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Key Points:

- Sustainable agricultural intensification alone will not suffice to meet future food demand in African countries
- Food insufficiency can be reduced by moderating diets and implementing water storage to irrigate during dry periods
- By halving current levels of food loss and waste, an additional 130 million people can be fed in Africa through domestic food production

Supporting Information:

Supporting Information may be found in the online version of this article.

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Future Food Security in Africa Under Climate Change

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Abstract Africa is a major hotspot of food insecurity with climate change and population growth as major drivers. Irrigation expansion can sustainably increase agricultural productivity and adapt crops to climate change. We use agro-hydrological, climate, and socio-economic models to quantify crop production with irrigation expansion and perform food security analyses for different adaptation scenarios for African countries under baseline and 3°C warmer climate conditions. We find that under a 3°C warmer climate the total food production in Africa can only feed 1.35 billion people, when the continent's population is expected to reach 3.5 billion, leaving a food deficit equivalent to 2.15 billion people. Increasing agricultural productivity with irrigation alone will not be enough to achieve food self-sufficiency. Therefore, future food demand will likely be met by other means such as cropland expansion or greater reliance on imports which would further expose African populations to uncertainty from the volatility in global food prices.

1. Introduction

The African continent is affected by malnutrition and food insecurity. In 2020, over 811 million people globally, including 282 million Africans (21% of the continent's population) faced undernourishment due to climate-related shocks, conflict, changes in land tenure and agrarian systems of production, high-income inequality and economic downturns worsened by the COVID-19 pandemic (FAO, IFAD, UNICEF, WFP and WHO 2021). Additionally, 426 million people do not have regular access to sufficient (and nutritious) food and are considered moderately food insecure (FAO, ECA and AUC, 2021). As of 2020, forty percent of the world's stunted children live in Africa (FAO, ECA and AUC, 2021). Stunting, which is typically defined as having height two standard deviations below the World Health Organization's median for that age group, is an indicator of chronic malnutrition and can have serious developmental and health consequences (De Onis & Branca, 2016; Graves et al., 2019). At the same time, Africa is considered the region with one of the fastest population growth rates in the world and is predicted to reach a population of about 2.5 billion people by 2050 compared to 1.3 billion today (United Nations, 2019). Population is already outstripping food supply in the Sahel Region (Graves et al., 2019) and increasing many countries' dependence on food imports (D'Odorico et al., 2014); crop production will need to be sustainably increased to prevent population from outpacing food supply (Beltran-Peña et al., 2020).

Aside from the reliance of African countries on agriculture for food, the agricultural sector also accounts for on average ~19% of their Gross Domestic Product (GDP, with some countries like Sierra Leone relying on agriculture for up to 61% of their GDP) and over 60% of full-time employment—making countries more susceptible to changes in agricultural production capability (ADBG, 2019; Pretty et al., 2012; World Bank, 2021). For reference, agriculture accounts for just 1%–3% of GDP for high income countries even if they are major agricultural producers such as the United States (World Bank, 2021). Indeed, Africa is a major hotspot for food insecurity and climate change vulnerability because most countries in Africa are not currently and will not be self-sufficient under a changing climate. Beltran-Peña et al., 2020 showed that this region will continue to be heavily reliant on imports throughout the 21st century. Population in this region is expected to grow significantly under middle-of-the-road and business-as-usual scenarios—increasing the number of people that may be food insecure (in terms of food availability) (Beltran-Peña et al., 2020). Anthropogenic climate change has already reduced total factor productivity by 34% since 1961 in Africa, where warmer regions (i.e., Sub-Saharan Africa) with low agricultural productivity suffer the greatest impacts (Ortiz-Bobea et al., 2021). In 2018, Ethiopia, Malawi, Kenya, Mozambique, Madagascar, Zambia, and Uganda were the most affected by climate shocks from adverse weather conditions, drought, floods, late or erratic rainfall (FAO, ECA and AUC, 2020). The World Meteorological Organization reports that 2019 was among the three warmest years on record for the African continent—characterized by continued increasing temperatures, rising sea levels and impacts associated with extreme weather and climate

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events (WMO, 2020). The Greater Horn of Africa and the Sahel are regions that experienced extreme shifts from dry conditions in 2018 to flooding due to heavy rainfall in 2019 while, undernourishment has increased by 45.6% in drought-prone sub-Saharan Africa since 2012 (WMO, 2020). Climate warming will continue to drastically affect crop productivity with more severe effects in Sub-Saharan Africa—jeopardizing the well-being of vulnerable populations disproportionately (FAO, ECA and AUC, 2021).

The degree to which the Earth's climate will warm above pre-industrial levels and by when is highly dependent on global climate action policies and programs enacted. The current Nationally Determined Contributions (NDCs) do not put us on track to meet the goals of the Paris Agreement to *"hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels"* and may give rise to an increase in temperature of at least 3°C above pre-industrial levels by the end of the century (UNEP, 2020; UNFCCC, 2015). According to the 2020 UNEP Emissions Gap Report, with the actual pre-COVID-19 policies in place, emissions will heighten by 2030 and the Earth may reach a warming of at least 3.5°C by 2100 (UNEP, 2020). Scientists have agreed that, to limit global warming to 1.5°C, "global net anthropogenic CO_2 emissions must decline by about 45% from 2010 levels by 2030 and net zero must be reached around 2050" relying heavily on carbon dioxide removal technologies (IPCC, 2018; Rosa, Sanchez, & Mazzotti, 2021; Terlouw et al., 2021). The 2021 Glasgow Climate Pact acknowledges that unless NDCs become more ambitious reflected by enhanced mitigation, reaching net-zero CO_2 emissions, adaptation, and finance actions, the 1.5°C and 2°C targets of the Paris Agreement may soon be out of sight (IPCC, 2021; Millar et al., 2017; UNFCCC, 2021). This pact (agreed upon by nearly 200 countries) explicitly calls upon parties to transition towards low-emission energy systems, phase out fossil fuels, and to strengthen their NDCs in 2022 (UNFCCC, 2021). In a race against time and the carbon budget, there is no certainty that these pledges will result in actionable policy urgently needed—thus a 3°C warmer future is not unlikely. At the same time, countries in the G20, account for approximately 80% of greenhouse gas emissions (GHG) while climate change disproportionately impacts underdeveloped countries and regions (Harrington et al., 2016; IPCC, 2018; O'Neill, Oppenheimer, et al., 2017; UNEP, 2020; United Nations Environment Programme, 2021a). It is estimated that at 3°C African regions may make up 27%–51% of the global exposed and vulnerable population to climate change (Byers et al., 2018).

Agricultural expansion onto new areas damages habitats, biodiversity, increases deforestation and causes other negative environmental impacts (Foley et al., 2011; Gibbs et al., 2010; Williams et al., 2021). Williams et al. (2021) project large increases in agricultural land area with significant habitat losses throughout Sub-Saharan Africa by 2050. Therefore, sustainable agricultural intensification on current croplands through greater infrastructural investments (in sustainable irrigation expansion, power production and grid development, and roads), narrowing yield gaps on underperforming lands, and reducing food loss and waste is the preferred adaptation approach to improve the supply and consumption of agricultural products from current croplands despite the rising land scarcity and degradation in Africa (FAO, ECA and AUC, 2021; Foley et al., 2011; Goyal & Nash, 2017; Mueller et al., 2012; Rosa et al., 2018). Implementing water storage management infrastructure, adopting soil water conservation practices, planting more suitable crops, and intensifying agricultural production through sustainable irrigation expansion onto currently water-limited rainfed croplands are viable strategies for climate adaptation (Rosa, 2022; Rosa, Chiarelli, Rulli, et al., 2020; Rosa et al., 2018). Today, only 6% of the total cultivated area in African countries is equipped for irrigation (You et al., 2010). In Sub-Saharan Africa, in up to 35% of currently rain-fed croplands, water resources will be locally available for an expansion of irrigation without negative environmental externalities on freshwater resources under a 3°C warmer climate (Rosa, Chiarelli, Sangiorgio, et al., 2020). However, opportunities for irrigation differ by country and some regions will experience a reduction in areas suitable for irrigation (Elliot et al., 2014). Recent studies have highlighted that relatively large annual water storage will be required to maintain a current irrigation potential in a 3°C warming scenario; conversely, in the absence of such water storage, about 120 million hectares of African croplands will become unsuitable for sustainable irrigation expansion (Rosa, Chiarelli, Sangiorgio, et al., 2020).

To date, it is still unclear to what extent the sustainable expansion of irrigation, access to water storage, and food loss and waste reduction strategies will affect food security in African countries. Here we expand recent food self-sufficiency analyses (Beltran-Peña et al., 2020) to account for the limits to sustainable irrigation expansion under climate change. We consider sustainable irrigation and freshwater storage potential, environmental flow requirements, future reliance on animal-based products for dietary consumption, estimates of population growth, and diverse pathways of food loss and waste. This study quantifies the future of food security in Africa under climate and societal change.

2. Materials and Methods

This study uses agro-hydrological, climate, and societal models to perform a food security and vulnerability analysis for 49 African countries under a 3°C warmer climate (compared to pre-industrial conditions) to determine potential adaptation strategies and the extent to which African countries will be reliant on external food sources to adequately feed their populations.

2.1. Crop Production and Availability

To determine the crop production potentially achievable under climate change, we use results from Rosa, Chiarelli, Sangiorgio, et al. (2020) who estimated rainfed and irrigated crop production for 130 primary crops based on the global cropland extent of the MIRCA2000 data set (Portmann et al., 2010). Their analysis determined the spatial extent of land suitable for sustainable irrigation expansion under baseline (long-term climatic data for the reference period for global agricultural data from 1996 to 2005 (Portmann et al., 2010)) and 3°C climate conditions. The analysis by Rosa, Chiarelli, Sangiorgio, et al. (2020) used in this study evaluated the ability of available water resources to meet the crop water demand both at the monthly timescale (assuming that short-term water deficits can be offset by reliance on small-scale water storages and water harvesting techniques) and at the annual time scale (i.e., assuming that seasonal water deficits can be compensated by using large reservoirs). In other words, a need for "large reservoirs" is found when at the annual time scale water availability is sufficient to meet the irrigation water demand while the monthly water balance shows periods of water scarcity. In these analyses the local water availability included surface and groundwater runoff and accounted for the need to preserve environmental flows.

Irrigation water requirements were determined (following Rosa, Chiarelli, Sangiorgio, et al., 2020) as the additional water needed to meet crop water requirements and prevent water stress conditions in croplands where rainfed crop growth is water stressed (green water scarcity) (Brouwer & Heibloem, 1986; Rosa, Chiarelli, Rulli, et al., 2020). The irrigation water requirements for a 3°C warmer climate were calculated using projections of monthly precipitation, evaporation, and runoff (using 30 by 30 arc-min resolution) from the GFDL-ESM2M, HadGEM2-ES, MIROC-ESM-CHEM global climate models in conjunction with the LPJmL, H8, and WATERGAP2 global hydrological models for the representative concentration pathway (RCP) 8.5 of the Coupled Model Intercomparison Project Phase 5 (CMIP 5) from the Inter-Sectoral Impact Model Intercomparison Project (Climate Hazards Group, 2015; Fekete et al., 2002; Harris et al., 2014; Rosa, Chiarelli, Sangiorgio, et al., 2020; Warszawski et al., 2014). Rainfed croplands facing green water scarcity but where irrigation water requirements do not exceed local water availability are considered suitable for sustainable irrigation expansion (Rosa et al., 2018). Following Rosa, Chiarelli, Rulli, et al. (2020), the maximum potential, current rainfed and current irrigated caloric production of each crop was then computed as the product of crop yield (in tons per hectare) from Monfreda et al. (2008) and Mueller et al. (2012); crop calorie content (in kilocalories per tons) from D'Odorico et al. (2014); and crop harvested area (in hectares) from Portmann et al. (2010).

Here, a yield gap is defined as the difference between water-limited potential yield and the actual yield that a farmer currently achieves on a cropland (Lobell et al., 2009; Rosa et al., 2018). Narrowing or closing yield gaps through sustainable irrigation expansion is an agricultural intensification strategy to boost crop production without threatening biodiversity-rich ecosystems through expansion of agricultural croplands (Beltran-Peña et al., 2020; Rosa, 2022; Van Ittersum et al., 2013). This study considers a target yield gap closure of 80% as the feasible limit proposed by Van Ittersum et al. (2016). In line with sustainable development goal 6.6 (protect and restore water related ecosystems), our study preserves 60% environmental flow requirements (EF) in all scenarios (80% EF considered under 3°C as well in Supporting Information S1).

The projected potential sustainable crop production, P, (in kcal) for each country (c) is calculated for six production adaptation scenario combinations (s) of climate (baseline or 3°C warmer climate), water maintained for EF requirements, and water storage strategies (WS) (monthly or annual) following Equation 1:

$$P_{c,s} = \left[R_{2000} + (I_{T,2000} - I_{U,2000}) + (I_{P,s} \times 0.8)\right] \quad (1)$$

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Table 1
Food Loss and Waste Percentages Derived From Food Loss Index and Food Waste Index

	Current	25% Reduction	50% Reduction
Food Loss			
North Africa	10.80%	8.10%	5.4%
Sub-Saharan Africa	14%	10.50%	7%
Food Waste			
Global	17%	12.75%	8.5%
TOTAL FOOD LOSS AND WASTE			
North Africa	27.8%	20.85%	13.9%
Sub-Saharan Africa	31%	23.25%	15.5%

Note. Green shaded boxes indicate SDG combination of food loss and waste.

Here, R_{2000} indicates rainfed caloric (kcal) production in year 2000, ($I_{T,2000} - I_{U,2000}$)represents sustainable irrigated caloric (kcal) production in year 2000 calculated as the difference between total and unsustainable production. Additional caloric production (kcal) potential under sustainable irrigation expansion for scenario s at 80% yield gap closure is represented as ($I_{P,s} \times 0.8$) with $I_{P,s}$being equal to zero in areas unsuitable to sustainable irrigation, and otherwise equal to the production gap calculated as the sum of yield gaps times cultivated areas across all crops.

The amount of crop calories produced that are actually available for direct or indirect human consumption is heavily dependent on the quantity of food this is lost or wasted. The Food and Agriculture Organization of the United Nations (FAO) and the United Nations Environment Program (UNEP) are working together to develop the Food Loss Index (FLI) and the Food Waste Index (FWI), respectively, to measure progress toward meeting this goal. The FAO defines food loss as "the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retail, food service providers, and consumers" (FAO, 2019a, 2019b, 2019c). The 2019 FAO State of Food and Agriculture Report provides the first estimates for the FLI and found that globally, 14% of food is lost. In the context of the FWI, the UNEP defines food waste as "food and the associated inedible parts removed from the human food supply chain in the retail, food service, and household sectors" (UNEP, 2021b). The 2021 Food Waste Index Report estimates that 17% of total global food production may be wasted (11% in households, 5% in food service and 2% in retail). Combining the global averages of the FAO FLI and the UNEP FWI, approximately 31% of food is lost and wasted. The current percentages of food loss in Northern and Sub-Saharan Africa were taken from the Food Loss Index (FAO, 2019a). Globally, there is insufficient data on food waste and the measurement methods vary widely. Therefore, we applied the global percentages of food waste from the FWI uniformly across all African countries in this study. SDG 12.3 sets the target of halving per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses by 2030 (U.N. DESA, 2016). Given this SDG, we calculated the 25% and 50% reductions from current values for each indicator (Table 1). The food loss and food waste percentage scenarios derived from the FLI and FWI are depicted as $\mathrm{FL}_{\%}$ and $\mathrm{FW}_{\%}$, where the percentage indicates the percent reduction (Equations 2.1 and 2.2).

$$\mathrm{FL}_{\%} = \mathrm{FL}_{\mathrm{current}} - (\mathrm{FL}_{\mathrm{current}} \times \%_{\mathrm{reduction}}) \tag{2.1}$$

$$\mathrm{FW}_{\%} = \mathrm{FW}_{\mathrm{current}} - (\mathrm{FW}_{\mathrm{current}} \times \%_{\mathrm{reduction}}) \tag{2.2}$$

We consider 3 pathways for food loss and waste (h)—no reduction, a 25% reduction and a 50% reduction. In this study we assessed the projected crop availability, $P_{\mathrm{AVAILABLE}}$ (in kcal) for direct or indirect human consumption per country and production adaptation scenario accounting for 80% yield gap closure and different food loss and waste reduction pathways (h) following Equation 3:

$$P_{\mathrm{AVAILABLE},c,s,h} = P_{c,s} \times (1 - \mathrm{FL}_{\%} - \mathrm{FW}_{\%}) \tag{3}$$

A schematic of the production and food loss/waste combinations considered in this study can be found in Figure 1.

2.2. Nutrition Thresholds

Nutritional requirements for individuals to be free from hunger have been associated with a minimum daily energy (calorie) intake (fh) of 1,829 kcal per capita per day (D'Odorico, Carr, Davis, et al., 2019; FAO, IFAD,

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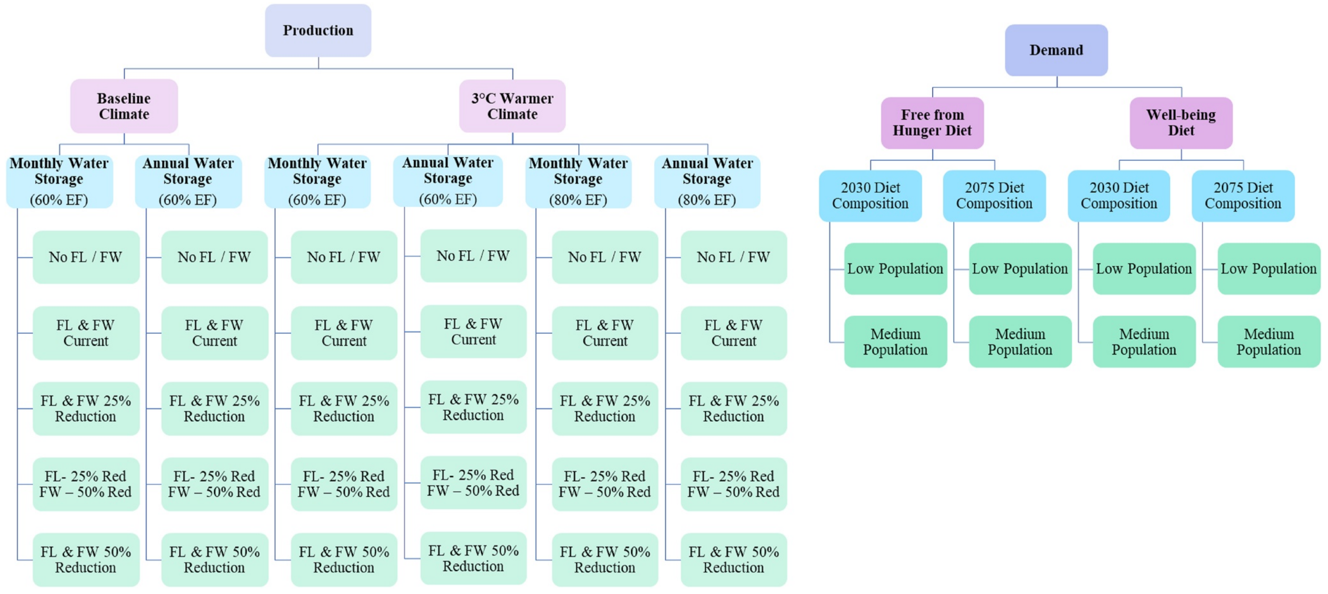

Figure 1. Scenario breakdown. This figure breaks down the different production and demand variables considered in this study. The adaptation strategy scenarios are made of distinct combinations of these variables.

UNICEF, WFP and WHO, 2021; Roser & Ritchie, 2013). According to the Food and Agriculture Organization of the United Nations, the minimum daily energy requirement of a population is the weighted average of the different demographic groups within that population (i.e., differences in age, sex, body mass index, etc.) (FAO, IFAD, UNICEF, WFP and WHO, 2021; Roser & Ritchie, 2013). Likewise, an individual would need to consume about 2,327 kcal per capita per day or more to be in a better state of well-being (*wb*) (D'Odorico, Carr, Davis, et al., 2019; FAO, 2014). These thresholds were adopted in this study as the base dietary consumption pathways (*x*)—meaning that we assume people consume at least 1,829 or 2,327 kcal per day depending on the dietary scenario.

2.3. Future Dietary Caloric Demand

This study assesses food security in African countries under a baseline and 3°C warmer climate. To estimate when the global average temperature is expected to exceed preindustrial conditions (1850–1900) by 3°C, we took the average year over a running mean timeframe of 10 years for the GFDL-ESM2M and MIROC 5 global climate models under CMIP5 RCP 8.5 from the Climate Analytics Warming Attribution Calculator (Climate Analytics, https://wlcalc.climateanalytics.org/choices; Taylor et al., 2012). Based on these criteria, we assume that the estimated year of exceedance for 3.0°C above pre-industrial levels is around 2075 (Table 2). It is important to note that there is some uncertainty on the exact year in which these temperature levels will be reached across models. However, the IPCC AR6 report projects that 3.0°C above pre-industrial level will be exceeded between 2075 and 2076 under the newly defined SSP3-7.0 scenario (Fyfe et al., 2021). Hence our estimate coincides well with recent studies. This projected year of exceedance, 2075, was used as the reference year to calculate the caloric demand per country (based on projected dietary composition patterns and population) during the time we expect the climate will reach 3°C of warming above pre-industrial levels.

Table 2
Estimated 10-Year Time Frame and Average Year of Exceedance for 3.0°C Above Pre-Industrial Levels for GFDL-ESM2M and MIROC 5 Global Climate Models

	GFDL-ESM2M	MIROC-5	Average year of exceedance
3.0°C	2077–2086	2063–2072	2075

Projected animal-based dietary consumption patterns were derived from the quantified scenario matrix produced as a GLOBIOM model emulation by Frank et al., 2021. Crop and livestock demand data was quantified for the SSP2 scenario in the GLOBIOM model (Frank et al., 2021). According to O'Neill, Kriegler, et al., 2017, SSP2 is a scenario in which, "social, economic, and technological trends follow historical patterns. Global and national institutions work toward but make slow progress in achieving sustainable development goals, there are no fundamental technological breakthroughs, environment systems experience degradation but there are some improvements, there is a decline in the overall intensity of resource and energy use, fossil fuel dependance decreases slowly but there is no reluctance in using unconventional fossil fuels, and global population growth is moderate" (Fricko et al., 2017; O'Neill, Kriegler, et al., 2017). The fraction of animal-based products (A) consumed in a diet was calculated as the ratio between the food demand for livestock products (including eggs and dairy) and the total demand for both crops and livestock (in kcal/cap/day) for the Sub-Saharan and North African regions (represented by the Sub-Saharan Africa, *SSA,* and the Middle East and Africa, *MAF*, regions in GLOBIOM).

The per capita (direct and indirect) crop caloric demand ($D_{c,t,x}$)—that is, food + feed crops—per country c in year t for dietary pathway x was determined through Equation 4, as the sum of plant-based caloric demand (v) and animal-based caloric demand from feed (f). The annual per capita demand was computed by multiplying the daily per capita demand by 365 days.

$$D_{c,t,x} = (v_{c,t,x} + f_{c,t,x}) \times 365 \tag{4}$$

The daily calorie consumption from food crops, v, is calculated as the fraction of plant-based products consumed in a diet $(1 - A_{c,t})$ multiplied by the daily calorie uptake, d_x which is equal to 1,829 or 2,327 kcal/day, depending on the diet type (free from hunger or well-being, respectively) (Equation 5). The daily calorie consumption from feed crops (i.e., consumed by feed-fed livestock), f, is assessed as the product of the direct animal-based calories consumed $(d_x \times A_{c,t})$, the plant to animal caloric conversion factor, q, and the fraction of total animal calories from feed-fed production in country c $(r_{c,t})$ (Equation 6). Values of q are country-specific and are taken from Davis et al. (2014).

$$v_{c,t,x} = d_x \times (1 - A_{c,t}) \tag{5}$$

$$f_{c,t,x} = \left[(d_x \times A_{c,t}) \times q_c \times r_{c,t}\right] \tag{6}$$

The value of $r_{c,t}$ changes over time according to trends in livestock consumption. It is assumed that any increase in livestock consumption entails only an increase in feed-fed production while grass-fed production is assumed to remain constant. Therefore, if $r_{c,inital}$ is the initial value of $r_{c,t}$ (i.e., circa year 2000), the value of r at time t per country c is calculated through Equation 7.

$$r_{c,t} = \frac{((d_x \times A_{c,t}) - (d_x \times A_{c,\text{initial}})) \times (1 - r_{c,\text{initial}})}{(d_x \times A_{c,t})} \tag{7}$$

where $r_{c,inital}$ is here taken from Davis et al. (2014) (Beltran-Peña et al., 2020). The total caloric demand of a country in a specific year depends on the projected population of that country in the year evaluated. Population projections were taken from the 2019 UN Population Prospects for the low and medium variants in the year (2075) (United Nations, 2019) when climate warming is projected to surpass 3°C (Table 2).

2.4. Food Sufficiency

The number of people that can be fed (Y) in a given country (c) and year (t) with the projected food availability under each production adaptation strategy scenario (s), food loss and waste pathway (h), and dietary pathway (x) was estimated by dividing the amount of food produced by the amount of food needed to feed a person in that country for that year (Equation 8).

$$Y_{c,t,s,h,x} = \frac{P_{\text{AVAILABLE},c,s,h}}{D_{c,t,x}} = \frac{\text{Production}\ \left(\text{kcal} * \text{year}^{-1}\right)}{\text{Demand}\ (\text{kcal} * \text{cap}^{-1} * \text{year}^{-1})} \tag{8}$$

2.5. Food Insufficiency

The number of people that can be fed was then subtracted from the projected population (low or medium variant) to determine the food insufficiency of a country. Food insufficiency here is defined as the remaining number of people that cannot be fed (N) per a given country (c), year (t), production adaptation strategy (s), food loss and waste pathway (h), dietary pathway (x), and population variant (p) (Equation 9).

$$N_{c,t,s,h,x,p} = \text{Population}_{c,t,p} - Y_{c,t,s,h,x} \tag{9}$$

These numbers were also converted to percentages. Figure 1 maps out the different combinations of demand and production variables that make up the different adaptation strategy scenarios.

2.6. National Food Deficit

The food deficit (Z) (kcal) of a country is defined as the amount of food (expressed in kcal) demand that cannot be met by the domestic food production and will need to come from external sources or even agricultural expansion. This study accounts for a zero hunger (free from hunger diet) or well-being (with higher caloric consumption) diet in the per capita caloric demand. Food deficit is estimated by multiplying the number of people that cannot be fed (N) (depending on population variant) by the annual per capita kcal demand (D) of a country in the year specified under either and fh or wb base-diet (Equation 10).

$$Z_{c,t,s,h,x,p} = N_{c,t,s,h,x,p} \times D_{c,t,x} \tag{10}$$

See Figures S5a and S5b in Supporting Information S1 for a visual representation of the model framework and variable descriptions.

2.7. Sustainable Development Goals Framework

A scenario was created to assess the extent to which African countries can domestically meet select sustainable development goals by 2075 and the magnitude of shortfalls. Our study considers only sustainable crop production through rainfed agricultural production, current sustainably irrigated crop production, and additional production potential through sustainable irrigation expansion on currently rainfed croplands under a 3°C warmer climate. Additionally, in our analysis a minimum of 60% environmental flow requirements is preserved for ecosystem health, addressing SDG indicator 6.4 "to ensure sustainable withdrawals and supply of freshwater to address water scarcity" and SDG indicator 15.5 "to take urgent and significant action to reduce the degradation of natural habitats" (Liu et al., 2021; FAO, 2019b; U.N. DESA, 2016). Considering monthly and annual water storage potentials and strategies under a warmer climate based on Rosa, Chiarelli, Rulli, et al. (2020) and Rosa, Chiarelli, Sangiorgio, et al. (2020), corresponds to SDG 13 on climate action by "promoting mechanisms for raising capacity for effective climate change-related planning and management in least developed countries." By halving food waste at the retail and consumer levels and reducing food losses along the production and supply chains by 25%, SDG 12 "responsible consumption and production" would be met. To ensure zero hunger and zero malnutrition (SDG 2), every person in a country is assigned a well-being diet, where everyone consumes a minimum base diet of 2,327 kcal a day. We address SDG 5 "gender equality" to an extent by assuming a low population trajectory. Since 2075 is more than 50 years from now, we reckon that there is enough time to implement policies (e.g., to promote women education, employment, and socio-economic development) to reach a low population trajectory by the time climate reaches 3°C of warming. In short, crop production and availability for this scenario are determined based on sustainable irrigation expansion and monthly and annual water storage potential under a 3°C warmer climate, 60% environmental flow requirements preserved, 80% yield gap closure, and food loss and waste reduction of 25% and 50% respectively. Food demand is measured based on SSP2 animal-product consumption estimates, allocating every person with a well-being base diet, and the low population variant. Table S1 in Supporting Information S1 details how the specific SDG goal targets are accounted for in this scenario.

2.8. Regional Breakdown

As previously described, this study incorporates data from different sources. Due to data availability limitations, not all data is provided at the country level. Hence, each country was assigned the data values based on the regions they belong to (i.e., North Africa or Sub-Saharan Africa). The countries were then further subdivided into five African regions (North, South, East, West, and Central) according to the United Nations M49 standard (United Nations, 1998) for statistical reporting purposes. The exceptions are Sudan and South Sudan which are both considered together and as part of Eastern Africa in this study due to data limitations. Each country is shown in only one region (United Nations, 1998). The regional breakdown of the African countries considered in this study can be found in Figure S4 and Table S2 in Supporting Information S1. The results of this study are presented at the regional level and further expanded to the country level to demonstrate the practicability of this analysis in climate adaptation planning. Additional data can be found in Supporting Information S1.

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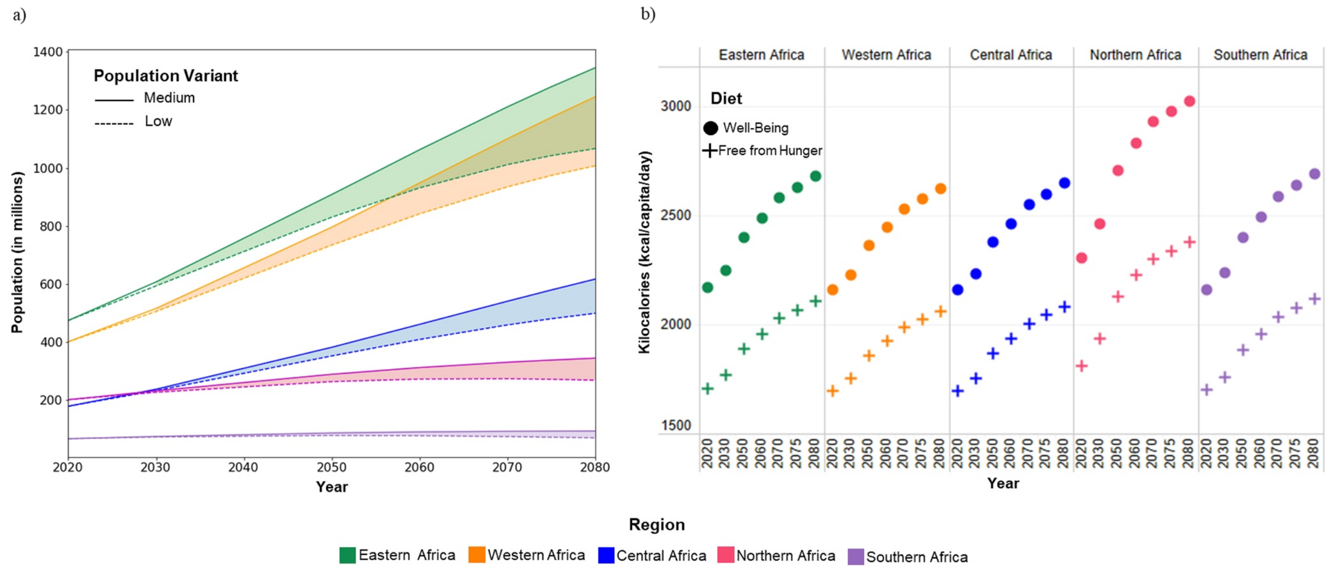

Figure 2. Population and dietary demand projections. Colors represent the five African regions. (a) Population projections from 2020 to 2080 for the medium (solid line) and low (dashed line) population variants. (b) Projected crop kilocalories required to meet daily per capita dietary demand (including feed-fed livestock products) for well-being (dot) and free from hunger (cross) diets from years 2020–2080.

3. Results

3.1. Caloric Demand

According to the 2019 United Nations Population Prospect (medium variant), the population in Africa is expected to increase from 1.37 billion people in 2021 to 1.68 billion people in 2030 and 3.68 billion people by 2080 (United Nations, 2019). Under the medium variant, Eastern and Western Africa are projected to experience the strongest population growth (roughly threefold) from 475 to 401 million people in 2020 to 1.34 and 1.24 billion people respectively in 2080. Central Africa's population is also projected to triple, while the Northern and Southern African regions will experience the lowest growth rates by comparison (Figure 2a). The regional breakdown of countries is shown in Table S2 in Supporting Information S1. Meanwhile, in line with historical patterns, economic growth, urbanization along with other factors will enable shifts toward diets with higher animal-sourced food products (OECD/FAO, 2021).

Figure 2b presents the expected crop kilocalories production per capita per day required to meet either the free from hunger diet of 1,829 kcal/cap/day or the well-being diet of 2,327 kcal/cap/day for each of the five African regions. The change over time reflects the shift toward diets with higher animal-based product consumption (based on SSP2 projections of the GLOBIOM model). Northern Africa will continue to have a higher proportion of animal product in diets compared to the regions in Sub-Saharan Africa. However, Sub-Saharan Africa will experience the largest population growth which will continue to outstrip food supply.

3.2. Production With Food Loss and Waste Pathways

This study evaluated five potential food loss and food waste (FL and FW) pathways—no FL and no FW, current FL and FW, 25% reduction in FL and FW, 50% reduction in FL and FW, and the SDG goal of food loss at 25% and food waste at 50% reduction (Figure 1). Even though it is not feasible to reach absolute zero food loss and waste, this scenario is included here as a refence point to demonstrate the impact food loss and waste have on the food calories available for human consumption. The pathway with no FL and FW also represents the total potential kcal production (Figure 3, in gray) with 80% yield gap closure, under the various adaptation strategies (i.e., 3°C climate, 60% EF, Monthly WS) for each of the five African regions. Hence, the estimated food production and availability outcomes of each adaptation strategy under a 3°C warmer climate can be compared across the regions (Figure 3a). Two baseline climate scenarios are included for comparability. The potential caloric production is greatest in Western Africa for each strategy than in the other regions, followed by Eastern and Central

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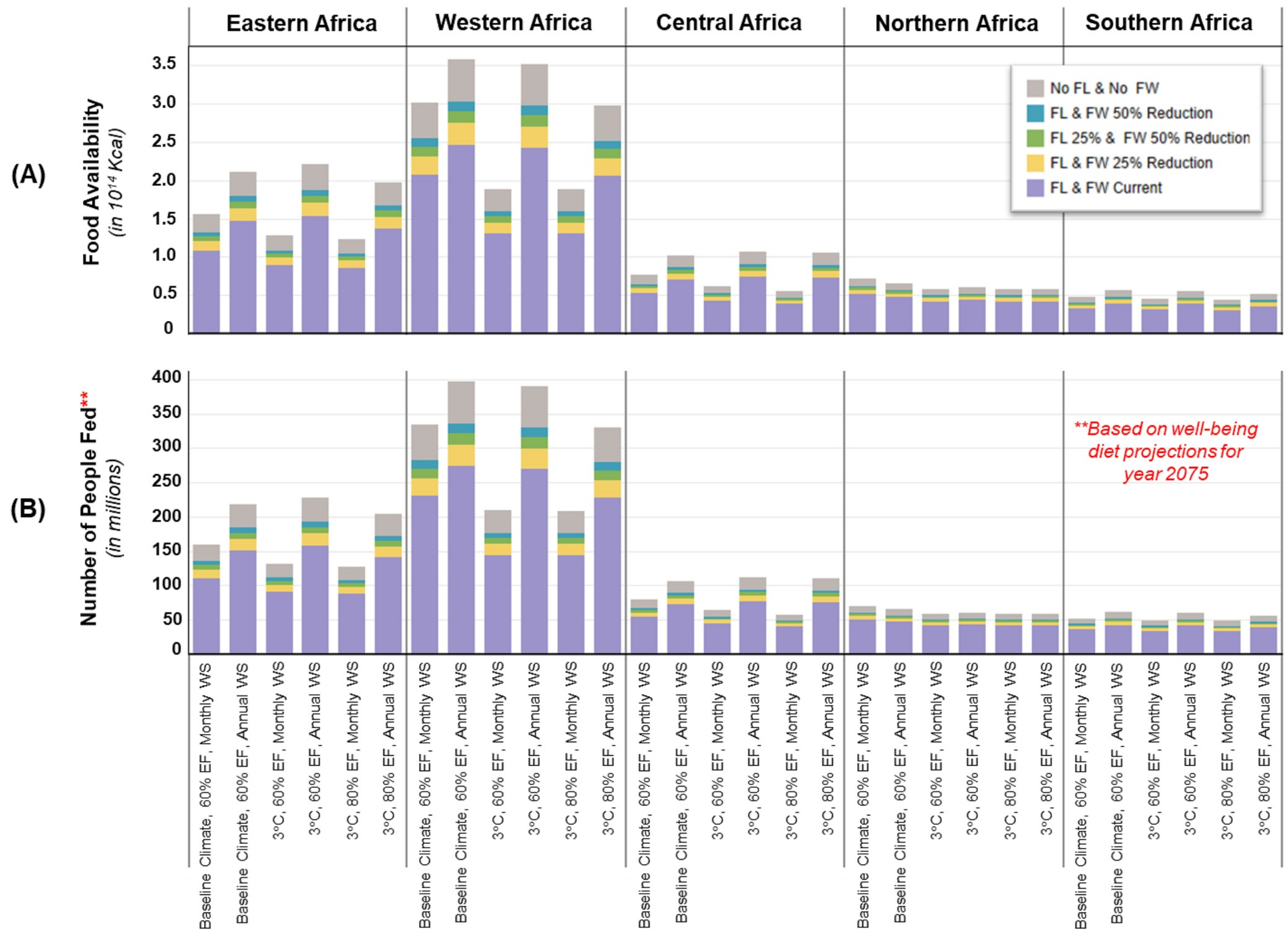

Figure 3. Regional food production and availability under different food loss and waste pathways. The colors represent the diverse food loss and waste pathways. Each bar within a region indicates a specific climate adaptation strategy scenario for crop production. Panel A shows the food available (in 10^{14} kilocalories) for direct or indirect human consumption while panel B displays the number of people that can be fed with a well-being diet (in year 2075) under each FL and FW pathway.

Africa. Northern, and Southern Africa have lower production capabilities with nominal differences between adaptation strategies. It is of note that both regions are composed of countries with large desert areas which would partly explain the lower production. In most cases, annual water storage allows for greater food production than monthly water storage. The advantage is much greater in a 3°C warmer world for Eastern, Western, and Central Africa where annual water storage is a recommended adaptation measure (Figure 3a). Likewise, under the baseline climate scenario, annual water storage allows for greater food calorie production than monthly water storage although the difference is much smaller for Northern and Southern Africa (Figure 3a). For 3°C climate, we assessed food calorie production capacity when preserving 60% or 80% of environmental flow requirements in inland freshwater ecosystems. Although less crop production is possible when reserving more freshwater for ecosystems, this maybe a tradeoff that countries consider to further protect the environment. Unfortunately, not all calories produced can be used to meet food demand. The actual crop kilocalories available under the food loss and waste pathways are represented in Figure 3a and Table S3 in Supporting Information S1.

Reducing food loss and waste from current levels, will boost caloric availability and the number of people that can be fed. SDG 12.3 aims to reduce food loss and half food waste (shown in green). Figure 3a shows the impact of FL and FW reductions on food availability while Figure 3b shows the impact of FL and FW reductions on the number of people that can be fed with a well-being diet in 2075 (the year projected to surpass 3°C) across the African continent. In the event the Earth's climate warms by 3°C above preindustrial levels, if 60% environmental flows are conserved and an annual water storage strategy is adopted, enough food will be produced domestically to feed (with a well-being diet of 2,327 kcal/cap/day) an estimated 851 million people in all of Africa if no food

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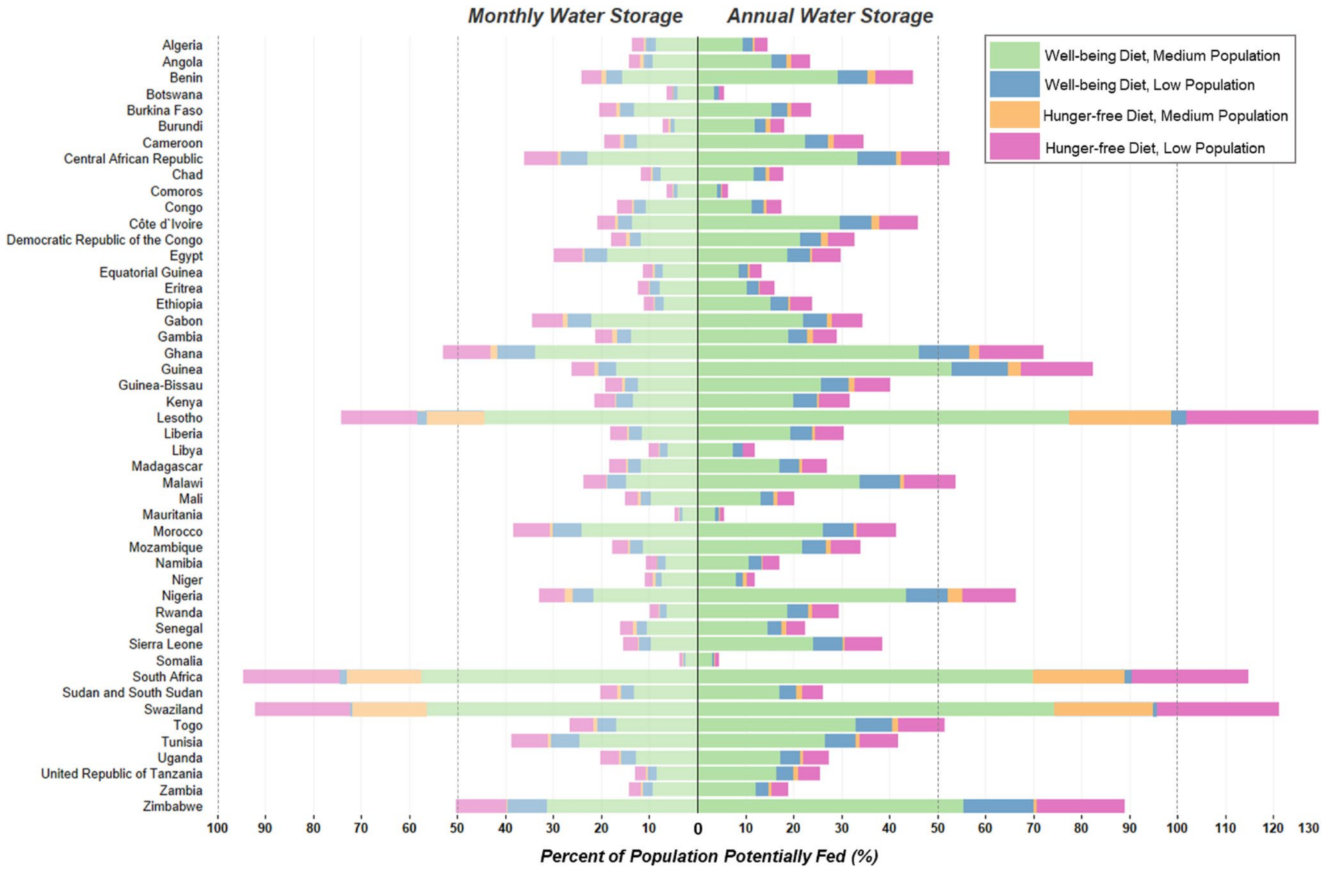

Figure 4. Percent of the population that could be fed (without food loss or waste) based on diverse adaptation strategies in a 3°C warmer world while preserving 60% environmental flow requirements. Four diet and population combinations are differentiated by color. Lighter shades represent results under monthly water storage (left) and darker shades are representative of annual water storage (right). Dashed lines indicate the 50% and 100% thresholds. The analyses in this figure are based on total domestic crop production available for human consumption not accounting for food lost or wasted.

is lost or wasted. However, if the current rate of food loss (10.8% in Northern Africa; 14% in Sub-Saharan Africa) and food waste (17% all of Africa) remains unchanged, there will only be enough food available to feed 590 million people—261 million people less than if there were no FL or FW. By reducing both FL and FW by 25%, the number of people potentially fed increases to 655 million (Figure 3b). Meeting SDG 12.3, enough food would be available for approximately 691 million people. Taking it one step further and halving both FL and FW, this number increases to 720 million people fed in Africa through domestic food crop production. Our results present the extent to which reductions in food loss and waste can contribute to reducing hunger across the different agricultural adaptation strategies.

3.3. Potential Futures for Africa in a 3°C Warmer World

To understand the different potential outcomes of various adaptation strategy combinations in a 3°C warmer world, we estimated the number of people that could be fed (both with the fh and wb diet) with the potential calories produced under combinations of 60% or 80% EF (Supporting Information S1), annual or monthly WS. The percent of the population that can be fed was determined based on either the low or medium population variants. The percent of population that can be fed also depends on the minimum number of calories each person consumes as well as the population. We look at two scenarios with average food consumption corresponding to the "free from hunger" (each person consumes 1,829 kcal/day) or "well-being" diets (2,327 kcal/day). Depending on several factors, by 2075, a country's population may follow the low or medium population variant—influencing the percentage of the population that can be fed with the calories produced. Figure 4 details the results of these adaptation strategy combinations based on total food production (not accounting for food loss or waste) when preserving 60% environmental flow requirements in terms of percent of the national population that can be fed split between monthly (left) and annual (right) water storage to allow for comparison. The plausible combinations of diet and population are differentiated by color. The corresponding results of the different adaptation strategies when 80% EF are preserved and how they compare with 60% EF are displayed in Figures S1 and S2 in Supporting Information S1, respectively. Figure 4 presents the theoretical extent of countries' self-sufficiency under the different potential futures assuming none of the food produced domestically was lost or wasted. For example, if Ghana relies on monthly water storage, there will be enough food to feed 34% of Ghana's population with a well-being diet and medium population variant; 42% with the well-being diet and low population variant; 43% with the free from hunger diet and medium variant, and 53% with the free from hunger diet and low population variant. As expected, the annual water storage approach would allow to support a higher percentage of the population, reaching 46% of the population with the well-being diet and medium population variant; 57% with the well-being diet and low variant; 59% with the free from hunger diet and medium variant; or 72% with the free from hunger diet and low variant (Figure 4).

Overall, if there were no food loss or waste, we found that relying on monthly water storage only five countries (Ghana, Lesotho, South Africa, Swaziland, and Zimbabwe) will be able to feed at least half of their population, but none will reach 100%. With annual water storage, ten countries will have enough food to feed at least 50% of their population and three (Lesotho, South Africa, and Swaziland) could have a surplus. In the "ideal case" scenario with the well-being diet, low population variant and annual water storage, seven African countries have enough to feed at least 50% of their population with four countries feeding more than 70%. Nonetheless, our results show that with monthly water storage 27 of the 49 countries evaluated in this study do not reach 20% and 5 of those (Botswana, Burundi, Comoros, Mauritania, and Somalia) cannot even feed 10% of their population in any population-diet combination. For most countries, implementing annual water storage techniques will increase their ability to feed people and strategize adaptation tactics. With annual water storage, 14 countries will not be able to feed 20% of their population (including four less than 10%)—less than with monthly water storage alone.

Importantly, the two diet scenarios are used here as a baseline to determine to what extent a country may achieve conditions of average self-sufficiency. Even when this happens, it doesn't mean that all people in that country are free from hunger or have access to the well-being diets. In other words, if on average food production is sufficient to meet free from hunger conditions or well-being food calorie needs per capita (depending on the diet scenario), inequalities in food access will lead to parts of the population consuming more than the average, leaving some groups or classes (typically the poor) with insufficient access (e.g., D'Odorico, Carr, Davis, et al., 2019). The role of inequality in the analysis of food availability and countries' self-sufficiency is beyond the scope of this study, which does not look at food security impacts of country-specific food access, distribution, utilization, or stability patterns.

3.4. 2075 Outlook Under Sustainable Development Goals

We determined the percent of a country's population (low trajectory) that can be fed with a well-being diet of 2,327 kcal per capita per day for both monthly and annual water storage strategies assuming irrigation is expanded in areas where it is sustainably possible while preserving 60% of environmental flows for ecosystem health; and efforts succeed to reduce food loss by a quarter and food waste by half compared to current levels in a 3°C future (Figure 5). For all African countries storing water annually results in a much higher proportion of the population being fed with a well-being diet. For example, 52% of Guinea's population in 2075 can be fed if annual water storage techniques are implemented, compared to 17% with monthly storage. With an annual storage approach, five countries can feed over half of their population, three of which can feed over 70% (Lesotho, South Africa, and Swaziland). On the other hand, with a monthly water storage approach, only two countries can feed over 50% of their population. The countries with the greatest difference between the percent of population that can be fed with annual versus monthly water storage are Guinea (Δ 36%), Lesotho (Δ 35%), Zimbabwe (Δ 25%), Nigeria (Δ 21%), and Malawi (Δ 19%). Countries with a difference between the two water storage strategies of less than 1% are Algeria, Niger, Mauritania, Somalia, Congo, Egypt, Comoros, Gabon, and Botswana. The countries that will not be able to domestically produce sufficient calories to feed over 10% of their population regardless of water storage strategies are Algeria, Botswana, Comoros, Equatorial Guinea, Libya, Mauritania, Niger, and Somalia. These countries will continue to heavily rely on imports under both current and 3°C climate conditions (see Table 3).

3.5. Caloric Deficits

We define *caloric deficit* as the number of calories needed to feed the remainder of a country's population whose dietary needs cannot be met through domestic crop production with a minimum daily consumption of either 1,829

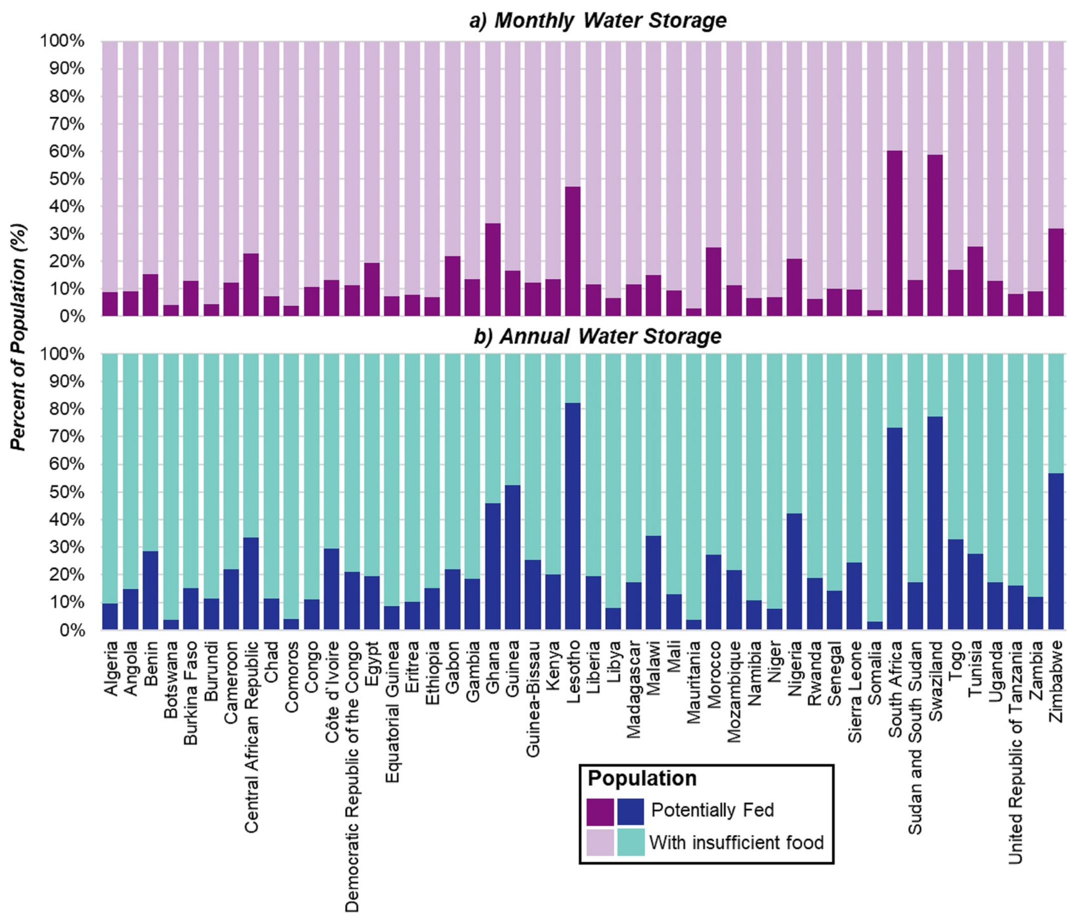

Figure 5. Percent of population that can or cannot be fed under the SDG scenario in a 3°C warmer climate based on (a) monthly or (b) annual water storage strategy. The SDG scenario considers a well-being diet, low population trajectory, 60% environmental flow (EF) preserved, and food loss 25% and food waster 50% reduction. Dark shaded bars represent percent of population fed through domestic crop production. Light shaded bars represent percent not fed, but more specifically, the percent of population that still needs to be fed through imports or other means to meet SDG 2- zero hunger and malnutrition. This figure shows the results for 60% EF preserved. See Figure S3 in Supporting Information S1 for results based on 80% EF reserved.

or 2,327 kcal. As mentioned earlier, this accounts for the additional crop calories it takes to produce animal-based calories (which depends on fraction of animal-based products in diets). Access to water storage systems, food waste/food loss rates, and the fraction of runoff allocated to environmental needs (i.e., as environmental flows) determine a country's rate of crop production and the associated food supply. Based on the adaptation strategy (e.g., water storage) and dietary goal pursued as well as population trajectory reached, the number of people and subsequently the caloric deficit differ. Considering only annual water storage and well-being diets, in addition to 25% food loss and 50% food waste reduction (SDG), Table 3 displays the caloric deficit and the corresponding number of people under three main scenarios for each region, while Table S4 in Supporting Information S1 in displays the caloric deficit by country.

3.6. Reference Scenario—Baseline Climate Conditions in 2030

According to the IPCC special report on global warming of 1.5°C, global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate" (IPCC, 2018). The reference period for global agricultural data from Portmann et al. (2010) is years 1996–2005. According to the Global Land-Ocean Temperature Index of the NASA's Goddard Institute for Space Studies, the Earth had warmed by approximately 0.68°C above preindustrial levels by 2005 (our baseline climate condition) (NASA/GISS, 2021). Thus, we created a frame of reference assuming baseline climate conditions remained in year 2030 and the SDG scenario framework was

Table 3
Regional Food Deficit and People Equivalent for Baseline and 3°C Warmer Climate

	Current Climate 60% Environmental Flows *(Year 2030, Medium Population)*		3°C Climate, 60% Environmental Flows *(Year 2075, Low Population)*		3°C Climate, 80% Environmental Flows *(Year 2075, Low Population)*	
Region	**Caloric Deficit** *(in 10^{13} kcal)*	**Number of People Equivalent** *(in millions)*	**Caloric Deficit** *(in 10^{13} kcal)*	**Number of People Equivalent** *(in millions)*	**Caloric Deficit** *(in 10^{13} kcal)*	**Number of People Equivalent** *(in millions)*
Central Africa	11.2	136.7	37.4	390.5	37.5	391.8
Eastern Africa	33.0	399.2	84.3	857.0	86.2	877.0
North Africa	14.7	169.6	22.0	221.4	22.2	223.0
South Africa	1.5	18.8	2.3	24.0	2.6	27.4
Western Africa	12.8	156.6	61.3	657.8	65.7	706.4
All Africa	73.2	880.9	207.2	2,150.7	214.1	2,225.6

Note. All three pathways represented in this table were formulated under the assumption that SDG food loss and waste (25%/50% reduction), the well-being diet, and annual water storage strategies are adopted. The results for the two environmental flow requirement targets (60% or 80% conservation) are presented for only a 3°C warmer climate.

effectuated. Since 2030 is just around the corner, this projection is paired with the medium population to give conservative estimates. Hence, according to this analysis, in 2030 Africa would need to import 73.2×10^{13} kcal of crops, corresponding to the food needed to feed 881 million people with a well-being diet. Regionally, Eastern Africa would need external supply of food for 399 million people, followed by Northern Africa (170 million people), Western Africa (157 million people), and Central Africa (137 million people). Ethiopia, Egypt, the Democratic Republic of Congo, Algeria, Kenya, and Tanzania would have the greatest caloric deficits in 2030 with baseline climatic conditions (Table 3).

3.7. At 3°C With SDG Framework

The subsequent two scenarios in Table 3 forecast the caloric deficits under a 3°C warmer climate (~year 2075) with an annual water storage approach and if the SDG framework is sustained (low population, well-being diet, food loss and waste reduction of 25% and 50% respectively). They differ only on the percentage of environmental flow requirements (60% or 80%) maintained. Looking at the 60% EF approach, Eastern and Western Africa will be in the toughest position, needing to procure (import) 84.3×10^{13} and 61.3×10^{13} kcal from outside sources to feed their populations. These food deficits correspond to the food needed to feed 857 and 658 million people, respectively, followed by Central Africa and Northern Africa with a food deficit of 390 and 221 million people. Comparatively, the relatively low food deficit of Southern Africa can be explained by the lower population density in the region. Nigeria (282 million people), Ethiopia (183 million people), the Democratic Republic of Congo (191 million people), Tanzania (142 million people), and Egypt (128 million people) will have the worst caloric deficits in the continent. In total, at a time when Africa's population is projected to reach 3.5 billion people, 207.2×10^{13} kcal for food and feed will need to be procured in Africa to feed 2.15 billion people (total projected African population of the food deficit expressed in number of people) on the continent who cannot be provided for with domestic production. The difference in the number of people that cannot be fed through domestic production between the 60% EF and 80% EF strategy in all of Africa is 75 million people. Note that these scenario combinations are assuming that we reduce food loss by 25% and food waste by 50% from current levels as per the SDGs, curtailing food loss and waste more would further reduce the caloric deficit to an extent.

4. Discussion

Our results echo the well-known dilemma that Africa is facing – population growth and food demand are outpacing the domestic agricultural production potential. We estimate that under a 3°C warmer climate with sustainable agricultural practices and reducing food loss and waste to achieve SDG 12.3, the total food production in Africa will only suffice to feed 1.35 billion people, at a time when the continent's population is expected to reach 3.5 billion, leaving a food deficit for 2.15 billion people. Africa holds just 9% of the world's surface water, while accounting for over 17% of the world's total population (Pekel et al., 2016; United Nations, 2019). Meanwhile, croplands constitute 10% of the total land area on the African continent (Latham et al., 2014). However, over half (58.4%) of African croplands are located on drylands, where crop production is becoming increasingly difficult due to 'water shortages, land degradation, climate change and persistent poverty' (Cherlet et al., 2018; Latham et al., 2014; Sarukhán el al., 2005; Tilman & Clark, 2015). Under climate change, in wet tropical regions drylands are expected to become wetter, while in Northern and Southern Africa, subtropical drylands will expand, and semi-arid zones may shift to arid or hyper-arid zones (Cherlet et al., 2018; Fischer et al., 2007; Safriel et al., 2005). Thus, Rosa, Chiarelli, Sangiorgio, et al. (2020) determined how the suitability of current global croplands for sustainable irrigation would change under 1.5°C and 3°C levels of warming above pre-industrial levels. By accounting for sustainable irrigation expansion potential on current croplands for 130 primary crops, modeling water storage potentials (Rosa, Chiarelli, Sangiorgio, et al., 2020), narrowing the yield gaps in underperforming lands, and simulating various food loss and waste reduction strategies, we are able to assess the number of people that could be potentially fed through sustainable agricultural intensification and the degree to which each country will be reliant on external food sources to meet the needs of their people as diets shift and population grows. Beltran-Peña et al., 2020 revealed that today, almost no African country is self-sufficient and as the Earth warms, they will be further unable to meet the food demands of their population through domestic production alone. Here we quantify the caloric deficit based on production potential, dietary trends, and population growth. The fraction of the population that cannot be fed under the SDG scenario (Figure 5) are indicative of import dependency that is required in each African country in order to meet SDG goal 2- zero hunger and malnutrition, while addressing SDG goals 5 (gender equality), 6 (clean water and sanitation), 12 (responsible consumption and production), 13 (climate action), and 15 (life on land). We project that Eastern and Western Africa will have the greatest import needs, but the actual demand and deficit can be lessened with more sustainable consumption patterns as well as by using annual water storages to rely on water stocks accumulated during the wet season for irrigation during dry periods of the growing season(s). Storages associated with surface reservoirs can be problematic because of concerns related to environmental impacts, safety, size of these investment infrastructure, increasing dependence on foreign credit, dispossession of rural indigenous communities, and loss of rural livelihoods (Carr, 2017; Tatlhego & D'Odorico, 2022; Muller et al., 2021). While we refrain from venturing in the heated debate on the pros and cons of large dam infrastructure and whether they are needed for economic development of these countries (Scudder, 2012), we point to the fact that water storage can also be achieved through managed aquifer recharge, farm-scale detention ponds (e.g., He et al., 2021; Van Der Zaag and Gupta, 2008), or small-scale reservoirs that could be less challenging both environmentally and financially (Ross & Hasnain, 2018; Sprenger et al., 2017). These options need to be adequately explored as a possible pathway for irrigation development in Africa.

4.1. Consumption Trends

The change in demand for animal-based products over time assessed in this study is based on the economic growth projections of SSP 2 in which "Gross Domestic Product (GDP) follows regional historical trends, with global average income (i.e., average GDP/capita) reaching about 60,000 (year-2005 USD/capita) by the end of the century. SSP 2 sees an increase of global average income by a factor 6 and depicts a future of global progress where developing countries achieve significant economic growth" (Dellink et al., 2017; Fricko et al., 2017; Riahi et al., 2017). According to Dellink et al., 2017, GDP per capita is projected to increase in all African countries considered in this study. Economic growth and rising incomes enable households to purchase foods with higher caloric and protein content (i.e., vegetables and animal products) which consequently drives up the demand for animal feed (Bennett, 1941; D'Odorico et al., 2018; FAO, ECA and AUC, 2021; OECD/FAO, 2021; Tilman et al., 2011). Our model considers these increases in dietary demand (Figure 2). Diverting crop products for feed-fed livestock production (we are assuming that grass-fed production remains constant to prevent overgrazing), reduces the crop calories available for direct human consumption and increases environmental impacts. In fact, we find that at 3°C none of the countries evaluated, will be able to meet the food demand of their populations through domestic production alone (Figures 4 and 5). The OECD/FAO Agricultural Outlook predicts that poultry and beef will account for the majority of meat imports in Africa to account for domestic supply deficits due to consumption growth outpacing domestic production (OECD/FAO, 2021).

With the projected rise in Africa's population from 1.37 billion people in 2021 to 3.5 billion people in 2075, changes in diets toward higher animal product consumption will strain the supply chain—augmenting the importance of reducing food losses and waste which increases crops available for direct or indirect human dietary consumption from current croplands (United Nations, 2019). Before the development of the FAO Food Loss and UN Food Waste Indices, the 2011 FAO report by the Swedish Institute for Food and Biotechnology, was the only study that estimated food lost and wasted throughout all stages of the food supply chain and across all food production sectors and has been widely cited by subsequent studies (FAO, 2011; FAO, 2019a, 2019b, 2019c; Gustavsson et al., 2013; Kummu et al., 2012). Contrary to popular belief, the UN Food Waste Index found that household per capita food waste generation is similar across country income groups, indicating the importance of addressing food waste in all countries (it was previously thought that food waste primarily occurred in developed nations while food loss was predominant in developing nations) (UNEP, 2021b). Sustainable Development Goal 12 aims to ensure sustainable consumption and production by halving global food waste and reducing food losses by 2030 (U.N. DESA, 2016). Here we take it a step further and calculate the additional calories that would become available by halving both food losses and waste. We found that halving both food loss and waste from current levels, will allow more food to be available to feed an additional 130 million Africans in a 3°C future (Figure 3). Hence, rebalancing diets with an overall lower fraction of animal products with an increase in poultry consumption in lieu of beef or other ruminant meats—a trend already observed around the world (Davis et al., 2015); and increased nutritional plant-based foods in addition to significantly reducing food loss and waste, will boost the number of people that can be fed through domestic production along with reducing import needs, the financial cost, and environmental impacts of diets (FAO, ECA and AUC, 2021; FAO, IFAD, UNICEF, WFP and WHO, 2020; Mekonnen & Hoekstra, 2012; Nijdam et al., 2012).

Additionally, improving socio-economic conditions (i.e., empowering women, reducing the gender gap), investing in infrastructure, and sustainably intensifying food production are essential interventions to improve availability and demand ratios (FAO, ECA and AUC, 2021; Graves et al., 2019; van Maanen et al., 2022). The intensification of food production, however, may strongly affect rural livelihoods, as small-holder farmers have more limited access to credit and financial resources to invest in high yield technology (e.g., irrigation, fertilizers, mechanization, concentrated livestock systems) and are therefore more likely to be displaced by agribusiness corporations. Low-technology agro-ecological methods, however, have been shown to be capable of sustaining higher yields (Altieri et al., 2012), and small-holders have been found to produce more (on a per unit area basis) than large scale farming (Herrero et al., 2017; Ricciardi et al., 2018).

4.2. Trade Implications

Africa is a net importer of agricultural products (i.e., cereals, meat, dairy products) and annually imports about 80 billion USD of food products, of which less than 20% is from intra-African trade (FAO and AUC, 2021). In our reference scenario (with baseline climate conditions) estimates a caloric deficit equivalent of 881 million people in Africa by year 2030. However, considering with global warming of 3°C, more animal products in diet compositions, and population growth the projected caloric deficit equivalent in year 2075 increases to 2.15 billion people in Africa. It is important to note that, under a changing climate, some countries outside of Africa may not have the resources to export food products and may experience deficits as well while others will have a surplus (Beltran-Peña et al., 2020). This poses two important questions that should be further explored. First, affordability—will countries be able afford to import the additional food needed to meet their population's demand? Second, to what extent can international trade be an adaptation mechanism? Janssens et al., 2021 demonstrates that "trade policies influence the sensitivity of hunger to climate change" and calls for better trade agreements with lower tariffs and preventing border restrictions while using cautions to avoid food price increases due to lower availability in exporting regions' (Janssens et al., 2021). On the other hand, it was also noticed that lack of tariffs has often allowed relatively cheap imports of agricultural products (often subsidized by foreign governments) to outcompete and displace local production systems in Africa, thereby limiting self-sufficiency, food sovereignty, rural livelihoods, and the sustainable use of water resources (D'Odorico, Carr, Dalin, et al., 2019; Friedmann, 1993; Rosa et al., 2019). Moreover, trade-dependency may limit the resilience of food systems, as observed in recent food crises when some countries adopted export bans as a tool to control escalating domestic food prices, while leaving import-dependent countries scrambling for agricultural commodities (FAO, 2021; Seekell et al., 2017). Improving intra-African trade is a top priority for the African Union Commission's Department of Agriculture, Rural Development, Blue Economy and Sustainable Development so that local stakeholders including farmers, small and medium agri-businesses, women and youth can benefit from the market while removing trade barriers among African countries (FAO and AUC, 2021). Still, if agricultural adaptation measures, stronger policies and infrastructural investments, and trade, are insufficient to meet future food demand under a changing climate, voluntary migrations or involuntary displacements may ensue which in turn may lead to lower agricultural productivity (Cherlet et al., 2018; FAO, ECA and AUC. 2021; McLeman, 2014; McLeman, 2019; Payne, 2013).

4.3 Limitations

There are four main pillars of food security—availability, access, utilization, and stability (FAO, 2008). They are all essential in ensuring food security of a population. However, the scope of this study only addresses the availability pillar—particularly production potential and trade dependency. The division between the free from hunger and well-being diets is an initial, but limited attempt to address nutritional quality of diets. A hunger-free diet allocates just enough daily calories (1,829 kcal) for people to not experience calorie intake deficits and thus hunger (addressing the SDG zero hunger target). A well-being diet allocates 2,327 kcal daily per person. The assumption is that the greater caloric allowance also implies the possibility of consuming more diverse food products (partially addresses the zero malnutrition SDG target). Further work is required to assess the nutritional quality of diets consumed and what will be required to ensure access to sufficient and nutritious diets. We consider 130 primary crops (Portmann et al., 2010) used for direct human consumption as well as for feed. Climate change is accounted for in terms of the irrigation area suitable for sustainable irrigation in a 3°C warmer climate. This study does not account for crop migration or the effects of CO_2 fertilization (Sloat et al., 2020). Importantly, irrigation expansion and a sustainable intensification of agriculture will require additional energy inputs, which could have added energy implications for African countries, such as energy import dependency and local energy access (Rosa, Rulli, et al., 2021). Besides water availability, nutrients are another major factor limiting crop production in African countries with high soil nutrient depletion and investments in soil fertility replenishment are needed to improve crop production (Sanchez, 2002). This study, however, does not assess the limitations of soil nutrient depletion or potential of soil fertility improvement on crop production.

The Sustainable Development Goals are set for year 2030. However, we are not on track to meet these goals by the set timeline (United Nations, 2021). There may be more ambitious targets for year 2075 and beyond, but since future targets and international agreements are not yet predictable, this study applies the SDG goals beyond 2030. Additionally, we present the data and our findings based on the population data for year in which 3°C above preindustrial levels is expected to be reached by the GFDL-ESM2M and MIROC 5 global climate models (~2075). However, the year we surpass 3°C is not certain and thus the results of this analysis may differ slightly depending on the population numbers of the actual year 3°C is reached.

Thus far, data availability for food loss and waste estimates around the world have been insufficient and reliant on extrapolations of data from few countries where limited data is available, but possibly outdated. The UNEP and FAO have recognized this challenge and created the Food Loss and Food Waste Indices to improve data reporting methods for countries to keep track of progress towards SDG 12.3 (FAO, 2019a, 2019b, 2019c; UNEP, 2021a). Here we use the most recent estimates of food loss and waste, but there are still uncertainties in these estimates which will only improve with increased reporting over time.

The SDGs are here used as a framework to analyze and interpret the results of our study. These goals are here taken as a given without investigating their merit. We did not assess the process that went into their definition, who contributed to it, to what extent the rural poor, indigenous communities, and more in general those who should (or would be expected to) benefit from "sustainable development" had a voice in this process. While the SDGs are here used to build a narrative on food security in Africa a more critical analysis of the SDG framework is beyond the scope of this study. We also understand and acknowledge the importance of local community engagement and community-centered approaches before implementing any adaptation and mitigation measures.

5. Conclusion

Ending hunger and malnutrition is the second target of the United Nations Sustainable Development Goals. Our work evaluated the feasibility of meeting this goal through sustainable irrigation intensification on currently rainfed croplands in African countries in a 3°C warmer climate considering changes in consumption patterns and population growth. Furthermore, we estimated the difference in production potential by implementing various strategies of runoff water storage and environmental flow requirements. Finally, this study determines the amount of food that each country will still need to acquire from other methods (i.e., agricultural expansion) or external sources in order to adequately feed their populations while taking into account other SDGs.

Our findings show the existence of a mismatch between population and food demand growth and agricultural production across the African continent. It also stresses how African populations would be hardly able to predominantly rely on local food production, in disagreement with the claims of local food movements. Interestingly, the analysis of the global patterns of international food trade (D'Odorico et al., 2014) indicate that African countries are poorly integrated in the global agricultural market, which could limit their resilience to production shocks. The results of this study provide a preliminary assessment of the potential for sustainable agricultural intensification and water storage capacities under climate change in Africa; as well as data on the potential extents of future import needs based on varying consumption (including food loss and food waste) patterns to local decision makers.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data for crop production potentially achievable under climate change, we use results from Rosa, Chiarelli, Sangiorgio, et al. (2020) who estimated rainfed and irrigated crop production for 130 primary crops based on the global cropland extent of the MIRCA2000 data set (Portmann et al., 2010). Current rates of food loss and food waste were taken from the Food and Agriculture Organization of the United Nations Food Loss Index (FAO, 2019a) and the United Nations Environment Program Food Waste Index (UNEP, 2021b). Projected animal-based dietary consumption patterns were derived from the quantified scenario matrix produced as a GLOBIOM model emulation by Frank et al., 2021 available at https://github.com/iiasa/GLOBIOM-G4M_LookupTable. The plant to animal caloric conversion factor which are country-specific were taken from Davis et al. (2014). Population projections were taken from the 2019 UN Population Prospects for the low and medium variants (United Nations, 2019). Figures were made using Tableau version 2021.2 available under the Tableau license at https://www.tableau.com/. Processed datasets are included in this paper and on a Zenodo repository (https://doi.org/10.5281/zenodo.6687342). Supporting Information S1 includes additional figures of interest.

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