control agencies, quality of trade and transport related infrastructure, ease of arranging competitively priced shipments, competence and quality of logistics services, ability to track and trace consignments, and timeliness of shipments in reaching destination.

Over the course of this research, we identified a dearth of evidence and understanding in the literature specific to Niger. Three avenues for future research are crucial in furthering development of these policy options. First, we need a better understanding of why technology adoption rates are low in Niger (Asfaw et al., 2016). What drives Nigerien farmers to adopt modern inputs, and what is the role of private agents and the market system (the demand side) in removing constraints? As identified in de Janvry and Sadoulet (2020), while a great deal of research has been conducted on the supply side with public agents intervening for technology adoption, the demand side (farmer adoption) is under-researched. The second priority avenue for future research relates to demographic behavior in Niger where the desired fertility rate appears to be even higher than the observed fertility rate (Shekar et al., 2016). Instead of adopting generic narratives, Nigerien-specific evidence is required to understand how much of this behavior is underpinned by conscious decision making, and how much is due to socially constructed gender inequality.

A final avenue for future research relates to regional market integration. Most of Niger's imports come from neighboring Sahelian countries which are also susceptible to productivity changes due to climate change. This may compromise the case for weather-related shock resistance through trade with neighboring countries. Against the backdrop of the Africa-wide Continental Free Trade Agreement, research into the role of international trade in shaping future food and environmental security has become even more important for Niger.

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Authors' contributions All authors contributed to the study conception and design. Data collection and analysis were performed by Kayenat Kabir with guidance from Thomas Hertel and Uris Baldos. Model code was prepared by Kayenat Kabir and Uris Baldos. The first draft of the manuscript was written by Kayenat Kabir and all authors commented and edited on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and material The baseline input data and the data to simulate shocks can be provided in GEMPACK files.

Code availability The code for the SIMPLE-Niger model are available in text. To use the code, the GEMPACK software with license is required.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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References

Abidoye, B. O., & Odusola, A. F. (2015). Climate change and economic growth in Africa: An econometric analysis. *Journal of African Economies, 24*(2), 277–301.

Aker, J. C. (2007). *Cereal Market Performance during Food Crises: The Case of Niger in 2005*. University of California-Berkeley.

Aker, J. C. (2010). Information from markets near and far: Mobile phones and agricultural markets in Niger. *American Economic Journal: Applied Economics, 2*(3), 46–59.

Alene, A. D., Abdoulaye, T., Rusike, J., Manyong, V., & Walker, T. S. (2015). The effectiveness of crop improvement programmes from the perspectives of varietal output and adoption: Cassava, Cowpea, Soybean and Yam in sub-Saharan Africa and maize in West and Central Africa. *Crop improvement, adoption and impact of improved varieties in food crops in sub-Saharan Africa* (pp. 74–122). Wallingford, UK: CABI.

Alston, J. M., Norton, G. W., & Pardey, P. G. (1995). *Science under scarcity: principles and practice for agricultural research evaluation and priority setting*. Cornell University Press.

Asfaw, S., Di Battista, F., & Lipper, L. (2016). Agricultural technology adoption under climate change in the Sahel: Micro-evidence from Niger. *Journal of African Economies, 25*(5), 637–669.

Asfaw, S., Pallante, G., & Palma, A. (2018). Diversification strategies and adaptation deficit: Evidence from rural communities in Niger. *World Development, 101*, 219–234.

Backiny-Yetna, P., & McGee, K. (2015). *Gender Differentials and Agricultural Productivity in Niger*. Washington, DC: World Bank Group. https://openknowledge.worldbank.org/handle/10986/21593 Policy Research Working Paper; No. 7199. License: CC BY 3.0 IGO.

Baldos, U. L. C., & Hertel, T. W. (2013). Looking back to move forward on model validation: Insights from a global model of agricultural land use. *Environmental Research Letters, 8*(3), 034024.

Baldos, U. L. C., & Hertel, T. W. (2014). Global food security in 2050: The role of agricultural productivity and climate change. *Australian Journal of Agricultural and Resource Economics, 58*(4), 554–570.

Baldos, U. L. C., & Hertel, T. W. (2015). The role of international trade in managing food security risks from climate change. *Food Security, 7*(2), 275–290.

Barrera, E. L., & Hertel, T. (2020). Global food waste across the income spectrum: Implications for food prices, production and resource use. *Food Policy, 98*, 101874.

Ben Mohamed, A. (2011). Climate change risks in Sahelian Africa. *Regional Environmental Change, 11*(1), 109–117.

Ben Mohamed, A., Van Duivenbooden, N., & Abdoussallam, S. (2002). Impact of climate change on agricultural production in the Sahel–Part 1. Methodological approach and case study for millet in Niger. *Climatic Change, 54*(3), 327–348.

Block, S. A. (2014). The post-independence decline and rise of crop productivity in sub-Saharan Africa: Measurement and explanations. *Oxford Economic Papers, 66*(2), 373–396.

Bloom, D. E., Canning, D., Fink, G., & Finlay, J. E. (2009). Fertility, female labor force participation, and the demographic dividend. *Journal of Economic Growth, 14*(2), 79–101.

Brown, M. E., Carr, E. R., Grace, K. L., Wiebe, K., Funk, C. C., Attavanich, W., Backlund, P., & Buja, L. (2017). Do markets and trade help or hurt the global food system adapt to climate change? *Food Policy, 68*, 154–159.

Buzan, J. R., & Huber, M. (2020). Moist heat stress on a hotter Earth. *Annual Review of Earth and Planetary Sciences, 48*, 623–655.

Canning, D., Raja, S., & Yazbeck, A. S. (2015). *Africa's Demographic Transition: Dividend or Disaster? Africa Development Forum*. Washington, DC: World Bank; Agence Française de Développement. https://openknowledge.worldbank.org/handle/10986/22036 License: CC BY 3.0 IGO.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R. K., Kwon, W. K., Laprise, R., & Magaña-Rueda, V. (2007). Regional climate projections. *Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11* (pp. 847–940). Cambridge: University Press.

Clapp, J. (2017). Food self-sufficiency: Making sense of it, and when it makes sense. *Food Policy, 66*, 88–96.

Clements, K. W., & Chen, D. (1996). Fundamental similarities in consumer behaviour. *Applied Economics, 28*(6), 747–757.

Cornia, G. A., Deotti, L., & Sassi, M. (2016). Sources of food price volatility and child malnutrition in Niger and Malawi. *Food Policy, 60*, 20–30.

Daouda, M., Ozer, P., & Erpicum, M. (1998). *Consequences of the drought on the length and amplitude of the rainy season in Niger*. In International Conference on tropical climatology, meteorology and hydrology in memoriam Franz Bultot, Bruxelles (Belgium), 22-24 May 1996. Royal Meteorological Institute of Belgium; Royal Academy of Overseas Sciences.

de Janvry, A., & Sadoulet, E. (2020). Using agriculture for development: Supply-and demand-side approaches. *World Development, 133*, 105003.

de Lima, C. Z., Buzan, J. R., Moore, F. C., Baldos, U. L. C., Huber, M., & Hertel, T. W. (2021). Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters, 16*(4), 044020.

Di Lorenzo, P., & Fadika, F. D. L. (2022). *Pathways to Sustainable Growth in Niger: A World Bank Group Country Economic Memorandum*. World Bank Group.

Diffenbaugh, N. S., & Giorgi, F. (2012). Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change, 114*(3–4), 813–822.

Diiro, G. M., Seymour, G., Kassie, M., Muricho, G., & Muriithi, B. W. (2018). Women's empowerment in agriculture and agricultural productivity: Evidence from rural maize farmer households in western Kenya. *PLoS ONE, 13*(5), e0197995.

FAO, Ifad, UNICEF, WFP, WHO. (2020). *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets*. Rome: FAO. https://doi.org/10.4060/ca9692en

Fuglie, K. O. (2011). Agricultural productivity in Sub-Saharan. In D. R. Lee & M. B. Ndulo (Eds.), *The food and financial crises in sub-Saharan Africa: origins, impacts and policy implications* (p. 22). CABI.

Fuglie, K. (2012). Productivity Growth and Technology Capital in the Global Agricultural Economy. In K. Fuglie, S. L. Wang, & V. E. Ball (Eds.), *Productivity Growth in Agriculture: An International Perspective.* Oxfordshire, UK: CAB International.

Fuglie, K. (2016). The growing role of the private sector in agricultural research and development world-wide. *Global Food Security, 10*, 29–38.

Fuglie, K. (2018). R&D capital, R&D spillovers, and productivity growth in world agriculture. *Applied Economic Perspectives and Policy, 40*(3), 421–444. https://doi.org/10.1093/aepp/ppx045

Fuglie, K., & Rada, N. (2013). *Resources, policies, and agricultural productivity in sub-Saharan Africa*. USDA-ERS. Economic Research Report No. 145.

Fuglie, K. O., & Wang, S. L. (2012). Productivity growth in global agriculture shifting to developing countries. *Choices, 27*(4), 1–7.

Gerbens-Leenes, P. W., Nonhebel, S., & Krol, M. S. (2010). Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. *Appetite, 55*(3), 597–608.

Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., & Foley, J. A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences, 107*(38), 16732–16737.

Griffith, R., Redding, S., & Reenen, J. V. (2004). Mapping the two faces of R&D: Productivity growth in a panel of OECD industries. *Review of Economics and Statistics, 86*(4), 883–895.

Haqiqi, I. (2019). *Irrigation, adaptation, and water scarcity*. Purdue University Graduate School. Doctoral dissertation.

Haqiqi, I., Grogan, D. S., Hertel, T. W., & Schlenker, W. (2021). Quantifying the impacts of compound extremes on agriculture. *Hydrology and Earth System Sciences, 25*(2), 551–564.

Hasegawa, T., Fujimori, S., Takahashi, K., & Masui, T. (2015). Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environmental Research Letters, 10*(1), 014010.

Hertel, T. W. (2011). The global supply and demand for agricultural land in 2050: A perfect storm in the making? *American Journal of Agricultural Economics, 93*(2), 259–275.

Hertel, T. W., & Baldos, U. L. C. (2016a). Attaining food and environmental security in an era of globalization. *Global Environmental Change, 41*, 195–205.

Hertel, T. W., & Baldos, U. L. C. (2016b). *Global change and the challenges of sustainably feeding a growing planet* (p. 22). Springer.

Hertel, T. W., Baldos, U. L., & Fuglie, K. O. (2020). Trade in Technology: A Potential Solution to the Food Security Challenges of the 21st Century. *European Economic Review, 127*, 103479.

Hertel, T. W., Ramankutty, N., & Baldos, U. L. C. (2014). Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. *Proceedings of the National Academy of Sciences, 111*(38), 13799–13804.

Hill, R. V., & Porter, C. (2017). Vulnerability to drought and food price shocks: Evidence from Ethiopia. *World Development, 96*, 65–77.

INS/Niger, Institut National de la Statistique-, & I. C. F. International. (2013). Niger Enquête Démographique et de Santéet àIndicateurs Multiples (EDSN- MICS IV) 2012. September. https://dhsprogram.com/publications/publication-FR277-DHS-Final-Reports.cfm

IPCC. (2021). Climate Change 2021: The Physical Science Basis. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

IPCC. (2014). *Climate Change: Impacts, Adaptation, and Vulnerability*. Cambridge University Press.

Jiang, L., & O'Neill, B. C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change, 42*, 193–199.

Jones, A. D., Ngure, F. M., Pelto, G., & Young, S. L. (2013). What are we assessing when we measure food security? A compendium and review of current metrics. *Advances in Nutrition, 4*(5), 481–505.

Lebel, T., & Ali, A. (2009). Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *Journal of Hydrology, 375*(1–2), 52–64.

Lesser, C., & Moisé-Leeman, E. (2009). *Informal cross-border trade and trade facilitation reform in sub-Saharan Africa*. Paris: OECD Publishing. https://doi.org/10.1787/225770164564 OECD Trade Policy Papers, No. 86.

Lobell, D. B., Baldos, U. L. C., & Hertel, T. W. (2013). Climate adaptation as mitigation: The case of agricultural investments. *Environmental Research Letters, 8*(1), 015012.

Ludena, C. E., Hertel, T. W., Preckel, P. V., Foster, K., & Nin, A. (2007). Productivity growth and convergence in crop, ruminant, and nonruminant production: Measurement and forecasts. *Agricultural Economics, 37*(1), 1–17.

Lutz, W., Scherbov, S., Makinwa-Adebusoye, P. K., & Reniers, G. (2004). Population–Environment–Development–Agriculture. In W. Lutz, W. C. Sanderson, & S. Scherbov (Eds.), *The end of world population growth in the 21st century: New challenges for human capital formation and sustainable development* (pp. 187–225). London, UK: Earthscan.

Martin, T. C. (1995). Women's education and fertility: results from 26 Demographic and Health Surveys. *Studies in Family Planning, 26*, 187–202.

McCarl, B. A., & Hertel, T. W. (2018). Climate change as an agricultural economics research topic. *Applied Economic Perspectives and Policy, 40*(1), 60–78.

Meagher, K. (2003). A back door to globalisation? Structural adjustment, globalisation & transborder trade in West Africa. *Review of African Political Economy, 30*(95), 57–75.

Minot, N. (2011). *Transmission of world food price changes to markets in sub-Saharan Africa*. International Food Policy Research Institute (IFPRI). IFPRI discussion papers 1059.

Montaud, J. M., Pecastaing, N., & Tankari, M. (2017). Potential socio-economic implications of future climate change and variability for Nigerien agriculture: A countrywide dynamic CGE-Microsimulation analysis. *Economic Modelling, 63*, 128–142.

Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., & Ambrosino, C. M. (2013). The projected timing of climate departure from recent variability. *Nature, 502*(7470), 183–187.

Moussa, B., Nkonya, E., Meyer, S., Kato, E., Johnson, T., & Hawkins, J. (2016). Economics of Land Degradation and Improvement in Niger. In E. Nkonya, A. Mirzabaev, & J. von Braun (Eds.), *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Cham: Springer. https://doi.org/10.1007/978-3-319-19168-3_17

Muhammad, A., Seale, J. L., Meade, B., & Regmi, A. (2011). *International evidence on food consumption patterns: an update using 2005 international comparison program data*. US: USDA-ERS. Technical bulletin No. 1929.

Neiken, L. (2003). *FAO methodology for estimating the prevalence of undernourishment (Proceedings: Measurement and Assessment of Food Deprivation and Undernutrition)*. Rome, Italy: FAO.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. In V.R. Barros, et al. (Eds.), *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Ndjeunga, J., Mausch, K., & Simtowe, F. (2015). Assessing the effectiveness of agricultural R&D for groundnut, pearl millet, pigeonpea, and sorghum in west and Central Africa and East and Southern Africa. *Crop Improvement, Adoption, and Impact of Improved Varieties in Food Crops in sub-Saharan Africa* (pp. 123–147). Wallingford: CAB International.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., & Levy, M. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169–180.

Otsuka, K., & Muraoka, R. (2017). A green revolution for sub-Saharan Africa: Past failures and future prospects. *Journal of African Economies, 26*(suppl_1), i73–i98.

Partey, S. T., Zougmoré, R. B., Ouédraogo, M., & Campbell, B. M. (2018). Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. *Journal of Cleaner Production, 187*, 285–295.

Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences, 109*(31), 12302–12308.

Potts, M., Gidi, V., Campbell, M., & Zureick, S. (2011). Niger: Too little, too late. *International Perspectives on Sexual and Reproductive Health, 37*(2), 95–101.

Potts, M., Henderson, C., & Campbell, M. (2013). The Sahel: A Malthusian Challenge? *Environmental and Resource Economics, 55*(4), 501–512.

Reij, C., Tappan, G., & Smale, M. (2009). *Agroenvironmental transformation in the Sahel: Another kind of "Green Revolution"* (Vol. 914). Intl Food Policy Res Inst.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., & Lutz, W. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153–168.

Sivakumar, M. V. K. (1992). Climate change and implications for agriculture in Niger. *Climatic change, 20*(4), 297–312.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences, 106*(37), 15594–15598.

Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters, 5*(1), 014010.

Schultz, T. P. (2002). Why governments should invest more to educate girls. *World Development, 30*(2), 207–225.

Shapiro, D. (2012). *Women's education and fertility transition in sub-Saharan Africa Vienna. Yearbook of Population Research* (pp. 9–30). Austrian Academy of Sciences Press.

Shekar, M., Yazbeck, A., Hasan, R., & Bakilana, A. (2016). *Population and Development in the Sahel: Policy Choices to Catalyze a Demographic Dividend. Health, Nutrition and Population Discussion Paper*. Washington, DC: World Bank. https://open knowledge.worldbank.org/handle/10986/25293 License: CC BY 3.0 IGO.

Shiffman, J., & Quissell, K. (2012). Family planning: A political issue. *The Lancet, 380*(9837), 181–185.

Sraboni, E., Malapit, H. J., Quisumbing, A. R., & Ahmed, A. U. (2014). Women's empowerment in agriculture: What role for food security in Bangladesh? *World Development, 61*, 11–52.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., & Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters, 8*(1), 014040.

Swinnen, J., & Squicciarini, P. (2012). Mixed messages on prices and food security. *Science, 335*(6067), 405–406.

Theil, H., & Finke, R. (1983). The consumer's demand for diversity. *European Economic Review, 23*(3), 395–400.

Thomas, T., & Rosegrant, M. (2015). Climate change impact on key crops in Africa: Using crop models and general equilibrium models to bound the prediction. In A. Elbehri (Ed.), *Climate change and food systems: global assessments and implications for food security and trade*. Rome: Food Agriculture Organization of the United Nations (FAO).

Thornton, P. K., & Herrero, M. (2015). Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change, 5*(9), 830–836.

Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N. P., & Zakieldeen, S. (2022). Africa. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. In Press.

United Nations, Department of Economic and Social Affairs, Population Division. (2020). *Estimates and Projections of Family Planning Indicators 2020*. United Nations.

UNDP. (2019). *Human Development Report 2019. Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century*. New York. http://hdr.undp.org/en/content/human-development-report-2019

UNFCC. (2016). *Intended Nationally Determined Contribution (INDC) of Niger*. http://hdr.undp.org/en/content/human-development-report-2019. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Niger%20First/Niger-INDC-final_Eng.pdf

United Nations, Department of Economic and Social Affairs, & Population Division (2017). *World Family Planning 2017 - Highlights (ST/ESA/SER.A/414)*. New York: United Nations.

United Nations, Department of Economic and Social Affairs, & Population Division (2019a). *World Population Prospects 2019a, Volume I: Comprehensive Tables (ST/ESA/SER.A/426)*. New York: United Nations.

United Nations, Department of Economic and Social Affairs, & Population Division (2019b). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. New York: United Nations.

United Nations Office for West Africa and the Sahel. (2018). *UN Support Plan for the Sahel*. https://unowas.unmissions.org/sites/default/files/english_summary_report_2.pdf

Van Duivenbooden, N., Abdoussalam, S., & Mohamed, A. B. (2002). Impact of climate change on agricultural production in the Sahel-Part 2. Case study for groundnut and cowpea in Niger. *Climatic Change, 54*(3), 349–368.

Van Ittersum, M. K., Van Bussel, L. G., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., & Yang, H. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences, 113*(52), 14964–14969.

van Wesenbeeck, C. (2018). *Disentangling urban and rural food security in West Africa*. Paris: OECD Publishing. https://doi.org/10.1787/e0c75266-en West African Papers, No. 15.

Vizy, E. K., & Cook, K. H. (2012). Mid-twenty-first-century changes in extreme events over northern and tropical Africa. *Journal of Climate, 25*(17), 5748–5767.

Walker, T. (2015). Genetic improvement of the crop in the 1998 initiative: Historical context and exploratory analysis. *Crop Improvement, Adoption, and Impact of Improved Varieties in Food Crops in sub-Saharan Africa* (pp. 44–73). Wallingford: CAB International.

Walker, T., Hash, T., Rattunde, F., Weltzien, E. (2016). *Improved crop productivity for Africa's Drylands. World Bank Studies*. World Bank. https://openknowledge.worldbank.org/handle/10986/24818

World Bank. (2019). *Economic Impacts of Gender Inequality in Niger*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35197 License: CC BY 3.0 IGO.

World Bank. (2021). *Niger Urbanization Review: Supporting Niger's Modern Oases*. Washington, DC: World Bank©. https://openknowledge.worldbank.org/handle/10986/35197 License: CC BY 3.0 IGO.

World Health Organization. (2020). *UNICEF/WHO/The World Bank Group joint child malnutrition estimates: Levels and trends in child malnutrition: Key findings of the 2020 edition*. http://www.who.int/publications/i/item/9789240003576

Zakari, S., Ying, L., & Song, B. (2014). Market integration and spatial price transmission in Niger grain markets. *African Development Review, 26*(2), 264–273.

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