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ORIGINAL RESEARCH

The impact of climate and societal change on food and nutrition security: A case study of Malawi

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Abstract

Society is currently facing an unprecedented challenge in terms of achieving food and nutrition security for a rapidly expanding global population while also minimising and reversing damage to the natural environment. Compounding this issue is climate change, which adversely affects the four pillars of food security: availability, access, utilisation and stability. This study aims to quantify the potential impact of future climate and societal change on food and nutrition security under a range of plausible scenarios. Malawi is used as a case study given it is one of the most food insecure countries in the world. Using the Food Estimation and Export for Diet and Malnutrition Evaluation modelling framework, the quantity and quality of the national food supply are assessed under a suite of future (2050) climate and socioeconomic scenarios. The results indicate that undernourishment prevalence could be reduced in Malawi under a best-case scenario; however, undernourishment is likely to increase assuming either a business-asusual or a pessimistic scenario. On the other hand, the quality of the food supply in Malawi (in terms of micronutrient provision) is likely to decrease even under a best-case scenario. Moreover, projected dietary change in the form of nutrition transition in Malawi is unlikely to improve micronutrient provision sufficiently to meet requirements. This is a consequence of the already low supply of micronutrient dense foods in Malawi, the negative impact of climate change on micronutrient dense crops and an insufficient increase in micronutrient dense foods associated with nutrition transition. This study highlights the importance of moving beyond the focus on dietary energy supply as a measure of food security since nutrient adequacy of diets may be a more pressing issue in the future than simply the quantity of food and supply of energy.

KEYWORDS

climate change, micronutrients, nutrition security, Sustainable Development Goals, undernourishment

1 | INTRODUCTION

1.1 | Background

Society currently faces an unprecedented challenge of meeting human nutritional needs in the context of natural resource scarcity and the rapid transformation of Earth's natural environment. The global population is projected to reach around 9.7 billion by 2050, rising to approximately 11 billion by the end of the century (UN, 2017). Coupled with the increasing demand for nutritious food are the issues of climate change and other environmental stressors (soil degradation, water scarcity, etc.) on the supply side. Climate change is likely already affecting food security across the globe (Kotir, 2011; Ray et al., 2019) and is projected to significantly affect our ability to meet future food demands (Myers et al., 2017). Despite major increases in food production over the past century which has largely kept up with demand, levels of food and nutrition insecurity remain high. An estimated 821 million people worldwide are undernourished (calorie intake below minimum requirements), two billion people suffer from a deficiency in one or more micronutrients, and 22% of children are stunted (shorter than average height for age) (FAO et al., 2018). Nowhere are these problems more pertinent than sub-Saharan Africa (SSA), where one in four people are undernourished (FAO et al., 2018).

Malawi is one of the most food-insecure countries in the world (Sahley et al., 2005). The most recent figures from the Food and Agriculture Organisation of the United Nations (FAO) estimate that 18.8% of Malawi's population were undernourished in the period 2017–19 (which equates to around 3.4 million people) (FAOSTAT, 2020). Micronutrient deficiencies are also common, particularly iron, zinc and vitamin A. For example, anaemia prevalence was estimated to be 42% in pregnant women and 34% in women of reproductive age (15–29 years) in 2016 (WHO GHO, 2019). Likewise, anaemia prevalence in children under five was estimated at 65% in 2011 (WHO GHO, 2019). Prevalence of zinc deficiency was estimated at 40% of the total population in 2005, which was considerably higher than the average for SSA for the same period (26%) (Wessells and Brown, 2012). Furthermore, prevalence of vitamin A deficiency was estimated at 14% in pregnant women and 59% in children under five during the period 1995–2005 (WHO, 2009). Malawi also ranks as 'alarmingly high' on the Global Hidden Hunger Index, which is calculated as the average of three nutritional indicators affecting children under five: prevalence of stunting, anaemia from iron deficiency and vitamin A deficiency (Muthayya et al., 2013).

As with the sub-Saharan region as a whole, there are biophysical, socioeconomic and political drivers of food insecurity in Malawi, which operate at the national, community, household and individual levels (Fisher & Lewin, 2013; Hajdu et al., 2009). On the demand side, Malawi has a young and rapidly growing population, expected to increase from 17.6 million in 2015 to 41.7 million by 2050, under a medium growth trajectory (UN, 2017). Thus, continued population growth increases the pressure on demand for agricultural products. At the same time, the agricultural sector struggles to keep pace with demand as it is dominated by smallholder farmers who grow mostly maize under rainfed conditions, leaving them vulnerable to climate shocks (Aberman et al., 2018). For example, severe flooding in 2000/2001 caused maize production to fall by 30%, leading to a shortfall of around 600,000 mega-tonnes and maize price increases of over 300% (Devereux, 2002). The situation caused widespread famine, with around one third of the population reliant on food aid at the peak of the crisis (Hajdu et al., 2009). Moreover, Malawi is one of the poorest countries in the world, with a Human Development Index of 0.477, positioning it 171 out of 189 countries and territories (UNDP, 2018). Both inequality and poverty are high, with more than 70% of the population living below the poverty line of 1.90 USD per person per day (World Bank, 2016). Thus, issues with the agricultural sector affect food availability, while persistent high levels of poverty and inequality affect people's ability to access food.

Despite the vulnerability of Malawi's food and agricultural system to external shocks, there is considerable uncertainty surrounding the nature and scale of future climate impacts which remains a barrier to adaptation planning (Warnatzsch & Reay, 2018). Due to the inherent uncertainty of climate projections at more local scales, most studies have projected climate impacts for Africa at the regional level, but a few have looked specifically at Malawi. For example, Mittal et al. (2017) projected climate change impacts in Malawi using results from recent climate model simulations. Using data from 34 Global Climate Models (GCMs) under the Representative Concentration Pathway (RCP) 8.5 (which is the most severe of the greenhouse gas (GHG) trajectories adopted by the IPCC), the study found a clear warming trend in annual temperatures since the 1970s (approximately 0.02°C per year), with strong agreement on continued future warming. The same study also found that more than half of the GCMs projected reductions in precipitation in Malawi to the 2070s, but results were much more uncertain.

A small number of studies have projected the future impact of climate change on crop production in Malawi (Adhikari et al., 2015; Saka et al., 2012; Stevens & Madani, 2016; Thornton et al., 2009). Adhikari et al. (2015) reviewed 160 studies that projected the impact of climate change on important food and cash crops in eight African countries, including Malawi. Using data synthesised from the studies, Adhikari et al. (2015) estimated yield losses of up to 13% for maize, 11% for rice, 7% for wheat, 34% for sorghum and 8% for soybean in Malawi by the 2090s relative to current levels.

However, using the DSSAT crop model and four GCMs, a study by Saka et al. (2012) projected maize yield increases in some parts of Malawi as a result of climate change. Under two of the GCMs, yield increases of between 5% and 25% were projected for the northern and central regions, with mixed results in the southern region (gains of more than 25% and losses of between 5% and 25% depending on the projected rainfall patterns). However, using the other two GCMs, DSSAT projected yield declines across most parts of Malawi, with the exception of the Shire Highlands in the south, which were projected to see increased yields of more than 25% by 2050. The yield increases projected for the northern and central regions were consistent with an earlier study by Thornton et al. (2009), which projected maize and bean crop yield changes in East Africa as a whole. The results of the Thornton et al. (2009) study are particularly noteworthy given that maize yields were projected to increase in Malawi despite an overall decrease in eastern Africa by 2050. Furthermore, a study by Stevens and Madani (2016) projected both increases and decreases in maize yields in Malawi as a result of climate change by 2050. Using the FAO's AquaCrop model, maize yield increases of between 4.6% and 5.4% were projected by the 2020s relative to a baseline period (1971–2000). These yield gains were attributed to the projected elevated atmospheric CO_2 concentrations and a marginal warming trend which could promote crop growth.

Using projections of future yield changes, some studies have attempted to quantify the future impact of climate change on food supply and resultant undernourishment in Malawi. For example, the aforementioned study by Saka et al. (2012) projected the change in numbers of malnourished children (under 5 years old) in Malawi by the 2050s, under multiple income and climate scenarios. Under a pessimistic scenario (i.e. high population growth, slow GDP growth and severe climate impacts), the number of malnourished children in Malawi was expected to increase from 850,000 in 2010 to around 1.15 million in 2030, and then gradually decline towards 2050. However, the dramatic increase in malnourishment from 2010 levels does not reflect the actual proportion of malnourished children, as population rises at a similar rate during those years. Under a more optimistic scenario (i.e. lower population growth, higher economic growth and less severe climate impacts), the number of malnourished children was expected to peak at around one million in 2030, and then decline rapidly towards 2050, falling to well below 2010 levels by the end of the century. The improvement towards the end of the century was due to the projected increase in calorie availability for the general population, reaching nearly 2,800 kcals capita^{-1} day^{-1} in the optimistic scenario by 2050. On the contrary, Stevens and Madani (2016) projected maize shortages in the Lilongwe district of Malawi by the 2080s. Yield reductions as a result of climate change, coupled with population growth, were expected to put between 0.1% and 12% of the population in Lilongwe at risk of food insecurity in the future.

1.2 | Rationale and research questions

This study aims to quantify the impact of climate and societal change on both food and nutrition security in Malawi. In order to move beyond the traditional focus on food security in terms of food supply quantity (dietary energy), we also examine quality of the food supply by including protein and key micronutrients in order to assess nutrition security. In this sense, the study extends the previous work by Hall et al. (2017) by using more recent climate and socioeconomic scenarios and assessing food supply quality (nutrient supplies) as opposed to just food quantity (undernourishment prevalence). Very few studies to date have examined the impact of climate change on future nutrient supplies as dietary energy intake remains the most common measure of food security, leading to a focus on staple crops. Yet, understanding the future impacts on a broad range of foods (as well as staple crops) is essential if micronutrient deficiencies, and their associated health risks are to be mitigated in the future. Indeed, the UN Sustainable Development Goals (SDGs) outline the aim to end hunger in all its forms—which includes both undernourishment and micronutrient deficiencies and their associated health problems. Given the already high rates of micronutrient deficiencies in Malawi, adverse climate change impacts could have serious nutritional consequences in the future.

Three key research questions are addressed in this study;

1. What is the potential impact of climate and societal change on the quantity of Malawi's food supply (and thus, undernourishment prevalence) under a range of future scenarios?
2. What is the potential impact of climate and societal change on the quality of Malawi's food supply (in terms of protein and micronutrients) under a range of future scenarios?
3. Could projected dietary changes help to mitigate the impacts of climate and societal change on the quantity and quality of Malawi's food supply?

2 | METHODS

2.1 | The FEEDME modelling framework

In order to assess the impact of future change on Malawi's national food supply, we used the Food Estimation and Export for Diet and Malnutrition Evaluation (FEEDME) modelling framework (Dawson et al., 2016). A detailed description of the FEEDME model is provided by Dawson et al. (2016) and Hall et al. (2017). In summary, the FEEDME model uses FAO food balance sheets (FBSs) (which provide estimates of food supply at the national level) in combination with the FAO methodology for estimating the prevalence of undernourishment. The country level statistics provided by FAOSTAT relating to food production, imports, exports, etc., can be varied within the FEEDME model depending on the research questions.

As the standard FBSs only provide estimates of dietary energy (kcals), protein and fat supply for each food commodity, this was extended to include estimates of micronutrients in order to project how the quality of Malawi's food supply might change in the future. It is important to emphasise that the intention of this study was to estimate the supply of nutrients at the national level. An estimation of consumption at the individual level is not possible using the FAO data. The data sets used to create the nutrient data set included the FAO trade data for the year 2010 (FAOSTAT, 2018), FAO production data for the year 2010 (FAOSTAT, 2018) and three food composition tables (FCTs) (Leung et al., 1968; Stadlmayr et al., 2012; USDA, 2014). The methodology used to estimate additional nutrients replicated that used by Macdiarmid et al. (2018), and is summarised in Figure 1. A detailed description of this methodology is provided in the Supplementary material (Section A). It is important to note that while we estimated nutrient supply, these values were adjusted to represent the edible amount (i.e. by subtracting inedible portions and household level waste) in order to avoid over-estimation of supply.

2.2 | Future scenarios

In order to quantify how climate and societal change might impact Malawi's food supply, we used crop yield projections under a range of socioeconomic and emissions scenarios as outlined by the International Food Policy Research Institute (IFPRI). While it is recognised that climate change will likely impact all dimensions of food security (availability, access, stability and utilisation of food), this study focuses on the availability dimension in terms of crop yields. We include a wide range of food crops in our analysis (including fruits and vegetables) in order to move beyond the focus on staple grains which are not always of significance at the more local level.

The crop yield changes for Malawi were based on a study by Wiebe et al. (2015) which examined the impacts of climate change on agriculture under a range of socioeconomic and emissions scenarios in 2050, relative to a 2010 baseline. Results for Malawi were provided for three scenarios which combined shared socioeconomic pathways (SSPs) with RCPs. The full range of SSPs are described by O'Neill et al. (2015) and Kriegler et al. (2012) and are intended to reflect how society might develop in the future in terms of demographics, economic development, technological development and policy change. RCPs describe four plausible future climate scenarios in terms of GHG emissions and radiative forcing (van Vuuren et al., 2011). Wiebe et al. (2015) combined each SSP with climate impacts for a unique RCP, based on the SSPs specific levels of emission mitigation efforts. Results for Malawi were provided for three scenarios: SSP1 with RCP 4.5, SSP2 with RCP 6 and SSP3 with RCP 8.5. The first of these can be described as an optimistic scenario as it assumes low population growth and high levels of economic growth, education, governance, globalisation, technological development and international cooperation (O'Neill et al., 2015) as well as the less severe climate impacts of RCP 4.5. The second scenario is a middle-of-the-road scenario as it assumes moderate population and economic growth as well as technological development, but with considerable heterogeneities between and within countries (O'Neill et al., 2015). Likewise, it is combined with the moderate emissions scenario RCP 6.0. The third scenario is a pessimistic scenario that assumes very high levels of population growth, low economic growth, low levels of environmental awareness and a push towards nationalism (O'Neill et al., 2015). This pessimistic socioeconomic pathway is combined with the severe emissions pathway RCP 8.5. A detailed description of how the crop yield projections were calculated is provided by Wiebe et al. (2015).

2.3 | Modelling the impacts on food and nutrient supply

The socioeconomic assumptions of the alternative future scenarios are embedded within the crop yield changes which were added into the FEEDME model, with the exception of population growth which was adjusted manually for each scenario. All food commodities in the FBSs were first assigned to one of eight reference crops (wheat, maize, rice, soybean, sugarcane, groundnuts, sunflower seed and other oilseeds) as presented by Wiebe et al. (2015). Given

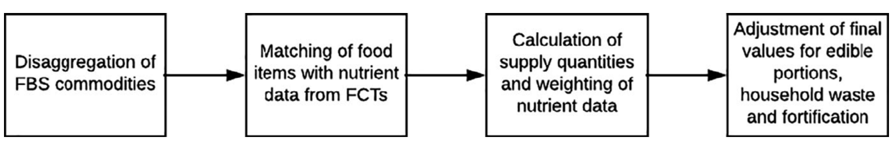

FIGURE 1 Flow chart summarising the methods used to update the standard FBSs with additional nutrient data

that the FBSs comprise 91 food commodities, all foods were mapped to one of the eight reference crops, or a 'meat' or 'aquatic' category. Food commodities were mapped to the reference crops using information provided by van Meijl et al. (2018) (Table S1 in the Supplementary material). While some food commodities were simply mapped to a reference crop that directly described them (i.e. wheat was mapped to wheat), the majority of food commodities were mapped to a 'generic' C3 crop (an average of wheat, rice and soybeans) in line with van Meijl et al. (2018). This is because no reference crop directly related to any of these commodities, and so an average was a best estimate of how climate change will affect them, for example all fruits and vegetables were mapped to this 'generic' crop. 'No change' was assumed for sweeteners, honey, wine, beer, fermented beverages and alcoholic beverages as no climate change estimates could be sourced for these items. 'No change' was also assumed for all meat and aquatic products because climate and socioeconomic impacts on these commodities are very uncertain. Once all of the FBS commodities were mapped to a reference crop or a 'no change' category, the FEEDME model was updated in order that yield changes of the reference crops would adjust the food supply values for all corresponding commodities.

2.4 | Estimating undernourishment prevalence and the quality of the food supply

Prevalence of undernourishment was estimated using the FAO measure of food deprivation (FAO, 2002) by comparing estimated energy supply (kcals capita^{-1} day^{-1}) with a per capita minimum daily energy requirement (MDER) value for Malawi. The MDER value for the baseline period of 2010 was extracted from the FAO statistics division (1,730 kcals capita^{-1} day^{-1}). A MDER was also calculated for the year 2050 in order to account for projected changes to population structure between 2010 and 2050 (1,807 kcals capita^{-1} day^{-1}). Protein adequacy was calculated by comparing the supply at the per capita level (from FBSs) with recommended intakes which were calculated using the FAO et al. (1981) report on human energy and protein requirements. A weighted average was calculated based on requirements of different age and sex groups in the population (including a pregnancy allowance) to give an average per capita requirement (similar to the MDER).

In order to estimate the adequacy of iron, zinc and vitamin A supplies in 2050, recommended nutrient intakes for each micronutrient were sourced from WHO (2004). For iron, a low bioavailability factor of 5% was assumed as Malawian diets are typically low in animal sources of iron (i.e. haem iron from animal products have a higher bioavailability than non-haem iron from plant-based foods) (IOM, 2001). Likewise, a low bioavailability factor of 15% was assumed for zinc as Malawian diets are predominately plant-based foods, which are high in phytates known to inhibit zinc absorption (Manary et al., 2000). Assuming low bioavailability results in a higher required intake. For vitamin A, 'recommended safe intake' values were used as the indicator of adequate supply (WHO, 2004). To calculate the extent of nutrient adequacy in the baseline period and the future scenarios, nutrient requirements were compared with the supply, and a percentage deficit or surplus was calculated for each nutrient. Energy and nutrient requirements in the 2010 baseline scenario are different from requirements in the 2050 scenarios due to the different population structures which were factored into all of the requirement estimates.

2.5 | The impact of dietary change

Malawi is expected to experience continued nutrition transition over the coming decades, whereby diets shift away from traditional starchy staples towards higher value commodities, such as animal products and processed foods (Popkin et al., 2012; Robinson et al., 2015). In order to assess the impact of these projected changes on future nutrient supplies, food supply estimates from a study by Wiebe et al. (2017) were incorporated into the FEEDME model for six major food groups: cereals, meat, fruits and vegetables, oilseeds, pulses, and roots and tubers. Dietary change projections for Malawi were extracted from the IFPRI IMPACT database (https://dataverse.harvard.edu/dataverse/impact) for a 2050 scenario that combined SSP2 with RCP 8.5 (HadGEM GCM). In the FEEDME model, the SSP2/RCP 6 scenario was used as a baseline from which to adjust the supply quantities to account for dietary change as both scenarios shared the SSP2 scenario family. Thus, the future scenario with dietary change was compared against the future scenario that assumed diets remained the same as in 2010. Despite the fact the dietary change scenario assumed RCP 8.5 climate impacts (as opposed to RCP 6.0 as these data were not available); the two scenarios were felt to be comparable as both sets of projections are quite severe.

3 | RESULTS

Projected yield changes of all reference crops are displayed in Table 1. Values represent the percentage yield gains (+) or losses (−) between the 2010 baseline and 2050 under the three future scenarios. Total yield gains were highest in the SSP1/RCP4.5 scenario and lowest in the SSP3/RCP 8.5 scenario in line with expectations. Although not shown in the results, the three future scenarios were first examined in the absence of climate change in order to assess the relative impact. In each scenario, the addition of climate change reduced the yields of most crops. However, this was not the case for maize and sugarcane yields which increased as a result of the addition of climate change. This is because temperature and precipitation changes as a result of climate change were expected to create more favourable growing conditions for these crops in Malawi. For example, the additional yield gains in maize that can be attributed to climate change were 31%, 30% and 32% in the SSP1, SSP2 and SSP3 scenarios, respectively. Similarly, the additional gains in sugarcane associated with climate change were 14%, 12% and 11% in the SSP1, SSP2 and SSP3 scenarios, respectively.

Estimated supplies and population-level requirements of energy, protein, and micronutrients for the baseline period and future scenarios are summarised in Table 2. As expected and in line with the projected yield changes, energy and nutrient supplies were highest in the SSP1 scenario and lowest in the SSP3 scenario. Estimated supplies of energy, protein, iron and zinc were higher in the SSP1 scenario than the 2010 baseline, whereas vitamin A supplies were lower than the baseline. Energy and nutrient supplies in the SSP2 and SSP3 scenarios were all lower than the 2010 baseline. Thus, despite the considerable yield increases projected for some crops between 2010 and 2050, per capita supply of energy and nutrients actually decreases in the SSP2 and SSP3 scenarios, largely due to population growth which offsets increases in supply. It should also be noted that while average supplies of energy and nutrients were higher than the requirement in some scenarios, this does not take into consideration the unequal distribution of national food supplies and people's access to food.

Using the projected energy supplies provided in Table 2, as well as a gini coefficient which accounts (to some extent) for inequalities in food distribution in Malawi, projected undernourishment prevalence in the baseline and future scenarios is illustrated in Figure 2. Undernourishment prevalence in 2010 was estimated at 12%, which was around 5% lower than the FAO estimate for the same period (17.3%) (FAOSTAT, 2020). This was due to the higher average energy supply estimated for the baseline period (Table 2). Of the future scenarios, undernourishment risk was lowest in the SSP1 scenario (5.1%), followed by the SSP2 scenario (30.8%), and was highest in the SSP3 scenario (62.4%).

Protein and micronutrient adequacy in the baseline scenario and three future scenarios is illustrated in Figure 3. Values represent the percentage difference between the per capita supply and requirement of each nutrient. Protein supplies were adequate in all scenarios. Supplies of iron, zinc and vitamin A were inadequate in all scenarios, with the exception of zinc in the SSP1 scenario.

The impact of dietary change on the supply of the six food groups is shown in Table 3. Supply of cereals and roots and tubers are projected to decrease as a result of future dietary change, while supply of meat, fruits and vegetables, oilseeds and pulses are expected to increase. Meat and fruits and vegetables are projected to experience the highest increases, at 130% and 61%, respectively.

The effect of dietary change on per capita food supply is summarised in Figure 4. The scenario with dietary change resulted in slightly less but adequate energy supply and adequate and slightly greater protein supply, although the changes were marginal in both cases (−1% and +2%, respectively). Dietary change made very little difference to the extent of iron and zinc inadequacy, leading to a reduction of less

TABLE 1 Percentage change in yields of all reference crops from the 2010 baseline period to 2050 under each future scenario

	SSP1/RCP 4.5	SSP2/ RCP 6	SSP3/ RCP 8.5
Groundnuts	+12.9	+1.7	−5.8
Maize	+159.1	+128.7	+114.5
Rice	+89.6	+71.5	+62.9
Sunflower seed	+3.6	−7.6	−11.4
Soybean	−3.2	−20.7	−25.9
Sugarcane	+23.5	+16.7	+10.1
Other oilseeds	+2.8	−4.7	−9.9
Wheat	+56.5	+33.1	+23.8

TABLE 2 Estimated supplies and requirements of energy, protein and micronutrients capita^{-1} day^{-1} in the baseline scenario and the three future scenarios

	2010		2050			
	Supply	Requirement	Supply (SSP1/ RCP 4.5)	Supply (SSP2/ RCP 6)	Supply (SSP3/ RCP 8.5)	Requirement
Dietary energy (kcals capita^{-1} day^{-1})	2,604.8	1,730.0	3,163.5	2,218.7	1,718.3	1,807.0
Protein (g capita^{-1} day^{-1})	64.6	36.3	77.6	54.7	42.5	39.0
Iron (mg capita^{-1} day^{-1})	23.9	33.0	28.7	20.1	15.5	34.3
Zinc (mg capita^{-1} day^{-1})	10.8	12.0	13.3	9.3	7.2	12.2
Vitamin A (RAE μg capita^{-1} day^{-1})	468.3	534.9	366.2	248.9	191.9	542.7

than 1% in both cases. Extent of vitamin A inadequacy was reduced by 11%. Thus, despite the projected increase in the supply of foods that are high in micronutrients (mainly meat and fruits and vegetables), dietary change did not increase supply of micronutrients enough to meet population-level minimum requirements.

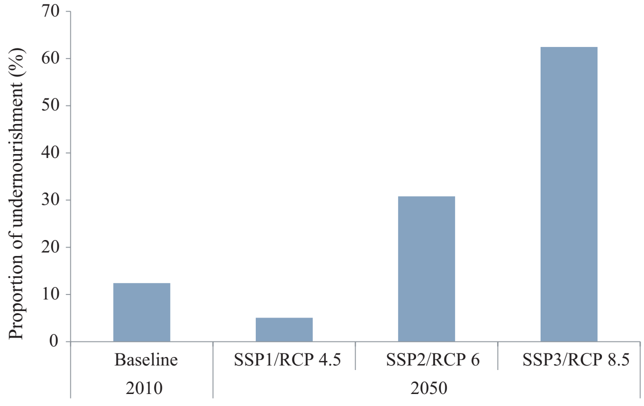

FIGURE 2 Estimated proportion of undernourishment in Malawi (% of total population) as simulated by the FEEMDE model for the baseline scenario and the three future scenarios

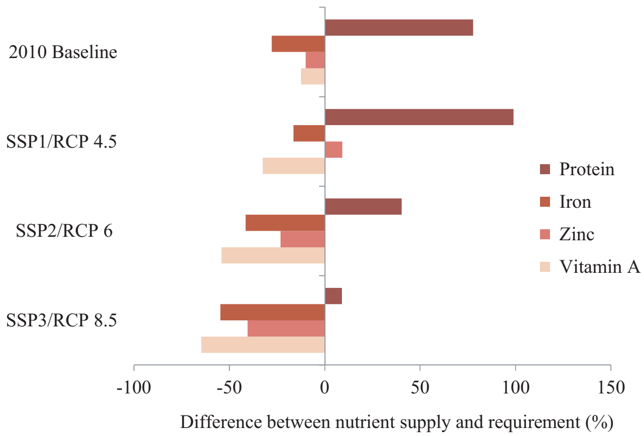

FIGURE 3 Estimated nutrient adequacy in the baseline and future scenarios. Values represent the percentage difference between supply and requirement of each nutrient (capita^{-1} day^{-1})

The proportion of energy, protein and micronutrients supplied by each food group in the future scenarios with and without dietary change is displayed in Figure 5. In both scenarios, cereals provided the majority of dietary energy, protein and micronutrients, except for vitamin A which was mostly supplied by roots and tubers, followed by fruits and vegetables and then meat. Due to the projected reduction in cereal supply as a result of dietary change, the share of nutrients provided by cereals was lower in the dietary change scenario compared to the baseline future scenario. Similarly, the projected reduction in roots and tubers supply as a result of dietary change reduced the quantity of vitamin A supplied by this food group from 57% to 43%. The other nutrients were largely unaffected by the change in the supply of roots and tubers. Dietary change resulted in a marginal increase in the percent supply of nutrients from pulses and oilseeds, while fruits and vegetables and meat contribute considerably more nutrients as a result of dietary change (due to the substantial increase in supply of these foods). Indeed, the percent contribution of meat to vitamin A supply doubled as a result of dietary change.

4 | DISCUSSION

4.1 | Undernourishment and micronutrient adequacy in the future scenarios

The results of this study suggest that food and nutrition security could be considerably worsened in Malawi depending on how the world develops over the coming decades. Undernourishment prevalence could be reduced (relative to 2010 levels) if the world develops in line with the SSP1 scenario. Under the SSP2 and SSP3 scenarios, undernourishment was estimated to be considerably higher than 2010 levels despite the projected increases in yields of major crops. This is due to more pessimistic socioeconomic and climate projections in these scenarios.

While energy and protein supplies exceeded requirements in all scenarios (except energy in SSP3), micronutrient supplies were inadequate in all scenarios (with the exception

TABLE 3 Change in the supply quantities (g capita^{-1} day^{-1}) of six different food commodities as a result of projected dietary change by 2050

	Supply quantities in 2050 assuming no dietary change (g capita^{-1} day^{-1})	Revised supply quantities in 2050 as a result of dietary change (g capita^{-1} day^{-1})
Cereals	467.4	444.7
Meat	9.3	21.4
Fruits & vegetables	113.3	182.5
Oilseeds	9.6	10.5
Pulses	16.2	19.2
Roots & tubers	340.5	320.8

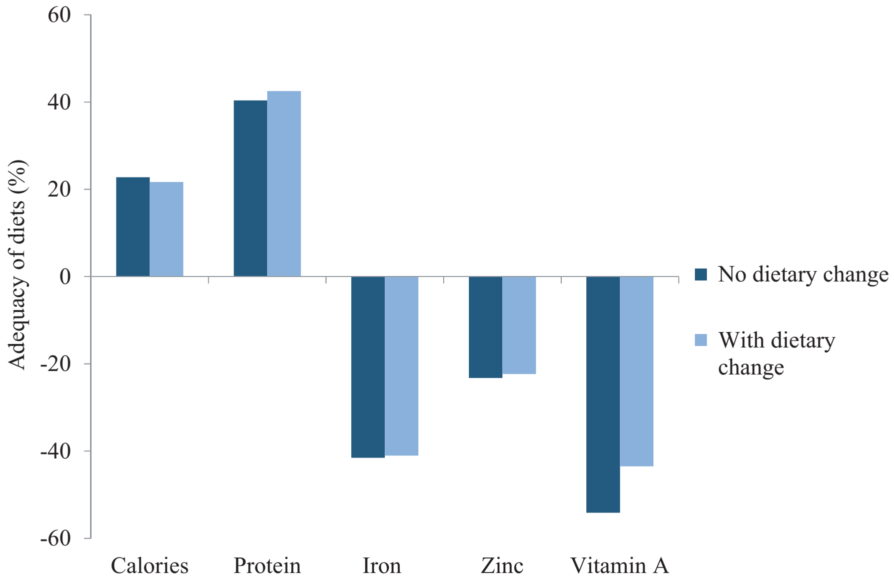

FIGURE 4 Percentage adequacy of per capita food supply with and without dietary change assumptions

of zinc in SSP1). What is particularly noteworthy is that in SSP1, even when energy supply was more than 1,000 kcals higher than the MDER and protein supply more than double the requirement, supplies of iron and vitamin A were still inadequate. These results emphasise (a) the need to move beyond focusing on energy supply (and possibly protein supply) as a measure of food security as adequate energy supply does not ensure a nutritious food supply, and (b) the importance of dietary diversity which is correlated with micronutrient intake (Galway et al., 2018; Johnson et al., 2013; Jones et al., 2014). Malawian diets remain heavily dominated by maize and lack diversity. Thus, the inadequate supplies of iron, zinc and vitamin A can be attributed to the already low levels of these nutrients in Malawi's food supply (i.e. all three were inadequate in the 2010 baseline scenario). Similarly, the major yield gains assumed for maize and sugarcane helped to mitigate undernourishment to some extent due to the provision of energy, but did not alleviate micronutrient inadequacy as these crops are low in the micronutrients of interest. Supplies of foods that are more micronutrient dense (fruits and vegetables, roots and tubers, and animal products) were not projected to increase sufficiently to meet requirements by 2050.

It should be noted that our estimate of undernourishment prevalence in the baseline scenario was not in line with the FAO estimate for the same year. This is due to the higher average calorie supply estimate for the baseline period (our estimate was 2,605 kcals, while the FAO's was 2,405 kcals). The higher overall calorie supply was predominantly due to two commodities: cassava and potatoes. Values for these commodities were estimated using the West African composition tables, which were the best available data source for Malawi (compared to the USDA tables for example, it is not clear which composition tables the FAO used). Given our baseline undernourishment estimates were lower than the FAOs, this could mean that our future projections err on the optimistic side, whereas if the FAO baseline had been used, future undernourishment would likely have been more severe. This should be considered when interpreting the results.

As was explained briefly in the results, climate change is expected to increase yields of maize and sugarcane relative to the same future scenarios in the absence of climate change (outlined in detail by Wiebe et al., 2015). This is because for those climate scenarios as modelled by the HadGEM GCM, projected changes in temperature and precipitation in Malawi are favourable for those crops. Indeed, maize yields in the scenarios with climate change are approximately 30% higher than the scenarios without climate change. Given that maize makes up a large proportion of the diet in Malawi and therefore provides a large majority of key nutrients (despite not being a micronutrient dense food), that is 45% of total calories, 45% of total protein, 44% of iron and 43% of zinc, projected yield increases have positive nutritional ramifications. Maize is very low in vitamin A, hence why the projected yield increases do not improve vitamin A supply. Indeed, vitamin A supply is decreased by the impacts of climate change due the reduction in yields of nutrient-dense crops (such as fruits and vegetables and edible oils which are important sources of vitamin A).

The impact of climate change on maize yields has been well studied; however, projections vary widely depending on the GCMs, crop models and climate scenarios used. While GCMs converge well at the global scale, they tend to show wide variation at more local scales (Connolley & Bracegirdle, 2007; Schmittner et al., 2005; Whetton et al., 2007; Giorgi & Mearns, 2003). There are a number of studies that suggest maize yields will decrease as a result of climate change in the future (Lobell et al., 2011; Lobell & Field, 2007; Schlenker & Roberts, 2009). However, it is important to note that many of these studies only consider the biophysical yield shocks caused by temperature and

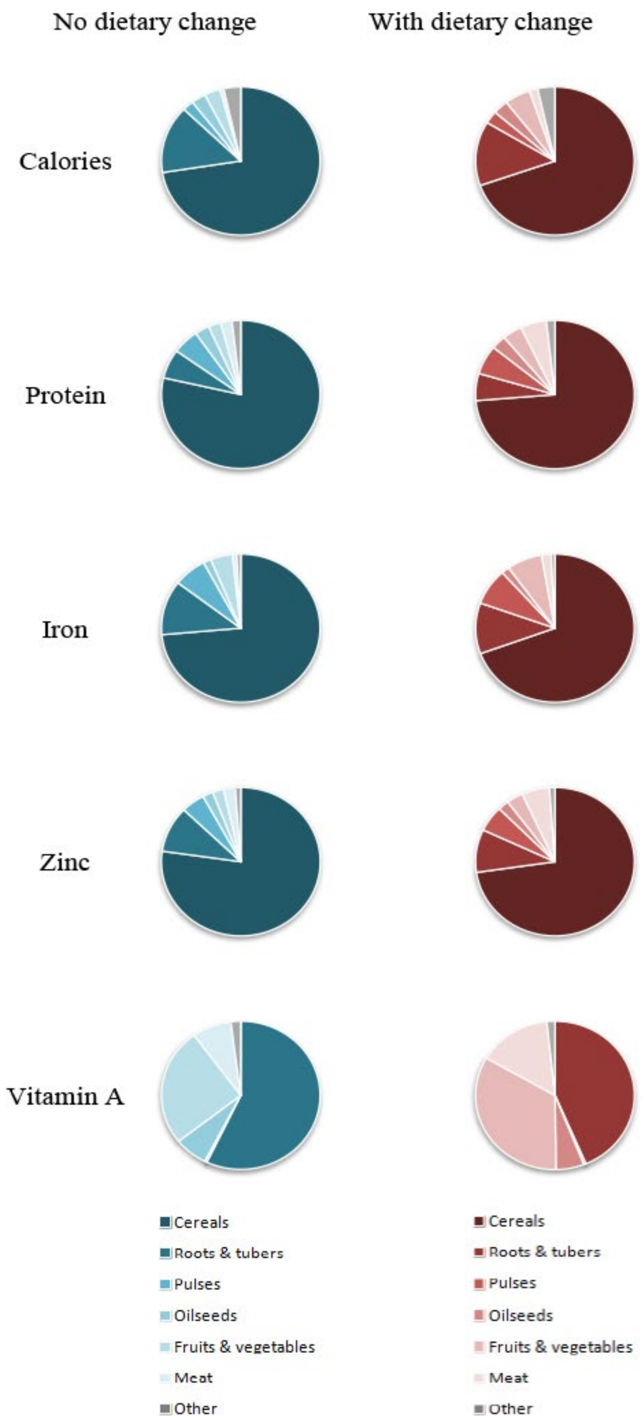

FIGURE 5 The proportion (% of total) of dietary energy and nutrients supplied by each food group in the future scenarios with and without dietary change

precipitation changes, whereas the yield projections used in this study also considered factors such as food prices, trade and market responses which affected final yield projections. In a study by Thornton et al. (2009), some yield gains in maize were projected in East Africa using the SRES A1FI and B1 storylines and HADCM3 and ECHam4 models. Using the same storylines and GCMs, Thornton et al. (2010) projected maize yield gains in Kenya and Rwanda of 15% and 11% by 2030, respectively, and 18% and 15% by 2050, respectively. Yield gains were attributed to increases in temperature in these areas which resulted in optimal growing conditions. However, yield losses were projected for some countries (Tanzania and Uganda) which were attributed to projected temperature increases higher than optimal growing conditions for maize. Thus, the yield projections used in this study are consistent with some studies in the wider literature, despite considerable variation between methods and models used which makes comparison difficult.

4.2 | The impact of dietary change

The results of this study suggest that projected future dietary change in Malawi will not increase the supply of micronutrients enough to meet per capita requirements in 2050. This can be explained by the fact that supply quantities of micronutrient dense foods were already very low in the 'no dietary change' 2050 scenario. For example, in this baseline scenario, estimated meat supply in Malawi was 9.3 g capita^{-1} day^{-1}, down from an estimated 20.5 g capita^{-1} day^{-1} in 2010 (due to population growth). Dietary change was projected to increase supply to 21.0 g capita^{-1} day^{-1}, which was only 0.5 g higher than 2010 levels. To put these figures into perspective, in 2010, meat supply in the UK was estimated at 222 g capita^{-1} day^{-1}, while in the United States, this figure was 326 g capita^{-1} day^{-1} (FAOSTAT, 2019). Indeed, animal-source foods make up a much larger proportion of the diet in developed countries than in SSA countries. Global average meat supply was estimated at 108 g capita^{-1} day^{-1} in 2010 and is projected to increase to 136 g capita^{-1} day^{-1} by 2050 assuming SSP2 in the absence of climate change (IFPRI, 2017). Similarly, average meat supply in Africa was estimated at 40 g capita^{-1} day^{-1} in 2010, which is projected to increase to 78 g capita^{-1} day^{-1} by 2050 (again assuming SSP2 in the absence of climate change (IFPRI, 2017)). Thus, even with dietary change, per capita meat supply in Malawi is projected to be 6.5 times lower than the global average and 3.7 times lower than the African average in the year 2050.

The same point can be made for other micronutrient dense foods such as fruits and vegetables. For example, in the baseline scenario, supply of fruits and vegetables was estimated at 134 g capita^{-1} day^{-1} with WHO recommendations being 400 g day^{-1} (FAOSTAT, 2019). Proposed dietary change only increased this to 182.5 g capita^{-1} day^{-1} which is still less than half the recommended intake. Thus, while the higher supply of these foods in the dietary change scenario does improve the quality of the food supply to some extent, it is an insufficient increase to meet minimum requirements. Again, this emphasises the need to improve dietary diversity in Malawi as even in the dietary change scenario the food supply is dominated by cereals.

4.3 | Implications and recommendations

This study has addressed a key gap in the literature by projecting the impact of climate change on not only food supply quantity, but also food supply quality. Only a limited number of other studies have extended the FBS data to address the nutrient adequacy of food supplies (e.g. Ritchie et al., 2018; Schmidhuber et al., 2018; Smith et al., 2016; Wuehler et al., 2005). Even fewer studies have projected how micronutrient supplies could be affected by future climate and socioeconomic change (apart from, e.g. Nelson et al., 2018). Thus, this study serves to highlight the importance of moving beyond the focus on dietary energy (and protein) in assessments of food and nutrition security, as our results demonstrate that even when energy and protein are adequate, the overall quality of the food supply could be inadequate in terms of nutrients. The results of this study suggest that micronutrient supply could be more problematic in future than energy and protein. This is particularly important for developing countries such as Malawi which already suffer from very high levels of micronutrient deficiencies. However, the results have far-reaching implications as this issue will not be limited to Malawi alone.

Our results also highlight the need for society to work towards a future in line with the SSP1 scenario, and avoid a future in line with SSP3, given the much worse projections for food and nutrition security. Given the already high rates of undernourishment and malnutrition in Malawi, and the possible worsening of the situation over the coming decades, strategies to improve food and nutrition security are a priority. Indeed, our results highlight the need for the agricultural and human health sectors to work together when working to achieve food and nutrition goals. In national development agendas, food security is very often a key priority for agricultural policies, but nutritional issues (such as stunting and wasting) are considered a health issue (Aberman et al., 2018). This lack of nutritional consideration within agricultural systems can be considered one of the main causes of food insecurity and malnutrition in today's society (Welch et al., 2013). The merging of these two sectors is likely to be essential in order to achieve the second SDG to end hunger 'in all its forms', including undernourishment and micronutrient deficiencies.

4.4 | Limitations

There are some key limitations that are important to consider when interpreting the results of this study. Firstly, it is important to emphasise that this study only addresses food supply (in terms of quantity and quality) and does not inform about actual food consumption or micronutrient deficiencies at the individual level. Rather, this study focuses on what is available at the national level which is important as this forms the basis of achieving food security (having adequate, nutritious food available). Thus, people's ability to access food and properly utilise nutrients is not accounted for. Similarly, using the FAO data it is not possible to inform about the distribution of food at the sub-national level. Thus, while we can apply the national supply data at the household level, these are average values which assume all households have equal supply of available food. The FAO undernourishment methodology takes distribution into account to some extent when looking at the supply of energy (using a gini coefficient) but this is not accounted for when looking at protein or micronutrients. It is also important to note that micronutrient deficiencies have multiple causes aside from just dietary (i.e. disease) which could not be accounted for in this study. Despite these limitations, assessing the change in food supply quantity and quality under different future scenarios is useful as without an adequate food supply, adequate consumption and effective utilisation is not possible.

There are some additional limitations of the FBS data and the FAO methodology for estimating undernourishment prevalence. Both over- and under-estimation of undernourishment can occur for different reasons, such as inaccuracies in the FBS data which will be time and country specific, and the sensitivity of the FAO measure to the exogenous parameters used (i.e. the mean calorie supply, MDER cut-off point and measure of inequality in access) (de Haen et al., 2011; Svedberg, 2000). In this study, is it possible that calorie and nutrient supplies were under-estimated as FAO production statistics are mostly confined to major, commercialised crops and can often miss subsistence level production, which in Malawi is likely to be an appreciable part of overall production. Despite these limitations, the FAO data remain the only food security indicator with a global coverage that allows for comparison between countries and within countries over time using a consistent methodology. While finer scale data such as household surveys provide more detail and can be used to identify sub-national trends, these are expensive and time-consuming, and variation in methodologies and survey techniques make comparison between countries difficult. In addition, given the yield impact data used in this study represented the projected impacts at the country level, applying these changes to the finer scale food consumption data would not have matched as well.

There are also uncertainties related to the future crop yield estimates. For example, the yield projections do not account for the effects of CO_2 fertilisation as the effect on crop yields is still highly uncertain as is discussed widely in the literature (Long et al., 2006; Tubiello et al., 2007; Wang et al., 2012). In this sense, the yield results may err on the pessimistic side as potential yield increases as a result of CO_2 are not accounted for. On the other hand, it could be argued that the yield projections err on the optimistic side as some potentially negative effects of climate change were unaccounted for. For example, extreme climatic events (such as floods and droughts), changes in pests and diseases, and changes in ozone levels were not captured by the crop models and GCM inputs used to produce the yield projections (Wiebe et al., 2015).

It is also important to note that while this study only included three micronutrients (as they are the most commonly deficient in Malawi and many other countries and are thus a focus of the WHO) there are several other micronutrients essential for health that have not been included in this study that are critical for nutrition security. Future studies should aim to include a wide range of micronutrients in order to ensure a holistic approach is taken for nutrition security.

Lastly, while some effects of trade are embedded in the crop yield estimates, trade changes to other commodities were not included which may influence the nature of the future food supply.

5 | CONCLUSIONS

The findings of this study suggest that future climate and societal change could have serious negative consequences for food and nutrition security in Malawi, depending on how the world develops. Our results show that undernourishment could be improved relative to baseline levels under an optimistic scenario, but could be worsened assuming higher population growth, lower economic growth and more severe climate impacts. Even under the optimistic scenario with very high supplies of energy and protein, micronutrient supplies were largely inadequate. Indeed, proposed dietary change in the form of nutrition transition did not increase micronutrient dense foods sufficiently to meet requirements. These results therefore highlight the importance of diversifying diets in Malawi (and indeed, other countries with similar nutritional problems) as well as moving beyond the focus on dietary energy as a measure of food security, as dietary quality in the form of micronutrient intake may be more problematic in the future.

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REFERENCES
Aberman, N. L., Meerman, J., & Benson, T. (2018). *Agriculture, food security, and nutrition in Malawi: Leveraging the links*. Food Policy Report. International Food Policy Research Institute. Washington, D.C. https://doi.org/10.2499/9780896292864

Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of impact on major crops. *Food and Energy Security*, *4*(2), 110–132. https://doi.org/10.1002/fes3.61

Connolley, W. M., & Bracegirdle, T. J. (2007). An Antarctic assessment of IPCC AR4 coupled models. *Geophysical Research Letters*, *34*(22), L22505. https://doi.org/10.1029/2007GL031648

Dawson, T. P., Perryman, A. H., & Osborne, T. M. (2016). Modelling impacts of climate change on global food security. *Climatic Change*, *134*, 429–440. https://doi.org/10.1007/s10584-014-1277-y

De Haen, H., Klasen, S., & Qaim, M. (2011). What do we really know? Metrics for food insecurity and undernutrition. *Food Policy*, *36*(6), 760–769. https://doi.org/10.1016/j.foodpol.2011.08.003

Devereux, S. (2002). *State of disaster: Causes, consequences & policy lessons from Malawi*. An ActionAid Report Commissioned by ActionAid Malawi. Retrieved from https://www.alnap.org/system/files/content/resource/files/main/113-1-state-of-disaster.pdf

FAO (2002). *Measurement and Assessment of Food Deprivation and Undernutrition*. International Scientific Symposium. Food and Agriculture Organisation of the United Nations, Rome. Retrieved from http://www.fao.org/3/y4249e/y4249e00.htm

FAO, IFAD, UNICEF, WFP and WHO (2018). *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition*. Food and Agriculture Organisation of the United Nations, Rome. Retrieved from http://www.fao.org/state-of-food-security-nutrition/en/.

FAO, WHO and UNU (1981). *Energy and protein requirements: Report of a Joint FAO/WHO/UNU Expert Consultation* [held in Rome from 5 to 17 October 1981]. World Health Organization. Retrieved from https://apps.who.int/iris/handle/10665/39527

FAOSTAT (2018). *FAO Statistical Database – FAOSTAT*. Retrieved from http://faostat.fao.org/.

FAOSTAT (2019). *FAO Statistical Database – FAOSTAT*. Retrieved from http://faostat.fao.org/.

FAOSTAT (2020). *FAO Statistical Database – FAOSTAT*. Retrieved from http://faostat.fao.org/.

Fisher, M., & Lewin, P. A. (2013). Household, community, and policy determinants of food insecurity in rural Malawi. *Development Southern Africa*, *30*(4–5), 451–467. https://doi.org/10.1080/0376835X.2013.830966

Galway, L. P., Acharya, Y., & Jones, A. D. (2018). Deforestation and child diet diversity: A geospatial analysis of 15 Sub-Saharan African countries. *Health and Place*, *51*, 78–88. https://doi.org/10.1016/j.healthplace.2018.03.002

Giorgi, F., & Mearns, L. O. (2003). Probability of regional climate change based on the Reliability Ensemble Averaging (REA) method. *Geophysical Research Letters*, *30*, 1629. https://doi.org/10.1029/2003GL017130

Hajdu, F., Ansell, N., Robson, E., van Blerk, L., & Chipeta, L. (2009). Socio-economic causes of food insecurity in Malawi. *Society of Malawi Journal*, *62*(2), 6–18.Retrieved from https://www.jstor.org/stable/29779290?seq=1#page_scan_tab_contents.

Hall, C., Dawson, T. P., Macdiarmid, J. I., Matthews, R. B., & Smith, P. (2017). The impact of population growth and climate change on food security in Africa: Looking ahead to 2050. *International Journal of Agricultural Sustainability*, *15*(2), 124–135. https://doi.org/10.1080/14735903.2017.1293929

IFPRI (2017). *Global Food Policy Report*. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896292529

IOM (2001). *DRI Dietary Reference Intakes: Applications in Dietary Assessment*. Food and Nutrition Board, Institute of Medicine. National Academy Press. Washington, D.C. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25057725.

Johnson, K. B., Jacob, A., & Brown, M. E. (2013). Forest cover associated with improved child health and nutrition: Evidence from the Malawi Demographic and Health Survey and satellite data. *Global Health: Science and Practice*, *1*(2), 237–248. https://doi.org/10.9745/GHSP-D-13-00055

Jones, A. D., Shrinivas, A., & Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food Policy*, *46*, 1–12. https://doi.org/10.1016/j.foodpol.2014.02.0010306-9192

Kotir, J. H. (2011). Climate change and variability in Sub-Saharan Africa: A review of current and future trends and impacts on agriculture and food security. *Environment, Development and Sustainability*, *13*(3), 587–605. https://doi.org/10.1007/s10668-010-9278-0

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., & Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, *22*(4), 807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005

Leung, T. W., Busson, F., & Jardin, C. (1968). *Food Composition Table for Use in Africa*. Food and Agriculture Organisation of the United Nations, Rome. Retrieved from https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GNFVTT

Lobell, D. B., Bänziger, M., Magorokosho, C., & Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, *1*(1), 42. https://doi.org/10.1038/nclimate1043

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, *2*(1), 014002. https://doi.org/10.1088/1748-9326/2/1/014002

Long, S. P., Ainsworth, E. A., Leakey, A. D. B., Nosberger, J., & Ort, D. R. (2006). Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. *Science*, *312*, 1918–1921. https://doi.org/10.1126/science.1114722

Macdiarmid, J. I., Clark, H., Whybrow, S., De Ruiter, H., & McNeill, G. (2018). Assessing national nutrition security: The UK reliance on imports to meet population energy and nutrient recommendations. *PLoS One*, *13*(2), https://doi.org/10.1371/journal.pone.0192649

Manary, M. J., Hotz, C., Krebs, N. F., Gibson, R. S., Westcott, J. E., Arnold, T., Broadhead, R. L., & Hambidge, K. M. (2000). Dietary phytate reduction improves zinc absorption in Malawian children recovering from tuberculosis but not in well children. *The Journal of Nutrition*, *130*(12), 2959–2964. https://doi.org/10.1093/jn/130.12.2959

Mittal, N., Vincent, K., Conway, D., Archer van Gerderen, E., Pardoe, J., Todd, M., & Mkwambisi, D. (2017). *Future climate projections for Malawi*. Country Climate Brief. Climate and Development Knowledge Network. Retrieved from http://www.lse.ac.uk/GranthamInstitute/publication/future-climate-projections-for-malawi/.

Muthayya, S., Rah, J. H., Sugimoto, J. D., Roos, F. F., Kraemer, K., & Black, R. E. (2013). The global hidden hunger indices and maps: An advocacy tool for action. *PLoS One*, *8*(6), e67860. https://doi.org/10.1371/journal.pone.0067860

Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., Dangour, A. D., & Huybers, P. (2017). Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, *38*, 259–277. https://doi.org/10.1146/annurev-publhealth-031816-044356

Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T. B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., & Rosegrant, M. (2018). Income growth and climate change effects on global nutrition security to mid-century. *Nature Sustainability*, *1*(12), 773–781. https://doi.org/10.1038/s41893-018-0192-z

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Popkin, B. M., Adair, L. S., & Ng, S. W. (2012). Global nutrition transition and the pandemic of obesity in developing countries. *Nutrition Reviews*, *70*(1), 3–21. https://doi.org/10.1111/j.1753-4887.2011.00456.x

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS One*, *14*(5), e0217148. https://doi.org/10.1371/journal.pone.0217148

Ritchie, H., Reay, D. S., & Higgins, P. (2018). Beyond calories: A holistic assessment of the global food system. *Frontiers in Sustainable Food Systems*, *2*, 57. https://doi.org/10.3389/fsufs.2018.00057

Robinson, S., Mason-D'Croz, D., Sulser, T., Islam, S., Robertson, R., Zhu, T., Gueneau, A., Pitois, G., & Rosegrant, M. W. (2015). The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3. Discussion Paper 01483, The International Food Policy Research Institute, Washington, D.C. Retrieved from http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825

Sahley, C., Groelsema, B., Marchione, T., & Nelson, D. (2005). *The governance dimensions of food security in Malawi*. Southern African Regional Policy Network. Retrieved from https://sarpn.org/documents/d0001649/P1998-USAID_Malawi_Sept2005.pdf

Saka, J. D. K., Siable, P., Hachigonta, S., Sibanda, L. M., & Thomas, T. S. (2012). Chapter 5 – Malawi. In S. Hachigonta, G. C. Nelson, T. S. Thomas, & L. M. Sibanda (Eds.), *Southern African agriculture and climate change: A comprehensive analysis.*. International Food Policy Research Institute. Retrieved from http://www.ifpri.org/publication/southern-african-agriculture-and-climate-change-comprehensive-analysis

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(37), 15594–15598. https://doi.org/10.1073/pnas.0906865106

Schmidhuber, J., Sur, P., Fay, K., Huntley, B., Salama, J., Lee, A., & Afshin, A. (2018). The Global Nutrient Database: Availability of macronutrients and micronutrients in 195 countries from 1980 to 2013. *The Lancet Planetary Health*, *2*(8), e353–e368. https://doi.org/10.1016/S2542-5196(18)30170-0

Schmittner, A., Latif, M., & Schneider, B. (2005). Model projections of the North Atlantic thermohaline circulation for the 21st century, assessed by observations. *Geophysical Research Letters*, *32*, L23710. https://doi.org/10.1029/2005GL024368

Smith, M. R., Micha, R., Golden, C. D., Mozaffarian, D., & Myers, S. S. (2016). Global Expanded Nutrient Supply (GENuS) model: A new method for estimating the global dietary supply of nutrients. *PLoS One*, *11*(1), e0146976. https://doi.org/10.1371/journal.pone.014697

Stadlmayr, B., Charrondiere, U. R., Enujiugha, V., Bayili, R. G., Fagbohoun, E. G., Samb, B., & Akinyele, I. (2012). *West African food composition table*. Food and Agriculture Organisation of the United Nations, Rome. Retrieved from http://www.fao.org/docrep/015/i2698b/i2698b00.pdf.

Stevens, T., & Madani, K. (2016). Future climate impacts on maize farming and food security in Malawi. *Scientific Reports*, *6*, 36241. https://doi.org/10.1038/srep36241

Svedberg, P. (2000). *Poverty and undernutrition: Theory, measurement, and policy*. Oxford University Press. https://doi.org/10.1093/0198292686.001.0001

Thornton, P. K., Jones, P. G., Alagarswamy, G., & Andresen, J. (2009). Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change*, *19*(1), 54–65. https://doi.org/10.1016/j.gloenvcha.2008.08.005

Thornton, P. K., Jones, P. G., Alagarswamy, G., Andresen, J., & Herrero, M. (2010). Adapting to climate change: Agricultural system and household impacts in East Africa. *Agricultural Systems*, *103*(2), 73–82. https://doi.org/10.1016/j.agsy.2009.09.003

Tubiello, F. N., Amthor, J. S., Boote, K. J., Donatelli, M., Easterling, W., Fischer, G., Gifford, R. M., Howden, M., Reilly, J., & Rosenzweig, C. (2007). Crop response to elevated CO2 and world food supply: a comment on "Food for Thought…" by Long et al., Science 312: 1918–1921, 2006. *European Journal of Agronomy*, *26*(3), 215–223. https://doi.org/10.1016/j.eja.2006.10.002

UN (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables* (Working Paper No. ESA/P/WP/248). The Department of Economic and Social Affairs of the United Nations, New York, USA. Retrieved from https://www.un-.org/development/desa/publications/world-population-prospects-the-2017-revision.html.

UNDP (2018). *Human development indices and indicators: 2018 Statistical update. Briefing note for countries on the 2018 Statistical Update: Malawi*. United Nations Development Programme. Retrieved from http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/MWI.pdf

USDA (2014). *Food Composition Table*. United States Department of Agriculture. Retrieved from https://ndb.nal.usda.gov/ndb/search/list.

van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Domínguez, I. P., Bodirsky, B. L., van Dijk, M., Doelman, J., Fellmann, T., Humpenöder, F., Koopman, J. F. L., Müller, C., Popp, A., Tabeau, A., Valin, H., & van Zeist, W.-J. (2018). Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environmental Research Letters*, *13*(6), 064021. https://doi.org/10.1088/1748-9326/aabdc4

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Wang, D., Heckathorn, S. A., Wang, X., & Philpott, S. M. (2012). A meta-analysis of plant physiological and growth responses to temperature and elevated CO_2. *Oecologia*, *169*(1), 1–13. https://doi.org/10.1007/s00442-011-2172-0

Warnatzsch, E. A., & Reay, D. S. (2018). Temperature and precipitation change in Malawi: Evaluation of CORDEX-Africa climate simulations for climate change impact assessments and adaptation planning. *Science of the Total Environment*, *654*, 378–392. https://doi.org/10.1016/j.scitotenv.2018.11.098

Welch, R. M., Graham, R. D., & Cakmak, I. (2013). *Linking agricultural production practices to improving human nutrition and health*. ICN2 Second International Conference on Nutrition: Food and Agriculture Organisation of the United Nations, Rome. Retrieved from http://www.fao.org/3/a-as574e.pdf

Wessells, K. R., & Brown, K. H. (2012). Estimating the global prevalence of zinc deficiency: Results based on zinc availability in national food supplies and the prevalence of stunting. *PLoS One*, *7*(11), e50568. https://doi.org/10.1371/journal.pone.0050568

Whetton, P., Macadam, I., Bathols, J., & O'Grady, J. (2007). Assessment of the use of current climate patterns to evaluate regional enhanced greenhouse response patterns of climate models. *Geophysical Research Letters*, *34*, L14701. https://doi.org/10.1029/2007GL030025

WHO (2004). *Vitamin and mineral requirements in human nutrition, second edition.* In: Report of a Joint FAO WHO Expert Consultation. World Health Organization, Switzerland. Retrieved from https://www.who.int/nutrition/publications/micronutrients/9241546123/en/.

WHO (2009). *Global prevalence of vitamin A deficiency in populations at risk 1995–2005*. WHO Global Database on Vitamin A Deficiency. World Health Organisation, Switzerland. Retrieved from https://www.who.int/nutrition/publications/micronutrients/vitamin_a_deficiency/9789241598019/en/

WHO GHO (2019). *World Health Organisation Global Health Observatory data repository*. Retrieved from http://apps.who.int/gho/data/node.home.

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H., & Willenbockel, D. (2015). Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, *10*(8), 085010. https://doi.org/10.1088/1748-9326/10/8/085010

Wiebe, K., Sulser, T. B., & Mason-D'Croz, D. (2017). The effects of climate change on agriculture and food security in Africa. In A. Alessandro De Pinto, & J. M. Ulimwengu (Eds.), *A thriving agricultural sector in a changing climate: Meeting Malabo Declaration goals through climate-smart agriculture* (Chapter 2, pp. 5–21). International Food Policy Research Institute. https://doi.org/10.2499/9780896292949_02

World Bank (2016). *Republic of Malawi Poverty Assessment. Poverty and Equity Global Practice Africa Region*. World Bank Group, Washington D.C. Retrieved from http://hdl.handle.net/10986/26488

Wuehler, S. E., Peerson, J. M., & Brown, K. H. (2005). Use of national food balance data to estimate the adequacy of zinc in national food supplies: Methodology and regional estimates. *Public Health Nutrition*, *8*(7), 812–819. https://doi.org/10.1079/PHN2005724

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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