Article:

Jennings, S., Challinor, A., Smith, P. et al. (50 more authors) (Accepted: 2023) Stakeholder-driven transformative adaptation is needed for climate-smart nutrition security in sub-Saharan Africa. Nature Food. ISSN 2662-1355 (In Press)

Stakeholder-driven transformative adaptation is needed for climate-smart nutrition security in sub-Saharan Africa

Stewart Jennings[1*], Andrew Challinor[1], Pete Smith[2], Jennie Macdiarmid[3], Edward Pope[4], Sarah Chapman[1], Catherine Bradshaw[4,5], Heather Clark[6], Sylvia Vetter[2], Nuala Fitton[2], Richard King[7], Sithembile Mwamakamba[8], Tshilidzi Madzivhandila[8], Ian Mashingaidze[8], Christian Chomba[9], Masiye Nawiko[9], Bonani Nyhodo[10], Ndumiso Mazibuko[10], Precious Yeki[10], Pamela Kuwali[**11**], Alfred Kambwiri[**11**], Vivian Kazi[12], Agatha Kiama[12], Abel Songole[12], Helen Coskeran[13], Claire Quinn[14], Susannah Sallu[14], Andrew Dougill[14], Stephen Whitfield[14], Bill Kunin[13], Nalishebo Meebelo[15], Andrew Jamali[16], Dhaquirs Kantande[17], Prosper Makundi[18], Winfred Mbungu[19], Frank Kayula[20], Sue Walker[21,22], Sibongile Zimba[13,23], Joseph Hubert Galani Yamdeu[24,25], Ndashe Kapulu[24], Marcelo Valadares Galdos[1,26], Samuel Eze[14,27], Hemant Tripathi[13,28], Steven Sait[13], Stefan Kepinski[13], Emmanuel Likoya[14], Henry Greathead[13], Harriet Elizabeth Smith[14], Marcelin Tonye Mahop[14,29], Helen Harwatt[7], Maliha Muzammil[7], Graham Horgan[30] and Tim Benton[7]

[1*]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.
[2]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, United Kingdom.
[3]The Rowett Institute, School of Medicine, Medical Sciences and Nutrition,, University of Aberdeen, Aberdeen, United Kingdom.
[4]Hadley Centre, Met Office, Exeter, United Kingdom.

[5]The Global Systems Institute, University of Exeter, Exeter, United Kingdom.
[6]Institute of Applied Health Sciences, School of Medicine, Medical Sciences and Nutrition, University of Aberdeen, Aberdeen, United Kingdom.
[7]Chatham House, The Royal Institute of International Affairs, London, United Kingdom.
[8]Food, Agriculture and Natural Resources Policy Analysis Network, Pretoria, South Africa.
[9]Agricultural Consultative Forum, Lusaka, Zambia.
[10]National Agricultural Marketing Council, Pretoria, South Africa.
[11]Civil Society Agriculture Network, Lilongwe, Malawi.
[12]Economic and Social Research Foundation, Dar es Salaam, Tanzania.
[13]School of Biology, Faculty of Biological Sciences, University of Leeds, Leeds, United Kingdom.
[14]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.
[15]Regional Network of Agricultural Policy Research Institutes, Lusaka, Zambia.
[16]Malawi National Planning Commission, Lilongwe, Malawi.
[17]Concern Worldwide, Lilongwe, Malawi.
[18]Environmental Management Unit, Ministry of Agriculture, Dodoma, Tanzania.
[19]Sokoine University of Agriculture, Morogoro, Tanzania.
[20]Kaypro Research Institute, Lusaka, Zambia.
[21]Agricultural Research Council, Pretoria, South Africa.
[22]University of the Free State, Bloemfontein, South Africa.
[23]Lilongwe University of Agriculture and Natural Resources, Lilongwe, Malawi.
[24]School of Food Science and Nutrition, University of Leeds, Leeds, United Kingdom.
[25]Section of Natural and Applied Sciences, School of Psychology and Life Sciences, Canterbury Christ Church University, Canterbury, United Kingdom.
[26]Sustainable Soils and Crops, Rothamsted Research, Harpenden, United Kingdom.
[27]Department of Agriculture and Environment, Harper Adams University, Newport, United Kingdom.

[28] UN Environment Programme, World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, United Kingdom.
[29] USAID West Africa Biodiversity and Low Emissions Development (WABiLED) Programme, Accra, Ghana.
[30] Biomathematics and Statistics Scotland, Aberdeen, United Kingdom.

*Corresponding author(s). E-mail(s): s.a.jennings@leeds.ac.uk;

Abstract

Improving nutrition security in sub-Saharan Africa under increasing climate risks and population growth requires a strong and contextualised evidence base. Yet, to date, few studies have assessed climate-smart agriculture and nutrition security simultaneously. Here we use an integrated assessment framework (iFEED) to explore stakeholder-driven scenarios of food system transformation towards climate-smart nutrition security in Malawi, South Africa, Tanzania and Zambia. iFEED translates climate-food-emissions modelling into policy-relevant information using model output implication statements. Results show that diversifying agricultural production towards more micronutrient-rich foods is necessary to achieve an adequate population-level nutrient supply by mid-century. Agricultural areas must expand unless unprecedented rapid yield improvements are achieved. Whilst these transformations are challenging to accomplish and often associated with increased greenhouse gas emissions, the alternative for a nutrition-secure future is to rely increasingly on imports, which would outsource emissions and be economically and politically challenging given the large import increases required.

Keywords: Nutrition security, transformation, adaptation, climate change

1 Main

Achieving an adequate supply of energy and nutrients to meet population dietary needs under climate change requires policy decisions made in the face of high uncertainty across multiple components of complex socio-environmental systems.[1] This challenge is particularly urgent in sub-Saharan Africa (SSA), where climate change could put millions more people at risk of food and nutrition insecurity by mid-century.[2] At country scales and above, policies need holistic evidence if adaptation to climate change is to avoid being siloed in different government departments.[3]

The evidence available to inform agricultural policies that are resilient to climate change and can supply sufficient energy and nutrients to a population can be grouped into two broad areas: climate-smart approaches and transformative adaptation. Climate-smart agriculture (CSA), and more broadly climate-smart food systems,[4] consider the need for increased productivity and adaptation to climate change, as well as the potential for mitigation i.e. reducing the greenhouse gas (GHG) emissions resulting from adaptations. Transformative adaptation consists of structural changes to shift away from undesirable food system trajectories, rather than incremental coping mechanisms that characterise most policy approaches to climate and nutrition.[5,6]

The methods used for assessing the efficacy of transformative adaptation and CSA strategies are varied, ranging from modelling-based approaches that quantify uncertainties in climate change impacts to stakeholder-driven approaches that examine capacities and vulnerabilities.[1] Integrated Assessment Models (IAMs) have been used to assess food system options and outcomes under different future conditions, including land use change, and environmental and economic impacts.[7] Uncertainties in possible food system futures can be explored using IAM scenario analysis[8,9,10,11,12] - for example, the widely-used Shared Socioeconomic Pathways focus on energy, land use and mitigation.[13] Other analyses have explored scenarios of food production and consumption given climate change and policy decisions,[14] and the health implications of different future diets.[7,15] Few large-scale studies integrate nutrition, or the importance of the trade-offs involved in achieving CSA - for example, optimising water use and GHG productivity in rice systems,[16] or trade-offs between biodiversity and crop productivity.[17]

Nutrition and nutrient adequacy to meet population-level dietary needs have yet to be assessed within an integrated CSA framework, risking sub-optimal adaptation from both health and environmental perspectives.[18] Equally, studies of transformative adaptation have shown that historical food system transitions can have sub-optimal nutritional and environmental outcomes,[19] with most studies focussing on a small number of cereal crops and food production.[20,21] This suggests that the evidence on which current adaptation strategies are based is insufficient for achieving the changes needed for sustainable, climate-smart nutrient supply.

Inclusive approaches to integrated assessment - involving stakeholders at every stage of the process - are critical for informing country-specific policy processes. We use an integrated assessment framework - the integrated Future Estimator for Emissions and Diets (iFEED[22]) - to combine climate-food-emissions modelling with stakeholder and academic expertise, assessing both CSA and food and nutrient supplies, and bridging the gap between modelling and national scale policy-relevant outputs.[23,24] We assess the adequacy of energy and nutrient supplies to meet dietary requirements at a population level (hereafter referred to as population-level nutrition security). We describe results for four focal SSA countries: Malawi, South Africa, Tanzania and Zambia.

Our approach has three major steps, corresponding to the headings that follow. We first co-develop different possible future scenarios with stakeholders, designed to explore as broad a range of context-specific food system futures as possible. Scenarios use integrated modelling to analyse nutrition-security and climate-smartness. We define nutrition security as having a sufficient supply of the right food to achieve all nutrient requirements at a population level. We then compare results across scenarios and countries, resulting in conclusions that are less sensitive to underlying assumptions and therefore more robust. Finally, we assess the policy implications of the findings.

2 Climate-smart, nutrition-secure scenario assessment

We explore stakeholder-driven scenarios that assess how climate-smart nutrition security can be achieved by mid-century given population growth and increasing climate volatility in each focal country. Modelling of climate and land use change and resulting impacts on domestic food production and agricultural GHG emissions are supported by comprehensive uncertainty reporting. The model results provide the basis for: (i) an analysis of how domestic production and trade interact in changing population-level nutrition security; (ii) a diverse array of implication statements, including environmental and social implications of the results. This provides information for assessing nutrition security and CSA for each scenario. We then compare scenarios to identify robust commonalities that lead to preferred CSA and nutritional outcomes, and lastly point to policy implications.

Stakeholders created a 2x2 scenario matrix for each country during participatory scenario workshops. The stakeholders were representatives of government, academia, civil society and the agriculture sector, representing a broad a range of food system expertise - see Table SI2 for stakeholder details. How adaptation to climate change is implemented in each scenario is directly informed by stakeholders, ranging from the incremental (consisting of changes in planting dates and currently existing crop varieties) to the transformative (where different crops are grown in new locations to maximise production). Contrasting trade vignettes explore how business-as-usual or changes to trade impact nutrition security given domestic policy decisions. Figure 1 summarises the outcomes of this process, including the assumptions around land use, crop yields, diversification and trade that underpin each scenario.

In all countries, the level of climate risk was selected by stakeholders as one of two critical uncertainties of food system futures. Low climate risk was characterised by 18 bias-corrected CMIP5 climate models under the RCP2.6 emissions scenario, and high climate risk by RCP8.5.[25] Whilst extreme climate events (such as droughts, floods and record-breaking high temperatures) feature in projections for all countries and scenarios, they do not directly affect average future levels of nutrition security or CSA outcomes. However, resilience to extremes, as achieved through crop diversification, was found to have some nuanced implications for nutrition security (see Section 3.1). Extreme events were also important to stakeholders and their implications are explored in Section SI1.

Stakeholders defined the second critical uncertainty around the agricultural transformative changes relevant to their country. These were the effectiveness of policy implementation (Malawi), the extent of land reform (South Africa), the extent of technological transformation (Tanzania), and the degree of market connectivity and functionality (Zambia). We refer to these simply as high transformation (HT) or low transformation (LT) scenarios. The result is four scenarios per country, comprising HT/LT x high/low climate risk.

Compared to the South Africa scenarios, Malawi, Tanzania and Zambia scenarios explore a larger range of adaptation options, from small incremental changes to the transformative, and therefore we focus on these comparisons in Section 3 to assess the potential of such changes for improving nutrition security. HT scenarios for these three countries were associated with the largest changes in agricultural systems, characterised as having a continuation of historical yield trends, crop switching to maximise production, and expansion of agricultural area and irrigation. These stakeholder-led scenario characterisations mean that yields generally increase in HT scenarios. LT scenarios in these three countries were characterised as more similar to the status quo, with incremental adaptation and minimal yield and area changes.

Figure 2 summarises climate-smartness and nutrition security outcomes for each scenario. CSA outcomes are assessed by whether each aspect (productivity, adaptation and mitigation) improves or worsens relative to the baseline. Descriptive result summaries for each scenario and country are available at https://ifeed.leeds.ac.uk/, as well as underlying model results and implication statements. In all four countries, agricultural transformation is a much larger driver of nutrition security and CSA outcomes than the degree of climate risk. In Malawi, Tanzania and Zambia, high population growth combines with LT conditions to reduce nutrition security. In contrast, HT scenarios show improvements to nutrition security. The South Africa high climate risk scenarios show the counter-intuitive effect of improving nutrition security. This is because stakeholder input to the scenarios indicated greater investment in adaptation under high climate risk. For example, new crop varieties, irrigation expansion and crop diversification, which lead to increased production and a more varied food supply.

In all scenarios where nutrition security improves, GHG emissions from agriculture increase due to agricultural expansion and higher yields. However, in these scenarios, soil organic carbon typically increases due to the increased organic inputs to the soil which partially compensates for the increased emissions, resulting in net emissions falling in several HT scenarios. Other analysis has shown that scenarios of intensification can result in lower emissions than scenarios of agricultural expansion.[26]

Figures 3 and 4 show nutrition security results for Tanzania and Zambia HT RCP2.6 and RCP8.5 scenarios assuming business-as-usual trade; all other nutrition security results assuming business-as-usual trade are in Section SI7. In Tanzania in the baseline, bovine meat production is approximately 200,000 tonnes, and in Zambia it is approximately 50,000 tonnes. In all HT scenarios, livestock meat (including bovine meat, sheep and goat meat, pig meat, and poultry meat) and dairy production (from bovine milk and sheep and goat milk) more than doubles due to a combination of increases to livestock feed from crops and livestock pasture expansion. The most common nutrients that fail to meet population requirements in these scenarios are fat, calcium and iron. This suggests that increases to livestock production - i.e. increases larger than projected population increases - could help meet these requirements given low baseline livestock consumption compared to many other countries, albeit with environmental costs. This trade-off is discussed further in Section 4.

3 Agricultural transformations for nutrition security

3.1 Micronutrient-rich, productive crops for nutrition security

In all LT scenarios, incremental adaptation is insufficient to ensure an adequate nutrient supply for the population by mid-century. In the HT scenarios, transformative adaptation improves nutrition security due to increases in micronutrient-rich crops such as fruit and vegetables. Our results suggest that a continued focus on maize will continue to lead to sub-optimal nutritional outcomes in all countries.

Reduced crop diversity was considered by stakeholders to be a possible outcome in Tanzania and Zambia HT-RCP8.5 scenarios, in contrast to HT-RCP2.6 scenarios, which were associated with increased diversification. In both Tanzania and Zambia HT-RCP8.5 scenarios, the resulting focus on fewer, higher-yielding crops (such as sugarcane, onions, cassava, and fruit and vegetable commodities) leads to per capita food supply exceeding requirements if assuming some degree of international trade. Whilst the increased supply of these commodities leads to increases in micronutrient-rich fruit and vegetables, there is also a significant over-supply of calories through expansion of maize and sugarcane - for example, there are more than 250% of required per capita calories in the Tanzania HT-RCP8.5 scenario. Overproduction of calories to improve micronutrient supplies is not realistic or desirable. Supplementary analysis shows that with none of the increased sugarcane production and 50% of the maize increase seen in the 2050 HT-RCP8.5 scenario, micronutrient supplies still improve relative to the baseline due to the increase in other more nutrient-rich commodities, but even with these reductions there was still an over-supply of calories, albeit smaller (139% of requirements; see Table SI1).

With increased crop diversification in the HT-RCP2.6 scenarios, per capita nutrient supplies also improve. In Tanzania, per capita calorie and micronutrient supplies are generally inferior (iron, zinc and calcium inadequacies) compared to the HT-RCP8.5 scenario due to reduced crop production. In Zambia, increased crop diversification but lower crop production in the HT-RCP2.6 scenario results in inadequate calorie and micronutrient supply, relative to both the HT-RCP8.5 scenario and, for most nutrients, relative to the 2000 baseline, owing to population increases outpacing agricultural production.

Several studies identify a relationship between crop diversification and climate resilience.[27, 28, 29] A trade-off is evident in our results between crop diversification and crop production, with the largest increases in production associated with HT scenarios that reduce crop diversity due to expansion of the highest-yielding crops, notably maize. However, the increase in maize monocultures implied by stakeholders in scenarios of reduced crop diversity can result in greater risks from crop pests and diseases, and given reduced risk-spreading across multiple crops, fewer opportunities for on-farm income generation, and greater detrimental health impacts, particularly for children, mothers and vulnerable and poor populations[29](see Section SI3). Our analysis also shows that maize is more susceptible to climate extremes than other crops, including soybean (see Section SI1). Soybean is one of a number of crops important for diversification policy agendas in the region due to its important role as a cash crop and climate-resilience[30] (see Section 4). If future food systems rely on fewer crops, there could be increased risks of obesity and associated non-communicable diseases, such as type II diabetes, cardiovascular disease and some forms of cancer,[31] continuing current trends in global food systems.[32] Thus, expansion of maize and not a diverse set of crops can have a number of negative consequences. There are challenges to expanding fruit and vegetable production, such as dealing with increased quantities of highly-perishable foods, which policies need to account for[33, 34](see Section SI3). There would be an increased need for infrastructural development, particularly for agricultural services such as storage, processing and transportation, in order to cut post-harvest losses, and additionally fruit and vegetable production is commonly input- and labour-intensive.[35]

3.2 Cropland expansion, yield trends and trade

Mid-century nutrient requirements remain only partially fulfilled in all scenarios, despite the transformative agricultural adaptation strategies employed in HT scenarios. In order to completely fulfil the populations' nutrition requirements, further changes to domestic production or trade are necessary - for example, reconfiguring domestic food production, or food import dependencies, to increase the supply of specific targeted food items.

Stakeholder-designed trade vignettes explored the nutrition security consequences of altering food imports and exports in each scenario. Of the 16 scenarios across all four countries, nine of these stakeholder-designed trade vignettes have net imports (notably including all high climate risk scenarios), with more than a doubling of imports compared to business-as-usual trade in some cases. For context, in South Africa, baseline maize exports are greater than imports. Imports are approximately five times larger than the other three countries at 5 million tonnes.[36] Although import increases generally lead to higher average per capita nutrient outcomes, in most cases this is still insufficient. Therefore, unless relying on greatly increased food imports, domestic production in these countries needs to increase to fulfil calorie and micronutrient requirements. In the absence of unprecedented yield increases, the scenarios show that the supply of calories and nutrients only improve by expanding agricultural areas.

Tanzania and Malawi HT scenarios show more favourable nutrition security outcomes than the Zambia scenarios, with most nutrient requirements satisfied. In the more favourable scenarios, the factors leading to increased production are broadly the same as in Zambia HT scenarios: increases to irrigation and yields, and a focus on maximising crop production through the highest-yielding crops. The key difference is in the future expansion of agricultural land in Tanzania and Malawi: arable land expands by over 50%, and as a result there are sufficient calories and nutrients, with the exceptions of marginally inadequate fat in Malawi, and marginal fat, calcium and iron supplies in Tanzania. By contrast, Zambia crop areas expand by only 5% in HT scenarios.

It is most likely that a combination of yield improvements for more micronutrient-rich crops and area expansion will be needed to achieve nutrition security for the growing SSA population by mid-century. Yield increases in HT scenarios in Malawi, Tanzania and Zambia are on average about 150%, matching the largest increases seen in the region from 1960 to 2010. Studies suggest that greater than three-fold yield gains in SSA are possible by mid-century through improved soil fertility and crop varieties.[37, 21] If productivity gains are not sufficient, area is available in SSA for agricultural expansion.[21, 38] There can be substantial biodiversity losses from such expansion (see Section SI4), suggesting that in future there should be prioritisation of productivity gains for calories and nutrients over land use expansion. A majority of agriculturally-suitable land is already in use in Malawi,[39] more so than in Tanzania and Zambia.[21, 38] Much of the non-agricultural land in Malawi consists of Miombo woodland, making expansion problematic due to loss of ecosystem services.[40] In addition, protected areas are increasingly under threat from agricultural expansion.[41] The importance of increasing productivity of micronutrient rich crops is therefore all the more important in this context.

4 Policy implications

This analysis highlights how various policy areas need to maximise synergies to improve climate-smart nutrition security in SSA by mid-century. The balance between imports and domestic production, agricultural land use expansion, and strategies to diversify and/or intensify production are key areas that require a climate-smart nutrition security lens. While our findings are relevant to other SSA countries with similar climate risks and nutrition security challenges, stakeholder engagement and bespoke analyses are crucial if seeking to influence country-specific policy development.

Due to increasing food price volatility from climate[42] and geopolitical factors[43] such as the war in Ukraine, relying on agricultural trade for an adequate supply of calories and nutrients is an increasingly risky option. This could also be economically unrealistic, especially when there is not a diverse range of source markets to improve supply resilience.[44] The southern hemisphere is particularly at risk of crop yield instability due to climate change.[45] Consequently, if countries prioritise local production and markets - rather than rely on a globally-connected food system - our analysis shows that SSA will need to increase domestic food production by mid-century given projected population growth, with a particular emphasis on commodities that will help address key nutrient deficiencies. Our results show that even with the impacts of climate change, relying on domestic food production increases - particularly of micronutrient rich foods - with business-as-usual trade can lead to improved supplies of micronutrients. More perishable foods such as fruit and vegetables are less likely to be available from imports in any case, and therefore as these micronutrient-rich commodities are required to achieve nutrition security, it is important that domestic production strategies provide for these.

The largest differences in micronutrient supplies are across the HT vs. LT scenarios, rather than across different climate change scenarios, giving further evidence that the future of nutrition security through adequate supplies of calories and nutrients is in the hands of domestic policy makers, even in the face of climate change uncertainty. That being said, the impacts of climate change extremes are important due to projected food production shocks increasing. Our results also point to sensible strategies to mitigate against these extreme impacts for example, crop diversification as a strategy to spread risks, and in particular from maize as a monocrop to reduce yield shocks, while recognising the cultural importance of maize in the diet.

Prior studies focus mostly on production and calories, suggesting that yield gap closure is needed to maintain or increase food production for major cereal crops.[46,20,47,21] Even with yield gap closure, agricultural land expansion in SSA is needed to fulfil cereal production demand by mid-century.[21] Our analysis shows that without expansion of more diverse, micronutrient-rich crops, which provide sufficient calories and nutrients (in particular, calcium, iron, fat and zinc), achieving nutrition security is challenging in SSA even with productivity improvements. This result is supported by other studies, showing that smallholder nutrition security can be improved by diversifying away from maize despite its cultural importance,[48,29,49] and that similar nutrient deficiencies can be expected without targeted interventions.[15]

Whilst maize will continue to be an important economic and staple crop, specific policy options do exist for transitioning away from maize, such as in the Zambian policy agenda. iFEED evidence is supporting this in the development of the forthcoming Second Generation National Agriculture Investment Plan (NAIPII 2022 - 2026), the National Crop Diversification Strategy (2020), and the Zambia Soybean Strategy and Investment Plan (2022). The Zambian National Agricultural Policy (2004) and Second National Agricultural Policy (2016) also provide a framework for crop diversification to achieve food and nutrition security and agricultural transformation. Soybean has also recently been highlighted as a crop with expansion potential across Africa,[30] primarily as a cash crop and a source of livestock feed. Our findings suggest that investment in soybean as an emergent crop has potential benefits for improving climate resilience and nutrition security through both direct consumption and as a source of livestock feed, increasing the supply of animal-based foods. Additionally, cash crops can have benefits for nutrition security that staple crops do not provide, such as increasing income and therefore access to a more diverse range of foods.[50] Alongside increases in productivity of micronutrient-rich crops, cash crops will continue to form a crucial part of incomes, and without adequate planning communities can adopt unsustainable alternative practises such as encroachment on protected areas through pastoral expansion.[51]

There is a need to rebalance livestock consumption globally given overconsumption in many high-income countries[52] and the lack of key micronutrients in SSA diets.[49] Whilst livestock production is associated with increased emissions and places significant demands on land and water (see Section SI4), it also provides essential micronutrients that are currently deficient in many people in SSA.[52] Historically, agricultural land use change has been driven by both population growth and increasing demands for animal products.[53] Increased production and consumption of animal-based products in the region could reduce nutrient gaps but should not aim to reach the unsustainable production levels currently seen in the global north. Following the trends in dietary changes with nutrition transition through economic development, seen in many low-and middle income countries, it is likely that consumption of animal products will increase.[32] Given the relatively low GHG emissions in SSA,[54] and the challenges associated with achieving nutrition security by mid-century, policies should focus on providing sufficient food to meet nutrient requirements if faced with the trade-off between increasing emissions and avoiding food and nutrition insecurity, and arguably some increases in emissions could be regarded as tolerable. In any case, without domestic food production increases, emissions would be outsourced if relying on increased imports. Crop breeding for biofortification[55] and increased production of crops such as millet and sorghum can contribute to alleviating calcium, iron and zinc shortfalls,[56,57] and reduce demands on land and water. Expansion of such traditional and neglected crops will require significant scientific and market investment, however.

Optimising climate resilience and nutrient supplies requires that crop-specific investments are not pursued in isolation but are grounded in holistic food system strategies. At country scales and above, studies that explore food system transformation are limited to providing assessments on future food[21] or nutrition[15] security. None of these analyses quantify impacts on climate smartness, despite this being a key component of complex trade-offs inherent to food system transformation.[58] Here, we provide a comprehensive assessment of the transitions needed for climate-smart nutrition security.

There are opportunities to focus on commodities that are more climate resilient and nutritionally important, and if climate-smart practises can increase productivity whilst minimising environmental impacts, policies can be designed to benefit social, environmental and nutrition security objectives. Additional agricultural inputs and access to improved seed varieties are necessary for yield gap closure in SSA;[37] addressing crop nutrient deficiencies alone could lead to 50% of yield gap closure.[59] Climate finance can help with the significant costs of such a transition, although more needs to be done to ensure that funds address productivity gains and climate change impacts on the most vulnerable.[60] For example, farmer insurance schemes could help to deal with increasing climate variability and boost productivity.[61] Crucially, the social, health and environmental benefits of transitioning to new diets are projected to be substantial,[62] highlighting the need to consider the benefits of transitions to more nutrient-secure diets to incentivise the public and private sectors to fund necessary transformations.

Without holistic approaches, adaptation will continue to be sub-optimal from health and environmental perspectives.[19, 18] The greater the focus on sustainable productivity increases that target nutrient requirements, the smaller the requirements for agricultural area expansion, increased emissions, and damaging environmental impacts.[63, 64, 65]

5 Methods

Note that iFEED methods and limitations have previously been fully described,[22] so a concise summary of the steps towards climate-smart nutrition security scenario assessment is provided here. We also provide further comparison with other integrated modelling approaches in Section SI5. Our modelling does not account for increased costs of production, instead focusing on the benefits of various adaptation decisions. This is because we do not advocate implementing any specific scenario, but instead seek to compare the positives and negatives of various scenarios to point towards robust pathways of change, which culminate in climate-smart nutrition security. Through post hoc discussion with stakeholders, these results can be used to inform agricultural policy development that is cognisant of the costs involved in seeking to implement desirable transformations.

5.1 Stakeholder-defined scenarios

Firstly, a scenario exercise is used to explore the range of possibilities that the future may hold.[11,12] Our analysis compares a baseline centred on 2000 (1990 to 2010) with a future centred on 2050 (2040 to 2060). Food system stakeholders identify a set of driving forces that shape future food system outcomes. Through discussion, two independent and impactful drivers (described as critical uncertainties) are selected for which there is high uncertainty, thus maximising the range of possible futures explored. The two critical uncertainties are used to create a 2x2 matrix that frames four potential future scenarios. Figure 1 summarises the scenarios for each country. In all countries, the level of climate risk was selected as one critical uncertainty, with low climate risk scenarios being characterised by RCP2.6, and high climate risk scenarios characterised by RCP8.5. In Malawi, South Africa, Tanzania and Zambia, respectively, the other critical uncertainty selected was the effectiveness of policy implementation (the degree to which agricultural and food system policies will be systemic, aligned, well-implemented and adopted, enabling progressive, nutritionally adequate and sustainable food system outcomes), the extent of land reform (from minor adjustments compared to today, to extensive "land restitution" to empower farm workers and reduce inequality), the extent of technological transformation (the degree to which general improvements in productivity from better implementation of agricultural technologies have taken place), and the degree of market connectivity and functionality (how connected international and domestic food system markets are to Zambia's agricultural system; technology was also an important factor linked with market connectivity). The scenarios with a high degree of change in this second critical uncertainty are known as "high transformation" (HT) scenarios, and the opposing scenarios known as "low transformation" (LT) scenarios. Please see https://africap.info/reports/ for full details of the stakeholder scenario workshops.

Stakeholders inform the modelling of these scenarios in terms of changes to crop yields, agricultural areas, crop varieties and diversity, irrigation and international trade. We represented increased / decreased crop diversification as a decreased / increased fraction of total cropped area taken by maize, and more / fewer crops sharing the majority of cropped areas. HT scenarios generally assumed a continuation of historical yield trends in the region, representing an optimistic view of future crop yields based on observed data. Crops were spatially-distributed within each country to maximise production in these scenarios - i.e. optimisation to maximise crop production given the prescribed crop area and yields.

Dietary demand trends in lower and middle-income countries are towards increasing consumption of ultra-processed foods and meat products. It is uncertain to what extent demand will shift in SSA towards “westernisation” of diets by 2050, although current trends are towards increased consumption of ultra-processed foods and meat and dairy.[32]

Whilst our modelling framework does not explicitly account for changes in demand, such trends in diets drive changes in food production systems. All high transformation scenarios include increased livestock production, primarily to explore how nutrition security could be ensured by mid-century, but also reflecting stakeholder recognition of known trends towards increased demand for livestock products, which informed the projections of future land use. In addition, trade vignettes cover a full range of trade possibilities, from self-sufficiency to stakeholder assessment of future imports and exports in each scenario, thus implicitly including any expected changes in demand. Therefore, whilst the focus of the analysis is explicitly on how agricultural transformation (via domestic policy decisions) could help deliver nutrition security (and what the implications of these transitions would be for climate smartness), changes in demand inherently underpin stakeholder assumptions around future production and trade.

5.2 Integrated modelling of climate, food and emissions

Integrated modelling provides each scenario with quantification of changes to crop and livestock production. All crop commodities grown in each country in the baseline (1990 to 2010) are included in the food production and nutrition security analysis. Crop production changes are calculated from yield and area changes specific to each scenario. Crop yield changes are the result of simulated climate change impacts using the General Large Area Model for annual crops (GLAM[66]) and yield trends applied as agreed with stakeholders. For each crop, continuation of historical trends as seen in FAOSTAT yield data[36] from 1960 to 2010 was applied in Malawi, Tanzania and Zambia HT scenarios. LT scenarios in these three countries assume no yield trend applied and only autonomous adaptation to climate change (consisting of changes to planting dates and crop varieties, although only those varieties that are currently available). All South Africa scenarios assumed an intermediate yield trend for each crop, being half of the historical trend. HT scenarios in all four countries accounted for adaptation to climate change in the form of changing of planting dates and new crop varieties that account for any warming-induced reduction in the length of the growing season. Area changes are also scenario-specific and determined in conjunction with stakeholders (Figure 1); maximum possible increases were determined using Land Use Harmonisation II data[67] and assumed all land was available for agricultural expansion if not forested, urban or protected according to The World Database on Protected Areas.[68]

Livestock production changes are calculated using projected changes to livestock pasture, crop residues and crop production used as livestock feed, and assuming historical relationships between livestock feed and livestock meat and dairy production remain the same by 2050. These relationships are calculated using data[69] in the following categories: bovine meat, bovine milk, sheep and goat meat, sheep and goat milk, pig meat, poultry meat, and eggs.

Nutrition security (defined here as adequate energy and nutrient supplies to meet dietary requirements at a population level, noting that we do not assess the distribution or access of food within the population) was quantified for each scenario given domestic food production changes, assuming medium-variant United Nations population projections for 2050, and contrasting trade scenarios referred to as trade vignettes: self-sufficiency (assuming no imports or exports and thus addressing how well domestic production matches domestic requirements); business as usual (imports and exports remaining in the same proportions to domestic production as at baseline); and stakeholder expectations (reflecting in-country expert judgements about likely future trade dependencies).

The FAOSTAT Food Balance Sheet (FBS) data provide an estimate of the supply of 96 food commodities based on domestic production, imports and exports, including stock variation of each commodity within each country.

These data are further categorised into supply for human consumption and other uses (e.g., feed, seed and losses). Although they provide an estimate of per capita supply of calories, protein and fat, data for micronutrients are not supplied in the FBS, therefore in iFEED the supply of energy and all nutrients are calculated for each country using an internally consistent method.[70] FBS food commodities are converted to food as eaten, adjusting for unavoidable waste (e.g. inedible peel, bones) and household waste (e.g. edible food). The food commodities are disaggregated into food items and matched to foods in country or region-specific food composition tables, which provide an estimate of the supply of calories, protein, fat, carbohydrate, saturated fat, fibre, calcium, zinc, iron, vitamin C, thiamin, riboflavin, niacin, folate and vitamin B6. Each food item is then weighted to represent the quantity of each food eaten at a country level, before being aggregated back to food commodity groups. We assume no changes to the weightings of foods within each food item between baseline and future for this calculation. Although dietary composition is likely to change, many of the changes may be expected to be between rather than within food items, although the rate and extent of this transition is uncertain. More generally, while changes to diets in these countries are likely, with economic development, to move through a nutrition transition to those observed in high income countries,[32] our focus was on food supply rather than demand so we have not commented on potential dietary changes for the weighting calculation. Lastly, total nutrient supplies are calculated. The marker of adequate nutrition supply is set to achieving the supply of population-level nutrient requirements taken from World Health Organization recommendations. The population-level nutrient requirements are country-specific and adjusted for projected demographic changes (population size, age, sex, and fertility rates) based on medium-variant UN projections to 2050.

We quantified changes to greenhouse gas emissions, soil organic carbon, and climate extremes to holistically assess climate-smart nutrition security. Extremes of climate change are analysed in terms of changes to extremes of temperature and precipitation and resulting impacts on crop yield shocks (i.e. years with approximately half of the mean baseline yield). Model results are summarised using calibrated statements - concise summaries that are associated with an assessment of confidence in model outcomes based on comparisons to the literature and expert judgement of model result uncertainty.

5.3 Integration of expert judgement and result summary process

Critical analysis of model outputs is undertaken by social, ecological and environmental scientists, who use the calibrated statements as the basis for implication statements. This allows iFEED to explore broader food system implications than models can alone; for example, how changes to agricultural land use and crop diversification might impact pest and disease risks, soil health, inequality and land use conflict. The calibrated and implication statements are collated at the level of each scenario, and then for each country, providing descriptive scenario and country-level summaries. These are available to view at https://ifeed.leeds.ac.uk/.

A scoring system was developed to summarise iFEED results for each scenario for each aspect of climate-smart agriculture and nutrition security, the results of which are shown in Figure 2. See Section SI6 for full details of the scoring system. For each aspect of climate-smart nutrition security:

- Blue = substantial improvement
- Amber = improvement inconclusive (either not a substantial change or trade-offs to improvements possible)
- Red = clear inadequacy

Following this assessment of each scenario, cross-scenario comparisons are made to draw out the commonalities that lead to improvements in nutrition security and climate-smartness. Using these cross-scenario comparisons, policy implications are co-developed with stakeholders by incorporating country-specific policy context with the integrated assessment outputs.

6 Data availability

Source data supporting conclusions are shown in Tables SI1-4.

Input data used in this study are from publicly available sources and referenced in Jennings et al. (2022). In summary, these consist of:

- The CDF-t bias-corrected CMIP5 data over Africa are available at http://amma2050.ipsl.upmc.fr/. To access the data, users must contact the lead author at moflod@locean-ipsl.upmc.fr.
- FAOSTAT yield and area and Food Balance Sheet data https://www.fao.org/faostat/

- Soil data were from the Regridded Harmonized World Soil Database v 1.2: https://daac.ornl.gov/SOILS/guides/HWSD.html
- Gridded area data from LUH2 (https://luh.umd.edu/) and WDPA (https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA).

7 Code availability

The methods used have been previously fully described in Jennings et al. (2022). The General Large Area Model for annual crops (GLAM) was used for the crop yield simulations. An older version of this model is available online https://licensing.leeds.ac.uk/product/general-large-area-model-for-annual-crops-glam. The version (version number 79e1615) used for the simulations in this paper is available upon reasonable request.

The ECOSSE model (Estimating Carbon in Organic SoilsSequestration and Emissions) provided projections of greenhouse gas emissions, soil organic carbon (SOC) and nitrogen (N) dynamics associated with agriculture in each future scenario, taking into account yield and land use changes. A spatial version of ECOSSEGlobal ECOSSE (version 6.2b)was used. See here for more information: https://soil-modeling.org/resources-links/model-portal/ecosse

An excel spreadsheet was developed for nutrition data analysis and is available upon reasonable request.

8 Acknowledgements

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

This work was supported by the Biotechnology and Biological Sciences Research Council through UK Research and Innovation as part of the Global Challenges Research Fund, AFRICAP programme, grant number BB/P027784/1.

This work was carried out with support from the CGIAR Initiative on Climate Resilience, ClimBeR. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders/.

9 Author Contributions Statement

SJ performed the crop modelling, land use allocation and food production analysis, and prepared the manuscript. AC led in designing the iFEED framework, along with contributions from SJ, RK, JM, HCl, NF, SV and PS. RK, JM, GH, and HCl performed the trade and nutrition analysis. NF, SV, and PS performed emissions and soil organic carbon simulations. EP, CB, and SC performed climate extremes analysis. SZ, JY, NK, MG, SE, HT, SSai, SK, EL, HG, HS, MMa, HH, and MMu contributed to the implication statements. TB, SM, TM, IM, CC, MN, BN, NMa, PY, PK, AKa, VK, AKi, AS, HCo, CQ, SSal, AD, SWh, BK, NMe, AJ, DK, PM, WM, FK, and SWa contributed to the scenario and integration workshops and result summaries. All authors contributed to the conception and design of the methods, and read and approved the submitted manuscript.

10 Competing Interests Statement

The authors declare no competing interests.

11 Figures

Fig. 1: **Scenario inputs to iFEED from stakeholder engagement.** LT = low transformation scenarios (low policy efficacy in Malawi; low market connectivity in Zambia; low technological development in Tanzania; low land reform in South Africa) and HT = high transformation. RCP2.6 = low climate risk. RCP8.5 = high climate risk. For Arable Area and Pasture Area, numbers given are percentage changes to land areas relative to a 1990-2010 baseline. The Malawi and Tanzania scenarios that feature agricultural area expansion use up all available land in mid-century (protected areas, urban areas and forests excluded), other than the Tanzania HT-RCP8.5 scenario where the livestock expansion was described by stakeholders to be smaller. Optimisation to maximise domestic crop production was assumed in HT scenarios in Malawi, Tanzania and Zambia. Increasing crop diversity refers to maize areas decreasing and other crop areas expanding; decreasing crop diversity refers to maize areas increasing and other crop areas contracting. For each box: Blue = increase; Amber = no change; Red = decrease. Note that the trade column refers to changes in imports / exports in the stakeholder-designed trade vignette, with the colour referring to increases / decreases in trade surplus, e.g. whether imports increase more than exports.

Fig. 2: **Results summary for all scenarios for the three pillars of CSA (productivity, adaptation, mitigation) and nutrition security.** LT = low transformation scenarios (low policy efficacy in Malawi; low market connectivity in Zambia; low technological development in Tanzania; low land reform in South Africa) and HT = high transformation. RCP2.6 = low climate risk. RCP8.5 = high climate risk. The scoring system was developed to summarise iFEED results for each scenario for each aspect of climate-smart agriculture and nutrition security. See the SI for full details of the scoring system. For each aspect of climate-smart nutrition security, Blue = substantial improvement, Amber = improvement inconclusive, Red = clear inadequacy. Note that a star indicates all aspects of productivity / adaptation / mitigation are improving / not worsening in that scenario; for nutrition security, a star indicates all nutrient requirements are met for all trade vignettes.

Fig. 3: **Per capita nutrient supplies with business-as-usual trade, relative to population requirements (100%) for a). HT-RCP2.6 and b). HT-RCP8.5 in Tanzania.** Black diamonds indicate baseline (2000) per capita nutrient levels. The five coloured diamonds indicate the projected outcomes in 2050 under different climate models. Grey areas indicate where per capita nutrient requirements are met and pink areas indicate that requirement are not achieved, with intermediate areas marginal. For all nutrients other than energy and fat, the first threshold represents the Lower Reference Nutrient Intake (LRNI); the second, the Estimated Average Requirement (EAR); the third, the Reference Nutrient Intake (RNI; principal target). For fat, thresholds correspond to minimum, min-max midpoint, and maximum recommended intakes respectively. For energy, the respective thresholds are MDER, ADER, and XDER (minimum, average and maximum dietary energy requirements). The dark pink area indicates where calories are greater than requirements. Vitamin A is measured in retinol activity equivalents (RAE).

Fig. 4: **Per capita nutrient supplies with business-as-usual trade, relative to population requirements (100%) for a). HT-RCP2.6 and b). HT-RCP8.5 in Zambia**. Black diamonds indicate baseline (2000) per capita nutrient levels. The five coloured diamonds indicate the projected outcomes in 2050 under different climate models. Grey areas indicate where per capita nutrient requirements are met and pink areas indicate that requirement are not achieved, with intermediate areas marginal. For all nutrients other than energy and fat, the first threshold represents the Lower Reference Nutrient Intake (LRNI); the second, the Estimated Average Requirement (EAR); the third, the Reference Nutrient Intake (RNI; principal target). For fat, thresholds correspond to minimum, min-max midpoint, and maximum recommended intakes respectively. For energy, the respective thresholds are MDER, ADER, and XDER (minimum, average and maximum dietary energy requirements). The dark pink area indicates where calories are greater than requirements. Vitamin A is measured in retinol activity equivalents (RAE).

References

[1] Vermeulen, S.J., Challinor, A.J., Thornton, P.K., Campbell, B.M., Eriyagama, N., Vervoort, J.M., Kinyangi, J., Jarvis, A., Läderach, P., Ramirez-Villegas, J., *et al.*: Addressing uncertainty in adaptation planning for agriculture. Proceedings of the National Academy of Sciences **110**(21), 8357–8362 (2013)

[2] Mbow, H.-O.P., Reisinger, A., Canadell, J., OBrien, P.: Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2). Ginevra, IPCC (2017)

[3] Horton, P., Banwart, S.A., Brockington, D., Brown, G.W., Bruce, R., Cameron, D., Holdsworth, M., Lenny Koh, S., Ton, J., Jackson, P.: An agenda for integrated system-wide interdisciplinary agri-food research. Food Security **9**(2), 195–210 (2017)

[4] Challinor, A.J., Arenas-Calles, L.N., Whitfield, S.: Measuring the effectiveness of climate-smart practices in the context of food systems: Progress and challenges. Frontiers in Sustainable Food Systems, 134 (2022)

[5] Hellin, J., Amarnath, G., Challinor, A., Fisher, E., Girvetz, E., Guo, Z., Hodur, J., Loboguerrero, A.M., Pacillo, G., Rose, S., *et al.*: Transformative

adaptation and implications for transdisciplinary climate change research. Environmental Research: Climate **1**(2), 023001 (2022)

[6] Fedele, G., Donatti, C.I., Harvey, C.A., Hannah, L., Hole, D.G.: Transformative adaptation to climate change for sustainable social-ecological systems. Environmental Science & Policy **101**, 116–125 (2019)

[7] Springmann, M., Mason-DCroz, D., Robinson, S., Wiebe, K., Godfray, H.C.J., Rayner, M., Scarborough, P.: Mitigation potential and global health impacts from emissions pricing of food commodities. Nature Climate Change **7**(1), 69–74 (2017)

[8] Stehfest, E., van Zeist, W.-J., Valin, H., Havlik, P., Popp, A., Kyle, P., Tabeau, A., Mason-DCroz, D., Hasegawa, T., Bodirsky, B.L., *et al.*: Key determinants of global land-use projections. Nature communications **10**(1), 2166 (2019)

[9] Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F., Lotze-Campen, H., *et al.*: Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change **8**(8), 699–703 (2018)

[10] Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., *et al.*: Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences **111**(9), 3274–3279 (2014)

[11] ONeill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., *et al.*: Achievements and needs for the climate change scenario framework. Nature climate change **10**(12), 1074–1084 (2020)

[12] Benton, T.G.: Using scenario analyses to address the future of food. EFSA Journal **17**, 170703 (2019)

[13] Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., Oneill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., *et al.*: The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change **42**, 153–168

(2017)

[14] Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-DCroz, D., *et al.*: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environmental Research Letters **10**(8), 085010 (2015)

[15] Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T.B., Mason-DCroz, D., Power, B., Gustafson, D., Herrero, M., *et al.*: Income growth and climate change effects on global nutrition security to mid-century. Nature Sustainability **1**(12), 773–781 (2018)

[16] Arenas-Calle, L.N., Whitfield, S., Challinor, A.J.: A Climate Smartness Index (CSI) Based on Greenhouse Gas Intensity and Water Productivity: Application to Irrigated Rice. Front. Sustain. Food Syst. **3**(105) (2019)

[17] Tripathi, H.G., Kunin, W.E., Smith, H.E., Sallu, S.M., Maurice, S., Machera, S.D., Davies, R., Florence, M., Eze, S., Galani Yamdeu, H., *et al.*: Climate-Smart Agriculture and trade-offs with biodiversity and crop yield. Frontiers in Sustainable Food Systems **6**, 868870 (2022)

[18] de Ruiter, H., Macdiarmid, J.I., Matthews, R.B., Smith, P.: Moving beyond calories and protein: micronutrient assessment of UK diets and land use. Global Environmental Change **52**, 108–116 (2018)

[19] Ambikapathi, R., Schneider, K.R., Davis, B., Herrero, M., Winters, P., Fanzo, J.: Global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity. Nature Food, 764–779 (2022). https://doi.org/10.1038/s43016-022-00588-7

[20] Schneider, J.M., Zabel, F., Schünemann, F., Delzeit, R., Mauser, W.: Global cropland could be almost halved: Assessment of land saving potentials under different strategies and implications for agricultural markets. PloS one **17**(2), 0263063 (2022)

[21] 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-DCroz,

D., *et al.*: Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences **113**(52), 14964–14969 (2016)

[22] Jennings, S.A., Challinor, A.J., Smith, P., Macdiarmid, J., Pope, E., Chapman, S., Bradshaw, C., Clark, H., Vetter, S., Fitton, N., King, R., Mwamakamba, S., Madzivhandila, T., Mashingaidze, I., Chomba, C., Nawiko, M., Nyhodo, B., Mazibuko, N., Yeki, P., Kuwali, P., Kambwiri, A., Kazi, V., Kiama, A., Songole, A., Coskeran, H., Quinn, C., Sallu, S., Dougill, A., Whitfield, S., Kunin, B., Meebelo, N., Jamali, A., Kantande, D., Makundi, P., Mbungu, W., Kayula, F., Walker, S., Zimba, S., Yamdeu, J.H.G., Kapulu, N., Galdos, M.V., Eze, S., Tripathi, H., Sait, S.M., Kepinski, S., Likoya, E., Greathead, H., Smith, H.E., Mahop, M.T., Harwatt, H., Muzammil, M., Horgan, G., Benton, T.: A new integrated assessment framework for climate-smart nutrition security in sub-Saharan Africa: the integrated Future Estimator for Emissions and Diets (iFEED). Frontiers in Sustainable Food Systems (2022)

[23] Webber, H., Gaiser, T., Ewert, F.: What role can crop models play in supporting climate change adaptation decisions to enhance food security in sub-saharan africa? Agricultural Systems **127**, 161–177 (2014). https://doi.org/10.1016/j.agsy.2013.12.006. Times Cited: 1 1

[24] Hamilton, S.H., ElSawah, S., Guillaume, J.H., Jakeman, A.J., Pierce, S.A.: Integrated assessment and modelling: overview and synthesis of salient dimensions. Environmental Modelling & Software **64**, 215–229 (2015)

[25] Famien, A.M., Janicot, S., Ochou, A.D., Vrac, M., Defrance, D., Sultan, B., Noel, T.: A bias-corrected CMIP5 dataset for Africa using the CDF-t method: a contribution to agricultural impact studies. Earth System Dynamics **9**(1), 313–338 (2018)

[26] van Loon, M.P., Hijbeek, R., Ten Berge, H.F., De Sy, V., Ten Broeke, G.A., Solomon, D., van Ittersum, M.K.: Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. Global Change Biology **25**(11), 3720–3730 (2019)

[27] Clay, N., Zimmerer, K.S.: Who is resilient in Africa's green revolution? Sustainable intensification and climate smart agriculture in Rwanda. Land Use

Policy **97**, 104558 (2020)

[28] Abberton, M., Batley, J., Bentley, A., Bryant, J., Cai, H., Cockram, J., Costa de Oliveira, A., Cseke, L.J., Dempewolf, H., De Pace, C., *et al.*: Global agricultural intensification during climate change: a role for genomics. Plant biotechnology journal **14**(4), 1095–1098 (2016)

[29] Mango, N., Makate, C., Mapemba, L., Sopo, M.: The role of crop diversification in improving household food security in central Malawi. Agriculture & Food Security **7**(1), 1–10 (2018)

[30] Foyer, C.H., Siddique, K.H., Tai, A.P., Anders, S., Fodor, N., Wong, F.-L., Ludidi, N., Chapman, M.A., Ferguson, B.J., Considine, M.J., *et al.*: Modelling predicts that soybean is poised to dominate crop production across africa. Plant, cell & environment **42**(1), 373–385 (2019)

[31] Haslam, D.W., James, W.P.T.: Obesity. The Lancet **366**(9492), 1197–1209 (2005). https://doi.org/10.1016/S0140-6736(05)67483-1

[32] Popkin, B.M., Adair, L.S., Ng, S.W.: Global nutrition transition and the pandemic of obesity in developing countries. Nutrition Reviews **70**(1), 3–21 (2012)

[33] Mason-D'Croz, D., Bogard, J.R., Sulser, T.B., Cenacchi, N., Dunston, S., Herrero, M., Wiebe, K.: Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. The Lancet Planetary Health **3**(7), 318–329 (2019)

[34] Siegel, K.R., Ali, M.K., Srinivasiah, A., Nugent, R.A., Narayan, K.V.: Do we produce enough fruits and vegetables to meet global health need? PloS One **9**(8), 104059 (2014)

[35] Sachdeva, S., Sachdev, T.R., Sachdeva, R.: Increasing fruit and vegetable consumption: challenges and opportunities. Indian Journal of Community Medicine: Official Publication of Indian Association of Preventive & Social Medicine **38**(4), 192 (2013)

[36] FAO: FAOSTAT, FAO Statistical Databases (2020)

[37] Sanchez, P.A.: En route to plentiful food production in Africa. Nature Plants **1**(1), 1–2 (2015)

[38] Chamberlin, J., Jayne, T., Headey, D.: Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food Policy **48**, 51–65 (2014)

[39] Li, G., Messina, J.P., Peter, B.G., Snapp, S.S.: Mapping land suitability for agriculture in Malawi. Land degradation & development **28**(7), 2001–2016 (2017)

[40] Ryan, C.M., Pritchard, R., McNicol, I., Owen, M., Fisher, J.A., Lehmann, C.: Ecosystem services from southern African woodlands and their future under global change. Philosophical Transactions of the Royal Society B: Biological Sciences **371**(1703), 20150312 (2016)

[41] Meng, Z., Dong, J., Ellis, E.C., Metternicht, G., Qin, Y., Song, X.-P., Löfqvist, S., Garrett, R.D., Jia, X., Xiao, X.: Post-2020 biodiversity framework challenged by cropland expansion in protected areas. Nature Sustainability, 1–11 (2023)

[42] Iizumi, T., Luo, J.-J., Challinor, A.J., Sakurai, G., Yokozawa, M., Sakuma, H., Brown, M.E., Yamagata, T.: Impacts of El Niño Southern Oscillation on the global yields of major crops. Nature Communications **5**(May), 3712 (2014). https://doi.org/10.1038/ncomms4712

[43] Anderson, K.: Government trade restrictions and international price volatility. Global Food Security **1**(2), 157–166 (2012)

[44] Zorya, S., Cramon-Taubadel, S.v., Greb, F., Jamora, N., Mengel, C., Würriehausen, N.: Price transmission from world to local grain markets in developing countries: Why it matters, how it works, and how it should be enhanced, (2014)

[45] Iizumi, T., Yokozawa, M., Sakurai, G., Travasso, M.I., Romanernkov, V., Oettli, P., Newby, T., Ishigooka, Y., Furuya, J.: Historical changes in global yields: major cereal and legume crops from 1982 to 2006. Global Ecology and Biogeography **23**(3), 346–357 (2014). https://doi.org/10.1111/geb.12120. Times Cited: 2 2

[46] Zhu, P., Burney, J., Chang, J., Jin, Z., Mueller, N.D., Xin, Q., Xu, J., Yu, L., Makowski, D., Ciais, P.: Warming reduces global agricultural production by decreasing cropping frequency and yields. Nature Climate Change **12**(11), 1016–1023 (2022)

[47] Ten Berge, H.F., Hijbeek, R., Van Loon, M., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., *et al.*: Maize crop nutrient input requirements for food security in sub-Saharan Africa. Global Food Security **23**, 9–21 (2019)

[48] Lovo, S., Veronesi, M.: Crop diversification and child health: empirical evidence from Tanzania. Ecological Economics **158**, 168–179 (2019)

[49] Galani, Y., Orfila, C., Gong, Y.: A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa. Critical Reviews in Food Science and Nutrition **62**(6), 1568–1591 (2022)

[50] Longhurst, R.: Cash crops, household food security and nutrition. IDS Bulletin **19**(2), 28–36 (1988)

[51] Baudron, F., Guerrini, L., Chimimba, E., Chimusimbe, E., Giller, K.E.: Commodity crops in biodiversity-rich production landscapes: Friends or foes? The example of cotton in the Mid Zambezi Valley, Zimbabwe. Biological Conservation **267**, 109496 (2022)

[52] Mehrabi, Z., Gill, M., Wijk, M.v., Herrero, M., Ramankutty, N.: Livestock policy for sustainable development. Nature Food **1**(3), 160–165 (2020)

[53] Alexander, P., Rounsevell, M.D., Dislich, C., Dodson, J.R., Engström, K., Moran, D.: Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. Global Environmental Change **35**, 138–147 (2015)

[54] Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F., Leip, A.: Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food **2**(3), 198–209 (2021)

[55] Msungu, S.D., Mushongi, A.A., Venkataramana, P.B., Mbega, E.R.: A

review on the trends of maize biofortification in alleviating hidden hunger in sub-Sahara Africa. Scientia Horticulturae **299**, 111029 (2022)

[56] Mahendrakar, M.D., Kumar, S., Singh, R.B., Rathore, A., Potupureddi, G., Kishor, P.K., Gupta, R., Srivastava, R.K.: Genetic variability, genotype× environment interaction and correlation analysis for grain iron and zinc contents in recombinant inbred line population of pearl millet [Pennisetum glaucum (L). R. Br.]. Indian Journal of Genetics and Plant Breeding **79**(03), 545–551 (2019)

[57] Devi, P.B., Vijayabharathi, R., Sathyabama, S., Malleshi, N.G., Priyadarisini, V.B.: Health benefits of finger millet (Eleusine coracana L.) polyphenols and dietary fiber: a review. Journal of Food Science and Technology **51**(6), 1021–1040 (2014)

[58] Cammarano, D., Olesen, J.E., Helming, K., Foyer, C.H., Schönhart, M., Brunori, G., Bandru, K.K., Bindi, M., Padovan, G., Thorsen, B.J., et al.: Models can enhance science–policy–society alignments for climate change mitigation. Nature Food, 1–4 (2023)

[59] Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A.: Closing yield gaps through nutrient and water management. Nature **490**(7419), 254–257 (2012). https://doi.org/10.1038/nature11420. Times Cited: 90 Ray, Deepak/F-7720-2012 91

[60] Roberts, J.T., Weikmans, R., Robinson, S.-a., Ciplet, D., Khan, M., Falzon, D.: Rebooting a failed promise of climate finance. Nature Climate Change **11**(3), 180–182 (2021)

[61] Gatti, N., Cecil, M., Baylis, K., Estes, L., Blekking, J., Heckelei, T., Vergopolan, N., Evans, T.: Is closing the agricultural yield gap a risky endeavor? Agricultural Systems **208**, 103657 (2023)

[62] Chichaibelu, B.B., Bekchanov, M., von Braun, J., Torero, M., *et al.*: The global cost of reaching a world without hunger: Investment costs and policy action opportunities. Food Policy **104**(12), 102151 (2021)

[63] Williams, D.R., Clark, M., Buchanan, G.M., Ficetola, G.F., Rondinini, C., Tilman, D.: Proactive conservation to prevent habitat losses to agricultural

expansion. Nature Sustainability **4**(4), 314–322 (2021)

[64] van Soesbergen, A., Arnell, A.P., Sassen, M., Stuch, B., Schaldach, R., Göpel, J., Vervoort, J., Mason-DCroz, D., Islam, S., Palazzo, A.: Exploring future agricultural development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit scenario-based assessment. Regional Environmental Change **17**, 1409–1420 (2017)

[65] Palazzo, A., Vervoort, J.M., Mason-DCroz, D., Rutting, L., Havlík, P., Islam, S., Bayala, J., Valin, H., Kadi, H.A.K., Thornton, P., *et al.*: Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. Global Environmental Change **45**, 227–242 (2017)

[66] Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Slingo, J.M., Grimes, D.I.F.: Design and optimisation of a large-area process-based model for annual crops. Agricultural and Forest Meteorology **124**(1-2), 99–120 (2004). https://doi.org/10.1016/j.agrformet.2004.01.002

[67] Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D.P., Wang, Y.P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change **109**(1), 117 (2011). https://doi.org/10.1007/s10584-011-0153-2

[68] UNEP-WCMC, IUCNe: Protected Planet: The World Database on Protected Areas (WDPA), Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net (2019)

[69] Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M.: Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences **110**(52), 20888–20893 (2013)

[70] Macdiarmid, J.I., Clark, H., Whybrow, S., De Ruiter, H., McNeill, G.:

Assessing national nutrition security: The UK reliance on imports to meet population energy and nutrient recommendations. PLoS One **13**(2), 0192649 (2018)