Food Policy 104 (2021) 102151

Contents lists available at ScienceDirect

Food Policy

journal homepage: www.elsevier.com/locate/foodpol

The global cost of reaching a world without hunger: Investment costs and policy action opportunities

Bezawit Beyene Chichaibelu [a,*], Maksud Bekchanov [b], Joachim von Braun [c], Maximo Torero [d]

[a] Center for Development Research, University of Bonn, Genscherallee 3, D-53113 Bonn, Germany
[b] Research Unit Sustainability and Global Change, Center for Earth System Research and Sustainability, Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany
[c] Center for Development Research, University of Bonn, Genscherallee 3, D-53113 Bonn, Germany
[d] Food and Agriculture Organization (FAO), Viale delle Terme di Caracalla, 00153 Rome, Italy

ARTICLE INFO

Keywords:
Hunger
Undernourishment
SDG 2
Policy options
Investment cost
Marginal abatement cost curve

ABSTRACT

This study developed a marginal abatement cost curve to identify a mix of least-cost investment options with the highest potential for hunger reduction, hunger here defined by the undernourishment concept of the Food and Agriculture Organization. Twenty-two different interventions are considered for reducing undernourishment relying on information drawn from best available evidence-based literature, including model- and large-scale intervention studies. Ending hunger by 2030 would require annual investments of about US$ 39 to 50 billion until 2030 to lift about 840 to 909 million people out of hunger, which is the 2020 estimate of hunger projection in 2030, also considering the effects of COVID-19. Investing in agricultural R&D, agricultural extension services, ICT - Agricultural information systems, small-scale irrigation expansion in Africa and female literacy improvement are low cost options that have a relatively large hunger-reduction potential. To achieve the goal of ending hunger by 2030, not only is it urgent not to lose any more time, but also to optimally phase investments. Investments that have more long-term impacts should be frontloaded in the decade in order to reap their benefits soon before 2030. A balanced approach is needed to reach the hungry soon – including those adversely affected by COVID-19 with social protection and nutrition programs.

1. Introduction

At the heart of the 2030 Agenda[1] was a promise to prioritize two objectives: to eradicate poverty and end hunger in all their forms. Worldwide, over 650 million people are estimated to have been undernourished in 2019. World hunger increased further in 2020 to 720 – 811 million people, exacerbated by the impact of COVID-19 (FAO et al., 2021). Recent global projections of hunger show that the world is not on track to achieve Zero Hunger[2] by 2030. Estimates in 2020 projected that the number of people affected by hunger will surpass 840 million by 2030, or 10 percent of the global population (FAO et al., 2020). Updated estimates in 2021 projected lower, but still alarming levels of hunger that will affect about 660 million people by 2030 (FAO et al., 2021). The world is also not on track to achieve the 2025 and 2030 targets for child malnutrition. In 2019, 21.3 percent of children under 5 years of age were stunted globally, or 144 million (UNICEF et al., 2020). In 2021, the number of children suffering from stunting increased further to 149.2 million. Although there has been some progress globally since 2000, rates of stunting reduction are far below what is needed to reach the targets of 40 percent reduction for 2025 and 50 percent reduction for (FAO et al., 2021).

COVID-19 is expected to further worsen the overall prospects for food security and nutrition. Food insecurity may appear in countries and population groups that were not previously affected. In 2020, the number of undernourished people increased by about 118 million people compared to the 2019 level as COVID-19 disrupted economies, job markets and supply chains, and inflated food prices. The pandemic is also expected to have a lasting effect beyond 2020, adding about 30

* Corresponding author.
E-mail addresses: bchichai@uni-bonn.de (B.B. Chichaibelu), maksud.bekchanov@uni-hamburg.de (M. Bekchanov), jvonbraun@uni-bonn.de (J. von Braun), Maximo.ToreroCullen@fao.org (M. Torero).

[1] In 2015, all of the UN member states adopted 17 goals as part of the 2030 agenda for sustainable development which set out a 15-year plan to achieve the goals.
[2] Most studies define 'zero hunger target' as the reduction of hunger levels to less than the 5 or 3 percent of population. 'Absolute zero hunger target' is used throughout this manuscript to refer to a complete eradication of hunger.

https://doi.org/10.1016/j.foodpol.2021.102151
Received 21 January 2021; Received in revised form 10 August 2021; Accepted 18 August 2021
Available online 17 September 2021

million more people to the total number of undernourished in the world in 2030 (FAO et al., 2021). Additionally, early estimates on the impact of COVID-19 on child malnutrition suggested an additional 6.7 million children suffered from wasting in 2020 as compared to pre-COVID-19 projections. The combined effect of the increase in wasting and a 25 percent reduction in the coverage of nutrition and health services due to COVID-19 could cause an additional 128,605 deaths in children younger than five years in 2020 (Headey et al., 2020). While these projections are an early estimate and may not fully capture the impact of COVID-19 on food security and nutrition, they emphasize the urgent need for actions to get back on track towards achieving targets 2.1 and 2.2 of Sustainable Development Goal No. 2 (SDG2).

Investments needed to end hunger are anticipated to be extensive, costly and difficult to implement, even without considering the impacts of the COVID-19 pandemic. As policymakers still need to prioritize the allocation of resources, identifying optimal and least-cost investment options is important for practical policy. In this regard, this study developed a Marginal Abatement Cost Curve (MACC) as an original contribution to identify a mix of least-cost investment options with the highest potential for reduction in hunger. Twenty-two different interventions are considered for reducing hunger. The information about the interventions are drawn from the findings of various model- and cost-benefit and impact evaluation studies on hunger reduction measures. Some of them are more short-term interventions (such as social protection), and some are more long-term (such as agricultural R&D, or soil fertility management). The MACC of hunger reduction can be considered when asking "what are the costs of ending hunger?," depending on the number of people who are to be brought out of risk of hunger by 2030. The assessment can broadly guide global and country efforts to achieve the SDG 2 targets by 2030.

The results from the MACC indicate that ending hunger would not be prohibitively expensive, provided that a mix of least-cost measures with large hunger reduction potential are prioritized. Ending hunger by 2030 is estimated to require US$ 39–50 billion annually until 2030. Of that, the G7 would need to contribute US$ 11–14 billion to meet their Elmau commitment of lifting 500 million people out of hunger by 2030[3], effectively doubling current aid flows for agriculture, food and rural development. A bundle of promising investments that deliver short-term and long-term impacts would meet the goal of ending hunger by 2030. Short-term measures are needed to reach the hungry soon – including those adversely affected by COVID-19 related job losses and other socio-economic consequences - with social protection and nutrition programs. Long-term measures, such as agricultural R&D and expansion of small- and large-scale irrigation, which require high up-front investments but also have a high long-term impact, also need to be included. Optimally phasing investments is crucial: those with longer-term impact should be frontloaded to reap their benefits soon before 2030.

2. Review of selected estimates of the cost of ending hunger

Here we review several estimates of the cost of achieving SDG 2, in particular, ending hunger and improving nutrition. We focus on the five most up-to-date estimates conducted by FAO, IFAD and WFP (2015), Rosegrant et al. (2017), Torero and von Braun (2015), Laborde et al. (2016), and Shekar et al. (2017). Since some of these studies, for example, the studies by FAO, IFAD and WFP (2015) and Torero and von Braun (2015), use the same methodology as earlier works, i.e. Schmidhuber and Bruinsma (2011) and Hoddinott et al. (2013), these earlier works are not included in our review. In the case of others, for example, in the paper by Laborde et al. (2016) titled "Ending Hunger: What Would It Cost", the applied methodology is similar to another ongoing work by Ceres2030 research group; we therefore present only the studies for which the final results are readily available (see also Fan et al., 2018). Summary of the findings of the reviewed studies are presented in Table 1. We further discuss the details and interpretations of these studies in the remaining part of this section.

The "Achieving Zero Hunger" study by the Food and Agriculture Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD), and the World Food Programme (WFP) (2015) presents the most extensive, but also most costly set of measures, including extensive social protection programmes and targeted pro-poor investments. The basic premise of the 'Achieving Zero Hunger' framework is that hunger is a result of lack of purchasing power which translates into a lack of access to sufficient and nutritious food, and therefore the target of eliminating hunger (SDG 2) can be achieved only by eliminating poverty (SDG 1). Unlike other models, it aims for absolute-zero levels of hunger globally by 2030. Note that hunger is measured here by the prevalence of undernourishment (PoU), defined as chronically inadequate dietary energy intake, in line with the methodology adopted in the FAO's 'The State of Food Security and Nutrition in the World 2019' report (FAO et al., 2019). The 'Achieving Zero Hunger' study draws upon a methodology previously used by Schmidhuber and Bruinsma (2011) and employs the partial-equilibrium model called Global Agriculture Perspectives System (GAPS). According to the modelling simulations, the twin-track approach of social protection and pro-poor development is expected to bring relatively fast but also sustainable eradication of poverty and hunger. In the short-term, public investment in social protection is expected to close the poverty gap and increase incomes, both directly and through increased productivity. In the long-run, the effects of social protection will be reinforced and sustained by targeted private and public pro-poor investments, especially in rural areas, and particularly so in agriculture (see Table 1). The overall cost of achieving zero hunger would be US$ 265 billion annually, out of which US$ 198 billion will cover pro-poor investments and US$ 67 billion social protection.

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) by the International Food Policy Research Institute's (IFPRI) was applied to analyse the potential contribution of agricultural investments to achieving SDG 2, and proposes a comprehensive investment package that can reduce hunger to 5 percent of the global population (Rosegrant et al., 2017). These investments focus on agriculture and include agricultural research and development (R&D); resource management, especially water and irrigation; and infrastructure, mainly transportation and energy. Out of the five estimates this is the only framework explicitly modelling the impact of R&D on agricultural productivity and hunger reduction; it is also the only one to account for climate change impacts. The IMPACT model is a highly disaggregated, global partial-equilibrium multi-market model. To overcome the limitations of a partial-equilibrium model, it is linked to a global computable general-equilibrium (CGE) model (GLOBE) which allows for estimating the impacts of investment in agriculture on the broader economy. Hunger is proxied by the risk of hunger based on the estimated calorie availability per day per capita. The cost of the agricultural investment package is estimated at US$ 52 billion annually for the developing world. These investments are expected to result in a reduction of the share of the population at risk of hunger to 5 percent, except for Eastern and Central Africa where hunger will remain at 10 percent level (Rosegrant et al., 2017).

"Toward a Zero-Hunger by 2030" study by Torero and von Braun (2015) provides global estimates for the investments necessary to reduce hunger to near zero by 2030, with the assumption that transitory undernourishment at around the 3 percent level, related to conflict and crises, would require different measures. The estimates are to a great extent extrapolated from Hoddinott et al. (2013) and consider hunger reduction through investing in: (i) accelerating yield enhancements, i.e.

[3] G7 heads of states at their Summit in Elmau in 2015 committed to lifting 500 million people out of hunger and malnutrition by 2030 as part of a broader effort to be undertaken with partner countries to support the 2030 Agenda for Sustainable Development, i.e. Sustainable Development Goal 2 (SDG 2) to end hunger and malnutrition by 2030.

Table 1
Overview of selected costing studies.

Model/ framework and institution/ author(s)	Research question/ time frame	Undernourishment reduction target	Investments/ interventions considered to achieve the target	Method used in the analysis	Discussed financial sources to reduce hunger	Total annual cost (billion US$) of reducing hunger	Per capita total cost of hunger eradication (US$) over 2015–2030 *
Achieving Zero Hunger (FAO, IFAD & WFP, 2015)	What are the additional investments needed to end poverty and hunger in all countries by 2030?	Zero hunger; eradicating extreme poverty	Pro-poor investments: primary agriculture and natural resources, agro-processing operations, infrastructure, institutional framework, R&D, extension; Social protection	Global partial-equilibrium model of country-wise projections of food supply and demand (called GAPS)	Public and private	**265, out of which 198 for pro-poor investments**	**4,035**
IMPACT (IFPRI/ Rosegrant et al., 2017)	How much would hunger decrease given investments to achieve target yield increases by 2030?	5 percent hunger	Agricultural R&D; irrigation expansion; water use efficiency; soil management; transport and energy infrastructure	Agricultural sector partial-equilibrium model linked to biophysical models and CGE model; impacts of climate change included	Public	**52**	**929**
Toward a Zero-Hunger by 2030 (Torero & von Braun, 2015)	What is the global cost to accelerate undernourishment reduction to a level that would almost eliminate hunger by 2030?	3 percent hunger; improved nutrition	Accelerating yield enhancements (agricultural R&D); market innovations (information and communication technologies, increasing competition in the fertilizer market); interventions that reduce micronutrient deficiencies (vitamin A, iodine, iron, zinc) and reduce stunting	Builds up on the Hoddinott et al. (2013) which used agricultural partial-equilibrium model (called IMPACT) for assessing the impacts of R&D investments and cost-benefit analysis for the remaining options	Public, including ODA	**30,** out of which **15** for ending hunger	**312**
MIRAGRODEP (IFPRI& IISD/ Laborde et al., 2016)	What is the minimum cost to end hunger for vulnerable households by 2030?	5 percent hunger	Social safety nets: food subsidies; farm support: production subsidies, fertilizer subsidies, investment grants, R&D, extension; rural development and infrastructure: reduction of post-harvest losses, irrigation, roads	Global multi-regional CGE model combined with household surveys for targeted interventions	Public, including ODA	**11**	**368**
Investment Framework for Nutrition (WB/ Shekar et al., 2017)	What is the minimum cost to meet the World Health Assembly targets on nutrition by 2025?	40 percent reduction in child stunting; 50 percent reduction in anaemia in women; 50 percent increase in exclusive breastfeeding rates; 5 percent child wasting	Targeted nutrition interventions (micronutrient and protein supplementation, public provision of complementary food, promoting good health and hygiene) and selected nutrition-sensitive interventions (staple food fortification and pro-breastfeeding policies)	Investment cost minimization ad cost-benefit-analysis	Public, including ODA, and private, including household contributions and innovative financing mechanisms	**7**	**Not applicable**

Note: * Total cost per person is calculated as total net discounted cost over the 15 years period (only for the ‘Achieving Zero Hunger’ study, the time frame is 14 years, i.e. 2016–2030). The discount rate is assumed to be 5 percent (Hoddinott et al., 2013). For each modelling framework, the absolute number of people lifted out of hunger by the proposed investments is calculated as the difference between the projected number of hungry people in the ‘business as usual 2030′scenario and the projected number of hungry people in the ‘2030 investment’ scenario. These figures are retrieved from each model. The per capita total cost of hunger eradication is then calculated as the total net discounted cost divided by the number of people lifted out of hunger. We calculate only the cost per person for the investments towards hunger reduction, but not for the investments towards improvement in nutrition due to the very specific nature and outcomes of each intervention.
Source: Adapted from Mason-D’Croz et al. (2019).

investments in agricultural R&D; (ii) market innovations, i.e. information and communication technologies (ICTs) and improving the functioning of fertilizer markets; (iii) and interventions that reduce micronutrient deficiencies (vitamin A, iodine, iron, zinc) and reduce stunting.

This framework of the study is somewhat similar to the work of Rosegrant et al. (2017) presented above, as both studies rely on IMPACT modelling assessments. Hunger level is also measured using a similar approach as in the "Achieving Zero Hunger" study (e.g., Rosegrant et al., 2017). However, the conceptual framework and the underlying assumptions vary to some extent. Agricultural R&D is expected to increase productivity, and the elasticity of yields to R&D expenditure is estimated based on a literature review. This yield growth entails both income and price effects, which will then affect the incidence of hunger. The original cost estimates for agricultural R&D in the underlying paper by Hoddinott et al. (2013) show that it would cost US$ 733 per person to reduce the number of undernourished by 210 million by 2050 (the original time frame of the baseline paper), which translates into a prevalence of hunger reduced to 5.9 percent. Torero and von Braun (2015) suggest to accelerate these investments up to 2030, and couple them with the remaining investment strategies, i.e. food markets and ICTs, as well as with programmes to reduce micronutrient deficiencies and stunting, which would lift 500 million people out of hunger and attain the objective of near-zero hunger. The total cost of all measures addressing hunger and malnutrition would be US$ 30 billion annually; out of which the cost of ending hunger would be US$ 15 billion annually.

The "Ending Hunger: What Would It Cost" study by IFPRI and the International Institute for Sustainable Development (IISD) combines micro-, meso- and macro-level inputs (Laborde et al., 2016). This modelling framework is based on a dynamic multi-country multi-sector CGE model (MIRAGRODEP) combined with household surveys. The framework that combines modelling with household surveys allows for more efficient targeting of interventions in the model assessment due to more detailed classification of households at risk of hunger. Based on the surveys, households are differentiated in accordance with their location (urban or rural), income sources and levels (farm or non-farm), and farm ownership. Consequently, strategies of social protection are matched with the households with lower income, measures of supporting farm production are considered for households which owns farm, and rural support were proposed to the rural households. This household-level targeting in the model is expected to result in estimations of improved spending efficiency of the hunger reduction investments in comparison to the other models which are based on national averages (Laborde et al., 2016). As noted by Fan et al. (2018), the MIRAGRODEP model's targeting approach, together with the narrow focus on reducing hunger in isolation of other SDGs, produces one of the lowest cost estimates, US $ 11 billion annually. Hunger is measured by the PoU, as defined above in the discussion of "Achieving Zero Hunger" study. Rather than targeting absolute-zero hunger, the MIRAGRODEP's objective is set to reducing PoU to 5 percent or less. Two other sub-goals of SDG 2, i.e. raising agricultural productivity and doubling smallholders' income (target 2.3) and ensuring sustainable agricultural systems (target 2.4) are also accounted for in the design of interventions. Three types of interventions are included in the MIRAGRODEP model: social safety nets, directly targeting consumers through food subsidies; farm support to increase farmers' productivity and incomes; and rural development, mainly through infrastructure investments (see Table 1). These interventions are expected to affect calorie consumption by increasing poor households' incomes, as in 'Achieving Zero Hunger' study, or by decreasing food prices. The importance of interventions addressing nutrition are also acknowledged, however because of household data limitations, they are not accounted for in the modelling framework (Laborde et al., 2016).

Finally, the "Investment Framework for Nutrition" was proposed by the World Bank (WB) (Shekar et al., 2017). This framework has a narrow scope in comparison to the other models and frameworks presented here, because its adopted methodological framework is very simple and transparent. Rather than aiming at reducing hunger, as in the other models, the WB framework estimates the financial needs for improved nutrition targets. More specifically it aims to (i) reduce the number of stunted children under five by 40 percent, (ii) reduce the number of women at reproductive age affected by anaemia by 50 percent, (iii) increase the rate of exclusive breastfeeding in the first six months up to at least 50 percent, and (iv) reduce and maintain childhood wasting to less than 5 percent. These targets correspond to the World Health Assembly's Targets for Nutrition, but also contribute to SDG 2 (Shekar et al., 2017). The case for investing in nutrition is very strong: ending malnutrition is critical for long-term human capital, labour productivity and broad economic development (Fink et al., 2016; Horton & Steckel, 2013; Hoddinott et al., 2008). At the same time, nutrition interventions are considered to be among the most cost-effective (Horton & Hoddinott, 2014). The interventions included in the framework are identified based on two criteria: (1) strong evidence of their impact; (2) relevance for low- and middle-income countries. The selected interventions range from staple-food fortification and micronutrient supplementation to public provision of supplementary food and behaviour promotion campaigns. To estimate the total cost of scaling up the selected nutrition interventions, financial needs are first analysed for the highest-burden countries based on the unit-cost data obtained from a literature review; these results are then extrapolated to all low- and middle-income countries. The estimates suggest that to reach the nutrition targets it will cost around US$ 7 billion annually between 2015 and 2025; more than half of this amount targeted at reducing stunting (Shekar et al., 2017).

The five estimation approaches presented above provide a very wide range of estimates for the total investment necessary to achieve SDG 2, i.e. ending hunger and improving nutrition. These differences are largely attributable to the different objectives and policy questions asked, interventions and investment strategies considered, as well as definitions, methods and assumptions used (Mason-D'Croz et al., 2019; Fan et al., 2018). The differences in the approaches adopted by the costing frameworks make it difficult to directly compare the resulting estimates. We calculated the estimated cost per person of hunger eradication for all the modelling frameworks except the WB's Investment Framework for Nutrition that only provides estimates of nutrition-specific interventions (Table 1). These estimated costs per person vary widely, from more than US$ 4,000 in 'Achieving Zero Hunger' study to just above US$ 300 in Torero and von Braun (2015). The number of people lifted out of hunger also differs substantially, from 650 million in 'Achieving Zero Hunger' study, 580 million in the IMPACT modelling study, 500 million in Torero and von Braun (2015), to only 290 million in the MIRAGRODEP modelling study. These differences are accounted for by differences in modelling assumptions, and the scope of each framework in terms of suggested investments and interventions. Rather than providing clear-cut answers, the studies suggest that a variety of diverse investment strategies can contribute to ending hunger.

Although all five estimation approaches address the issue of financial needs for the achievement of SDG 2, the scope of each framework is narrower than the scope of SDG 2 itself. SDG 2 has five targets, the first two concerned with ending hunger and ending all forms of malnutrition by 2030. The remaining three targets concern doubling agricultural productivity and the income of small-scale food producers by 2030, ensuring sustainable food production systems by 2030, and maintaining the genetic diversity of seeds, plants and animals, including wild species by 2020. Three of the models focus on either eradicating or substantially reducing hunger. However, the definitions of hunger vary between the studies, and are based either on food access, as in the 'Achieving Zero Hunger' and the MIRAGRODEP modelling studies, or food availability, as in the IMPACT modelling study; none consider all four dimensions of food security, i.e. food availability, access, utilization, and stability. Only two frameworks, the WB's Investment Framework for Nutrition and the estimates by Torero and von Braun (2015), explicitly model the nutrition outcomes; with the latter being the only one to address both objectives of hunger eradication and improved nutrition in one framework. The other four studies only assume that investment to reduce hunger will also help to reduce malnutrition. Finally, only one of the studies, MIRAGRODEP based 'Ending Hunger: What Would It Cost', factors in the question of sustainability in agriculture.

There are important trade-offs between the scope of a modelling framework and the complexity of the methodology used. Looking at the five frameworks reviewed here, it seems that the narrower the scope of the study, the more detailed and accurate the estimates, as in the case of the MIRAGRODEP model. The combination of macro-level and household-level data in the MIRAGRODEP model is an interesting methodological development in comparison to studies based on national averages of dietary intake, as it allows not only for assessing the cost effectiveness of interventions but could also better capture the distributional effects of investments across heterogeneous households based on their specific socio-economic characteristics, which are largely omitted in most analyses. Also, only a few models explicitly include the investments necessary to create enabling environments for achieving SDG 2; admittedly, these are relatively difficult to present in monetary terms.

Last but not least, the financing strategy with respect to the pacing of investments, allocation of financial resources between competing objectives, distribution of the burden of investment between various financing sources, and the sustainability of results beyond 2030, especially in the context of large economic, climatic or political shocks, is rarely considered in detail in the reviewed frameworks. In particular, the issue of how to spread investments over time is not discussed in much detail in any of the models; instead, the costing estimates are presented in terms of annual averages. However, this has serious implications not only for the resource mobilization strategy and therefore the feasibility of timely investments, but can also affect the economy-wide outcomes of the intervention.

Another question is how to allocate limited financial resources between the various SDGs and the development targets specific to SDG 2. Of course, the case for investing in zero-hunger target is evident, as the right to food is considered to be among the most basic of human rights. However, in the context of scarce financial resources, the potential synergies between different objectives, as in the case of eradicating hunger (SDG 2) and poverty (SDG 1), need to be found. Also, potential conflicts, for example between doubling agricultural productivity (SDG 2.3) while preserving the natural environment (Sachs et al., 2019), e.g. ensuring sustainable food production systems (SDG 2.4), need to be addressed to make the proposed investment strategies efficient. Additionally, the long-term sustainability of the proposed investment frameworks are rarely explicitly addressed. The time horizon of the models ends in 2030, aside from the 'Investment Framework for Nutrition' which ends in 2025 (Shekar et al., 2017). The latter is the only one to include a 5-year maintenance period (2021–2025); in general, however, the question of how to sustain the results beyond 2030 is not discussed. In the broader frameworks, like the 'Achieving Zero Hunger' or MIRAGRODEP frameworks, the implicit assumption is that pro-poor investments in agriculture and their expected long-term economy-wide growth effects will be sufficient to maintain zero or 5 percent hunger levels worldwide. While this might hold if the proposed frameworks' scenarios hold, the reduction in hunger might be reversed in the case of major economic, climate or political shocks, as the last decade has proven (FAO, 2018). Only the IMPACT model-based study includes the effects of climate change in its modelling framework (Rosegrant et al., 2017); and none of the models discuss the challenges of achieving zero hunger in fragile states, i.e. conflict and post-conflict states.

3. Overview of approaches to reducing hunger

Despite continued global agricultural output growth and considerable reduction in hunger since the 1960 s, food insecurity still persists, albeit with huge differences between countries, within countries and even households (FAO et al., 2015). The nature of food insecurity has been also changing as increasing demand for processed food and consequently higher consumption of unhealthy fats, sugars and salts are exacerbating obesity and micronutrient deficiency (Barrett, 2021). Thus, interventions focused on agricultural productivity improvement alone will not be enough to achieve the goal of sustainable food security. Achieving global food security would require not only improvements along food supply chains but also additional efforts in health, education, information and research systems. A sustainable development of the food system should go along with ensuring food and nutrition security and without compromising the social, economic and environmental futures for the generations to come (HLPE, 2014). This study looks within and beyond agricultural system to identify the intervention options and investments needed to alleviate hunger or undernourishment.[4] Performing food systems analysis considering multiple interventions entails an assessment of the relevant processes that influence the four dimensions of food security food availability, access, utilization and stability.[5] Food availability emphasises the need to address the supply side of food security to ensure sufficient quantities of food is available to individuals either through food production or imports. Food access on the other hand points to the importance of ensuring individuals have the resources necessary to obtain sufficient quantities of food. Going beyond availability and access to food, food utilization focuses on dietary quality and highlights the importance of ensuring individual's ability to utilize the energy and nutrients in the food they consume. Food stability reflects the stability of the three dimensions and reminds us of the importance of taking into consideration seasonal or temporary food prices and shocks in hunger prevention policies.

Food security can be enhanced through multiple investment options that intensify agricultural production and improve agricultural productivity. For instance, agricultural research and development and extension efforts to enhance crop and livestock production can boost food supply. Innovations in improved crop varieties, methods to improve soil fertility, and efficient irrigation technologies can also increase agricultural productivity and address food availability. The resulting increase in agricultural productivity further contributes to increased agricultural income, improved purchasing power and reduced food prices, which when combined with innovations in post-harvest technologies can improve access to food, increase calorie consumption, increase dietary diversity, and thus enhance food accessibility and utilization.

Market platform and infrastructure improvements help in reducing post-harvest losses and enhance access to food. Improved storage systems, better roads, availability of food processing, and equitable food distribution systems can greatly improve access to food by consumers. Trade rules at the international and intra-national level also greatly impact on food access. Some infrastructural improvements such as electricity access and information and communication technologies (ICTs) can improve food supply, distribution and access systems. For example, using mobile phones, farmers can access information about the weather and market conditions, allowing them to better manage water resources and fetch higher prices for their produce. ICT and storage systems are also important to plan and predict food supplies and hence, stabilize food market prices. At the same time, interventions that can enhance the incomes and purchasing capacity of the population can

[4] This study uses the prevalence of undernourishment (PoU) as the main indicator for hunger. The PoU identifies the proportion of the population whose habitual, daily, per capita Dietary Energy Consumption (DEC) level is lower than their dietary energy requirement (Cafiero & Gennari, 2011). It is computed from aggregated country-level data on food availability that is annually compiled in FAO's Food Balance Sheets and data on food consumption from surveys which is available for certain countries.

[5] Future work on estimating the cost of ending hunger could further consider interventions that can address the two additional dimension "agency" and "sustainability" that have become crucial for transforming food systems towards the direction needed to meet the SDGs (HLPE, 2020)

improve food affordability, which is an important aspect of food access. For some marginalized groups with inadequate income and informal jobs, social security programmes such as food vouchers and financial assistance can be considered.

Severe cases of child malnutrition, caused by nutrient insufficiency and certain diseases, require nutrition-specific interventions. According to Bhutta et al. (2013), at least 20.3 percent of the current child stunting rate could be averted if ten evidence-based nutrition-specific interventions were scaled up to cover 90 percent of the population in countries with high stunting burden. These interventions include periconceptional folic acid supplementation or fortification, maternal balanced energy protein supplementation, maternal calcium supplementation, multiple micronutrient supplementation in pregnancy, promotion of breastfeeding, appropriate complementary feeding, vitamin A and preventive zinc supplementation in children aged 6–59 months, management of severe acute malnutrition, and management of moderate acute malnutrition.

The quality of maternal- and child-care practices is also one of the non-nutritional factors that affect the nutritional outcomes of children (Smith & Haddad, 2015). Women play a key role in children's nutritional outcome as they give birth to them, breastfeed them and are their primary caretakers. Hence, maternal education has numerous positive impacts on the quality of maternal care that mothers receive during and after pregnancy and consequently on the quality of care that their children receive, ranging from the amount of breastfeeding to seeking health care in case of illnesses (Ruel et al., 2013). The strong link between female education and nutritional outcomes of children, particularly for stunting, has been well established (Headey, 2013; Smith & Haddad, 2015). The specific intervention options considered in this study are described in the next section.

4. Marginal abatement cost curve approach and investment scenario assumptions

4.1. The marginal cost curve and key steps of the process

Policymakers need to prioritize the allocation of resources to competing hunger-reduction measures by identifying the sets of least cost investment options that have the potential to yield the greatest reduction in hunger in a defined time horizon. It is therefore essential that policymakers and practitioners can compare the different hunger reduction measures and make economically efficient investment decisions. In this regard, Marginal Abatement Cost Curves (MACC) can be helpful as a policy tool in ranking investments options. Applications of MACCs are common in the economic assessment of climate change mitigation options (Schneider et al., 2007; Kesicki & Ekins, 2012; Bockel et al., 2012; IPCC, 2014; Eory et al., 2018) and have been also extended into the assessment of effective water policies (Addams et al., 2009). This study implements MACC approach in hunger reduction research. By developing a realistic and policy-relevant global MACC of different hunger reduction measures, the study allows to assess their cost-effectiveness and contributes to the evaluation of actions that should be prioritized and implemented to achieve target 2.1 of SDG 2 by 2030.

MACCs are developed based on either modelling outcomes or multiple expert opinions (Kesicki, 2013). MACCs derived from top-down modelling provides internally consistent estimations, follows to smooth and continuous dynamics but do not account for the effects of specific interventions (Klepper & Peterson, 2006). Expert based MACCs, despite being criticized for double counting and interaction possibility, are richer in terms of reflecting technology details as they are constructed by summarizing and synthesizing the average costs and abatement effects of multiple interventions. As our assessments are based on the cost and hunger reduction effects of multiple interventions from multiple studies, the framework of expert-based MACC is relevant here.

The global hunger reduction MACC represents the relationship between the cost-effectiveness of different hunger reduction interventions

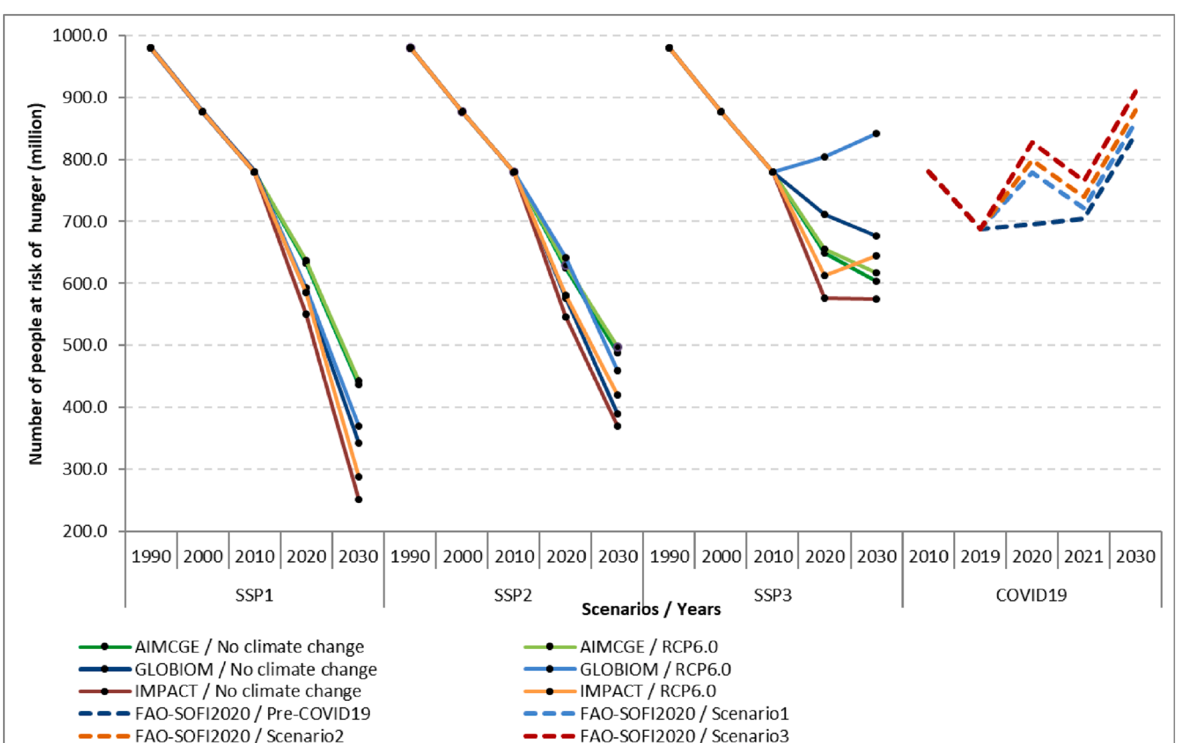

Fig. 1. Hunger levels expected under various socio-economic and climate change scenarios. Source: Authors' own elaboration based on FAO et al. (2020) and Hasegawa et al. (2018).

and the hunger reduction potential of each intervention. It reflects the additional costs of lifting people out of hunger by each intervention. Elaboration of the MACC were conducted step-by-step, by first identifying the variety of intervention options that can effectively reduce hunger, and then by determining the cost and hunger reduction potential of the interventions. The related assessment is conducted through a literature review and an integrated evaluation of model-based, econometric or cost-benefit analysis studies. While the cost and hunger reduction potential (number of people lifted out of hunger) were readily found in the literature for some of the interventions, additional calculations or assumptions based on expert assessments were considered for others. Particularly, hunger reduction potential was derived through additional calculations considering conversion factors and elasticity coefficients when food security enhancement effects such as additional food supply, income, or prevented levels of undernourishment due to the interventions are available. The cost of implementing some interventions were also estimated considering the prices of food, costs of social protection, or transaction costs of trade (details of these calculations and assumptions behind are provided in the Supplementary Material). Finally, the interventions are ranked from the cheapest to most expensive, based on their marginal costs (average cost of lifting an individual out of hunger) to represent the cost of achieving incremental levels of hunger reduction.

4.2. Reference scenarios of hunger trend and investment options

In a MACC based economic assessment of investment options, reference scenarios are built either based on a "business as usual" scenario, using historical trends to identify future developments, or based on alternative scenarios that consider climate change impacts and socio-economic developments of the future. Model-based foresight exercises highlight how food and agricultural systems could evolve in an inherently uncertain future. These foresight exercises provide alternative scenarios on food security in which challenges are addressed to varying degrees, building on historical trends of factors that determine the performance of socio-economic and environmental systems. According to the bio-economic model-based assessments of AIM/CGE, GLOBIOM and IMPACT, under various climatic and socio-economic development scenarios the world will be home to between 251 and 842 million undernourished people in 2030 (Fig. 1; Hasegawa et al., 2018). If population growth were to be largely controlled, high economic growth rates (SSP1) were maintained and climate change effects were neglected (dark green, blue and brown lines in the first bunch of the lines), the number of undernourished people would be reduced to between 251 and 437 million. Yet, when climate change (RCP6.0) is considered in the modelling assessments the number of undernourished people is expected to be between 288 and 443 million (light green, blue and orange lines in the first bunch of the lines). Under the worst scenario, with high population growth, economic stagnation, high-income inequality (SSP3), and a climate change impact (RCP6.0), the number of undernourished people is expected to be between 617 and 842 million (light green, blue and orange lines in the third bunch of the lines). All three modelling assessments indicate similar trends of hunger reduction under various socio-economic and environmental changes. Yet, the magnitude of the reduction differs across the modelling assessments.

The worst scenarios of the projected number of undernourished people in 2030 lie close to the projection presented in the recent report of the state of food security and nutrition in the world without considering the impact of the COVID-19 pandemic, i.e. about 840 million (Fig. 1; FAO et al., 2020). The pandemic is expected to further accelerate the projected increase in the number of people facing hunger, at least in the immediate future. As the global economy contracts due to containment measures of COVID-19, it is anticipated that hunger will also increase globally, hampering the progress of global efforts geared towards achieving the SDG 2 targets. A 4.9 to 10% decline in global GDP growth is estimated to lead to an additional 100 to 194 million people into hunger globally in 2020 and 2021. In the worst-case scenario, the pandemic could potentially increase the number of undernourished people to 909 million by 2030 (FAO et al., 2020).

In the MACC analysis, the reference scenarios of hunger trends presented above serve in determining the number of the undernourished people that would need to be lifted out of hunger to achieve target 2.1 of SDG 2 by 2030 and hence the investments required to reach the target. In this study, the projection that consider the impact of COVID-19 is used as the reference scenario for the population at risk of hunger in 2030, since it is the recent authoritative foresight study on hunger that considers the impact of the pandemic on hunger.

The cost and hunger reduction potential of the various investment options considered in this study are also analysed relative to a "business as usual" or reference scenario of investments, wherein the costs of investments are assumed to remain frozen or grow following historical trends. The costs in the reference scenario include all investments required to achieve the projected level of implementation of the intervention options by 2030, including the capital, operational, and programme costs where applicable. For instance, the IMPACT model-based projection, from the study by Rosegrant et al. (2017), is used as a reference scenario for the interventions such as agricultural R&D, water resource management, and infrastructure. Rosegrant et al. (2017) used IFPRI's IMPACT model together with a global computable general-equilibrium model (GLOBE) and several linked post-solution models to evaluate investment requirements, land-use changes, greenhouse gas (GHG) emissions, biodiversity, water quality, and micronutrient availability and dietary diversity under the business as usual scenario. In addition to the climate change assumptions, Rosegrant et al. (2017) consider investment in agricultural R&D, water resource management, and infrastructure under the business as usual scenario. The projections of these investments under the business as usual scenarios are based on historical trends and expert opinions of long-term developments in the agricultural sector. Investments in water resource management are modelled endogenously combining the IMPACT model with a suite of water models. Similarly, all investment options considered in this study are compared to a reference scenario to identify the incremental cost of implementing the investments.

4.3. Opportunities of investments in policies and programs for hunger reduction

For estimating hunger reduction potential, twenty-two interventions were selected based on the framework described in section 3. Details of these interventions and overview of data and approaches used in calculating their hunger reduction potential and implementation costs are presented briefly in Table 2 to make all of the assumptions transparent. This would address the common critique, inherent in MACC, of a lack of transparency. Twelve of the twenty-two interventions are related to interventions for enhancing crop yields at farm levels through improved technologies, extension services, crop protection measures, soil fertility management and irrigation development. Five of the interventions are related to improved ICT, infrastructure and trade that

Table 2
Investment options for hunger reduction and investment scenarios assumptions.

	Interventions	Sources	Modelling framework	Calculations and assumptions
1	Agricultural R&D	Rosegrant et al., 2017	IMPACT 3 modelling suite	This option considers the hunger-reduction potential of increased investments in the CGIAR plus increased complementary investments in national agricultural research systems (NARS), where US$ 1.97 billion and US$ 0.99 billion per year are invested by the CGIAR and NARS respectively.
2	Agricultural R&D efficiency enhancement	Rosegrant et al., 2017	IMPACT 3 modelling suite	This option considers the hunger-reduction potential of higher CGIAR agricultural R&D efficiency so that the yield impact of investments is 30 percent higher. Agricultural R&D efficiency enhancement scenario is assumed to cost 30 percent of the annual average incremental investment in agricultural R&D with a total of US$ 0.89 billion.
3	Agricultural extension services	Blum & Szonyi, 2014; Ecker & Qaim, 2011; FAO et al., 2019; Ragasa & Mazunda, 2018; World Bank, 2020a	Econometric model	Hunger-reduction potential of increased investment in extension service is estimated for 38 low and lower-middle-income countries using the methodological note for calculating PoU (FAO et al., 2019) and the impact of extension services on Dietary Energy Supply (DES). The DES is estimated based on Ragasa and Mazunda's study (2018) that shows 36 percent increase in value of farm production due to the extension services, and Ecker and Qaim (2011) that indicates the elasticity of DES to income to be 0.66. Based on Blum and Szonyi (2014), the implementation cost is assumed to be 1 percent of the 38 low and lower-middle-income countries GDP in 2019 (based on WDI in 2019 (World Bank, 2020a)).
4	Irrigation expansion - Large-scale irrigation expansion	Rosegrant et al., 2017	IMPACT 3 modelling suite	This option reflects the hunger-reduction potential of large-scale irrigation expansion in developing countries by 2030, with projected irrigated area expansion of 20 million hectares by transforming rainfed areas.
5	Irrigation efficiency enhancement	Rosegrant et al., 2017	IMPACT 3 modelling suite	This measure considers the hunger-reduction potential of a 15percentage increase in basin efficiency by 2030 due to increased water infrastructure investment and water management improvement in food production units.
6	Irrigation expansion - Small scale irrigation expansion in Africa	FAO, 2020; You et al., 2011; Passarelli et al., 2018; Ecker & Qaim, 2011	Econometric model	Hunger-reduction potential of increased investment in small-scale irrigation expansion in Africa is estimated using the methodological note for calculating PoU (FAO, 2020) and the impact of the expansion on DES. The DES is estimated based on Passarelli et al. (2018) that finds 2.5 times increase in agricultural income, and Ecker and Qaim (2011) that indicate an elasticity of DES to income of 0.66. The total annual cost of the expansion is assumed to be US$ 3.8 billion per year based on the estimate by You et al. (2011).
7	Soil-water management	Rosegrant et al., 2017	IMPACT 3 modelling suite	This measure considers the hunger-reduction potential of water availability enhancement technologies such as no-till agriculture and water harvesting with an investment of about US$ 4.6 billion annually.
8	Crop protection - insects	Rosegrant et al., 2014	Decision Support System for Agrotechnology Transfer (DSSAT) crop model and IMPACT 2 modelling suite	This measure simulates hunger-reduction potential of investments that promote the adoption of crop protection technologies for insects. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 50 per ha cost.
9	Crop protection - diseases	Rosegrant et al., 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger-reduction potential of investments that promote the adoption of crop protection technologies for diseases. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 40 per ha cost.
10	Crop protection - weeds	Rosegrant et al., 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger-reduction potential of investments that promote the adoption of crop protection technologies for weeds. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 60 per ha cost.
11	Nitrogen-use efficiency	Rosegrant et al., 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger-reduction potential of investments that promote the adoption of agricultural management practices and improved crop varieties to enhance crop nitrogen-use efficiency. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 500 per ha cost.
12	Integrated soil fertility management	Rosegrant et al., 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger-reduction potential of investments that promote the adoption of integrated soil fertility management. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 100 per ha cost.
13	ICT - Agricultural information services	FAO et al., 2019; Hoddinott et al., 2013	Econometric model and cost-benefit analysis	Hunger reduction potential of improved access to market information through ICT is estimated by extending Hoddinott et al. (2013); poverty reduction assessments in six countries were extrapolated to cover 69 low and lower-middle income countries. The estimated poverty reduction levels are then

(*continued on next page*)

Table 2 (*continued*)

	Interventions	Sources	Modelling framework	Calculations and assumptions
				converted into the corresponding hunger-reduction levels using an estimated equivalence coefficient of 0.68 (FAO et al., 2019).
14	Infrastructure (Road, Rail, Electricity)	Rosegrant et al., 2017	IMPACT 3 modelling suite	This option simulates the hunger-reduction potential of a mix of infrastructure improvements in developing countries, focusing primarily on improvements to transportation infrastructure (road building, road maintenance, and railroads) and increased rural electrification.
15	Food loss reduction along the value chain	Rosegrant et al., 2015	IMPACT 2 modelling suite	The hunger-reduction potential of increased investments in post-harvest reduction is estimated assuming a scenario where a 10 percent reduction in the post-harvest loss is maintained globally by 2030 through increased investments in infrastructure.
16	International trade - Completing the Doha Development Agenda (DDA)	Anderson, 2018; FAO et al., 2019	Cost-benefit analysis	Hunger-reduction potential of enhancing international trade is estimated converting Anderson's (2018) poverty reduction estimate of about 160 million using an estimated equivalence coefficient of 0.68 (FAO et al., 2019). Following Anderson (2018), 5 percent of the estimated annual benefit in 2025 is assumed to be the adjustment cost of the trade reform for the period of ten years, amounting to an annual total investment of US$ 30 billion.
17	Intra-African trade - African continental Free Trade Area (AfCFTA) agreement	Anderson, 2018; FAO et al., 2019; World Bank, 2020b	Global dynamic CGE model and cost-benefit analysis	Hunger reduction potential of AfCFTA is estimated converting World Bank's (2020b) poverty reduction estimate of 30 million by 2035. The poverty reduction by 2030 is first calculated using linear interpolation and converted into hunger reduction using an estimated equivalence coefficient of 0.68 (FAO et al., 2019). To estimate the implementation cost of AfCFTA, we follow Anderson (2018) in assuming 5 percent of the economic gains from the continental free trade agreement estimated to be US$ 450 billion by 2035 in the study by World Bank (2020b) over ten years period. Then, the adjustment cost of the trade reform is then assumed to be US$ 2.25 billion per year.
18	Social protection - Scaling up existing programmes	FAO et al., 2020; Hidrobo et al., 2018; reviewed papers in Table A2	Cost-effectiveness analysis	Based on a review of cost-effectiveness studies of social protection programmes across different countries, the minimum per dollar cash transfer cost of per capita is identified at US$ 35.7 and used to calculate the annual per capita cost of scaling existing programmes. Based on the review of the current coverage of social protection programmes, we estimated that about 103.1 million people could be targeted.
19	Social protection - Establishing new programmes	FAO et al., 2020; Hidrobo et al., 2018; reviewed papers in Table A2	Cost-effectiveness analysis	Based on a review of cost-effectiveness studies of social protection programmes across different countries, the maximum per dollar cash transfer cost per capita is identified at US$ 88.9 and used to calculate the annual per capita cost of establishing new programmes. Based on the review of the current coverage of social protection programmes, we estimated that about 103.1 million people could be targeted.
20	COVID-19 - Social protection	FAO et al., 2020; Hidrobo et al., 2018; reviewed papers in Table A2	Econometric model estimates-based simulation and cost-effectiveness analysis	Following the less pessimistic COVID-19 impact scenario estimated by FAO et al. (2020) and based on the reviews of cost-effectiveness studies of social protection programmes across different countries, the maximum per dollar cash transfer cost per capita is identified at US$ 88.9. This is further used to calculate the annual per capita cost of social protection coverage for individuals that would fall into hunger due to COVID-19. Based on the less pessimistic scenario of COVID-19 impact on hunger estimated by FAO et al. (2020), we estimated that about 137.9 million people could be targeted.
21	Nutrition program	Shekar et al., 2017	Lives Saved Tool (LiST) for nutritional outcomes	This option considers increased investment in scaling up 7 nutrition specific interventions to 90 percent coverage in 37 countries that account for 90 percent of the stunted children globally to reduce stunting among children below 5 years of age. The estimated stunting reduction levels are then converted into the corresponding hunger reduction levels using an estimated equivalence coefficient of 0.997.
22	Female literacy improvement	Smith & Haddad, 2015; Shekar et al., 2017; World Bank, 2020a	Econometric model and cost-effectiveness analysis	Stunting reduction potential of investment in women's education is estimated using Smith and Haddad's (2015) elasticity of stunting to female secondary school enrolment (-0.166) for 37 countries that account for 90 percent of the stunted children globally. It is also assumed that the female secondary enrolment rate between 2011 and 2015 is maintained over the next ten years, which is about 6.66 million additional female students enrolled at a per capita cost of US$ 130. The estimated stunting reduction levels are then converted into the corresponding hunger reduction using an estimated equivalence coefficient of 0.997.

Table 3
Hunger reduction potential of interventions and cost of implementation from 2020 to 2030.

Least-cost rank	Interventions	Number of people lifted out of hunger (Million)	Cumulative number of people lifted out of hunger (Million)	Annual cost (US$ Million)	Cumulative amount of annual cost (US$ Million)	Annual cost per individual lifted out of hunger (US$)	Total cost per person lifted out of hunger (US $) over 2020–2030
1	Agricultural R&D efficiency enhancement	69.9	69.9	888	888	12.7	98
2	Agricultural extension services	81.5	151.4	2,096	2,984	25.7	199
3	ICT - Agricultural information services	26.6	178.0	698	3,682	26.2	114
4	Small-scale irrigation expansion in Africa	142.3	320.3	3,790	7,472	26.6	206
5	Agricultural R&D	92.0	412.3	2,960	10,432	32.2	249
6	Female literacy improvement	2.6	414.9	87	10,518	33.1	261
7	Social protection - Scaling up existing programmes	103.1	518.0	3,677	14,195	35.7	154
8	Crop protection - Insects	10.1	528.0	700	14,895	69.7	536
9	Social protection - Establishing new programmes	103.1	631.1	9,158	24,053	88.9	385
10	COVID-19 - Social protection	137.9	769.0	12,255	36,308	88.9	165
11	Crop protection - Diseases	8.8	777.8	875	37,183	99.4	768
12	Integrated soil fertility management	16.6	794.4	1,750	38,933	105.1	814
13	Crop protection - Weeds	9.4	803.8	1,050	39,983	111.7	863
14	Trade - African Continental Free Trade Area (AfCFTA)	15.3	819.1	2,250	42,233	147.1	1,136
15	Nitrogen-use efficiency	56.5	875.6	8,750	50,983	154.9	1,196
16	Nutrition-specific interventions	30.9	906.6	4,950	55,933	160.0	1,237
17	Food loss reduction	36.0	942.6	8,580	64,513	241.7	1,841
18	Irrigation efficiency enhancement	18.6	961.2	4,590	69,103	246.3	1,906
19	Trade - Doha Development Agenda	108.8	1,070.0	30,000	99,103	275.7	2,129
20	Infrastructure (Road, Rail, Electricity)	33.8	1,103.8	10,810	109,913	320.0	2,470
21	Soil-water management	12.2	1,116.0	4,580	114,493	374.5	2,899
22	Irrigation expansion - Global large-scale irrigation expansion	7.6	1,123.6	3,520	118,013	473.4	3,577

Note: Number of people lifted out of hunger and annual cost of each intervention are compiled and computed based on the studies and assumptions presented in Table 2. For each intervention, the number of people lifted out of hunger by the proposed investments is calculated as the difference between the projected number of hungry people in the business as usual 2030 scenario and the projected number of hungry people in the 2030 investment scenario. The annual cost per individual lifted out of hunger is then calculated as the annual cost divided by the number of people lifted out of hunger. The cumulative figures for the number of people lifted out of hunger and annual costs across the interventions reflect the total hunger reduction possible from all interventions and the total annual investments required. Total cost per person lifted out of hunger is calculated as total net discounted cost over the 10 years period (with the exception of COVID-19 social protection, ICT and scaling new and existing social protection programmes where the time frame is 2 to 5 years respectively, i.e. 2020–2021 and 2020–2024). The discount rate is assumed to be 5 percent, following Hoddinott, et al. (2013). The total cost per person lifted out of hunger is then calculated as the total net discounted cost divided by the number of people lifted out of hunger.

improve food distribution efficiency. Three of the interventions consider supporting marginal groups of society increasing access on food. The last two interventions serve to reducing child malnutrition through enhanced child and maternal care. The details of the calculations to estimate the hunger reduction potential and costs of the interventions are presented further in the Supplementary Material.

4.4. Investments to reduce hunger: Marginal cost curve results

After ranking the considered interventions in accordance with their average cost per undernourished, a MACC of hunger reduction potential was elaborated (Fig. 2). Specific parameters of MACC such as the width (number of people lifted out of hunger) and length (annual cost per individual lifted out of hunger) of each bar (intervention) and additional indicators such as cumulative costs and cumulative hunger reduction potentials are provided in Table 3. According to the estimation, overall, the measures included in the MACC have the potential to lift over a billion people out of hunger over ten years between 2020 and 2030. To meet the G7 commitment of lifting 500 million people out of hunger by 2030, an average annual investment ranging between about US$ 11 to 14 billion will be required.[6] This would be achieved through a mix of least-cost intervention options –agricultural R&D efficiency enhancement, agricultural extension services, agricultural R&D, ICT -

[6] As can be seen from Fig. 2, the per capita cost estimate of lifting 500 million people out of hunger is within range of the prior estimates by Torero and von Braun (2015) and Laborde et al. (2016) that vary between US$ 30 to 38 per person lifted out of hunger.

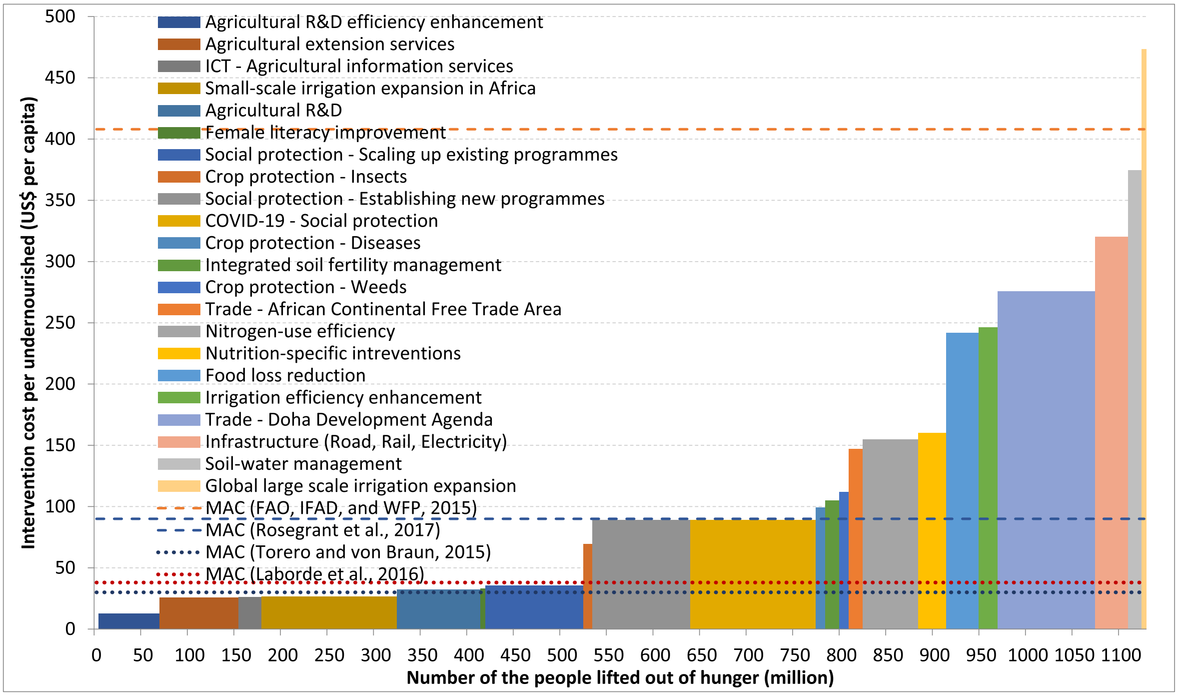

Fig. 2. Marginal cost curve of the suggested interventions to eradicate hunger. Note: The MACC for hunger shows the cost of each hunger reduction measure such that each bar represents a single intervention where the width shows the number of individuals lifted out of hunger, the height its associated annual per-capita cost, and the area its associated total annual cost. The total width of the MACC reflects the total hunger reduction possible from all interventions, while the sum of the areas of all of the bars represents the total annual cost of reducing hunger through the implementation of all interventions considered. The positions of the bars along the MACC reflect the order of each intervention by their cost-effectiveness based on the annual per-capita costs. When moving along the MACC from left to right, the cost-effectiveness of the interventions worsens as each next intervention becomes more expensive than the preceding. It is important to note that this figure is subject to considerable uncertainty given various assumptions made in the calculation, missed synergies and potential overlap between interventions and impact of extreme events not considered when estimating the costs.

agricultural information services, small-scale irrigation expansion in Africa, female literacy improvements, and scaling up existing social protection. Following the 2030 hunger projection by FAO et al. (2020) and taking the preliminary estimates on the impact of COVID-19 on hunger (based on the less pessimistic scenario) into consideration, the global goal of ending hunger by 2030 may require an investment of about US$ 39 to 50 billion to lift about 840 to 909 million people out of hunger.

As illustrated in Fig. 2, investing in agricultural R&D efficiency enhancement, agricultural extension services, 'ICT - Agricultural information systems', are low cost options that have a relatively large hunger-reduction potential. Scaling up existing social protection programmes and establishing new programmes to serve food insecure households can reduce the number of people at risk of hunger by about 206.2 million at an annual per capita cost of about US$ 35.7 and US$ 88.9 per undernourished. To address the potential increase in the number of people at risk of hunger estimated in 2020 and 2021 of about 137.9 million, an additional US$ 12.3 billion will need to be spent in social protection. While investing in women's education also provides a least cost option to reduce hunger, investment in nutrition-specific investments can significantly reduce hunger by about 30 million at a total incremental average cost of about US$ 5 billion per year.

Investments in 'African Continental Free Trade Area (AfCFTA) agreement', 'Food loss and waste reduction', 'Irrigation efficiency enhancement', improvements in international trade (completion of the DDA), 'Infrastructure', 'Soil-water management', and 'Large-scale irrigation expansion' can considerably decrease undernourishment by about 232.2 million. These hunger-reduction measures are relatively expensive investment options that require a longer time for implementation and hence would need to be frontloaded earlier in the decade to have a large effect soon before 2030.

It is also important to note that the marginal cost curve elements include many investments that contribute to long term development and sustainability, beyond 2030 and not restricted to hunger reduction. For instance, investments in agricultural R&D and research efficiency, irrigation expansion and water use efficiency, soil water management and infrastructure all have long term impact going further to 2050 and also have much broader development impacts beyond the reduction of hunger, like poverty, child malnutrition, and the environment (Rosegrant et al., 2017). The composition of the investments facilitates an increase in resilience for populations affected by hunger today or at risk of hunger in this decade. Since it is beyond the scope of this study, such lagged benefits of investments and their impact on other development outcomes beyond hunger has not been considered in this study and hence the estimates presented might understate the full benefits of these investments.

5. Uncertainties and caveats of the assessment

5.1. Uncertainties associated with data and assumptions

The developed MACC of hunger reduction can considerably contribute to debates over the prioritization of efforts and allocation of investments to achieve the global goal of ending hunger. However, it is important to note that the cost assessments and rankings of the interventions are subject to various levels of uncertainties due to various assumptions made in the calculations. Thus, these estimates should be perceived as only the best possible estimations based on available data. Due to the limited availability of data for conducting a proper quantitative analysis of uncertainty, we here present a qualitative analysis of uncertainty (Table 4). This assessment is related to the description of calculation steps presented in Table 2. We further use narrative analysis

Table 4
Uncertainties of potentials and implementation costs of the hunger reduction interventions.

Least-cost rank	Interventions	Uncertainties for number of people lifted out of hunger (Million)	Uncertainties for annual cost per individual lifted out of hunger (US$)
1	Agricultural R&D efficiency enhancement	++	+++
2	Agricultural extension services	+	+++
3	ICT - Agricultural information services	++	+
4	Small-scale irrigation expansion in Africa	+	+
5	Agricultural R&D	++	++
6	Female literacy improvement	+	+
7	Social protection - Scaling up existing programmes	++	+
8	Crop protection – Insects	++	+++
9	Social protection - Establishing new programmes	++	+
10	COVID-19 - Social protection	+++	+
11	Crop protection – Diseases	++	+++
12	Integrated soil fertility management	++	+++
13	Crop protection – Weeds	++	+++
14	Trade - African Continental Free Trade Area (AfCFTA)	+	+++
15	Nitrogen-use efficiency	++	+++
16	Nutrition-specific interventions	+	++
17	Food loss reduction	+++	++
18	Irrigation efficiency enhancement	++	++
19	Trade - Doha Development Agenda	+	+++
20	Infrastructure (Road, Rail, Electricity)	+++	++
21	Soil-water management	++	++
22	Irrigation expansion - Global large-scale irrigation expansion	++	++

Note: Levels of uncertainty are defined with "+" for 'low', "++" for 'moderate' and "+++" for 'high'. Evidence-based data estimated through econometric assessment or obtained from reliable statistical sources were considered with 'low' uncertainty. We assume 'moderate' uncertainty if the data was found out from simulation modelling studies or derived through additional calculations considering data with low uncertainty. 'High' uncertainty emerges in case value was obtained through additional calculations based on data with 'moderate uncertainty' or based on pure assumptions.

of potential impacts of various uncertainties on the levels of costs and hunger reduction potential and shape of the MACC.

According to the assessments, despite the very low cost of 'Agricultural R&D efficiency enhancement', this cost level is subject to 'high' uncertainty and hunger reduction potential is subject to 'moderate' uncertainty (Table 4). The cost of 'Agricultural extension services' is characterized with 'low' uncertainty but its hunger reduction potential is characterized with 'high' uncertainty. Most of the remaining interventions except 'Small-scale irrigation in Africa' and 'Female illiteracy improvement' are subject to 'moderate' or 'high' levels of uncertainty.

5.2. Missed synergies, overlaps and other investment options

As each intervention in the MACC is considered independently with its marginal costs and hunger reduction effects, beneficial synergies among interventions are not captured. For instance, interventions such as constructing irrigation systems and implementation of ICT in water distribution systems may have additional synergetic benefits. Yet, the presented MACC indicates conservative estimates of mixes of interventions. Consequently, it is possible that the costs are overestimated and hunger reduction impacts are underestimated for such cases.

Some overlap or double counting may also exist between the considered interventions as there are likely a group of people who have already been lifted out of hunger through one policy yet may benefit from the second policy. It may occur for example in places where many people are quite near the threshold of undernourishment. This implies that a certain group of people could be counted multiple times and hunger reduction potential of the interventions might be overestimated. Also, in places where the gap between adequate and actual nourishment is high, a bundle of complementary interventions may be required to lift people out of hunger rather than a single policy (Banerjee et al. 2015; Barrett et al., 2020). Hence, there may be some undercounting in the event of bundled programs which could instead lead to an underestimation of the hunger reduction potential of interventions and overestimation of the costs. However, since the MACC is built based on an aggregated assessment of interventions at the global level, our study does not highlight such details. Further studies should differentiate hunger levels, their exact causes and precise solutions to address this issue. Bottom-up integrated assessment models may capture such synergies and reduce double-counting, consequently allowing for developing consistent MACCs.

Analysing the hunger-reduction potential and costs of the selected twenty-two options available from the recent studies, it is likely that we omitted other hunger-reduction interventions where costs and hunger-reduction potentials were either not available or not widely discussed in the literature. As an example, food production and harvesting in marine environments including the production and harvesting of seafood and seagrasses were excluded as the option was not widely assessed at the global level for hunger prevention. Likewise, alternative foods produced from insects and non-traditional food crops were not considered as their health safety and upscaling potential have not been properly examined. With more advances in the sciences, new interventions can come into the scene and they may change the shape of the marginal abatement cost curve for hunger-reduction.

5.3. The impact of extreme events on the cost of hunger reduction

Investment options reviewed in this study did not explicitly include climate change or the effects of extreme events like conflicts, pandemics and extreme weather events on hunger-reduction. Even though it is understood that important drivers of acute food insecurity in 2020 were conflict, economic fallout of COVID-19, and extreme weather events. In 2020 an estimated 99 million people were in acute food insecurity because of conflict situations (Food Security Information Network & Global Network Against Food Crises, 2021). This statistic may only be roughly compared with the statistic of undernourishment (768 million) as the two statistics are based on very different concepts.

In 2019, six out of ten people eligible for global humanitarian food assistance were residing in countries with ongoing conflicts (Development Initiatives, 2020). Also, the share of children suffering from stunting residing in conflict zones has considerably increased within the last two decades (FAO et al., 2017). Conflicts directly and indirectly impact on food insecurity. For instance directly through resource loss when fields are rendered unusable due to mines, and indirectly through disruption of markets and trade. Barrett (2021) makes the argument that the hunger crises today and of the future are fundamentally humanitarian and conflict resolution issues rather than shortcomings with agri-food systems, and addressing hunger requires targeted humanitarian and conflict resolution efforts instead of agri-food innovations. While it is widely regarded that conflict resolution can have a profound impact on hunger reduction, estimating the cost, such as diplomatic and peace keeping engagements, and impacts on other interventions would be multifaceted and quite complex (Kemmerling, Schetter, & Wirkus, 2021), and hence was not considered in this study.

Studies reviewed in our analysis were conducted before the COVID-19 pandemic and did not consider the impacts of such an event or similar pandemics on the goal of hunger reduction and the cost to other interventions. Nonetheless, it is noteworthy that as a pandemic event like COVID-19 impacts all aspects of society and the economy it surely would have a considerable impact on the effort to achieving zero hunger before 2030, given that all the resources needed to achieve this goal would be directed towards the fight against the pandemic. This is especially true for financing, which is mainly from wealthy nations but immediately repurposed and prioritized for healthcare investments and economic stimulus for their citizenry, thus leaving the fight against hunger in peril, howbeit temporarily. The extent and impact of this temporary neglect due to the pandemic are not assessed in this study.

Climate change impacts not only hunger levels but also the costs and potential of the targeted hunger prevention interventions. Rising temperatures and consequent drought increases the value of water and reduce the efficiency of the projects related to irrigation improvement (IPCC, 2019). Also, intensified flooding events induced by temperature rise destroys agricultural production systems as well as affect hydraulic infrastructure reducing the resilience capacity to cope with temperature anomalies and systems, exposing the farmers and rural community to hunger. Meanwhile, climate change mitigation efforts are increasingly and deservedly prioritized, but sometimes at the expense of the efforts to reduce hunger. For instance, available land likely to be used for solar power generating projects instead of agriculture, hydroelectric power dams are prioritized regardless of the impact on surrounding farms, and available public funds are allocated to climate change mitigation efforts limiting finance to hunger-reduction programmes. In our study, these linkages and the extent of the impact on the interventions were not considered.

5.4. Effects of scaling on marginal costs

As the marginal cost of each intervention is assumed to be fixed per undernourished person lifted out of hunger, the aggregated marginal cost curve appears like a staircase (step) function. Growing marginal cost in the aggregated marginal cost curve is due to the ranking of the individual interventions. In reality, increasing (not fixed) marginal costs of hunger reduction are expected for each intervention. Due to the scaling effects, it is not surprising that the additional cost of reducing the number of undernourished people increases with the number of undernourished people lifted out of hunger. Lifting the first group of people out of hunger requires less investment than the last group of hungry people since the cost of reaching the most vulnerable and hard to reach populations is a lot more than to reach those that are less in need of food assistance and support. Based on our data collected from the literature review of contributions and costs of various interventions, continuous aggregated MACC can be derived by replacing the staircase graph with the polygon graph (Supplementary Material 2). The polygon-type graph can be fitted to obtain smoothly growing cost functions that are similar to the ones obtained through modelling. Combining interventions considering their varying marginal costs is an alternative option to assess aggregated MACC yet it may require top-down modelling application (Klepper & Peterson, 2006). Such assessment would most likely change the shape of the aggregated MACC, having more people lifted out of hunger at a low price at the beginning but increasing the costs of interventions even further for the remaining groups of people who require food support the most.

5.5. Other limitations and some strengths of the marginal cost curve approach

MACC can be used to identify promising policies and programmes for investment. This facilitates priority setting by governments and investment stakeholders from the private sector and civil society. An advantage of MACC analysis is also its transparency. However, the concept has several limitations which have been already highlighted in previous studies (Kesicki & Ekins, 2012; Bockel et al., 2012; Eory et al., 2018). One of the limitations relates to the fact that the MACC presents the incremental cost of reducing hunger for a single point in time. Hence, it cannot capture intertemporal dynamics and technological inertia. Education and R&D investments for example yield gains after sometime. In a static MACC, lagged effects for such investments are not effectively captured in the MACC.[7] Another aspect is that the MACC concentrates on hunger reduction and thus attributes the entire cost of the interventions only to hunger reduction. This is an overestimation in terms of economic cost-benefit considerations, as most of the interventions considered in this analysis generate various ancillary benefits, including reducing poverty and enhancing health, environmental sustainability, and education. Nevertheless, the MACC can be considered useful for an assessment of various potential interventions to reduce hunger based on a synthesis of studies from different fields based on multiple methodologies.

Additional analysis – for example at regional or perhaps national levels – is also warranted for prioritizing the measures for implementation and setting policies to promote them. Additional studies could focus on extending the analysis by identifying additional cost-effective measures in specific country contexts which can further contribute to hunger reduction. Technical and behavioural challenges to implementing the identified least-cost measures need to be considered in the prioritization process, despite their economic attractiveness.

While most of the parameters used in building the global hunger MACC are compiled from system- and economy-wide model-based studies, the cost and hunger reduction potential of several interventions were assessed based on a specific and large-scale cost-effectiveness studies. A next step, in this respect would be to evaluate the various measures using bottom-up integrated assessment modelling that could capture synergies and trade-offs between the different measures, as well as risks and uncertainties. Theoretically, that would be an advantage, but it remains difficult to embed the level of granularity and programmatic detail in such modelling, as pursued with the 22 interventions considered in the MACC approach here. Yet, additional quantitative sensitivity analysis and interpretation of the different results would be helpful to policymakers to support their decision-making.

6. Policy implications of MACC analyses

This study has synthesized the findings of various model- and cost-benefit analysis-based studies on food and nutrition security interventions to assess the expected levels of the hunger reduction and the costs of achieving zero-hunger by 2030. The most recent 'State of Food Security and Nutrition in the World' report estimated levels of undernourishment by 2030 to be about 630 million without considering the impact of COVID-19, or 660 million when considering the impact of COVID-19 on hunger.

MACC analyses are a basis for policy strategies and policy mobilization. The MACC for hunger reduction developed by synthesizing the

[7] However, Rosegrant et al. (2017) capture the lag effects of investments in agricultural R&D in the investment-yield estimation model using a perpetual inventory method, where investments in agricultural R&D contribute to the stock of knowledge over time. The lag structure in the perpetual inventory method used in the study followed a gamma distribution where the impact of R&D investments peaked after ten years from initial investment and then sunk to zero after ten years from its peak.

outcomes of multiple studies indicates the overall potential of the interventions identify what it takes to end hunger by 2030. Considerable investment is required, but it is a question of political commitment to get the finance mobilized at national and global levels and the actual investments implemented in sound ways. Compared to the hundreds of billions of US$ for economic rescue packages to mitigate COVID-19 in many OECD countries, the investments to end hunger presented in this analysis are rather modest. The results from the MACC indicate that:

- Achieving target 2.1 of SDG 2 need not be prohibitively expensive, provided that a mix of least-cost measures with large hunger reduction potential are prioritized.
- Investments with long-term effects should be frontloaded in the decade to have a large effect soon before 2030.
- To end hunger by 2030, options that require high up-front investments but also have a high long-term impact need to be in the investment mix.
- Overall, the measures included in this MACC analysis have the potential to lift about a billion people out of hunger over ten years till 2030.

Yet, given the finding that investments to end hunger are rather modest, the troublesome question arises, what political economy forces prevent the required actions? Obviously, the spending priorities of those who could mobilize the resources seem not sufficiently oriented toward overcoming hunger, and the voice and influence of the undernourished seem too weak to enforce the investment action. Attempting to comprehensively answer this question goes beyond the scope of this paper. However, research into assessing the political economy for each of the considered interventions in the MACC might help to identify a set of politically acceptable second-best MACC elements that might differ from the marginal costs.

CRediT authorship contribution statement

Bezawit Beyene Chichaibelu: Conceptualization, Data curation, Methodology, Writing – original draft. **Maksud Bekchanov:** Methodology, Visualization, Writing – review & editing. **Joachim Braun:** Conceptualization, Validation, Writing – review & editing, Supervision. **Maximo Torero Cullen:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank Dr Zaneta Kubik, Dr Lukas Kornher, Dr Heike Baumüller, Dr Nicolas Gerber, Dr Alisher Mirzabaev, Dr Tekalign Gutu Sakketa and Dr Muhammed Abdella Usman for their helpful comments and inputs. The authors would also like to thank Dr Henry Kankwamba and Madina Japakhova for their technical support and assistance and the three anonymous reviewers for their insightful suggestions and careful reading of the manuscript. This research was funded by the German Federal Ministry for Economic Cooperation and Development (BMZ).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2021.102151.

References

Addams, L., Boccaletti, G., Kerlin, M., Stuchtey, M., 2009. Charting our water future: economic frameworks to inform decision-making. McKinsey & Company, New York http://www.2030wrg.org/wp-content/uploads/2014/07/Charting-Our-Water-Future-Final.pdf.

Anderson, K., 2018. In: Prioritizing Development: A Cost Benefit Analysis of the United Nations' Sustainable Development Goals. Cambridge University Press, pp. 192–218. https://doi.org/10.1017/9781108233767.011.

Barrett, C.B., Benton, T.G., Cooper, K.A., Fanzo, J., Gandhi, R., Herrero, M., James, S., Kahn, M., Mason-D'Croz, D., Mathys, A., Nelson, R.J., Shen, J., Thornton, P., Bageant, E., Fan, S., Mude, A.G., Sibanda, L.M., Wood, S., 2020. Bundling Innovations to Transform Agri-Food Systems. Nat*ure* Sustain*ability* 3 (12), 974–976.

Barrett, C.B., 2021. Overcoming Global Food Security Challenges through Science and Solidarity. Am. J. Agric. Econ. 103 (2), 422–447. https://doi.org/10.1111/ajae.v103.210.1111/ajae.12160.

Banerjee, A., Duflo, E., Goldberg, N., Karlan, D., Osei, R., Parienté, W., Shapiro, J., Thuysbaert, B., Udry, C., 2015. A multifaceted program causes lasting progress for the very poor: Evidence from six countries. Science 348 (6236). https://doi.org/10.1126/science.1260799.

Bhutta, Z.A., Das, J.K., Rizvi, A., Gaffey, M.F., Walker, N., Horton, S., Webb, P., Lartey, A., Black, R.E., 2013. Evidence-based interventions for improvement of maternal and child nutrition: What can be done and at what cost? The Lancet 382 (9890), 452–477. https://doi.org/10.1016/S0140-6736(13)60996-4.

Blum, J.M., Szonyi, J., 2014. Investment requirements in extension to achieve zero hunger and adapt to climate change. Journal of Agricultural Science and Technology A 4, 552–562. https://doi.org/10.17265/2161-6256/2014.07.002.

Bockel, L., Sutter, P., Touchemoulin, O., Jönsson, M., 2012. Using marginal abatement cost curves to realize the economic appraisal of climate smart agriculture policy options. FAO. http://www.fao.org/3/a-bq866e.pdf.

Cafiero, C., Gennari, P., 2011. The FAO indicator of the prevalence of undernourishment. FAO. http://www.fao.org/fileadmin/templates/ess/ess_test_folder/Workshops_Events/Food_Security_for_All_FEB2011/Background_paper.pdf.

Development Initiatives, 2020. Global Humanitarian Assistance Report 2020. Development Initiatives, Bristol, UK.

Ecker, O., Qaim, M., 2011. Analyzing nutritional impacts of policies: An empirical study for Malawi. World Dev. 39 (3), 412–428. https://doi.org/10.1016/j.worlddev.2010.08.002.

Eory, V., Pellerin, S., Garcia, G.C., Lehtonen, H., Licite, I., Mattila, H., Lund-Sørensen, T., Muldowney, J., Popluga, D., Strandmark, L., Schulte, R., 2018. Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential. J. Cleaner Prod. 182, 705–716. https://doi.org/10.1016/j.jclepro.2018.01.252.

FAO, 2020. FAOSTAT Statistical Database. FAO, Rome. http://www.fao.org/faostat/en/.

FAO, IFAD, WFP, 2015. Achieving zero hunger: The critical role of investments in social protection and agriculture. FAO, Rome. http://www.fao.org/3/a-i4951e.pdf.

Fink, G., Peet, E., Danaei, G., Andrews, K., McCoy, D.C., Sudfeld, C.R., Smith Fawzi, M.C., Ezzati, M., Fawzi, W.W., 2016. Schooling and wage income losses due to early-childhood growth faltering in developing countries: National, regional, and global estimates. The American journal of clinical nutrition 104 (1), 104–112. https://doi.org/10.3945/ajcn.115.123968.

Fan, S., Headey, D., Laborde, D., Mason-D'Croz, D., Rue, C., Sulser, T.B., Wiebe, K.D., 2018. Quantifying the cost and benefits of ending hunger and undernutrition: Examining the differences among alternative approaches. In: IFPRI, Washington DC. https://doi.org/10.2499/9780896292994.

FAO, 2018. The future of food and agriculture – Alternative pathways to 2050. FAO, Rome. http://www.fao.org/3/I8429EN/i8429en.pdf.

FAO, IFAD, UNICEF, WFP, WHO, 2017. The state of food security and nutrition in the world 2017. Building Resilience for Peace and Food Security. Transforming food systems for affordable healthy diets. FAO, Rome.

FAO, IFAD, UNICEF, WFP, WHO, 2019. The state of food security and nutrition in the world 2019. Safeguarding against economic slowdowns and downturns. FAO, Rome. http://www.fao.org/3/ca5162en/ca5162en.pdf.

FAO, IFAD, UNICEF, WFP, WHO, 2020. The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. FAO, Rome. https://doi.org/10.4060/ca9692en.

FAO, IFAD, UNICEF, WFP, WHO, 2021. The state of food security and nutrition in the world 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets. for all. FAO, Rome. https://doi.org/10.4060/cb4474en.

Food Security Information Network, Global Network Against Food Crises, 2021. *Global Report on Food Crises 2021*. Food Security Information Network. http://https://www.fsinplatform.org/sites/default/files/resources/files/GRFC2021.pdf.

Hasegawa, Tomoko, Fujimori, Shinichiro, Havlík, Petr, Valin, Hugo, Bodirsky, Benjamin Leon, Doelman, Jonathan C., Fellmann, Thomas, Kyle, Page, Koopman, Jason F.L., Lotze-Campen, Hermann, Mason-D'Croz, Daniel, Ochi, Yuki, Pérez Domínguez, Ignacio, Stehfest, Elke, Sulser, Timothy B., Tabeau, Andrzej, Takahashi, Kiyoshi, Takakura, Jun'ya, van Meijl, Hans, van Zeist, Willem-Jan, Wiebe, Keith, Witzke, Peter, 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Change 8 (8), 699–703. https://doi.org/10.1038/s41558-018-0230-x.

Headey, D.D., 2013. Developmental drivers of nutritional change: A cross-country analysis. World Dev. 42, 76–88. https://doi.org/10.1016/j.worlddev.2012.07.002.

Headey, D., Heidkamp, R., Osendarp, S., Ruel, M., Scott, N., Black, R., Shekar, M., Bouis, H., Flory, A., Haddad, L., Walker, N., 2020. Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. The Lancet 396 (10250), 519–521. https://doi.org/10.1016/S0140-6736(20)31647-0.

Hidrobo, M., Hoddinott, J., Kumar, N., Olivier, M., 2018. Social Protection, Food Security, and Asset Formation. World Dev. 101, 88–103. https://doi.org/10.1016/j.worlddev.2017.08.014.

HLPE, 2014. *Food losses and waste in the context of sustainable food systems*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. FAO, Rome.

HLPE, 2020. *Food security and nutrition: building a global narrative towards 2030.* A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. FAO, Rome.

Hoddinott, J., Maluccio, J.A., Behrman, J.R., Flores, R., Martorell, R., 2008. Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. The Lancet 371 (9610), 411–416. https://doi.org/10.1016/S0140-6736(08)60205-6.

Hoddinott, J., Rosegrant, M., Torero, M., 2013. Hunger and Malnutrition. In: Lomborg, B. (Ed.), Global Problems, Smart Solutions: Costs and Benefits. Cambridge University Press, Cambridge, pp. 332–389. https://doi.org/10.1017/CBO9781139600484.008.

Horton, S., Steckel, R.H., 2013. Malnutrition: Global economic losses attributable to malnutrition 1900–2000 and projections to 2050. In: Lomborg, B. (Ed.), How much have global problems cost the world? Cambridge University Press, pp. 247–272. https://doi.org/10.1017/CBO9781139225793.010. A scorecard from 1900 to 2050.

Horton, S., Hoddinott, J., 2014. Benefits and costs of the food and nutrition targets for the post-2015 development agenda: Post-2015 consensus. *Food Security and Nutrition Perspective Paper*. In: Copenhagen Consensus Center. http://www.copenhagenconsensus.com/sites/default/files/food_security_and_nutrition_perspective_-_horton_hoddinott_0.pdf.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2019. Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

Kemmerling, B., Schetter, C., Wirkus, L., 2021. Addressing Food Crises in Violent Conflicts: Food Systems Summit Brief Prepared by Research Partners of the Scientific Group for the Food Systems Summit. Center for Development Research, Bonn https://hdl.handle.net/20.500.11811/9142.

Kesicki, F., Ekins, P., 2012. Marginal abatement cost curves: A call for caution. Climate Policy 12 (2), 219–236. https://doi.org/10.1080/14693062.2011.582347.

Kesicki, F., 2013. Marginal abatement cost curves: combining energy system modelling and decomposition analysis. Environ. Model. Assess. 18 (1), 27–37.

Klepper, G., Peterson, S., 2006. Marginal abatement cost curves in general equilibrium: the influence of world energy prices. Resources and Energy Economics 28 (1), 1–23.

Laborde, D., Bizikova, L., Lallemant, T., Smaller, C., 2016. Ending Hunger: What would it cost? International Institute for Sustainable Development (IISD) and IFPRI Briefing Note. IISD, Winnipeg, MB, Canada https://www.iisd.org/publications/ending-hunger-what-would-it-cost.

Mason-D'Croz, Daniel, Sulser, Timothy B., Wiebe, Keith, Rosegrant, Mark W., Lowder, Sarah K., Nin-Pratt, Alejandro, Willenbockel, Dirk, Robinson, Sherman, Zhu, Tingju, Cenacchi, Nicola, Dunston, Shahnila, Robertson, Richard D., 2019. Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. World Dev. 116, 38–53. https://doi.org/10.1016/j.worlddev.2018.12.006.

Passarelli, S., Mekonnen, D., Bryan, E., Ringler, C., 2018. Evaluating the pathways from small-scale irrigation to dietary diversity: Evidence from Ethiopia and Tanzania. Food Security 10 (4), 981–997. https://doi.org/10.1007/s12571-018-0812-5.

Ragasa, C., Mazunda, J., 2018. The impact of agricultural extension services in the context of a heavily subsidized input system: The case of Malawi. World Dev. 105, 25–47. https://doi.org/10.1016/j.worlddev.2017.12.004.

Rosegrant, M.W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R.D., Fisher, M., Cox, C. M., Garrett, K., Perez, N.D., Sabbagh, P., 2014. Food security in a world of natural resource scarcity: The role of agricultural technologies. IFPRI. https://www.ifpri.org/publication/food-security-world-natural-resource-scarcity-role-agricultural-technologies.

Rosegrant, M.W., Magalhaes, E., Valmonte-Santos, R., Mason-D'Croz, D., 2015. Returns to investment in reducing postharvest food losses and increasing agricultural productivity growth: Post-2015 Consensus. *Food Security and Nutrition Assessment Paper*. Copenhagen Consensus Center. http://www.copenhagenconsensus.com/sites/default/files/food_security_nutrition_assessment_-_rosegrant_0.pdf.

Rosegrant, M.W., Sulser, T.B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., Willaarts, B., 2017. Quantitative foresight modeling to inform the CGIAR research portfolio. (Project Report for USAID). IFPRI.

Ruel, M.T., Alderman, H., Maternal and Child Nutrition Study Group, 2013. Nutrition-sensitive interventions and programmes: How can they help to accelerate progress in improving maternal and child nutrition? The Lancet 382 (9891), 536–551. https://doi.org/10.1016/S0140-6736(13)60843-0.

Sachs, Jeffrey D., Schmidt-Traub, Guido, Mazzucato, Mariana, Messner, Dirk, Nakicenovic, Nebojsa, Rockström, Johan, 2019. Six transformations to achieve the Sustainable Development Goals. Nat. Sustainability 2 (9), 805–814. https://doi.org/10.1038/s41893-019-0352-9.

Schmidhuber, J., Bruinsma, J., 2011. Investing towards a world free of hunger: Lowering vulnerability and enhancing resilience. In: Prakash, A. (Ed.), Safeguarding food security in volatile global markets. FAO, Rome, Italy, pp. 523–549 http://www.fao.org/3/i2107e/i2107e.pdf.

Schneider, Uwe A., McCarl, Bruce A., Schmid, Erwin, 2007. Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agric. Syst. 94 (2), 128–140.

Shekar, M., Kakietek, J., Eberwein, J.D., Walters, D. (Eds.), 2017. An Investment Framework for Nutrition: Reaching the Global Targets for Stunting, Anemia, Breastfeeding, and Wasting. Washington, DC: World Bank.

Smith, L.C., Haddad, L., 2015. Reducing child undernutrition: Past drivers and priorities for the post-MDG era. World Dev. 68, 180–204. https://doi.org/10.1016/j.worlddev.2014.11.014.

Torero, M., von Braun, J., 2015. *Toward a Zero-Hunger Goal by 2030: Some preliminary estimates of what it would cost*. Mimeo.

UNICEF, WHO, World Bank, 2020. Levels and trends in child malnutrition: Key findings of the 2020 edition of the Joint Child Malnutrition Estimates. UNICEF/ WHO/ World Bank Group. https://www.who.int/publications/i/item/jme-2020-edition.

World Bank, 2020a. *World Development Indicators* [Database]. The World Bank. https://databank.worldbank.org/source/world-development-indicators.

World Bank, 2020b. The African Continental Free Trade Area: Economic and distributional effects. The World Bank. http://hdl.handle.net/10986/34139.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun, Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 36 (6), 770–782. https://doi.org/10.1016/j.foodpol.2011.09.001.