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ORIGINAL ARTICLE

Future responses to environment-related food self-insufficiency, from local to global

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Abstract

In the coming decades, communities may become exposed to local food self-insufficiency due to climate change, land degradation and land scarcity. Rapid population growth may exacerbate this. To support mitigating policies, answers are needed to the following two research questions: (i) Where and to what extent will environment-related food self-insufficiency occur or increase over the period from 2015 to 2050 and (ii) How will local communities respond to increased food self-insufficiency? Potential responses to food self-insufficiency are agricultural expansion, agricultural intensification, import, migration, starvation and violent conflict. Answering these research questions is hampered for different reasons. A persistent debate is ongoing on whether environmentally induced food deficit may cause migration and violent conflict at all. Although a clear relationship is assumed as self-evident by many scholars and politicians, as yet no convincing evidence has been found, in contrast to the relevance of socioeconomic factors. Moreover, a lack of consistent and accurate data on local food supply and demand hampers mapping of food self-insufficiency in the present and future. In this article, we explore the difficulties to find a clear relationship between environmentally induced food deficit, migration and violent conflict, and propose and test an operational methodology that does provide preliminary answers to the research questions: *the necessary conditions approach*. The results are presented in maps and tables of environment-related food self-insufficiency and of plausible responses for 2015 and 2050. Over that period, local food self-insufficiency roughly doubles as well as the number of people living in conditions that favour starvation, migration and violent conflict. The increase in food self-insufficiency is mostly caused by a significant population growth on the one hand—hence the demand side—and a stagnating or even slightly declining food production on the other. In contrast, food self-sufficiency stays high and constant on the global scale.

Keywords Environmental food self-insufficiency · Migration · Conflict · Starvation · Intensification · Scenario

Introduction

2020 was the warmest year ever recorded (NASA 2021). The predicted impacts that arise from global warming are troublesome (IPCC 2021). The world should rather urgently prepare to absorb the impact. One of the pivotal questions is: 'can we feed the world by 2050?' This is an even more serious topic when the unprecedented growth, by around 2 to 3 billion people since 2015 on the one hand (European Commission 2018a) and increasing land scarcity and land degradation on the other (Van der Esch et al. 2017; IPBES 2018; IPCC 2020; FAO, IFAD, UNICEF, WFP, WHO 2020) are taken into consideration. Food insecurity will inevitably lead to survival strategies. When hunger looms, communities have limited options. Large-scale migration is one of them. Individuals or groups will try to escape the dire conditions. Expansion of agricultural activities into 'new' spaces may be explored, but these spaces become progressively scarce, leading to increased competition over space,

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land and other resources and even jobs. Therefore, these strategies may in turn lead to tensions, conflicted situations or even full swing armed confrontations. Of course, many people have no other choice than to 'freeze', meaning reduce food intake and starve. But, the number of people that do not simply accept this fate may be numerous. And even if they do, the humanitarian imperative has it that the world cannot watch people starve without an appropriate reaction such as improving local productivity or importing food (World Food Programme 2022). The following global analyses is an attempt to explore where these potential survival strategies—freeze, flight, fight, expand, intensify or import—are most likely to occur. This may serve as a useful early warning tool that may help mitigate disasters of a much larger magnitude than, for instance, the COVID-19 pandemic.

Hasegawa et al. (2015) and Doelman et al. (2019) found an overall improvement in food security for all 25 world regions[1] up to 2050. In their scenarios, the projected increase in food production compensates both the increase in food demand and potential loss from climate change, land degradation and land scarcity. However, this overall improvement may not exclude occurrence of pockets of increasing food self-insufficiency on local scales (Van Ittersum et al. 2016; IPCC 2020; Breman et al. 2019). FAO, IFAD, UNICEF, WFP, WHO (2019, 2020) recently expressed concerns about stagnating regional food productivity. In these 'less favourable' areas various factors may coincide in such a way that future prospects will turn negative.

The two research questions of this analysis are therefore: (i) where and to what extent will local communities potentially be exposed to food self-insufficiency from climate change, land degradation and/or land scarcity in the context of rapid population growth over the period 2015 to 2050 and (ii) how will these local communities likely respond to this challenge given the local environmental, socioeconomic and governance conditions? This article explores ways to answer these questions and proposes a 'necessary conditions approach' as a potentially appropriate methodology. It also presents preliminary results in the form of response maps to local food self-insufficiency in 2015 and in 2050, for methodological discussion, further elaboration and, eventually, policymaking as called for by De Bruin et al. (2022).

Methodology

The methodology section consists of two sub sections. The first elaborates on the development of maps of local food self-insufficiency in present and future, based on supply, demand and scale. The second and more extensive sub section elaborates on probable responses to food self-insufficiency. The environmental factors climate change, land degradation and land scarcity are chosen because their combination covers an extensive list of human-induced changes. For this analysis, these are broadly defined as 'the changes in climate and land that may affect production of food on local scales and as such local food self-sufficiency over the next decades'. These changes may concern soil erosion, nutrient depletion, crustation, compaction, pollution, drought frequency and intensity, flooding, extreme temperatures and rainfall, biodiversity, desertification, presence and limitations of fertile land suitable for agriculture, amongst others. Short-term impacts from natural disasters are not part of this study.

Food self-insufficiency in present and future

For our purpose, we defined 'potential local food self-insufficient areas' as spatial units in which food demand exceeds food production. The term 'food self-insufficient' is chosen because the focus is on insufficiency (the hardly readable alternative would be 'potential local areas that are not food self-sufficient'). The hypothetical local deficit in 2050 is expressed as the 'number of people without food', assuming zero migration over the period 2015 to 2050, taking local changes in climate, land productivity, land scarcity and demography into account. A few global maps of food self-sufficiency exist. Pradhan et al. (2014) identify how local a region can be in meeting its food demand. Baer-Nawrocka and Sadowski (2019) and Beltran-Peña et al. (2020) assess food self-sufficiency on the country scale in the present and in the twenty-first century, respectively. However, they all lack information on the extent of food self-insufficiency on the intended local scale of this analysis.

Food production

We identified three global sources of data about food production: (i) annual data on the national scale from FAO (2019); (ii) food production in the year 2010 at 10 by 10-km pixels from IFPRI (Gilbert et al. 2018) and (iii) data from the IMAGE model at 50 by 50-km pixels (IMAGE contributors 2019). For this analysis, we selected the FAO database as the most primary and transparent source of annual food production data for most countries in the world. The databases of IFPRI and IMAGE are derived from the FAO data as well, but have been transformed to specific years or scales, which make them less suitable for our purpose. FAO produces data on national food production in terms of biomass based on national statistics, annually. Their coherence is limited because they are measured according to differing

[1] These 25 world regions are derived from IMAGE contributors 2020a (see Online Resource 1 Table 3).

national procedures. Especially in low-income countries, the accuracy is on the lower end (FAO 2020).

For our purpose, we transformed the annual national data of food crops into local data for 2015 and 2050 in four steps. In the first step, we calculated a 5-year average over 2013–2017 to avoid single-year outliers and gaps. In the second step, the average national food production was locally redistributed to 1 × 1-km pixels of cropland using NDVI satellite values at 1 × 1-km resolution as a proxy for relative productivity (ESA 2017; European Commission 2018b). In the third step, the production in 2050 was calculated by superimposing 1 × 1 km 2001–2017 NDVI trends from MODIS (Didan 2015) over the current production and extrapolating those to 2050. These observed trends involve the combined effects of recent local climate change, land degradation and land scarcity which are all long-term phenomena. Obviously, these trends do not include changes that start to occur after 2017. Upgoing trends are limited to the local production potential taking environmental factors and potential management improvements into account according to the IMAGE model (IMAGE contributors 2020b). In the fourth step, biomass has been converted into dry matter weight using conversion factors for 38 crops from the IMAGE model (IMAGE contributors 2022c). The amount of animal-based food has been calculated in a similar manner as food crops (see Online Resource 1).

Food demand

On the *food demand side*, we used the 2-Up model (Huijstee et al. 2018) to determine the number of people per 1 × 1-km pixel in 2015 and 2050. The population change per pixel is according to the demographic growth in the SSP2 scenario, a broadly accepted and widely used middle-of-the-road scenario (European commission 2018a; Huijstee et al. 2018). The scenario is based on national birth and death rate data under the hypothetical condition of zero migration. The latter condition required a slight adjustment of the 2-Up model that originally includes migration in its calculations for 2050. We applied a minimum of 1050 kg dry matter production per capita per year based on the Average Daily Energy Requirement of 2350 kcal (Hiç et al. 2016). From Alexander et al. (2017), we derived a *dry matter production/dry matter food* ratio of 3 to 1. This is the middle of the global ratio of around 4 to 1 for plant and animal-based food and 2 to 1 for plant-based food only. This arbitrary choice relates to the generally less efficient food systems and lower animal-based food consumption in developing countries (FAO 2020). Dry matter food production and demand per pixel are expressed in terms of grain equivalents.

Spatial scale

A remaining question is the 'local' scale on which food self-insufficiency is determined and mapped. In practice, surpluses and deficits of food are settled in a wider area than in 1 × 1 km pixels. This is an informal process between citizens on the local scale or a more formal process on a wider scale by trade via the market place. Traditionally, cities function as the central places where food is redistributed over a wider area. Cities import food from rural areas. In part, this food can be re-allocated to other rural areas with unfulfilled demand. In this respect, cities and their rural surroundings act as more meaningful units for self-(in)sufficiency than pixels of one or a few km^2. For this analysis, we arbitrarily take moderate cities, larger than 50,000 inhabitants in the year 2015, plus their surrounding rural area with smaller towns within a 3-h travel time contour as meaningful spatial units (Diao et al. 2019). We call these 'city regions'. They are considered one single food and labour market. Areas that do not belong to a city region are assessed per 5 × 5-km pixel assuming predominantly local trade at walking distance, the 'remote regions'. In the maps, these remote regions are aggregated to 50 × 50 km for visual purposes.

For this analysis, food self-insufficiency per city region and remote region in 2015 and 2050 is calculated as the difference between its production and demand in terms of dry matter food per capita per year in *number of people without food*. The extent of the city and remote regions is kept constant over time.

Considering responses to food self-insufficiency

In this second methodological section, we first take a step back and briefly consider a more generic discussion about the very existence and quantification of 'environment-related migration and violent conflict'. We found structural obstacles to prove and quantify such a relationship with statistical regression techniques or surveys. Therefore, we suggest an alternative methodology, the 'necessary conditions approach'. We focus on environment-related *food self-insufficiency* as potential driver of migration and violent conflict *and* consider another four alternative responses to local food self-insufficiency, instead of migration and violent conflict in isolation: starvation, agricultural extensification, intensification and import. For each response, we construct a minimum set of necessary environmental, socioeconomic and governance conditions to enable them (henceforth 'response conditions'). As an illustration of the approach, for methodological discussion and further development, these necessary response conditions are compared to those actually found in 2015 and those expected in a projection for 2050.

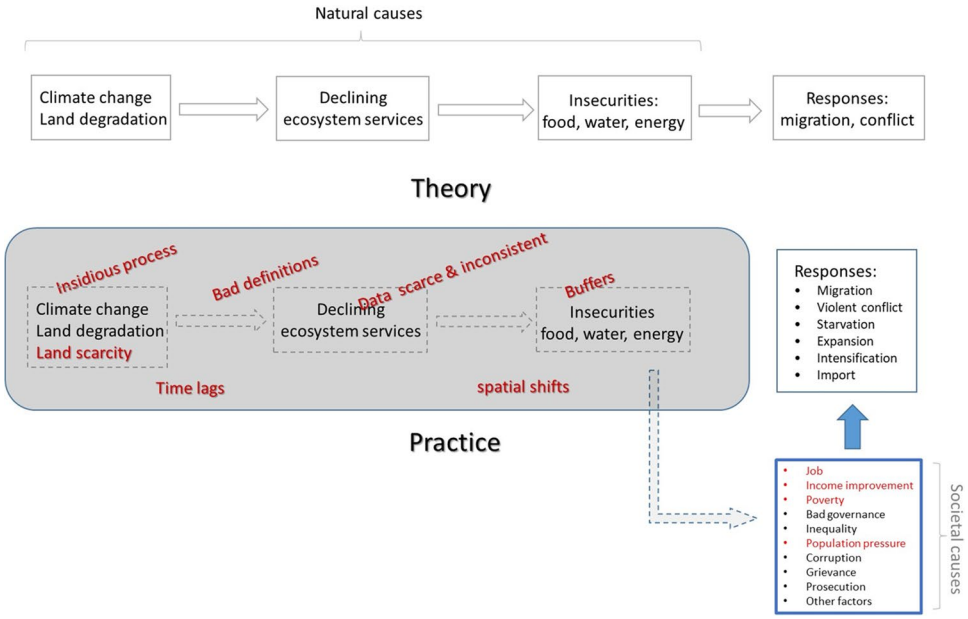

Fig. 1 Stylised representation of the cause-effect chain 'environmental change to migration/conflict' as theoretical concept (top) and as it may become obscured in practice by disturbing factors (in red) (bottom). The blue box right below shows socioeconomic causes of migration and conflict as found in statistical analyses and surveys. Various socioeconomic factors (in red) may play a mediating role between environmental causes and human responses. Besides migration and conflict four alternative responses to food self-insufficiency are possible

Environmental migration and violent conflict

Environmental factors such as climate change, land degradation and land scarcity are issues of growing concern in the light of social stability. According to many—scholars, civilians, politicians, military and other institutions—these factors may cause serious societal disruption that can lead to forced migration or violent conflict on a large scale (Malthus 1826; Hsiang et al. 2013; Adger et al. 2014; US Department of Defence 2014; Burke et al. 2015; USAID 2016; Ionesco et al. 2017; UNCCD 2017; FAO, IFAD, UNICEF, WFP, WHO 2020). Responding to this widely felt concern, scientists extensively studied this topic using statistical analyses and surveys. However, convincing evidence of a strong relationship between environmental change and both migration and violent conflict has not been found yet, in contrast with socioeconomic and governance factors which do strongly relate (Buhaug et al. 2008, 2014; Mach et al. 2019; Visser et al. 2019; Appiah-Nyamekye Sanny et al. 2019; Hoffmann et al. 2020; Mcmahon et al. 2021; Hoch et al. 2021). Notwithstanding this lack of evidence, various scholars expressed an intuitive perception of a causal relationship, directly or indirectly (Barnett and Adger 2007; Cattaneo and Peri 2016; Afifi 2011).

At first glance, the conclusion that there is a low relationship may be as surprising as it seems inevitable. However, an alternative option could be that a serious causal relationship actually does exist but has not been proven yet for reason that the methodologies applied so far might be unsuitable for this type of research. We identified five factors that may obscure the relationship (Fig. 1). Firstly, the concepts of environmental change such as land degradation, climate change and land scarcity, as well as the responses migration and violent conflict lack clear and broadly accepted definitions. Oliver-Smith (2009) observed many forms of migration, which are in practice transitionally in nature, such as voluntary or forced, temporarily or permanent, initiated from physical or economic danger, long or short distance, amongst others. 'Land degradation' can stand for any change in a component or function of the soil or vegetation, hampering consistent and comparative studies (Van der Esch et al. 2017). 'Land degradation is in the eye of the beholder' (CBD 2014). Even the occurrence of a relative unambiguous phenomenon such as local 'climate change' has been contested as a causal factor in the Syrian war (Selby et al. 2017). Similar problems apply to violent conflict and land scarcity. Blurred definitions make them hard to measure consistently and therefore difficult for use in comparative studies (Visser et al. 2020). Secondly, the cause-effect chain from environmental factors to migration and violent conflict is long, due to many intermediate environmental, socioeconomic and governance variables. The length of the chain weakens the correlation between the original cause and the ultimate effect. Socioeconomic and environmental buffers, non-linear processes and differences in the spatial and temporal scope of the variables add to this obscurity. They disrupt and mask statistical correlations as well as people's perception of the root causes for their decision to migrate or act violently when asked in surveys (Hibbs 1973; Appiah-Nyamekye Sanny et al. 2019). There are several examples of obscuring non-linear processes and socioeconomic and environmental buffers. To mention a few: the process of soil and vegetation depletion, environmental income to overcome periods of scarcity (WRI et al. 2005), individual food rationing from undernourishment,

starvation, depletion of assets and savings such as cattle, land, housing, reducing labour force, seasonal labour migration, remittances, informal social security networks, lack of means to migrate (poverty trap, migration hump), denial, cover up of status loss, food aid and subsidies, etcetera. Thirdly, there are serious and persistent data lacks in all domains over time and space. The data that are available often lack global coherence, are anecdotic and/or of low spatial and temporal resolution (Visser et al. 2020). Fourthly, there is a lack of a shared language, a generic conceptual framework and common methodologies between the natural and social sciences. This hampers well-defined, compatible and targeted research (Piguet et al. 2011). In surveys, environmental root causes may be easily framed as socioeconomic root causes: seeking jobs or better income. These socioeconomic factors may be actually mediating factors resulting from production decline. Finally, analysing environment-related migration or violent conflict requires a broad approach. The factor 'land scarcity' is regularly overlooked as a serious environmental root cause of migration or violent conflict next to land degradation and climate change. In cases of continuing population growth, the availability of fertile land for agriculture eventually comes to an end. Nineteenth and early twentieth century emigration within and from densely populated Europe forced many second and third farmers' sons into search for land (Ionesco et al. 2017). Moreover, violent conflict and migration are just two out of six responses to environment-related food self-insufficiency. They should not be considered in isolation but in conjunction with alternative responses, i.e. starvation, agricultural expansion, intensification and import (Fig. 1).

In conclusion, environmental factors may be distant root causes of migration or violent conflict though dominated by socioeconomic factors as mediating proxy drivers in statistical empirical analyses or surveys. This is strikingly stated by Oliver-Smith (2009): '(..) seeking single agent causality in the environment tends to elide the fact that the environment, and its resources as well as its hazards, is always channelled for people through social, economic and political factors, even in the best of times.' Given the above obstacles, we conclude that the 'socioeconomic versus environmental cause controversy' between scholars may well be a paradox. Regular methodologies such as statistical correlations (regression techniques) and surveys may be unsuitable tools to prove or reject this complex relationship. Structural Equation modelling (SEM) might be a more appropriate methodology to cope with this complexity for it explicitly takes mediating, moderating and confounding factors in the cause-effect chain into account. However, the serious data constraints in this field of research make applying SEM unfeasible in the near future as well.

The necessary conditions approach

Given the fact that the regular methodologies may very well be unsuitable tools to prove or reject the complex relationship between migration or conflict and environmental factors, we developed a coarse but operational approach to cope with the constraints as listed in the previous sub section, the so-called necessary conditions approach (NCA). 'Necessary conditions' is the supposed set of conditions postulated as minimally required to make a specific response happen. This approach comprises three steps:

i) *Specify the environmental change-human response cause-effect chains* in terms of the role of and relationship between the factors;
ii) *Specify a minimum set of 'necessary response conditions'* required for a particular response;
iii) *Test the actual local conditions against the necessary response conditions t*o determine plausible responses.

Step i: Fig. 2 specifies the environmental change-human response effect chain. Climate change, land degradation and land scarcity are environmental factors; food production is an ecosystem service and food self-insufficiency is a human insecurity in the context of demographic change (left side). Instead of two, we selected six potential responses to food self-insufficiency: starvation, violent conflict, migration, agricultural expansion, intensification and import (right side). In essence, these responses aim to create or maintain a livelihood for individuals and their household: a place and means to live and grow food or to have an off-farm job to be able to buy food on the market produced by others. In this scheme, we perceive livelihood (speckled) as a *mediator* amidst a chain of *causal* factors starting with environmental change (root causes at the left) via intermediate environmental, socioeconomic and governance factors in the middle up to 6 human primal responses at the very right (dark blue). The better actual local conditions fit the necessary conditions for a particular response, the more plausible its occurrence (stars representing the testing of the fit). A method similar to the necessary conditions approach is used in ecological modelling in cases of very complex and data demanding processes. In habitat suitability modelling, a set of key environmental conditions is used to assess the 'chance of occurrence' of a species in a particular area (see, for example Visconti et al. 2016). *Moderators* are factors that can amplify or attenuate the plausibility of a certain response, but are not necessary as such to lead to that response. Governance and socioeconomic factors are often *confounders* (green). Confounders are factors that influence both causal and response factors.

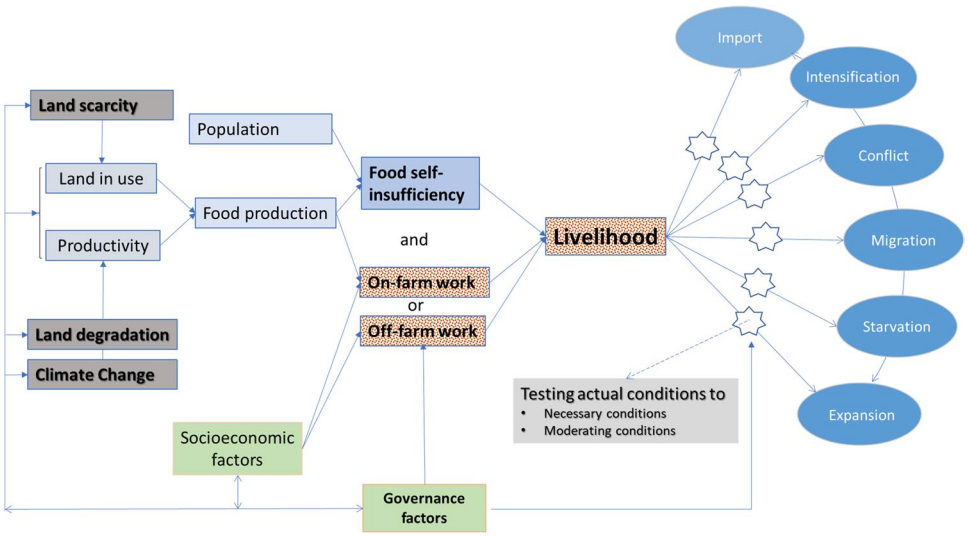

Fig. 2 Stylised scheme of the 'environmental change - food production - food self-insufficiency - human response' cause-effect chain. Causes: grey to blue; mediators: brown; responses: deep blue; confounders: green

Step ii: 'Necessary response conditions' are defined as the supposed conditions that are minimally required to lead to a specific response. A single necessary response condition consists of a necessary factor and a trajectory over which the factor is favourable for that response. It consists of a fully favourable trajectory and one or two adjacent trajectories with a linearly declining favourability. Without these linearly declining intervals favourability would be binary (0 or 1), while in reality it is transitional in nature. Next to necessary factors, we distinguish moderating factors. Moderating factors do not cause a response but may amplify or attenuate the favourability of 'actual local conditions' for that response. Similar to necessary factors, they are transitional in nature. Only those necessary factors and moderators are selected for which globally consistent and high-resolution data are available for the past, present and a future scenario.

Step iii: By comparing the *actual local conditions* to the *necessary and moderating response conditions*, we assess the potential for each response to happen at a particular location (stars in Fig. 2). Each factor has a score between 0 and 1, from an unfavourable to a fully favourable condition. Then, all individual scores are multiplied resulting in a total favourability score of the response between 0 to 1. Consequently, if only one single condition is unfavourable, the total score of a location will be unfavourable as well. Moderators may amplify or attenuate the favourability of a location. Their moderating effect is preliminarily set at a maximum of 1.2 increase or 0.8 decrease of the favourability score, respectively. In case of more moderators, their combined impact to the favourability score is limited to a factor 1.6 and 0.5, respectively. If the favourability score exceeds 1, it is truncated to 1 (fully favourable). In case of two mutually substitutable single necessary conditions A and B, the most favourable condition for the response is taken. In our test, we chose an arbitrary favourability score > 0.25 to ensure all necessary conditions are present for at least a minimum level to enable a particular response. After mapping the food self-insufficient regions, we determined the favourable responses per region as well as their extent, expressed in the 'number of people without food inclined to that response' (see Results). Local conditions for 2015 and 2050 were derived from data sets listed in Online Resource 1 Table 4. The economic, social and governance conditions in 2050 are derived from the middle-of-the-road-scenario SSP2 scenario (Huijstee et al. 2018) or kept the same as in 2015 if not derivable.[2]

Necessary conditions per response

This section argues a minimum list of necessary conditions and moderators for each of the six responses according to step ii. Literature on favourable response conditions is scarce and if present qualitative at best. Consequently, a number of conditions postulated and described below may lack (adequate) references at this stage of research and should be considered as *first estimates* from the authors to test the approach. They are further specified in Table 1 and Online Resource 1 Table 4.

We consider *starvation as* a primal strategy of inaction in absence of alternative response options, avoiding waste of energy in the expectation for better times. It does not require spare productive land to cultivate, nor skills,

[2] In this respect, it is worth noting that governance and institutional features are persistent in nature (Williamson 1996, Acemoglu and Robinson 2012). According to Williamson's four-layer model, institutions, governance structures, formal rules and culture and traditions hold from decades up to hundreds of years.

Table 1 Overview of necessary conditions and moderators per response

Response Factor	Starvation	Expansion	Migration	Violent Conflict	Intensification	Import	IR-purchase	Min-max
Environmental								
Spare fertile natural land % food deficit	0-20>30	100-30>10	0-20>25	0-20>25	0-10>20	0-10>20		0-∞
Yield gap dry matter					20>30-100	0-20>30		0-100
Rainfall mm/y	0-300>400	400>500-∞	0-300>400		300>400-∞ or*	0-300>400		0-∞
Irrigation distance km Altitude diff in m					0-10>20 and -∞-0>10 or*	10>20-∞ 0>10-+∞		0-∞
Economic								
GDP/cap k$	0-1.5 or 1.5-3>5 *	3>4-∞	0-1.5 or 1.5-3>5 *	0-1.5>3 or 1.5-3>5 *	12>15-∞	3>6-∞	1.5>3-∞	0-∞
Gini	40-∞ *		40-∞ *	40-∞ *				0-100
GDP growth %	-∞-1>1.5		-∞-1>1.5		1>2.5-∞ **	1>2-∞		-100 - +100
GDP agriculture %	100-30>10%		100-30>10%	100-30>10%	0-10>30 or 10-30>50 **	0-10>30		0-100
Export surplus $/cap/day						3-∞		0-∞
National/regional[1] food surplus % resp.						<0	>0	0-∞
Market distance hr	∞-6>3	∞-6>3	3-0	∞-6>0	0-3>6	0-3>6		0-∞
Social								
Pop growth %	∞-2>1.5	∞-2>1.5	∞-2>1.5	∞-2>1.5				-100 - +100
Pop density cap/km2					Poor soils 200>300-400>500 Rich soils 150>300-400>700			0-∞
Illiteracy rate %	30>50-100	30>50-100	40>50-100		50>30-0			0-100
Political stability Conflict deaths/25y				1500>2500-∞	0-250>1500			0-∞
Soc fragmentation				1-0.5>0.4	0.5>0.4-0			0-1
Governance								
Effective government	-3--1>0	-3--1>0	-3--1>0		0>1-3	0>2-3		-3 - +3
Rule of law				-3--1>0 or*	0>2-3			-3 - +3
Distance to regulating power hr				∞-6>3				0-∞
Land tenure security %	0-50>100		0-50>100		0>50-100			0-100
Corruption	0-40>50		0-40>50	0-40>50	50>60-100			100-0
Freedom of speech Liberal democracy index				0-0.3>0.5				0-1
Conflict regulat mech Freedom House Index				10>25-50>60 or*				-5-60
Access to firearms nr/100 cap				∞-50>10				0-∞

Notes: Code 10 > 25–50 > 60 means: the interval from 25 to 50 is 100% favourable for the response; the intervals from 10 to 25 and 50 to 60 have an ascending and descending favourability from 0 to 100% and 100 to 0% to the response, respectively.

*Linked conditions: and-and

or* linked conditions: or-or

Green: attenuator Red: amplifier

[1]Regional: food surplus > 0 in other city or remote regions than the region concerned

investments, infrastructure, markets and regulation systems that are required for agricultural intensification or import, nor does it require physical vitality, means and social skills needed to migrate or to use or organise violence as elaborated below. Although it is obviously an extremely unattractive response, famine is widespread (Caparros 2014). More than 800 million people are structurally undernourished (FAO, IFAD, UNICEF, WFP, WHO 2020). Starvation is favoured in case of bad conditions in all domains: environmental, economic, social and governance (Conley and De Waal 2019).

According to FAO IFAD UNICEF WFP WHO (2020), 'weak, stagnant or deteriorating economic conditions are underlying causes of increasing poverty and undernourishment'. Altered environmental conditions contribute to vicious circles of poverty and hunger, while fragile institutions, high rates of inequality and unemployment exacerbate this relationship (FAO, IFAD, UNICEF, WFP, WHO 2019, 2020). We assume the following necessary conditions for starvation: little spare fertile natural land available compared to food deficit (no potential for agricultural expansion); low GDP/cap or medium GDP/cap with high inequality GINI > 40 (we assume no possibilities for import, interregional purchase or intensification); high agricultural dependency and low GDP growth (we assume for both low alternative job opportunities for off-farm income). Although often not explicitly found in literature we postulate as amplifying moderators: low annual rainfall (less expansion and intensification opportunities); high population growth (declines job opportunities); high illiteracy rate (less economic development and job opportunities); medium to high transport distance to markets (impede import); low land tenure security; low effective government and high to medium levels of corruption (weak institutions impede intensification or import). Table 1 shows the preliminary quantitative trajectories of the necessary conditions and moderators of starvation and the other five responses as applied in the illustration of the method.

Agricultural expansion is a primal and common response to cope with food self-insufficiency as long as there is fertile and accessible land available (Boserup 1965; Gibbs et al. 2010; Kebede et al. 2019; Jellason et al. 2021). Obviously, in most cases, expansion goes with less skills or personal hardship than migration, starvation or violent conflict on the one hand and does not require the list of necessary conditions for intensification or import on the other (Boserup 1965; see paragraphs below). As only necessary condition, we assume the regional presence of spare fertile natural land suitable for agriculture as defined by the IMAGE model (IMAGE contributors 2020d) that can reduce a substantial part of the food self-insufficiency within the city or remote region. Global data on the ownership of land and its actual availability for expansion do not exist and is therefore not included. Moderating factors are many and may interact with each other leading to divergent outcomes in different situations (Geist and Lambin 2002; Kebede et al. 2019; Jellason et al. 2021). Including these dynamics goes beyond the scope of this analysis. Taking the global availability of data into account, we selected the following amplifying moderators: high population growth (growing demand of suitable land for food, especially in lower income countries (Gibbs et al. 2010; Estes et al. 2016; Jellason et al. 2021)); medium to high annual rainfall (less production insecurity (Chamberlin et al. 2014; Estes et al. 2016)); high illiteracy rate (we assume less economic development and consequently less off-farm jobs); medium to high distance to markets (we assume this encourages local solutions for food self-insufficiency and impedes import and intensification for reasons of transportation cost) and low effective government (less control on land use change, in particular in remote regions (Angelsen et al. 1999; Sassen et al. 2013)). As *attenuating* moderator, we selected medium to high per capita income (in higher income countries, Lambin and Meyfroidt (2010) found growing preference of intensification above expansion).

Clearly, *migration* manifests itself in infinite forms and motives, from daily short distance labour migration on the one hand to permanent long distance intercontinental migration on the other. For this analysis, we define migration as 'a permanent displacement out of a food self-insufficient city-region or remote-region of birth (as defined in subsection Spatial scale) to escape from food insecurity. Migration can be in-country as well as international. Neumann et al. (2015) find no global consistent picture of environmental drivers of human migration in drylands. Income and employment play a key role in explaining migration, although these are largely determined by environmental change including land degradation and drought. Boas et al. (2019) found it impossible to distinguish climate from non-climate migrants. Some people move but others are immobilised by climate change. Quantitative relations have been found though. Beine and Jeusette (2018) conclude that climate-related migration concerns primarily developing countries because of a higher exposure and less coping capabilities. According to Cattaneo and Peri (2016), poor countries show a migration *decline* with a stronger temperature increase: + 1 °C leads to a 80% migration decrease. Middle-income countries, however, show a migration *increase* with a stronger temperature increase: + 1 °C leads to a 20% migration increase. Temperate regions with average annual temperatures between 10 and 20 °C show no or a small increase in income and productivity, where warm regions with average annual temperatures between 20 and 25 °C show a decline in income and productivity. The rate of migration grows with income, up to a certain level. Cattaneo and Peri conclude that the initial heat factor as such is less relevant to migration than income. According to De Melo (2018), the international migration rate from poor towards rich (OECD) countries is hump-shaped increasing up to an income of 6000$/cap/year and declining thereafter down to around 25,000$/cap/year. Hatton and Williamson (2002) find a significant relation between the number of young people and international migration. This can be explained by the physical strength, eagerness and not-much-to-lose-position of young people. According to Cattaneo and Peri (2016) and Hoffmann et al. (2020), agricultural dependence is also a relevant factor, for it determines the vulnerability to changes in national food production. Agricultural dependence differs between poor and middle-income countries. The average agricultural share of GDP is around 35% in poor and 16% in middle-income

countries. So the share of people vulnerable to changes in food production and loss in particular can be expected to be larger in poor countries too. Urban income is less affected by temperature change. About two-thirds of urban-population growth originates from rural-to-urban migration. From the above, we conclude that 'climate change' as such is an inappropriate causal factor since it can both increase and decrease food production, depending on the initial local conditions. Taking 'food self-insufficiency' as a more 'downstream factor' in the cause-effect chain avoids this ambivalence. It takes the actual impact of climate change into account on food production, as well as the impact from land degradation and land scarcity in the context of demographic change and environmental limits.

We assume similar necessary conditions and moderators of migration as starvation (see above). In contrast, where remoteness from markets may favour starvation over migration, proximity to markets may favour migration reducing mental and economic barriers (Table 1).

Violent conflict. According to the human needs theory collective need deprivation can lead to violence (Gurr 1970, 2001; Turnbull 1972; Azar 1990; Walton and Seddon 1994; Homer-Dixon 1994, 1999; Collingham 2011; Demmers 2017). However, deprivation of food alone is not enough to initiate violent conflict, other responses to food deficit are possible too. As Demmers (2017) stated: Besides to 'an accumulating set of toxic societal structures, affections and needs it is also about factors as agency, calculations and interest'. This makes violent conflict a rather contingent and unpredictable phenomena (Acemoglu and Robinson 2012; Demmers 2017; Levitt 2019). This analysis reduces the complexity by dealing with a limited number of operational indicators to distinguish more or less favourable conditions. Knoope (2016) mentioned a combination of necessary conditions for igniting violent conflict that reflect the findings of many scholars (Collingham 2011; Kilcullen 2013; Demmers 2017; Tjassing 2018; Holslag 2019; Levitt 2019). The first condition 'Verelendung' we consider as the (looming) deprivation of food due to local food self-insufficiency as determined in this article. The second condition, 'no access to alternative means of existence' is in particular the absence of local jobs. Alternative means are assumed low in poor countries with low GDP/cap or with medium GDP/cap combined with high-income inequality, with a high dependency on the agricultural sector, and without opportunities for agricultural expansion, similar to starvation and migration. Identity loss and distrust is a third condition. Suppression, discrimination, neglect and exclusion of particular identity groups will affect their identity and self-esteem, an important factor for well-being (Maslow 1943). Identity loss in combination with distrust of the government, institutions and others groups may give a sense of unprotectedness, loss of autonomy and control, and consequently fear and anger. Perceptions, framing and stresses play a role in a mental shift from rational behaviour and acceptance towards an emotional mood and anger to arrange justice and take back control yourself, violently if necessary (Ballentine 2004; Van Leeuwen and Van der Haar 2016; Demmers 2017). Identity loss and distrust is assumed high in situations of high corruption and restricted freedom of speech as indicated by the Liberal Democracy Index. The fourth condition, 'absence of adequate conflict regulating mechanisms or institutions' is a necessary condition to violence as a last resort to fight perceived injustice. Conflict regulation mechanisms comprise the full spectrum from persuasion to coercion (Kilcullen 2013). Violent conflict may break out at the lower end of the spectrum, in the absence of adequate mechanisms, but also at the high end when people perceive the cost of coercion higher than the cost of revolt (Acemoglu and Robinson 2012; Kilcullen 2013; Demmers 2017). Muller (1985) found an upturned U correlation in the effect of regime repressiveness. At low levels of repression, the incidence of violent conflict is low, as people have non-violent means for seeking change. At extreme levels of repression, the incidence of violent conflict is also low inhibiting any violence. We applied the Freedom House Index or rule of law for the presence or absence of adequate conflict regulation mechanisms. 'Powerful leadership' is a necessary condition to mobilise mass power. Individuals are less inclined to act alone with probably high cost and low benefits. Leadership that adequately frames common interests and related groups moves the balance between potential costs and benefits of violence swiftly to the latter (Demmers 2017). Regrettably, we did not find a suitable indicator of powerful leadership that may project its absence or presence in the future. We assumed the following amplifying moderators: high societal fragmentation due to a diversity of ethnic groups, religions and/or languages (vulnerable to mistrust and a feel of being neglected or excluded); low political stability (measured in conflict deaths) due to unresolved societal conflicts and resentments (Collier et al. 2003); high access to firearms (eases the choice for violence); high population growth (youth bulge disfavours local job opportunities for all and increases the stock of potentially violent young men (Heinsohn 2003)); large distance to markets (reduce job opportunities) and large distance to state regulating power (may play a weakening role in its effectiveness).

Intensification of agricultural production and its underlying conditions were described by Esther Boserup (1965). According to her theory, the production per unit area will increase with increasing human density and food demand. Generally speaking, this leads to innovation and increasing investments in labour, inputs, skills and technology. Decisive favouring conditions for intensification are the absence of spare fertile natural land for agricultural expansion (such as bad soils, water and land scarcity) in combination with a large potential of increasing food productivity per ha, the yield

gap. In many regions, there is a wide gap between current and potential yields (IAASTD 2009; Neumann et al. 2010; Van Ittersum et al. 2016; Breman et al. 2019). Yield gaps are particularly wide in Sub-Sahara Africa. Serious improvements are possible in all other regions except for South Asia. Estimates of the potential vary between modelling groups (OECD 2008; Rosegrant et al. 2009; Bruinsma 2003; Stehfest et al. 2009). Closure of yield gaps requires a considerable list of measures over the entire production chain, adapted to the region-specific bio-physical and socioeconomic conditions, amongst others: minimum and maximum levels of human density, land tenure security, access to proximate markets with purchasing power, reliable infrastructure and information networks, financial services, storage facilities, extension services, research and development programmes (Pretty et al. 2003; Bruinsma 2003; IAC 2004; Koning et al. 2008; Lobell et al. 2009; Eenhoorn and Becx 2009) IAASTD 2009; Gurib-Fakim et al. 2009; Ten Brink et al. 2010). We selected the following minimum set of necessary conditions and moderators: low amount of spare fertile land; large yield gap; medium to high precipitation or availability of water for irrigation; medium to high GDP/cap; low agricultural share of GDP or medium agricultural GDP with medium to high GDP growth; low to medium market distance; a minimum and maximum to the population density; low illiteracy rate; high political stability; effective government and rule of law; low levels of corruption and high land tenure security. Low societal fragmentation may act as amplifier favouring political stability.

Food import as response to food self-insufficiency depends on effective and affordable transport systems. Reliable transport systems gave rise to economically powerful cities and development of rural areas (Rodrigue and Notteboom 2020). We distinguish 'import' from 'interregional purchase'. Import concerns *international* food transport to city and remote regions, interregional purchase concerns *domestic* food transport between city and remote regions. Necessary conditions for *interregional purchase* are quite self-evident: a food surplus in other regions within the country, and—in contrast to starvation and migration—a medium to high per capita income to cover the costs of food and interregional transport. For *import*, we assume more demanding necessary conditions than for interregional purchase: a medium to high GDP/cap (to bear the transport cost from foreign producer to final user, infrastructure investments and cross-border transaction cost (Anderson and Wincoop 2004)); sufficient foreign currency from non-food export as means of payment and a low to medium distance to the market (to limit cost of transport and infrastructure (Anderson and Wincoop 2004)), i.e. the national entry points of import. Other necessary conditions are a lack of suitable environmental conditions for agricultural expansion and intensification (being domestic responses to food self-insufficiency) and a low agricultural share of GDP (assuming more powerful developed economies or economies in transition with improved farmer incomes and a relative large share of households with income from off-farm sectors (Van Arendonk 2015; Foster and Rosenzweig 2017)). For this analysis, we assume that import is only applicable to those regions located in self food-insufficient *countries* as far as the deficit cannot be solved nationally by interregional purchase. As amplifying moderators are selected: a medium to high GDP growth and an effective government to build and maintain a well-functioning infrastructure for international transport, storage and domestic distribution (Rodrigue 2020).

Obviously, the above six potential responses to food self-insufficiency do not occur in isolation, are not confined to a particular place and can act in consecutive order. They may happen simultaneously when parts of the population suffer famine, often the more vulnerable like elderly and children (Conley and De Waal 2019), while others decide to migrate or to rebel, often vital young individuals. Different people perceive different threats and have different positions and opportunities while living in the same affected region. Responses can occur consecutively in case the one ignites the other (Fig. 2). Agricultural expansion or migration can lead to competition for scarce land, natural assets or jobs and eventually to violence that in turn may lead to more migration or famine. When room for expansion becomes exhausted it may incentivise intensification. All these are dynamic processes that change over time and space and in which contingency plays a significant role (Acemoglu and Robinson 2012; Demmers 2017). These circular dynamics make it difficult to distinguish cause and impact, begin and end.

It is worth noting the necessary conditions for starvation, migration and violent conflict have many similarities as opposed to intensification and import. The former group has detrimental 'Malthusian' characteristics while the latter group has characteristics directing towards a more prosperous 'Boserupian' development consisting of an increasing food productivity and per capita income, job diversification, industrialisation and interregional food purchase and import. The shift from the first group to the second seems to be a difficult one. It requires a combination of specific conditions from the environmental, socioeconomic, political and governance domains, as described by amongst others Boserup (19651983), Acemoglu and Robinson (2012) and Breman et al. (2019). Because this process is highly contingent, it will be difficult to predict.

Results

Mapping potential areas of food self-insufficiency

Figure 3 shows food self-(in)sufficiency in city regions and remote regions in 2015, and by 2050, under the SSP2 scenario

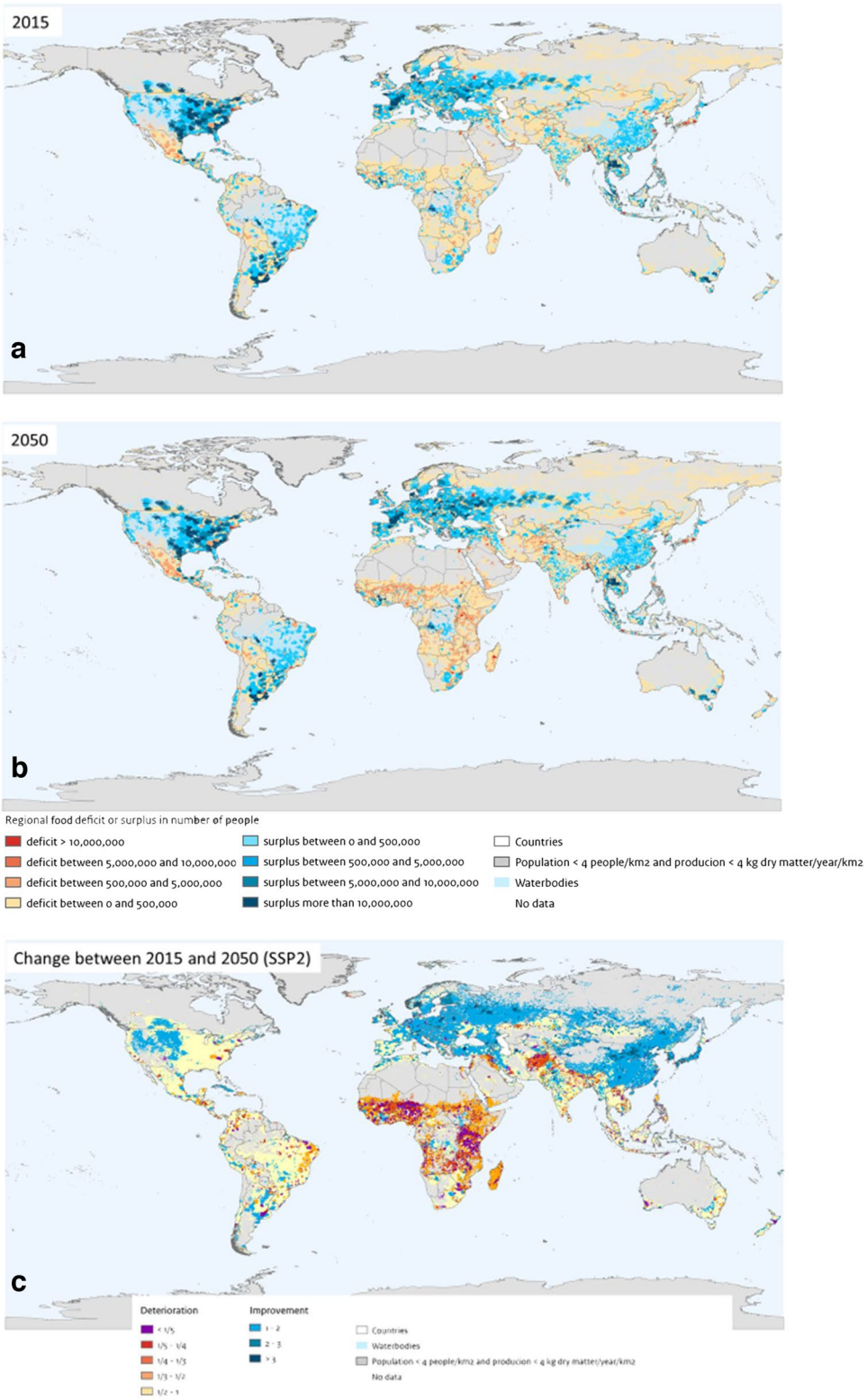

Fig. 3 Food production surplus and deficit per city region and remote region in 2015 (top) (**a**) and 2050 (middle) (**b**) expressed in number of people without food, and change over time (below) (**c**)

assuming zero migration over the 2015–2050 period. In 2015, most regions are near self-sufficient or show a surplus (Fig. 3a). This may be expected, for the development of regional food demand will also depend on the regional opportunities for food supply. Pockets of moderate to highly self-insufficient regions can be found in Sub-Sahara Africa, Middle East, Latin America and the Stan-region. Not surprisingly, many capital cities and mega-cities pop up as food self-insufficient city regions, as

well as current food belt regions with large surpluses in North America, Latin America, Europe and China.

The situation in 2050—as defined in the scenario—shows an increase in the number of potential self-insufficient regions (Fig. 3b) and roughly a doubling of the total number of people exposed to potential deficits living in food self-insufficient countries, in particular in Sub-Sahara Africa, Middle East and Stan-region (Online Resource Table 1 and 2). A few regions show a stunning increase in potential food deficit with a factor three to five (Fig. 3c). It may concern millions of people per region, a huge challenge for policymakers in the coming decades to cope with. Most of the times, the increase by 2050 is caused by a significant population growth on the one hand—hence the demand side—and a, stagnating or even declining food production on the other. Around 20% of the affected people live in regions with declining food production and around 80% in regions with stagnant or increasing production. Supply can, hence, not keep pace with demand. Food self-insufficiency is not only a local concern, but it is also a national and international concern. Food self-insufficiency on the *national* scale is often smaller than determined on the regional scale (Table 2) for regions with a supply deficit may be compensated by regions with a surplus. Total food self-insufficiency in self-insufficient countries increases with roughly 60% over the period 2015 to 2050 (Online Resource 1 Table 1 and 2). On the scale of *world regions*, Southern Africa, Middle East and the Japan/Korea regions stay food self-insufficient up to 2050, while Eastern Africa becomes self-insufficient by 2050. In contrast, on the *global* scale food self-sufficiency stays high and constant implicating large improvements in already self-sufficient world regions (Online Resource 1 Table 3).

Mapping favourable conditions per response by 2050

Figure 4 and Table 2 show a selection of the responses. An overview of all response maps and the number of people inclined to a specific response can be found in Online Resource 1 Table 1 and 2, and Online Resource 2 Fig. 2. Although the outcomes are primarily an illustration of the methodology, some salient results come through. Most *developed* countries and related world regions show improvement in food self-sufficiency by 2050. Regional deficits can be solved by intensification, import, interregional purchase and agricultural expansion. In *developing* countries, in particular in Sub-Sahara Africa and to a lesser extent the Stan-region, the extent of food self-insufficiency roughly doubles as do the number of people living in conditions that favour 'Malthusian' responses starvation, migration and violent conflict. Most countries show favourable conditions for agricultural expansion and interregional purchase. These responses can mitigate deficits in many city regions and remote regions, though often not enough, as is particularly the case in Sub-Sahara Africa and Middle East (Online resource 1 Table 1 and 2). In oil-producing developing countries and highly industrialised countries such as the Japan/Korea region, food import is a favourable and adequate response. Areas with favourable conditions for starvation, migration and violent conflict substantially overlap (Fig. 4 and Online Resource 2 Fig. 2). This overlap is not surprising as we have seen—and still see—in regions where they co-occur in inextricable dynamics (Camargo et al. 2020; Turnbull 1972; Sadliwala and De Waal 2018; United Nations 2022).

In this first exercise, a number of regions do not pass the favourable conditions threshold > 0.25 for any of the responses (Fig. 4d). These regions with an 'unclear response' may be interesting though when situated in countries in economic transition. These might be vulnerable to setbacks from a development-oriented pathway of intensification, import and interregional purchase towards a 'Malthusian' pathway.

Discussion

In answer to the research questions, this article indicates locations where and to what extent environment-related food self-insufficiency may occur in the coming decades. The article then indicates the probability of six potential human responses in light of local environmental, socioeconomic and governance conditions. During the effort to generate these answers, the authors found persistent methodological constraints: in particular, a serious lack of consistent data over time and space, highly muddled definitions and still limited understanding of the factors and mechanisms that may lead to the different responses described. These constraints clarify why usual methodologies, such as statistical empirical analyses and surveys, were found less suitable to attain the objectives of this study. As an alternative, the authors developed and applied a 'necessary conditions approach' that do provide preliminary answers to the research questions. Nevertheless, more work has to be done: further elaboration of the framework, relevant factors and mechanisms; improving data across the entire calculation chain; implementing sensitivity analyses of response conditions, assumptions and alternative scenarios, and testing the results against real world measurements. Uncertainties are, at least partly, also due to the fact that authors chose to opt for a global approach. Focused analyses with *local* data will certainly lead to more accurate results. So where, for instance, intensification may not pop up as a plausible response in this analysis it may still occur in reality. This may for example be the case in the direct close neighbourhood of rapidly developing mega cities with relative high economic opportunities that differ from the *national* economic data used in this analysis. However, contingency plays a significant role in any societal development and may

Table 2 Number of people without food inclined to specific response in food self-insufficient countries by 2050 (in million)[1]

	Violent conflict	Migration	Starvation	Violent conflict, migration and starvation	Violent conflict, migration or starvation	Agricultural expansion	intensi-fication	Import	Inter-regional purchase	no response	Total regional food insuffi-ciency	Total national food insuffi-ciency	Total popula-tion 2050
Afghanistan	36.5	49.0	50.0	34.0	52.0	17.0	0.0	0.0	1.5	1.0	60.5	52.5	205
Algeria	0.0	0.0	0.0	0.0	0.0	0.5	0.0	17.0	1.0	0.0	28.5	18.0	69
Angola	1.0	0.0	1.0	0.0	1.0	31.0	0.0	0.0	5.0	0.0	43.5	36.0	164
Bahrain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.5	0.0	3.5	2.5	3
Benin	0.0	6.0	6.0	0.0	6.0	1.0	0.0	0.0	0.0	0.0	11.5	6.0	35
Botswana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	3.5	1.5	19
Burkina Faso	10.0	1.0	10.0	1.0	10.0	0.5	0.0	0.0	0.0	0.0	34.0	10.0	65
Burundi	6.0	6.0	6.0	6.0	6.0	2.0	0.0	0.0	0.5	0.0	15.0	6.5	21
Central African Rep	5.0	6.0	6.0	5.0	6.0	5.0	0.0	0.0	0.0	0.0	7.5	6.0	34
Chad	11.0	7.0	11.0	7.0	11.0	1.5	0.0	0.0	1.0	0.0	18.0	12.0	80
Congo	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.5	0.0	5.5	2.0	30
Egypt	8.0	0.0	1.0	0.0	8.0	0.0	0.0	0.0	85.5	1.5	95.0	95.0	267
Eritrea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	10.5	4.0	19
Ethiopia	0.0	0.0	0.0	0.0	0.0	19.5	0.0	0.0	87.5	0.0	131.5	107.0	227
Ghana	0.0	0.0	1.0	0.0	1.0	2.0	0.0	0.0	12.0	0.0	29.0	14.0	49
Haiti	6.0	5.0	5.0	5.0	6.0	2.0	0.0	0.0	1.0	0.0	7.5	7.0	14
Iraq	0.0	0.0	1.0	0.0	1.0	0.0	0.0	28.0	1.0	0.5	48.5	29.5	88
Israel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	2.5	3.0	12.5	9.0	15
Jamaica	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	1.5	1.5	2
Japan	0.0	0.0	0.0	0.0	0.0	43.0	46.0	47.0	3.0	0.0	61.0	50.0	67
Jordan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5	13.0	9.5	54
Kenya	53.0	63.0	50.0	43.0	65.0	49.5	0.0	0.0	3.0	1.0	80.5	67.0	214
Kuwait	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	6.0	4.0	15
Liberia	0.0	6.0	6.0	0.0	6.0	5.0	0.0	0.0	0.0	0.0	9.0	6.0	14
Madagascar	21.5	65.5	65.5	21.0	66.0	64.0	0.0	0.0	1.0	0.0	66.5	66.5	198
Malawi	3.0	25.0	25.0	3.0	25.0	20.5	0.0	0.0	0.0	0.0	31.5	25.0	121
Mali	8.0	9.0	9.0	8.0	9.0	2.5	0.0	0.0	0.0	0.0	20.5	9.0	170
Mauritania	5.5	3.0	3.0	3.0	5.5	0.0	0.0	0.0	0.5	0.0	8.0	6.0	28
Mongolia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	2.5	1.5	40
Mozambique	16.0	19.0	19.5	16.0	20.0	19.5	0.0	0.0	2.5	0.0	37.5	22.0	169
Namibia	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	3.0	2.0	19
Nepal	9.0	9.0	2.0	2.0	9.0	4.5	0.0	0.0	0.0	1.0	12.5	10.0	80
Niger	1.0	14.5	16.0	1.0	16.0	0.5	0.0	0.0	0.0	0.0	41.0	16.0	133
Nigeria	109.0	132.5	65.5	48.5	133.5	30.5	0.0	0.0	46.5	1.0	277.0	180.0	428
Oman	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	22
Rwanda	3.0	3.0	3.0	3.0	3.0	14.0	0.0	0.0	0.0	4.0	18.5	17.0	29
Saudi Arabia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0	39.5	0.0	63.5	57.5	411
Senegal	1.0	0.0	5.5	0.0	5.5	0.5	0.0	0.0	2.0	1.5	17.5	9.0	27
Sierra Leone	2.5	2.5	2.5	2.5	2.5	0.0	0.0	0.0	0.0	0.0	2.5	2.5	12
Singapore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0	7.0	7.0	4
South Korea	0.0	0.0	0.0	0.0	0.0	16.0	0.0	0.0	0.0	5.0	25.0	24.0	52
Sudan	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	41.0	0.0	64.0	42.0	278
Tanzania	33.5	50.5	45.5	27.0	52.0	42.0	0.0	0.0	7.5	0.0	74.5	58.0	2
Togo	3.0	3.0	3.0	3.0	3.0	1.0	0.0	0.0	0.0	0.0	4.5	3.0	13
Uganda	89.0	102.0	101.5	74.5	116.0	76.0	0.0	0.0	14.0	0.0	116.0	116.0	253
United Arab Emirates	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.5	0.0	16.5	14.5	22

Table 2 (continued)

	Violent conflict	Migration	Starvation	Violent conflict, migration and starvation	Violent conflict, migration or starvation	Agricultural expansion	intensification	Import	Inter-regional purchase	no response	Total regional food insufficiency	Total national food insufficiency	Total population 2050
Venezuela	0.0	0.0	8.5	0.0	8.5	14.0	0.0	0.0	7.5	0.0	41.0	21.5	70
Yemen	39.0	0.0	37.0	0.0	45.0	4.0	0.0	0.0	6.0	0.0	66.0	45.0	77
Zambia	14.0	14.5	12.5	11.5	14.5	8.0	0.0	0.0	0.5	0.0	25.5	15.0	120
Zimbabwe	4.0	4.0	0.5	0.5	4.0	2.5	0.0	0.0	0.0	1.0	8.5	4.0	33

[1]The top fifty countries with the largest food self-insufficiency at the national scale

give rise to unpredicted developments (Demmers 2017). In this complex field, any outcome from any method will contain inaccuracies and should be critically examined.

Notwithstanding the uncertainties and illustrative character of the application, the big picture for 2050 that emerges from this approach looks grim. In vulnerable countries, the total food deficit in self-insufficient regions roughly doubles (Online Resource 1 Table 1 and 2). In many regions, we find that the conditions are particularly favourable for one or multiple 'Malthusian' responses: agricultural expansion, starvation, violent conflict and migration (Fig. 4 and Online Resource 2 Fig. 2). The simultaneous occurrence of these different responses should not be surprising for they share partly overlapping response conditions (Table 1) and have all in common that they do not address the root causes. Which one of the responses prevails will, as expected, depend on specific local conditions that cannot be covered by this global analysis. Moreover, response patterns are highly contingent in nature. Individuals base their choices on their individual circumstances, opportunities and personalities (Demmers 2017; Czaika and Reinprecht 2022). So evidently, migration, starvation (Afifi 2011), violent conflict and expansion will often occur next or consecutively to each other. A probably more robust division between regions with predominantly 'Boserupian', 'Malthusian' or 'transitionary' conditions as shown in Fig. 4 might be more appropriate in the short-term than a focus on individual response maps (Online Resource 2 Fig. 2).

According to our scenario, up to 2050 *regional* production cannot cope with the growth of the population at numerous locations, a phenomenon as predicted by—amongst

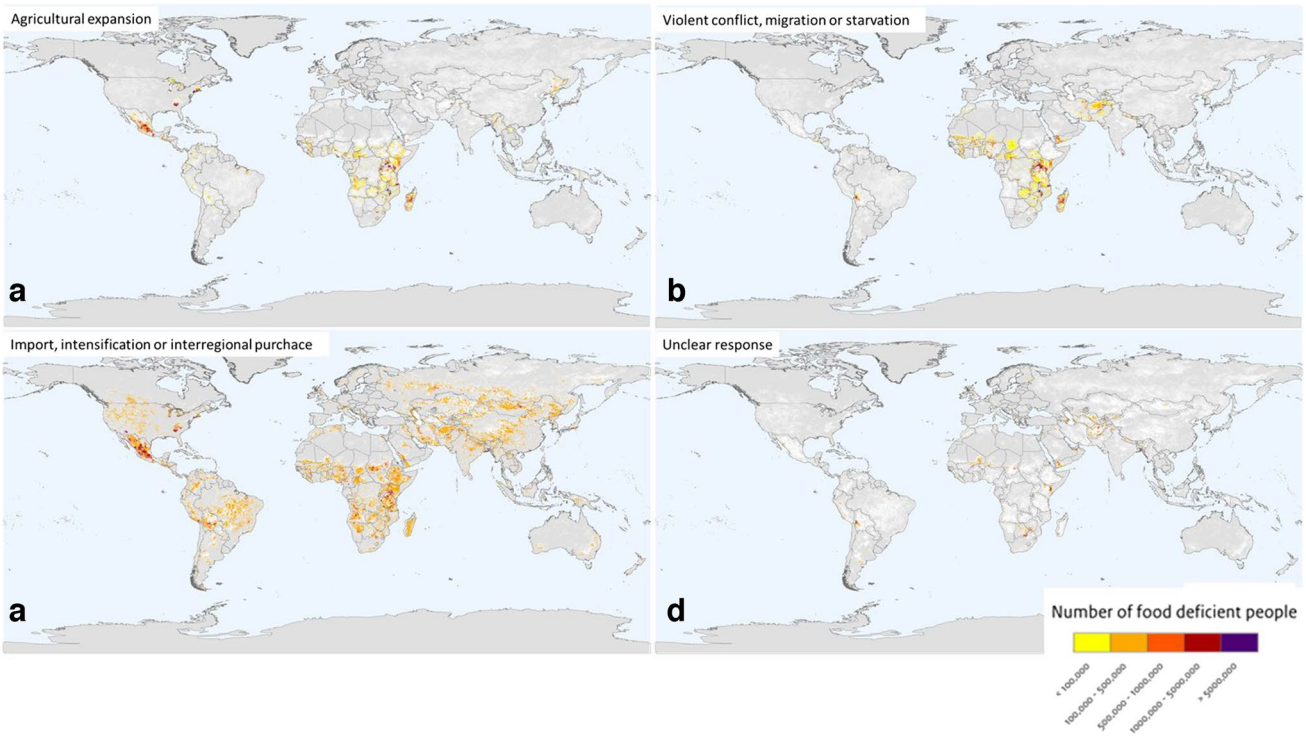

Fig. 4 Food self-insufficient regions in 2050 and the number of people without food inclined to agricultural expansion (top left) (**a**); violent conflict, migration or starvation (top right) (**b**); import, interregional purchase or intensification (bottom left) (**c**); unclear response (bottom right) (**d**)

others—Homer-Dixon (1999). The extent of food self-insufficiency declines when taken on the *country* and *world region* scale and even disappears on the *global* scale (Online Resource 2 Tables 1, 2 and 3). World regions with a food surplus can fully compensate world regions with a food deficit. However, an increase in food production in city and remote regions in the past does not guarantee a similar increase in the future, as we assumed in our SSP2 scenario. Obviously, the outcome of this study would change dramatically if food production increases over the period 2001 to 2017 would turn into a stagnating or descending trend in the near future. In fact, FAO, IFAD, UNICEF, WFP, WHO (20192020) did express concerns about stagnating food productivity. Mitigation of such stagnation may be possible in certain global regions through changes in diet (less animal proteins) or innovations in food production. But, the opportunities for this mitigation will be mostly found in developed countries, not in developing countries (Ten Brink et al. 2010). Persistent stagnation as signalled by FAO would probably further increase dependency on international and, in particular, intercontinental trade, the importance of which became clear in the Russian invasion of Ukraine.

Finally a few technical observations and a political one. The map of regions where intensification is favourable is surprisingly empty (Online Resource 2 Fig. 2). This relates to the absence of the many necessary conditions required to intensify in extensive parts of the world. Moreover, most regions suitable for intensification are located in currently food self-sufficient regions. They do not show up in this analysis focussing on food self-insufficiency. Although the six responses are all coping mechanisms to address food self-insufficiency, they differ in temporal and spatial scale, degree of organisation and effort. For example, intensification is a gradual process that normally requires long-term investments for many years, extensive areas and significant governmental support, and it involves a variety of people and sectors active along the production chain, as described earlier. This is in contrast to agricultural expansion, starvation, violent conflict and migration that we consider as more individual and instant responses. Furthermore, it should be stressed that results in this study presents the order of magnitude of food self-insufficiency and responses over the *full period* between 2015 and 2050 on the *regional and national* scales, *if* current environmental trends continue and demographic changes take place as assumed in the SSP2 scenario. It goes without saying that a dynamic approach would be a significant improvement to the static approach as developed in this article taking the various responses as a continuous process over time. It should be noted that the numbers of people exposed to food self-insufficiency will be considerable higher than those mentioned in the maps and tables. In reality, food deficit is divided over many more people than the hypothetical 'number of people without food' as was applied as calculation unit. Despite these technical observations, the scenario does highlight the societal and political challenges that require an answer to accommodate the upcoming developments in the next decades. Preferably in a peaceful and timely manner.

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Data Availability Data produced in this analysis are available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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