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# Achieving Zero Hunger by 2030

## A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals

**by Hugo Valin, Thomas Hertel, Benjamin Leon Bodirsky, Tomoko Hasegawa, Elke Stehfest**

***The authors are:***

**Hugo Valin**, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

**Thomas Hertel**, Purdue University, West Lafayette, USA

**Benjamin Leon Bodirsky**, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

**Tomoko Hasegawa**, Ritsumeikan University, Kusatsu, Japan

**Elke Stehfest**, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands

# ABSTRACT

The Sustainable Development Goal 2 “Zero hunger” (SDG2) sets clear global targets for ensuring access to sufficient food and healthy nutrition for all by 2030, while keeping food systems within sustainable boundaries and protecting livelihoods. Yet, the current trends show the level of challenge ahead, especially as the COVID-19 pandemic worsens the global development prospects. Intrinsically, SDG2 presents some points of tension between its internal targets and brings some synergies but also strong trade-offs with other sustainable development goals.

We summarize in this paper the main relations between SDG2 targets and the other development goals and explain how the modelling literature has analyzed the SDG interactions around “Zero hunger”. SDG2 integrates four ambitious objectives – adequate food, no malnutrition, in increased incomes for smallholders, greater sustainability – that will require careful implementation to be conducted in synergy. We show that the compatibility of these objectives will depend on the interplay of future food demand drivers and the contribution of productivity gains across the food system.

Analyzing the SDGs’ interrelations reveals the strong synergies between SDG2 and some other basic subsistence goals, in particular Goal 1 “No poverty” and Goal 3 “Good health and well-being”. These goals need to be jointly addressed in order to succeed on “Zero hunger”. Several other SDGs have been shown to be key enablers for SDG2, in particular on the socioeconomic side. On the other hand, agricultural production substantially contributes to the risks of exceeding critical global sustainability thresholds. We illustrate how recent modelling work has shed light on the interface between future food and nutrition needs, and the various environmental dimensions. Specifically, several important SDGs have been shown to compete directly with SDG2 through their common demands for scarce natural resources – including land for climate (SDG13), for biodiversity (SDG15) and for cities (SDG11), as well as the provision of water, both for the environment and for human needs (SDG6). Quantitative assessments show that more efficient production systems and technologies, pricing of externalities, and integrated resource management can mitigate some of these tradeoffs, but are unlikely to succeed in resolving these altogether.

The success of achieving SDG2 in the face of these challenges will require new investments, smoothly functioning trade and effective markets, as well as changes in consumption patterns. Forward-looking analyses of global food systems indicate that deep transformations combining various measures will be needed to simultaneously achieve SDG2 targets while remaining within the planetary boundaries. These require fundamental changes, both on the supply side and on the demand side, and highlight the importance of SDG12 on “responsible production and consumption”.

# 1. Introduction

In 2015, 192 countries endorsed the United Nations 2030 Agenda for Sustainable Development, defining 17 Sustainable Development Goals (SDGs) and associated targets to be reached over the next decade. SDG2 "Zero Hunger" represents a reinvigoration of the long-standing efforts by governments and international organizations to fight undernourishment and malnutrition across the globe. This battle is far from over, as 8.9% of the world population was still undernourished in 2019, 1.5 billion were unable to access essential food nutrients, and adult obesity now exceeds 13% globally (FAO et al., 2020); and just now, the COVID-19 pandemic has increased food insecurity in many places around the world, due to the effect of sanitary measures and their socioeconomic consequences (Laborde et al., 2020; von Braun et al., 2020). At the same time, there has been increasing recognition that human activities, among which agriculture, spur large-scale environmental changes, driving us out of the Earth's safe operating space (Steffen et al., 2015). Therefore, the 2030 Agenda has integrated environmental sustainability into the core of the future development agenda (UN, 2015). The global food system modelling community has strived to better understand the synergies and trade-offs between these dimensions by quantifying the degree of compatibility of the different goals, to help identify the most efficient strategies and overcome the points of tensions between the SDGs.

This paper provides an overview of the state of findings from the global modelling literature on the potential avenues for achieving SDG2 and the interrelations between this objective and attainment of other SDGs – particularly those related to environmental sustainability (Figure 1). For the most part, it looks at these questions from a global, macroscopic perspective, without entering in detailed regional and local specificities, although recent efforts are seeking to better integrate cross-scale interconnections.[1] It complements in that sense previous analyses focusing on synergies and trade-offs from a conceptual point of view. For instance, the International Council for Science analyzed some of the most critical interfaces for SDG2 (ISC, 2017), emphasizing SDG1 (No poverty), SDG3 (Good health and well-being), SDG5 (Gender equality), SDG6 (Clean water and sanitation), SDG7 (Affordable and clean energy), SDG13 (Climate action) and SDG15 (Life on land). Pradhan et al. (2017) conducted a similar work across all the SDG scope and identified relations mostly synergistic between SDG2 and SDG1-6, 10 and 17, mixed relations with SDG 7-9 and mostly conflictual relations with SDG 11-13 and 15.

Here, synergies and trade-offs between the achievement of SDG2 and the other SDG dimensions are examined based on the most recent modelling literature in the natural and social sciences. The work relies *inter alia* on large-scale forward-looking studies analyzing the evolution of the SDG2 target compared to other sustainability goals, at continental and global scales. Many of these studies adopt a medium to long term perspective, therefore our analysis will often look beyond 2030, and up to 2050. With Figure 1, we present our own depiction of how SDG2 interacts with other SDGs based on this literature. We identify many synergies with socioeconomic SDGs in general, while highlighting possible tensions the environmental SDGs. Not all these dimensions have been explored with a similar level of depth by modelling studies. This is because quantitative models are stronger at analyzing some specific structural relations (e.g. macroeconomic indicators, environmental account balances) than some others (e.g. detailed social impacts, anthropometric indicators). For historical and technical reasons, some areas have also been relatively understudied (e.g. modelling malnutrition and obesity) compared to some others (e.g. climate change and food

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[1] See for instance AgMIP (www.agmip.org), FABLE (www.unsdsn.org/fable) or GLASSNET (https://mygeohub.org/groups/glassnet) initiatives.

security). We provide more context in Box 1 on the different types of models used, and on their strengths and limitations.

The paper is structured as follows: in Section 2, we analyze in detail the inherent challenges of achieving SDG2. Section 3 focuses on the synergies between SDG2 and other SDGs, with an emphasis on the key companion goals – poverty and health - and the large set of socioeconomic enablers. Section 4 examines the trade-offs between SDG2 and other goals, looking at the food systems impacts and their mitigation, but also the reverse pressures from other objectives. We finally present in Section 6 an overview of possible food system transformation levers. These are key to the resolution of the trade-offs previously presented while setting the ground to more sustainable pathways for the coming decades.

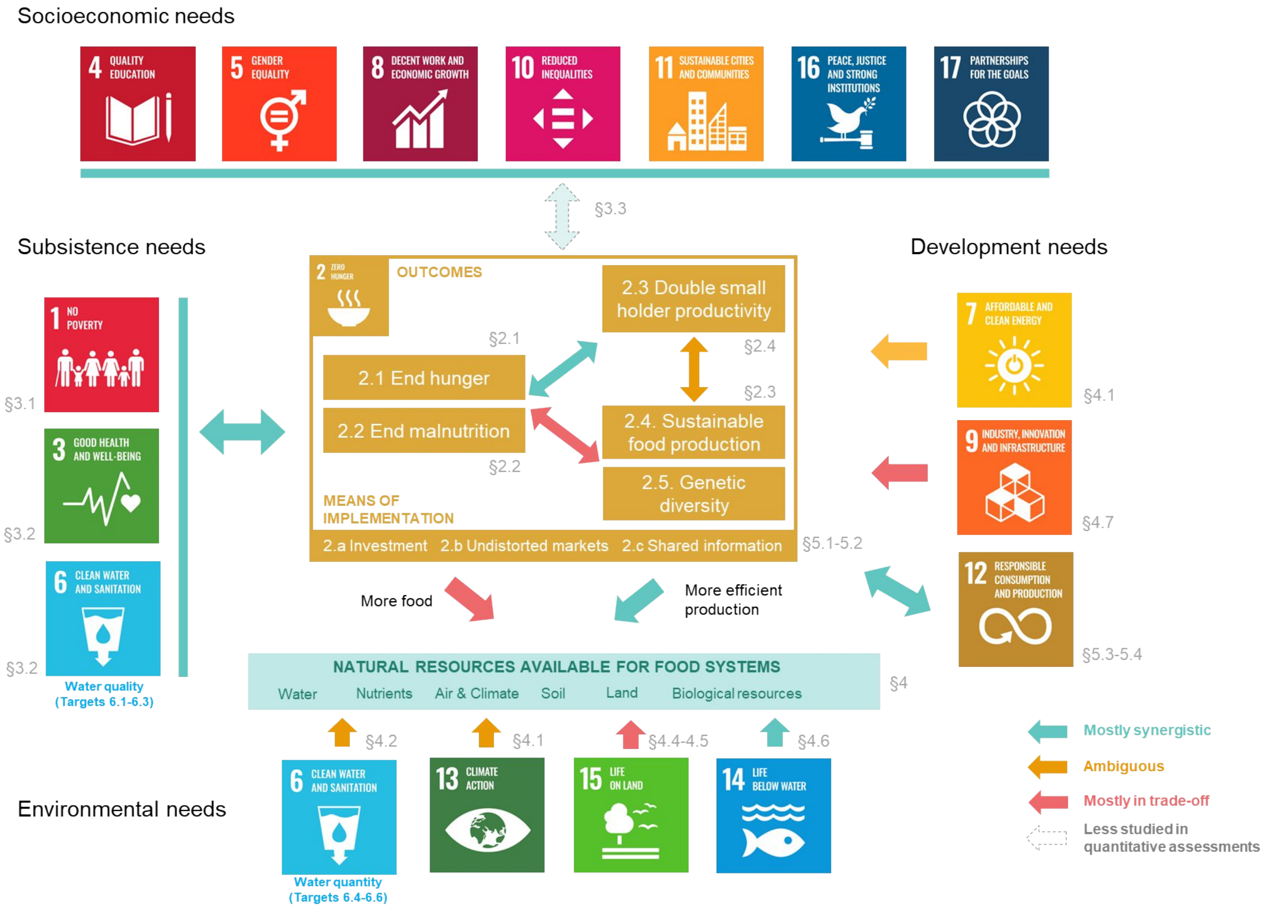

***Figure 1.*** *SDG2, its targets and relations to other SDGs, as analyzed in this paper. Colored arrows represent direction and nature of main SDG relations (mostly synergistic or in trade-off). Relations less studies are marked with pale colors/dashed arrow outlines. References to specific sections of the paper addressing the various targets/goals and their interaction are in grey text (§X.X). SDG2 "Zero hunger" encompasses five outcome targets that can be summarized as follows: 2.1: ending hunger and ensure access to safe, nutritious and sufficient food, 2.2: ending all forms of malnutrition, 2.3: doubling agricultural productivity and income of small-scale food producers, 2.4: ensuring sustainable and resilient food production systems, and 2.5: maintaining the genetic diversity of farm assets. Not visualized here are the three "mean of implementation" targets defined to support the achievement of the outcomes above: 2.a: increasing investment in agriculture and rural development, 2.b: avoiding international trade restrictions and market distortions, 2.c: better collaborate for agricultural market functioning. See Appendix for full description or the UN official website at [https://sdgs.un.org/goals/goal2](https://sdgs.un.org/goals/goal2).*

## Box 1. Modelling approaches for quantitative analysis of the global food system

A large set of modelling frameworks has been used to represent the global relations within the food system and its interactions with other socioeconomic and environmental components. These are rooted in different traditions: integrated assessment models of climate and environment (Parson and Fisher-Vanden, 1997), agricultural and trade models (Tongeren et al., 2001; von Lampe et al., 2014), computable general equilibrium models (Böhringer and Löschel, 2006; Hertel et al., 2009; Hertel et al., 2012), land system models (Foley et al., 1996; Haberl et al., 2007; Lotze-Campen et al., 2005), or household-level microsimulations (van Wijk et al., 2014). All these frameworks have their own strengths and weaknesses and can also be combined to broaden the scope of their applications across domains or scales (van Wijk, 2014; Wicke et al., 2014).

As we will show below, these model families have been applied to a large set of topics related to the food systems and SDG interactions. Food security has been often approached under the availability angle in that literature (Baldos and Hertel, 2014; Gerten et al., 2020; Hasegawa et al., 2015; Valin et al., 2014; van Dijk et al., 2021), with substantial emphasis on the long-term food need prospects, the environmental impacts of food systems expansion and the threat of climate change. Aspects related to food access have been primarily considered through the effect of exogenous increase of income (Valin et al., 2014; Yu et al., 2004), or the effect of rising agricultural prices on consumers (Golub et al., 2012; Hasegawa et al., 2018; Nelson et al., 2014), while the favorable income effects of rising prices on people employed in agriculture have only been considered in CGE modelling and household simulations (Hallegatte and Rozenberg, 2017; Hertel et al., 2010). Efforts to explicitly model poverty and food access inequality reduction in IAMs to tackle food insecurity are more recent (Hasegawa et al., 2019; Soergel et al., 2021). Similarly, investigating food utilization is relatively new to that literature (van Meijl et al., 2020b). New emphasis on the question of stability and resilience is also now developing, both under the framing of extreme climate change events, and following the COVID-19 crisis (Swinnen and McDermott, 2020).

***Drivers, scenarios, policy interventions and transformations.***

Foresight studies have been a common way to approach the modelling of SDGs with these tools. They typically quantify the development of alternative scenarios over time and analyze the interplay of macro-level drivers and their impact on the long-term system trajectories. This approach is mainstream in the environmental (Millennium Ecosystem Assessment, 2005; OECD, 2012) and climate change domains (O’Neill et al., 2014; van Vuuren et al., 2011b) with the definition of archetype socioeconomic scenarios, such as the Shared Socioeconomic Pathways (SSPs), which are now applied to many other disciplines (O'Neill et al., 2020). These allow for discussion and assessment of a number of key uncertainties related to climate, demography and macroeconomics. In the case of agriculture and food systems, foresight analyses and scenario approaches have also been widely used (FAO, 2018; IAASTD, 2009; OECD, 2016; van Meijl et al., 2020a; von Lampe et al., 2014; Zurek et al., 2021). Many modelling analyses also focus on the impact of specific policy interventions (OECD and IIASA, 2020; Rosegrant et al., 2017; Stehfest et al., 2013), for which static analyses using equilibrium models are more common (Dixon and Parmenter, 1996; Hertel, 1997). These two approaches are currently on track to converge, as the policy interventions needed for attaining the SDGs are becoming increasingly relevant for analysis of system transformations to achieve sustainable pathways, as stressed by various recent initiatives (Food and Land Use Coalition, 2019; Sachs et al., 2019; Steiner et al., 2020) – see Section 5 and Table 1.

### ***Strengths, limitations of models and possible improvements***

Models are powerful tools to highlight structural tensions and interrelations between key variables in the food system in an integrated manner. As we illustrate in this paper, a large number of studies has assessed the economic and nutritional benefits of agricultural investments or the trade-offs with environmental domains. Much progress has been achieved through model comparisons in communities like the Agricultural Model Intercomparison and Improvement Project (AgMIP - Rosenzweig et al., 2013), the Integrated Assessment Model Consortium (IAMC - van Vuuren et al., 2011c), the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP - Warszawski et al., 2013) or the Global Trade Analysis Project (GTAP - Hertel, 2012a).

In spite of these efforts, several important limitations must be noted: i) the full set of malnutrition indicators remains underdeveloped in modelling approaches, and efforts in representing micronutrients and diet-related health burdens should be continued; ii) current models often lack sufficient granularity for accurate assessment of SDGs, with limited representation of heterogeneity across and within households, including gender-related one, or in the geographical details. Even though highly disaggregated approaches may bring difficulties, many new questions related to inequality of conditions and hotspots of impacts cannot be captured through aggregated representations; iii) the food system as a whole is often only partly or roughly represented. Aspects concerning the food environment, institutional, social and individual drivers are generally not well considered. Many models also do not represent the full supply chain from ‘farm to fork’, or only do so in an aggregated way, ignoring the role of economics of value chains, in particular for price transmission, and the political economy of food system actors (Barrett et al., 2019); iv) some important drivers of food security are difficult to model, such as the role of conflicts or institution and governance. These elements are often captured through scenarios only; v) models results remain by nature uncertain even though the modelers try to characterize this uncertainty and delineate it through scenario envelops and model comparisons. Sources of uncertainty in particular include: uncertainty in the system drivers (e.g., climate, population), uncertainty in the model parameters, and uncertainty in model structure, in particular in the way the food system is represented. For this reason, there is great value in working with ensembles of independent models.

Last but not least, it is important to highlight that models’ value also depends critically on the quality of underlying data and behavior representations. With the COVID-19 crisis, the adequacy of the statistics currently used, and the relevance of the behaviors being assumed so far based on long-term historical observations are to be questioned, as new trends could emerge. Therefore, critical thinking and monitoring of recent developments are even more important to confront to model results for the years to come, to ensure that any new status in food systems conditions, and new paradigm can be adequately reflected in the models’ behavior.

# 2. Modelling SDG2: the inherent challenges to sufficient, nutritious, sustaining, and sustainable food

SDG2 covers a broad objective encompassing food security and sustainable production described as: *"End hunger, achieve food security and improved nutrition and promote sustainable agriculture"* (UN, 2015). This goal covers five outcome targets (Figure 1). This objective contains its own intrinsic set of tensions and challenges.

The first two targets relate directly to the concept of food security and nutrition (FSN) developed around the recognition of human rights to adequate food (UN, 1996), and structured around the four following pillars: i) availability, ii) access, iii) utilization, and iv) stability (FAO, 1996).[2] These dimensions are key to understanding how to achieve SDG2, in particular Target 2.1 and 2.2 on adequate food supply and malnutrition. The food security pillars highlight the importance of producing enough food ("availability") but also the role of income and food prices ("access" pillar), which raises the questions of the cost of nutritious and healthy food, independently from the diversification of food sources ("utilization" pillar), which also touches to malnutrition. Targets 2.3, 2.4 and 2.5 extend the scope of SDG2 to the modalities of agricultural production. Target 2.3 puts a strong emphasis on farm income for small-scale farmers, linking to SDG1 ("No poverty"), through an increase of their farm productivity. This target should however be reached without jeopardizing Target 2.4 that emphasizes sustainable production practices, and Target 2.5 that highlights the importance of keeping genetic diversity.

The different SDG2 targets therefore represent a consistent pathway to sustainable food systems but also can contain their own points of tension: how can we produce more, in a manner that is more healthy, more sustainable and more equitable -- all at the same time? This question garnered significant attention in the literature and needs to be first examined as it conditions many of the subsequent relations to other goals.

## 2.1. Providing adequate food for all and reducing hunger (Target 2.1)

The capability of humanity to produce enough food for its own subsistence has long been a source of concern. Malthus (1798) questioned the feasibility of a continuous population increase, and the Club of Rome report emphasized the limits to a continuous economic growth within a finite world (Meadows et al., 1972). The current UN projections predict 9.7 billion people globally in 2050 (+25% compared to 2020) with nearly a doubling of population in Africa (UN, 2019). And food demand will be further boosted by other drivers: income changes, dietary transition, urbanization, globalization, etc. (Kearney, 2010). FAO estimates that the total food calorie demand will increase by 39% between 2015 and 2050 (Alexandratos and Bruinsma, 2012; FAO, 2018),[3] and agricultural output will grow somewhat faster (40-45%), due to the need to produce feedstuffs for growing livestock consumption (Keyzer et al., 2005). Several authors anticipate even higher demand by mid-century with alternative assumptions on animal product demand: compared to FAO projected levels, Tilman et al. (2011) anticipate an increase of crop needs 50% higher by 2050, and Bijl et al. (2017) a 30% higher increase in food demand. Valin et al. (2014) compared estimates across global model projections and found a range of +43%–70% in food demand increase from 2015 to 2050,

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[2] The High-Level Panel on Food Security also proposed to extend the food security concept with two additional pillars: v) agency and vi) sustainability, which would follow the broader approach taken by SDG2 (HLPE, 2020).

[3] For the projection from FAO (2018), the results from the BAU scenario for 2012-2050 were rescaled to the period 2015-2050 for comparability, assuming a constant growth rate.

slightly above FAO estimates. And even when models reviewed disagree on the future level, most found much higher animal product consumption increase by 2050, with a range of 45%–160% spanning well above FAO's projected increase (55%). This anticipation is also supported by more empirical estimations (Gouel and Guimbard (2018) with 64–95%, Bodirsky et al. (2015) with 81%–102%, Bodirsky et al. (2020) with 76%).[4]

Under these conditions, the capacity of the global food system to sustainably supply all the food required has been questioned. To understand the possible food security implications, food availability is usually estimated using the average dietary energy supply of the food system, in kilocalories per capita per day, but also using more sophisticatedly metrics such as the prevalence of undernourishment (Goal indicator 2.1.1). FAO estimates that 688 million people (8.9%) were undernourished in 2019, a trend increasing following the COVID-19 crisis (FAO et al., 2020). To calculate such prevalence, the food distribution supply profile per capita, in dietary energy terms, is compared to the average minimum dietary energy requirement in the population (Cafiero et al., 2014). This framework effectively captures the availability pillar of food security (more domestic supply reduces undernourishment) and can also be used in modelling to examine the response to average price or income changes (access pillar). Alternative metrics have also been proposed to measure undernourishment, such as the prevalence of underweight, based on up-scaled medical surveys (Bodirsky et al., 2020), or the number of children malnourished.[5]

Undernourishment metrics were implemented in various global economic models (Baldos and Hertel, 2015; Bodirsky et al., 2020; Hasegawa et al., 2015; Hasegawa et al., 2019), where it is also possible to capture the role of prices and income, as these determine the final level of food demand (Valin et al., 2014). Past modelling studies have often predicted a progressive decrease in undernourishment by 2050 following this indicator, under the effect of increased incomes and reduced inequality (which decreases the food distribution spread): down to 318 million (3.5%) undernourished in Alexandratos and Bruinsma (2012), 528 million (5.7%) underweight[6] in Bodirsky et al. (2020), less than 100 million (1%) undernourished for a middle-of-the-road scenario (SSP2) in Hasegawa et al. (2015). Overall, these results are very sensitive to the projections in inequality. For instance, the most unequal scenario (SSP3) in Hasegawa et al. (2015) results in a comparable level for undernourishment compared to today's situation.

The prevalence of undernourishment (PoU) indicator has been the workhorse of the modelling community recently to approach the question of hunger. However, this metric completely ignores the composition of the diets and the role of protein and micro-nutrients intake for a healthy diet (Springmann et al., 2016b). It also overlooks the multi-dimensionality of food security. Some first steps towards broadening the food security framework have been made recently (van Meijl et al., 2020a). In addition, it has been implemented across frameworks without harmonization of inequality projections within countries, which explains the large range of undernourishment projections (only average incomes per capita are harmonized for the SSPs quantified elements, for

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[4] The 2005-2050 estimates from Valin et al. (2014), 2010-2050 results from Gouel and Guimbard (2018) and 1990-2050 estimates were all rescaled to 2015-2050 for comparability, assuming a constant growth rate.

[5] This indicator was also traditionally used in the IMPACT model (Rosegrant et al., 2017) using correlations between dietary energy supply and malnourishment statistics (Smith and Haddad, 2000). Even though more determinants of malnourishment could possibly be considered with the relation defining this metric, the indicator would primarily be determined by the average food availability, sole endogenous variable in the model entering the calculation, which gives it the same characteristics as the prevalence of undernourishment indicator.

[6] Underweight and undernourishment values are relatively comparable. The global estimate of underweight people is 744 million in 2010 (Bodirsky et al., 2020), against 668 million for undernourished (FAO, 2020). However, regional and temporal patterns diverge, being lower for underweight prevalence in Sub-Saharan Africa and higher for Asia and showing a later decline than for undernourishment.

instance). Last, but not least, that indicator ignores the role of heterogeneity in income and price effects, and in particular the contrasted dynamics between rural and urban households (Hertel et al., 2010; Laborde Debucquet and Martin, 2018). More detailed analyses are therefore needed to better inform efforts aimed at tackling the challenge of Target 2.1 and 2.2 of SDG2, better integrating especially poverty modelling (see Section 3.1).

### 2.2. Dietary needs, nutrition transition and the triple burden of malnutrition (Target 2.2)

What we eat is as important as how much we eat when it comes to maintaining food security. This is why the "utilization" pillar is a key for food security. The example of animal production illustrates well various aspects of the challenges accompanying economic development. The nutrition transition influences our demand for nutrients like proteins and fat, and this also applies to other products (Bijl et al., 2017; Bodirsky et al., 2020; Gouel and Guimbard, 2018). At the same time, producing more livestock products is resource-intensive and comes with large sustainability impacts (Herrero et al., 2013; Steinfeld et al., 2006; Wirsenius et al., 2010). Consumption of seafood also provide high value nutrients (Béné et al., 2015; Hicks et al., 2019) but brings additional environmental challenges as one third of marine catches are unsustainable (FAO, 2020b) and fast expansion of aquaculture adds to resource pressure and generates local pollution (Ahmed et al., 2018). Some other food products have very specific footprints due to their yield and production location, and trade mediated impacts can occur (Henders et al., 2015; Kastner et al., 2012). The choice of the diet can therefore have large implications for health and environment (Tilman and Clark, 2014). We explain below the different nutritional challenges associated to dietary patterns and discuss further in Section 3.2 the consequences for health as part of the synergies with SDG3.

To disentangle the complexity between nutrition needs and its impact, modelling diet composition is fundamental. Macronutrients are not the only important elements to represent, micronutrients are also essential to health (Burchi et al., 2011). Only a few modelling studies have examined the prospects on both macro and micronutrient provision at global level. Nelson et al. (2018) analyzed such scenarios at the horizon 2050 and found that dietary energy requirements would certainly be met in all regions, as well as protein intake needs, to the exception of a few least advanced countries. However, they anticipate insufficient supply of fat in low-income countries, and severe and persistent deficiencies in calcium, iron and folate, as well as several key vitamins (A, E, B12) in many parts of the developing world. These malnutrition impacts would be worsened under the effect of climate change, in particular as micronutrient concentrations in crops are expected to decrease under future elevated $CO_2$ concentration in the atmosphere (Beach et al., 2019; Myers et al., 2014).

Beside undernourishment and micronutrient deficiencies, a third important nutritional challenge is overweight and obesity, leading to the notion of the "triple burden of malnutrition" (Gomez et al., 2013). In 2016, the global "obesity pandemic" (Swinburn et al., 2011) was affecting 13.1% of adults around the world (FAO et al., 2020), and costing 3.3% of GDP in advanced economies (OECD, 2019). Projecting obesity in the context of food demand studies is rather recent. Based on detailed body mass distribution data, Bodirsky et al. (2020) calculated that about 45% of the population would be overweight by 2050, compared to 29% in 2010, based on the continuation of current food consumption patterns, and 1.5 billion people would become obese by mid-century (16%). Overconsumption of food associated to overweight brings large inefficiencies in the food system. Hasegawa et al. (2019) estimated that halting overconsumption by 2030 would reduce total caloric requirement by 6% and protein requirement by 9% globally. Therefore, even if these reductions would not suffice to address future food needs, there is a paradox of food distribution, with food deprivation for the poorest and overconsumption of food for another part of the population, illustrating the possible win-wins within the SDG Target 2.2 on malnutrition.

### 2.3. Producing more but growing more sustainably (Target 2.4)

Satisfying adequate dietary needs and eliminating malnutrition will require more food production as highlighted above, which may pose important risks for environmental sustainability of the food systems. The impacts of agricultural production increases on natural resources are well known (Springmann et al., 2018a; Tilman et al., 2001) and researchers have warned about the risks of exceeding a number of planetary limits (Rockstrom et al., 2009) due to agriculture intensification and expansion. Therefore, Targets 2.1 and 2.2 oriented towards provision of more adequate food and nutrition may be in tension with Target 2.4 that emphasizes the need of sustainable food production systems, improved agricultural practices, and ecosystems protection.

One of the most salient elements of the tension between adequate food supply and protection of the environment relates to land use. On the one hand, land needs mirror the concern that our current planet capacity may not suffice to feed its future population, and on the other hand, land use change has important implications for a number of SDG sustainability dimensions: carbon stocks for SDG13, biodiversity for SDG15, and the occurrence of zoonotic epidemics affecting SDG3. Many models have investigated the interplay of macroeconomic drivers, diet changes and future yield to determine the future land use requirements by the mid-century and beyond (FAO, 2018; Hertel et al., 2016; Popp et al., 2017; Schmitz et al., 2014; Smith et al., 2010; Stehfest et al., 2019). These studies usually find that agricultural land will continue its expansion with a range of ~5–20% for cropland and ~-10–+25% for pasture land (based on Smith et al. (2010) and Stehfest et al. (2019)). Figure 2 shows, through a simplified scenario decomposition, how different drivers of food demand – population, income per capita, diet preferences, overconsumption and waste - may influence the future demand by 2050, and how this future demand would result into a net land use change, after adjusting for projected technical change and climate change impact.

Virtually all studies predict further encroachment of cropland expansion into natural ecosystems (forests, biodiverse savannahs, wetlands) and the possibilities to avoid such damages remains disputed. The special report on land from the IPCC (IPCC, 2019) identified that out of 13 Gha of surface land, 9.3 Gha were already used, and only a quarter of the unused part (940 Mha) was unforested land (outside of barren, rocks etc.). Based on agroclimatic suitability consideration, FAO estimates that 400 million ha of non-protected areas would be suitable for rainfed cultivation expansion, mostly in low and middle income countries, in particular Africa and South America (FAO, 2018). This estimate would be reduced to about 260 Mha when considering 6h of distance to market as an extra criterion (Deininger and Byrlee, 2010). Some other literature assumes much higher availability, with less constraining criteria on land status or suitability (Eitelberg et al., 2014). Yet, when these estimates are subject to closer scrutiny, they are significantly reduced. For instance, Fritz et al. (2013) reduces availability estimates from remote sensing data by 300–400 Mha when using field level information. Looking at various social and ecological trade-offs, Lambin et al. (2013) also reviewed data from global scale assessment in specific locations and found that effective availability would be less than a third of the theoretical top-down estimates. On the other hand, land suitability is not a static concept under climate change, and new regions could become cultivable as temperature and precipitation patterns evolve in the coming century, particularly in the Northern hemisphere (Sloat et al., 2020; Zabel et al., 2014).

The question of the pressure of agricultural production on natural resources extends much beyond land use expansion but also relate to land quality and many other elements (water, climate, nutrient balance, etc.). We present these in more details in Section 4 examining the impacts from SDG2 on other environmental SDGs.

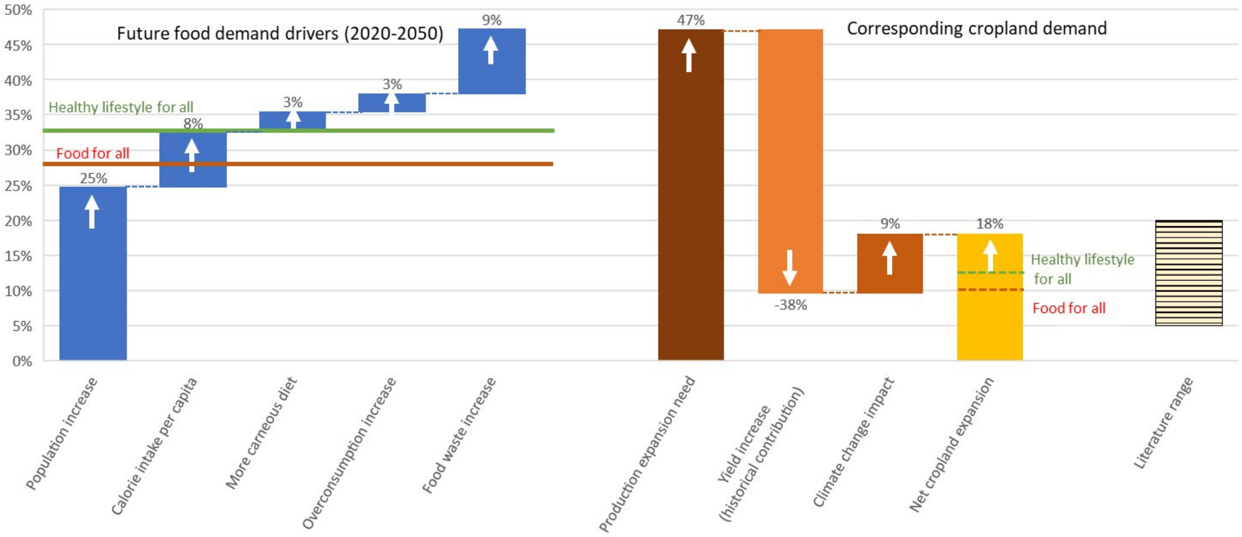

***Figure 2.*** *Decomposition of future food demand from 2020 to 2050 (left-hand side, blue bars) and potential implications for cropland expansion based on stylized assumptions (right-hand side, warm colors). Total food demand increase (sum of blue bars – 47%) is the cumulated effect from population increase, calorie consumption per capita increase driven by economic growth, diet preference changes leading to more meat consumption and feed needs, overconsumption, and waste increase. The final demand increase (brown bar) is partly offset by the increase in yields (here based on an average 80% contribution share to match historical observations, orange), and future expected impact of climate change (dark orange). The net cropland expansion (yellow) can be compared to the literature range (striped bar). Food for all line in blue (yellow) bar corresponds to the level of increase in food (land) corresponding for sufficient caloric nutrition for all. Healthy lifestyle line corresponds to the increased level where all consumers with inactive lifestyle adopt a moderately active lifestyle. Sources: population increase: UN DESA; consumption per capita and livestock consumption impact Stehfest et al. (2019), based on GLOBIOM model; Overconsumption and waste impacts: Bodirsky et al. (2020); Historical yield contribution consistent with Smith et al. (2010), Burney et al. (2010), Fuglie et al. (2019); Climate change impact: RCP8.5 data from Leclère et al., 2014. Literature range: Stehfest et al. (2019) and Smith et al. (2010).*

### 2.4. The crucial role of agriculture productivity (Target 2.3 & 2.5)

Most common arguments against a Malthusian vision of the future rely on the idea that technical change could keep pace with future food demand growth and limit impacts on natural resources (Borlaug, 2002). Past productivity increases in agriculture have been substantial, moving from an input and machinery-based period of global productivity improvements during the Green revolution, to a knowledge-based one over the past three decades (Fuglie, 2010). There is still scope for further development of productivity as numerous innovations and new technologies emerge (Herrero et al., 2020; Ludena et al., 2007). And productivity gains will be crucial for future food security through their capacity to support income and offer lower food prices (Hertel et al., 2016), provided it also benefits to small producer net food seller (see also Section 5.2 on the role of trade). SDG target 2.3 highlighting productivity and income for smallholders therefore appears fully aligned with the food security objectives of SDG2.

Among the different sources of agricultural productivity increase, land productivity has been particularly scrutinized, and is usually perceived as a key factor of economic development that allows mitigating the impacts emphasized above. Modelling studies have highlighted the direct role of yield on future trajectories of land use requirements (Balmford et al., 2005; Hertel et al., 2016;

Stehfest et al., 2019). The prospects on future yield increase remains positive. On the one hand, technical margins exist to increase attainable yields through improved technologies and crop breeding (Fischer et al., 2009) and agricultural investments should support further progress (Baldos et al., 2018). On the other hand, the assessment of yield gaps indicate that large potentials exist to increase actual yields to the level achieved under best practices, but remain subject to local climatic and management constraints (Licker et al., 2010; van Ittersum et al., 2013). Mueller et al. (2012) identify that closing yield gaps globally could increase global crop production by 45%–70%, by optimizing water and nutrient management, and Folberth et al. (2020) estimate that reallocating crops accordingly could reduce cropland area by 50%. Simulation models have used such assessments to better anticipate future possible scenarios of yield development (van Zeist et al., 2020). Yield projections scenarios have clearly highlighted the substantial land sparing effects, but also pointed to the nitrogen consumption trade-offs (Tilman et al., 2011), and the greenhouse gas (GHG) emission reductions (Burney et al., 2010) as well as food security co-benefits (Valin et al., 2013).

From an economic standpoint, increasing productivity can however lead to an ambivalent effect. On the one hand, the lower demand for resources per unit of output can lead to some environmental benefits. On the other hand, lower prices obtained through total factor productivity gains can lead to a rebound of consumption and increased exports, thereby partially or fully offsetting these benefits, an effect called the Jevons paradox (Alcott, 2005; Hertel, 2012b). This effect has been particularly identified in the case of cropland intensification (Byerlee et al., 2014; Ewers et al., 2009; Phalan et al., 2016; Villoria et al., 2013), but also irrigation water efficiency (Grafton et al., 2018). Modelling studies have illustrated how strategies oriented towards increasing yields could lead to mixed effect as food security (through increased production) and environmental outcomes would come in direct trade-off (Hertel et al., 2014; Valin et al., 2013). The potential for Jevons paradox calls for more attention to the ambiguous role that productivity gains (Target 2.3) could have on the environment (Target 2.4), as well as the need for protecting environmentally sensitive lands in the context of high rates of technological progress.

The other challenge associated with productivity increases is to ensure that, while saving on land resources, it does not bring any other environmental degradation. This is a particular concern for land intensification, as damages from high-input agriculture on ecosystems services have been well documented (Matson, 1997), most notably for biodiversity (Donald et al., 2001). A lot of attention has been devoted to identifying routes for sustainable intensification in the domain of nutrient and water management, pest control, soil protection to find win-win solutions (Foley et al., 2011; Tilman et al., 2002) – see also Section 4 on the relation between nutrient management, soil quality and food security. In the case of livestock, mixed intensive systems could leverage substantial environmental benefits both in terms of nutrient cycling, GHG emissions and land sparing, compared to extensive ones (Havlík et al., 2014). This is also the case for the fish sector where substantial productivity gains can be achieved in aquaculture (Waite et al., 2014). Therefore, improvements in agricultural productivity, in particular total factor productivity (related to all production factors), offers an opportunity to simultaneously lower the pressure on the environment and increase farmer income by decreasing the input requirements (Figure 3). To guide this change, Seppelt et al. (2020) illustrate how an optimum intensification level can be reached across production and environmental objectives by using a measure of *green* total factor productivity – or total resource productivity. Taking the case of biodiversity, they explain how such approach could support sustainable intensification in low- and middle-income countries, and ecosystems value recovery in highly intensified regions. However, simulations towards 2050 suggest that more sustainable yield both for crops and livestock may also require drastic adjustments in our consumption patterns to avoid further deforestation (Erb et al., 2016).

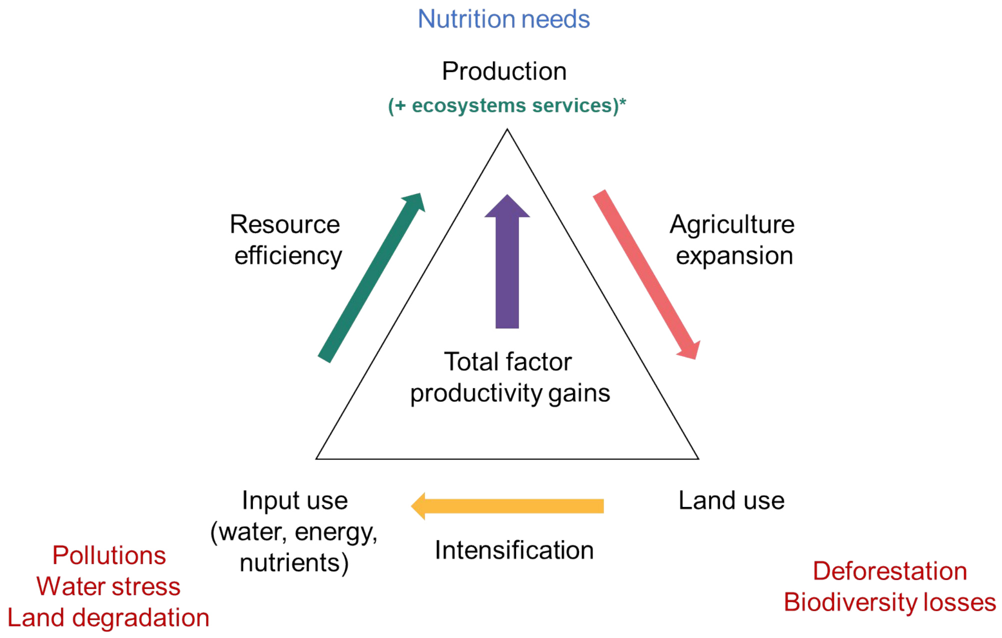

***Figure 3.*** *The role of total factor productivity (TFP) gains to limit impact of agricultural production on the environment (in red).*

** Ecosystems services only for green TFP: indeed, some ecosystems services may be negatively affected while focusing on standard TFP gains (e.g. biodiversity). Accounting for ecosystems services value defines a green TFP that can guarantee a sustainable use of agricultural productivity gains (Seppelt et al., 2020).*

Finally, increasing agricultural productivity is also key in the context of ongoing climate change impacts which are expected to grow over the coming decades and substantially affect crop yields (Rosenzweig et al., 2014), irrigation capacity (Schewe et al., 2013), labor productivity (de Lima et al., 2021), micronutrient availability (Beach et al., 2019) and ultimately food security (Hasegawa et al., 2016; Hertel et al., 2010; Janssens et al., 2020; Lloyd et al., 2018; Springmann et al., 2016b; Wheeler and von Braun, 2013). This paper does not delve further into the interplay of climate change impact and food security, as it has been extensively reviewed (Mbow et al., 2019). The importance of adaptation measures through yield responses has been largely emphasized and identified as a key factor to limit food security impacts (Leclère et al., 2014; Nelson et al., 2014; Weindl et al., 2015). Agricultural practices should also encourage resilience, to resist to occurrence of extreme events. Crop genetic diversity (Target 2.5) is representative of the measures fostering adaptation to climate change and resilience, also in the context of possible occurrences of new diseases and pest outbreaks.

## 3. Synergies between SDG2 and other sustainability dimensions

The “Zero Hunger” goal – and its different targets – is very closely connected to some other goals with which it operates in synergy, and, for some, even in full symbiosis. One of these is poverty elimination (SDG1), crucial for food access, and another is good health and well-being (SDG3), and the need for clean drinking water (SDG6). But beyond these, a broader set of socioeconomic SDGs supports the progress of SDG2 and has been identified as key enablers (SDG4, 5, 8, 10, 11, 16, 17). We illustrate below how these have been approached by the modelling literature.

### 3.1. Food access and poverty (SDG1)

As analyzed in Section 2.1, food security does not only rely on food availability but also on food access. For that reason, considering the situation of households and individuals is important to correctly represent food security conditions, but is typical of large scale modeling (Müller et al., 2020; van Wijk, 2014). For instance, aggregated approaches to prevalence of undernourishment described above remain on the stylized representation of food distribution from FAO (Cafiero et al., 2014). Compared to the optimistic trends on hunger presented in Section 2.2, Laborde Debucquet and Martin (2018) look for instance at the implications of economic growth slow down for poverty in 29 developing countries with a sample of 300,000 households. They predict that in half of the countries, the extreme poverty rate will remain above 5% by 2030, with important consequences for food security. At a larger scale, Hallegatte and Rozenberg (2017) simulate the impact for 1.4 million representative households of a shift in agricultural prices and farm income due to climate change and find that the higher price effect would be predominant and increase poverty, which in turn would increase stunting (Lloyd et al., 2018). Other studies based on household modelling have illustrated the adverse impacts of food price increases on poverty (Hertel et al., 2010; Ivanic et al., 2012). However, higher prices could also in some situations increase farmer revenues and bring food security benefits (Hertel, 2015). Many scholars highlighted that, if in the short term, food price increases could be seen as detrimental for the poor, sustained food prices could be in the long term the best way to reduce rural poverty and improve food security for smallholders (Headey and Martin, 2016; Ivanic and Martin, 2014; Swinnen and Squicciarini, 2012). Therefore, if food security and poverty can be seen as part of a same battle, reduction of poverty should not only be sought through lower food prices but also through higher income – as highlighted by Target 2.3. In addition to the question of income, it is worth noting that SDG1 also insists on the role of access by poor households to land, natural resources and technologies (Target 1.4) and reduce exposure to climate events and relative risks (Target 1.5), two objectives that also strongly resonate with the Target 2.3 associating smallholder productivity gains and income increase.

### 3.2. Health and sustainability co-benefits from dietary changes (SDG3)

The relation between SDG2 and SDG3 on good health and well-being is also strongly synergistic, as nutrition is a key element of good health. First of all, malnutrition and health issues are strongly related in least developed countries, facing severe nutrition challenges. Maternal undernourishment and nutrient-deficiencies lead to fetal and child nutrition and development problems, reinforced through nutrient-inadequacies in breastfeeding (Black et al., 2013). The resulting stunting and wasting can increase mortality risks when children are exposed to infectious diseases. Conversely, many infectious diseases, such as measles, diarrhea, pneumonia, meningitis or malaria, can lead to increased risk of wasting and stunting risks for young children (ibid).

Furthermore, in all regions, adequate diet does not only limit the risk of malnutrition, but also prevents the prevalence of a number of non-communicable diseases, such as cardio-vascular diseases, diabetes, or cancer: in 2017, 17 million deaths and 255 million disability-adjusted life years would be attributable to dietary risks such as high sodium consumption, low intake of whole grain or low intake of fruits (Afshin et al., 2019). GHG emission-intensive products such as red meat are also contributing risk factors, which have led scholars to emphasize the co-benefits between health and sustainable agriculture. Tilman and Clark (2014) compare the impact of a conventional omnivorous diet with a pescatarian diet, a Mediterranean diet and a vegetarian diet, and find that moving away from current diets would be a win-win solution, with strong health benefits for the three alternative diets (5-40% relative risk decrease in cancer, diabetes and coronary mortality), and strongest outcome on environmental side with a vegetarian diet (more than 2 $GtCO_2e$ per year and 740 Mha of cropland saved by 2050). Springmann et al. (2016a) extend this type of analysis by looking at the implication of shifting to more plant-based diets by 2050 and find a decrease in global mortality of 6–10% and an abatement of emissions of 29–70%, leading to economic benefits of 1–31 trillion USD. More recently, the EAT-Lancet Commission proposed a more detailed sustainable and healthy diet prescription integrating a large number of dietary risks, with ambitious nutritional and planetary synergies (Willett et al., 2019). They find that adopting such a diet would allow reduce mortality by 19–23.6% by 2050. However, they also point out that providing such diet to all would require bridging the yield gaps by 75%, requiring substantial resource management improvements in order to be sustainably attainable. One other important limitation to the adoption of these healthy diets is the question of affordability. Hirvonen et al. (2019) estimated that the EAT-Lancet diet would cost at minimum 2.84 USD per day at 2011 prices and would be therefore inaccessible to 1.58 billion poor, due primarily to the share of fruits and vegetables required, and secondly to animal products. The diet was also found to be 60% more expensive, on average, than a least cost diet aimed at providing nutrition adequacy for 20 nutrients. In a follow-up analysis, the FAO et al. (2020) determined that healthy diets would be five times more expensive than a minimum energy diet, illustrating the extent of the income boost for impoverished households which would be necessary to make this diet accessible to all. Therefore, improving access to healthy diets cannot be dissociated from the progress on poverty elimination (SDG1).

One additional synergy between SDG2 and SDG3, comes from environmental health through a more sustainable agriculture (Target 2.4). Agricultural activities indeed substantially contribute to global pollution through various channels. First, through air pollution as biomass burnings from field management and land clearing contribute to fuel combustion emissions, responsible for 85% of all the air pollution burden, itself the largest source of pollution-related diseases (Landrigan et al., 2018). Agriculture ammonia emissions also impact human health by contributing to formation of fine particle matters in the air (Stokstad, 2014), and generating several hundred thousand premature deaths per year globally (Giannadaki et al., 2018). A second channel of impact occurs through water pollution: excessive fertilizer application and manure management lead to pollution in the watersheds (Section 4.3) to which add more complex compounds coming from pesticide and herbicide applications (Evans et al., 2019; Schwarzenbach et al., 2010). A third channel of impact comes directly through the food and beverage we eat, with traces of pesticide leading to closely monitored ingestion levels (Nougadère et al., 2012). Chronic exposure to pesticide – directly for farmers or indirectly through air, water and food - have be found to increase risk diseases (Alavanja et al., 2004; Landrigan et al., 2018). Such impacts on health are not yet modelled at large scale due to the methodological uncertainties but reduction of pesticide use has been highlighted as a key component of sustainable agriculture (Möhring et al., 2020; Nicolopoulou-Stamati et al., 2016).

A last area of synergy between SDG2 and SDG3 attracted more attention since the COVID-19 crisis: the risk of zoonosis epidemic associated to expansion of human settlements and agriculture into wilderness areas (Morse et al., 2012), directly referred to in Target 3.3. Even though no foresight study is available to date to predict the link between future scenario for agriculture and risk of emergence of new diseases, the role of land use change in the zoonosis risk is now well recognized (Gibb et al., 2020; Patz et al., 2004). Furthermore, intensive livestock farming is also well-known for increasing risks of zoonosis emergence (Jones et al., 2013) leading to considering the concept of "One health" as a key component of the food systems sustainability (Coker et al., 2011).

### 3.3. Education, gender equality, decent work and other socioeconomic enablers (SDG4, 5, 8, 10, 11, 16, 17)

A comprehensive view of food systems encompasses a large set of socioeconomic drivers and outcomes (Ericksen, 2008; HLPE, 2017; Ingram, 2011). Therefore, many other SDGs are also connected to SDG2 and support its achievement. These have been identified in Figure 1 as a single block of socioeconomic enablers but obviously interact in a more complex manner with SDG2. These are education (SDG4), gender equality (SDG5), decent work and economic growth (SDG8), reduction of inequality (SDG10), sustainable cities and communities (SDG11), peace, justice and strong institutions (SDG16), and partnership for the goals (SDG17). These are usually not well represented in global quantitative studies, therefore will be only briefly covered here. However, some of these enablers can play important roles for food security and other SDG2 dimensions. Therefore, better assessing the associated synergies around these goals for food systems should be an important objective for future quantitative assessments.

Among these goals, education (SDG4) is a first important development driver influencing consumption patterns and healthy diet choice (Hiza et al., 2013). Target 4.7 highlights education to sustainable lifestyle, which goes one step further into supporting sustainable food systems. And Target 4.b insists on the importance of training in science and engineering, which can support more sustainable management and research (Target 2.a). In developing regions, education is also an important pillar for the improvement of maternal and child nutrition (Alderman and Headey, 2017; Ruel and Alderman, 2013). As highlighted above, food security and poverty are also closely associated. Higher smallholder incomes (Target 2.3) should therefore help for schooling of children in rural areas by limiting contribution to family labor in agriculture.

Gender equality (SDG5) is another key goal for food security as female workers are a substantial share of the agricultural workforce – 40-50% in developing countries (FAO, 2011) with even larger shares in some sectors and regions (e.g. 70% for upland rice in Indonesia). Women, however, face difficulties to access land, livestock, education, extension and financial services, and also equal employment conditions to those of men (wage, stable contract, off-farm opportunities). According to FAO (2011), targeting these inequalities would allow to reduce undernourishment by 100-150 million persons. At the same time, women play a key role for food security in the household, and their nutritional status also influences those of their young children (Black et al., 2013). SDG5 can therefore support income and productivity increases (Target 2.3) for small-scale women farmer by enhancing their access to land and natural resources (Target 5.a) (Agarwal, 2018) and empowering them to safeguard the nutritional status in the households.

Decent work and economic growth (SDG8) and reduction of inequality (SDG10) can also support better nutrition by going beyond SDG1 and bringing economic resources (Target 8.1 and 10.1) to households for accessing healthy food. Targets 8.2-8.4 also put emphasis on productivity, diversification, technological upgrading, formalized small-scale enterprises, and resource efficiency – all supportive of Targets 2.3-2.5. Nonetheless, economic growth can also steer unsustainable behavior for the food systems, such as overconsumption and waste (Section 5.4). Sustainable cities and communities (SDG11) put an important emphasis on urban and rural areas harmonious integration and planning, which would support Target 2.1 of greater access to sufficient and nutritious food in cities.

Peace, justice and strong institutions (SDG16) have a key role to play for food security as conflict remains one of the most severe drivers of severe undernourishment and food crises (FAO et al., 2017). Furthermore, farmers' rights, in particular land tenure, and solid institutions are key to secure the situations and income of small-scale farmers. Partnership for the goals (SDG17) emphasizes the role of Development Assistance, for rural economic development in developing countries, and the need to address the most serious food crises through humanitarian aid. It also encourages international knowledge transfers, which directly supports Target 2.a (see Section 5.1).

# 4. Trade-offs between SDG2 and environmental goals

Feeding the world sustainably will unfortunately not be achievable without tensions. As illustrated in Section 2.3, growing more food for SDG2 will pose some serious challenges for natural resources, and the final impacts will depend on future food demand and our capacity to create a more resource-efficient and sustainable agriculture globally. One of the commonly adopted frameworks to represent global sustainability in the Anthropocene is the planetary boundaries approach, which defines thresholds on resources and ecosystems usage which must not be exceeded if we are to remain within a sustainable exploitation of our planet (Rockstrom et al., 2009; Steffen et al., 2015). In the analysis of the boundaries as proposed by Rockstrom et al. (2009), six are directly relevant to agriculture (climate change, biodiversity, nitrogen, phosphorus, freshwater use, land use change), and three of these boundaries have already been exceeded: nitrogen cycle, biodiversity loss and climate change. In an update to that framework, Steffen et al. (2015) additionally identified phosphorus and land-use as having exceeded the Earth's safe operating space. Several papers have subsequently analyzed the extent to which agriculture contributes to these environmental challenges in the future. Using a global agricultural market model, Springmann et al. (2018a) projected that if current trends were to continue without any change of technical level, the number of boundaries crossed by 2050 would be up to five: in addition to GHG emissions, cropland use, nitrogen and phosphorus application, the extraction of blue water would be an additional limit exceeded. Gerten et al. (2020) analyzed that half of the current production system would already transgress some of these boundaries globally and respecting these environmental limits would allow to only feed 3.4 billion people globally. All these authors propose mitigation measures and transformations that would allow overcoming these limitations while also achieving food security and environmental sustainability by 2050. These system transformations will be discussed in Section 6.

Figure 4 illustrates how the different planetary boundaries would be crossed by 2050 according to selected modelling studies. Here, displayed ranges of expansion for each variable are based on projections from economic and integrated assessment models taking into account technical change. Under that assumption, three boundaries are crossed already in 2010, and GHG emissions are crossed by 2050. Land use and water withdrawals are not marked as crossing boundaries by 2050 but only at "increasing risk", to the difference of Springmann et al. (2018a), because technical change buffers a part of the future impact.

The challenges highlighted through the planetary boundary framework provide an overview of the larger set of trade-offs enshrined within the SDGs. We explain in this section in more detail how these different challenges have been studied in modelling studies and what their mitigation options are. Furthermore, the success of the Agenda 2030 also depends on the achievement of other goals. We highlight here how some SDGs, associated to ambitious targets, may enter in competition with SDG2 and bring additional challenges for the food system.

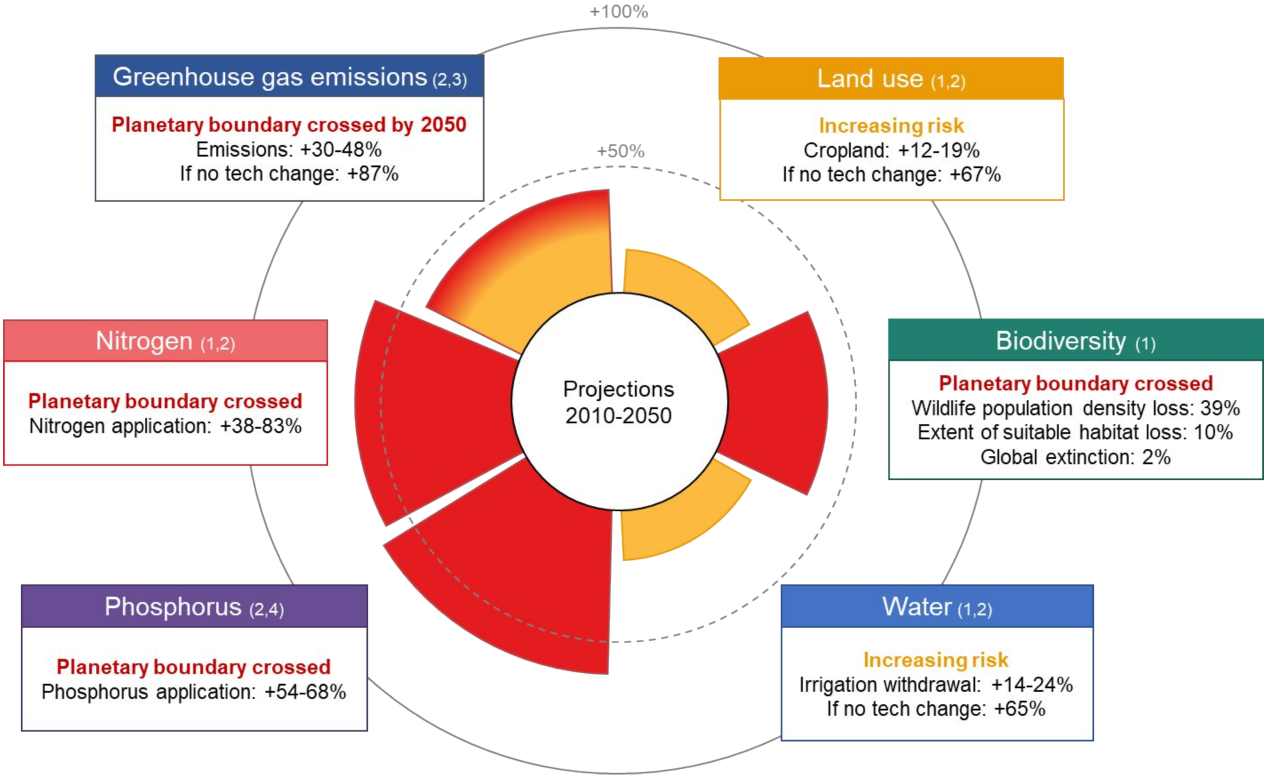

***Figure 4.*** *Projections of the food systems pressure along selected environmental dimensions (Visual representation inspired from the planetary boundaries, Steffen et al., 2015). Colors of the sectors indicate the status for each planetary boundary: green = no risk (none); orange = at risk of crossing by 2050; red = boundary crossed (plain if crossed already in 2010, gradient if crossed by 2050). Sector size corresponds to the range of values covered by the sources (subscripts in the box titles). For source (2), no technical change is assumed for the projection, which may significantly increase the impact; these numbers are therefore only reported for information when out of the range of other studies, and not used to calculate the sector size. Greenhouse gas emissions only account for non-CO$_2$ emissions from agriculture. Sources used (box title subscripts): 1 – Leclère et al. (2020): GLOBIOM, IMAGE, AIM, MAgPIE models; 2 – Springmann et al. (2018), baseline (without technical change), IMPACT model; 3 – Frank et al. (2018), GLOBIOM, IMAGE, CAPRI, MAGNET models; 4 – Mogollon et al. (2018a), IMAGE model.*

### 4.1. Contribution to climate change and trade-offs with nature-based solutions (SDG13)

One of the most widely studied adverse environmental impacts of the food system is its contribution to climate change. The food system (including agriculture, food supply chain and waste management) is considered to represent today 34% of total anthropogenic GHG emissions (Crippa et al., 2021) and direct emissions from agriculture are expected to keep growing over the coming decade, mostly through direct $CH_4$ and $N_2O$ emissions (Popp et al., 2010), whereas land use change emissions would decline (Popp et al., 2017; Valin et al., 2013). The unabated increase in agricultural emissions could potentially compromise the feasibility of the Paris Agreement (Clark et al., 2020). For that reason, agriculture is expected to contribute to mitigation efforts (Wollenberg et al., 2016), but this reduction of emissions should be achieved without compromising food security (Smith et al., 2013). How can agricultural emissions be reduced? Internalizing the GHG emissions externality from agriculture would result in much higher production costs and food prices, thereby giving rise to diminished food availability and affordability. Based on a multi-model analysis, Hasegawa et al. (2018) found that applying the same carbon tax to agriculture as to other sectors for a +2°C climate stabilization scenario could put on average 70 million more people at risk of undernourishment. This number could rise to 160 million for a +1.5°C ambition (Fujimori et al., 2019). However, a differentiated policy of taxation focusing on the land use sector would limit these risks and keep food security impact at lower level (Golub et al., 2012; Havlík et al., 2014; Tabeau et al., 2017), thanks to the low costs of $CO_2$ abatement in the land using sector (Golub et al., 2009; Kindermann et al., 2008). Non-$CO_2$ emissions likely to be more costly to abate (Frank et al., 2018a; Frank et al., 2018b), in particular in the livestock sector (Havlík et al., 2014). Some win-win technical solutions exist however, in particular with yield improvements in crops (Valin et al., 2013) and feed conversion efficiency improvements and market adjustments for livestock (Havlík et al., 2014; Henderson et al., 2017). Improving soil organic carbon sequestration through conservation tillage would also be a promising option to reduce GHG emissions, improve yields and income, as well as food security (Frank et al., 2017; Lal, 2010). Budget neutral taxation schemes that recycle carbon tax revenues to support the poor and to improve food security could even decrease global poverty rate and foster SDG1 and SDG2 simultaneously globally (Soergel et al., 2021).

Reducing emissions from the food systems is only one of the climate change mitigation channels. In addition, land may also be used as a resource to help decarbonize the economy by producing cleaner sources of energy and substituting fossil fuels, which raises a food-energy-environment trilemma (Tilman et al., 2009). Indeed, while a substantial part of the energy system can be electrified, some other sectors like aviation, shipping and to some extent heavy load transport will have difficulties to decarbonize with other forms of renewable fuels than biofuels (IRENA, 2020). In addition, limiting emissions will not be sufficient to stabilize the climate (IPCC, 2019), and negative carbon technologies will be necessary, for which increasing the land sink through afforestation, soil carbon sequestration and bioenergy with carbon capture are among the most scrutinized options (Field and Mach, 2017; Smith et al., 2015). Current biofuel policies have already raised significant concerns as to their feedback on food security (Ewing and Msangi, 2009; Persson, 2015; Searchinger et al., 2015). Large deployment of bioenergy for climate mitigation would imply much larger land demand (Creutzig et al., 2012; IPCC, 2018; Popp et al., 2017). In a multi-model comparison, Lotze-Campen et al. (2014) found that pressure of second-generation biofuels on the food market could remain limited to 3–10% increase if land expansion were to occur mostly in new land, an impact lower than the one from climate change. Havlík et al. (2015) also reach a similar conclusion by comparing bioenergy deployment to other mitigation efforts in the agricultural sector. However, much larger scale deployment would not prevent competition with food. Hasegawa et al. (2020) find that for a level of deployment of 200-300 EJ of high yield bioenergy (500 Mha) necessary for negative emissions, cropland would reduce by 53 Mha on average and food prices increase by up to 40%, leaving 0-25 million people at risk of hunger. Similarly, Kreidenweis et al. (2016) find that afforesting the land surface by 0.9-1.6 Gha would trigger a food price increase of 50-90% by 2050. For that reason, the incentives for growing new forest and plantations will have to be used with care and more efforts of abatement will be needed in other sectors to limit reliance on negative emissions (Grubler et al., 2018; van Vuuren et al., 2018).

### 4.2. Water resource competition and environmental flow requirements (SDG6)

Overconsumption of water resources is another critical challenge faced by agriculture. Irrigation represents today 70% of global water withdrawals, and this demand is expected to continue to increase in the coming decades (FAO, 2020a; Lotze-Campen et al., 2008; Palazzo et al., 2019; Tilman et al., 2001). Due to their higher productivity, irrigated areas could serve as an option for improving food security in some contexts. However, this solution would not be suitable for all regions. Palazzo et al. (2019) estimate that increasing irrigated areas by 32% in developing regions by 2050 would require an average annual investment cost of 26 billion USD and would not be sustainable for regions like Northern Africa and South Asia. Globally, ~30% of total water withdrawals are considered non-sustainable today, either because they compromise ecosystems' functioning or because they exceed the renewal capabilities of underground water reserves. This situation will likely worsen with the impact of climate change (Schewe et al., 2013), in particular with the development of new hotspots of water scarcity (Byers et al., 2018). Unsustainable withdrawals may reach ~40% by end of the century (Wada and Bierkens, 2014).

Reducing water consumption to a level respecting environmental flow requirements of water streams would require substantial reductions in irrigation, decreasing irrigated production's share of global output from 40% to 20% by 2050 and reducing irrigated areas (20% of current cultivated area) by nearly one-thrid (Pastor et al., 2019). However, imposing constraints on irrigation could put close to 1 million people at risk of hunger by 2050 and degrade other SDGs according to Liu et al. (2017). Therefore, improving water use efficiency appears crucial to boost water's footprint per crop calorie (Brauman et al., 2013), and animal protein (Heinke et al., 2020). However, water efficiency investments could also lead to rebound effects in line with the Jevons paradox and such investments would be mostly only be beneficial if accompanied with other resource conservation measures (Grafton et al., 2018). In addition to productivity gains, inter-basin water transfers and international trade are also cited as additional options to facilitate the sustainable use of irrigation (Liu et al., 2017). For instance, Pastor et al. (2019) find that an increase in international trade by 10-13% would compensate for a sustainability constraint on irrigation by 2050, or by 17-20% if the impact of climate change is also considered. As a consequence, safeguarding environmental flows in some regions could add some pressure on the competition for productive land and lead to further land expansion in other places (Bonsch et al., 2015). For these reasons, it appears clear that the best mitigation strategy for water will require adapted solutions based on the local context, with the right balance between water-efficient technologies, resource preservation, improved market access and adaptation capacity for more resilience.

To add to this challenge, water needs for domestic and industrial use, including clean electricity production from hydropower, are also expected to grow (Fitton et al., 2019; Strzepek and Boehlert, 2010). According to Wada and Bierkens (2014), both domestic and industrial uses of water could increase by about 65% from 2010 to 2050, which would mean their share of water extraction would increase from 30% globally to 40% under the assumption that irrigation area would not expand. This indicates growing tension around the use of scarce water resources. Consequently, a large literature has emerged to try to better represent the challenges at the food-water-energy nexus (Endo et al., 2015), illustrating the entanglement of various SDGs around the water resource, beyond the SDG2-SDG6 relation.

### 4.3. Nitrogen and phosphorus pollution (SDG6)

Nitrogen (N) and phosphorus (P) cycles represent two planetary boundaries estimated as critically exceeded (Steffen et al., 2015). The leaching and run-off of N and P surplus in agriculture trigger eutrophication of terrestrial and marine ecosystems, including the development of hypoxic conditions in coastal waters causing fish mortality. In addition, excess of N generates acidification of soils and freshwater; $N_2O$ climate-warming emissions; air pollution through ozone formation; groundwater contamination from nitrate; and stratospheric ozone depletion induced by $N_2O$ emissions (de Vries et al., 2013; Kanter et al., 2020; van Vuuren et al., 2011a). Nutrient cycle imbalances therefore threaten at least directly five SDGs (SDG3 on health, SDG6 on water, SDG13 on climate, SDG14 life in water, SDG15 on life on land). And yet, the additional input of these nutrients is key to increase yields in food insecure regions (Mueller et al., 2012; van der Velde et al., 2013).

Nitrogen use has historically been rising faster globally than crop production (Lassaletta et al., 2014), and future global agricultural projections let anticipate large further increases in nitrogen application (Bodirsky et al., 2014; Eickhout et al., 2006; Mogollon et al., 2018b; Sinha et al., 2019). As a consequence, nitrogen pollution is expected to increase. Bodirsky et al. (2014) anticipate a +25% increase in nitrogen surplus between 2010 and 2050 for a business as usual scenario, whereas Mogollon et al. (2018b) come with a much larger estimate at +90% for their central case between 2005 and 2050. At the same time, increased nitrogen application in some regions can bring environmental co-benefits through land sparing. Tilman et al. (2011) find that focusing N increase in developing low-yielding regions would allow to reduce emissions induced by agriculture by two third and land expansion by 80% by 2050 compared to a similar N application increase in high yielded developed regions. Considering the high heterogeneity in performances, improving crop nitrogen use efficiency appears as an important source of mitigation potential for the fertilization pollution impacts (Zhang et al., 2015). Redistributing current fertilizer use more efficiently would allow to increase production by 30% (Mueller et al., 2014). To bring surpluses below critical thresholds in pollution hotspots, efficiency improvements are however not always sufficient and stronger local solutions will be needed. Better livestock management, spatial relocation and lower animal production levels - requiring diet changes and food waste reduction - are among the measures usually simulated to reduce further N environmental impacts (Bodirsky et al., 2014; Bouwman et al., 2011; Gerten et al., 2020; Havlík et al., 2014).

The prospects of phosphorus present similar dilemma, with a substantial increase in demand for the coming century under current scenarios. Springmann et al. (2018a) anticipate an increase in P application in agriculture by 54% from 2010 to 2050, whereas Mogollon et al. (2018a) project an increase of 68% for the same period.[7] This latter work extends the previous estimates from van Vuuren et al. (2010) anticipating with the same model a 63-105% increase for three out of four scenarios of P consumption. Accumulation and saturation of P in soils could however also result in lower increases or a stabilization of fertilization needs by 2050 compared to current levels (Sattari et al., 2012). Van Vuuren et al. predict that P reserves would remain sufficient to satisfy the strong increase by the end of the century, in spite of the risk of resource exhaustion. Phosphorus cycle across regions however reveals substantial disparities in surplus and deficit (MacDonald et al., 2011;

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[7] Mogollon et al. (2018) results are rescaled from an initial 79% increase on the period 2005-2050.

Zhang et al., 2017), which may require resource rebalancing between regions through trade. In regions with surplus, environmental impacts on fresh water can be significant (Carpenter and Bennett, 2011). Phosphorus pollution mitigation would primarily require a reduction of soil erosion and the recycling of manure in landless livestock systems. Moreover, point sources to aquatic systems from wastewater, aquaculture and manure disposal have to be eliminated. A greater consideration to international imbalances due to traded P embedded in food products could also support a more efficient P global recycling (Lun et al., 2018).

### 4.4. Terrestrial biodiversity impacts and conservation needs (SDG15)

The global food system is among the main causes behind the sixth massive species extinction on Earth. Land use change and overexploitation of resources, closely associated with the food sector, are estimated to be the largest drivers of biodiversity losses, followed by climate change impacts and water pollution, both of which are also partly driven by the food system (IPBES, 2019; Maxwell et al., 2016). Expansion of agriculture into various other natural ecosystems significantly contribute to impacts on biodiversity through loss of ecosystems intactness, abundance and richness of species (Creutzig et al., 2019; Jung et al., 2019; Newbold et al., 2016). Newbold et al. (2015) find that past pressures from land use change have reduced globally on average within-sample species richness by 13.6% and abundance by 10.7% over the past centuries with much higher losses in hotspot regions (76.5% and 39.5% respectively). Using integrated assessment model-driven land use scenarios, they anticipate that this decline will continue with, on average, a further loss of -3.4% in species richness by the end of the century (+25% impact on top of historical losses), with much larger local consequences. This work confirms the results of several previous forward-looking analyses using simpler indicators of biodiversity (Sala, 2000; van Vuuren et al., 2015). New generations of integrated global land use scenarios with advanced ecosystems services modelling have been developed recently (Kim et al., 2018). Combining four global land use economic models and nine models of biodiversity, Leclère et al. (2020) found, under a business-as-usual scenario, a continuous degradation in a large range of biodiversity indicators over the period 2010-2050. Those indicators experiencing these losses included: wildlife population density, extent of suitable habitat, local compositional intactness, regional and global extinctions. Only drastic mitigation measures combining demand side measures (diets shift, waste reduction), supply side adjustments (yield increase, trade policies), and increased conservation (protected areas, land restoration payments) would enable mitigating these impacts. It is also possible to approach the role of the food system at a more granular level. Using an attribution approach based on patterns of land use, Chaudhary and Kastner (2016) determine that domestic food consumption was responsible for 83% of the biodiversity losses attributable to agriculture-driven land use change, versus 17% for traded food products. They also highlight the substantial role of crops such as sugar cane, palm oil, rubber and coffee in imported biodiversity losses. All of these studies emphasize the critical role played by agricultural development in hotspots of biodiversity in the tropics which is well in line with the empirical literature (Busch and Ferretti-Gallon, 2017).

To mitigate the collapse of biodiversity, some ambitious measures of conservation and also large land restoration programs are proposed, as illustrated by the aspirational target of returning half of the earth's surface back to nature as proposed by Wilson (2016). The food system impact from such ambitious restoration measures would be high. Using a static analysis, Mehrabi et al. (2018) find that saving Half-Earth would imply a decrease of cropland by 15-31%, pasture by 10-45%, and require a 3-29% and 23-25% decrease in food and non-food crop calories, respectively. Additionally, at least 1 billion people would need to be resettled (Schleicher et al., 2019). Forward-looking assessments have been used to explore more precisely the extent of land return to nature needed to restore biodiversity. Using a multi-model analysis, Leclère et al. (2020) found that biodiversity losses could be halted by 2050 by restoring 430 to 1,460 Mha of land. This would require substantially increasing the commitments taken in the context of the Bonn Challenge (350 Mha by 2030). However, they also show that if land conservation and restoration were implemented alone, food prices would increase by up to 20%. These authors conclude such measures need to be complemented with other changes on the production and demand side policies to allow reverting biodiversity losses without impact on food security.

In addition to these impacts on the agricultural extensive margin, intensive agricultural practices can also affect biodiversity, as already highlighted in Section 2.4. Avoiding these impacts while still fulfilling SDG2 requires adoption of sustainable intensification strategies (Cunningham et al., 2013; Deguines et al., 2014). As illustrated by the land sharing vs land sparing debate (Phalan et al., 2011), a balance needs to be found between the possible impacts from cropland on local biodiversity and the losses induced by agricultural land expansion. Some authors insist on the importance of the local context and the analysis of specific landscape scenarios to assess the best strategy for biodiversity between an intensification (sparing) or an extensification (sharing) approach (Law and Wilson, 2015).

### 4.5. Land degradation (SDG15)

Land degradation is an additional growing threat specially identified through Target 15.3 aiming for degradation neutrality. Among the various ecosystem services affected, agriculture is one of the most exposed (Nkonya et al., 2016). According to UNCCD (2017), 20% of cropland and 19% of grassland showed a persistent decline in productivity over the period 1998-2013, which directly impacts agricultural production in these areas. This dynamic can lead to rural poverty traps and food insecurity: Barbier and Hochard (2018) estimate that 1.3 billion people lived on degraded land in 2010 and this population rose by 11.1% between 2000 and 2010. Land degradation is partly driven by external factors (climate change, sea level rise, human occupation pressures), but agricultural practices also play a role in degrading the soil conditions (erosion, compaction, loss of structure and nutrients). In rural areas, soil degradation and food insecurity are intimately related, due to the importance of soil for crop fertility and nutrient provisioning (Lal, 2009). Increased aridity, affecting 40% of arable land, is a major factor in arable land degradation when coupled with unsustainable land management, followed by soil erosion with 20% (Pravalie et al., 2021), which depletes nutrient stocks, in particular phosphorus (see Section 1.1). This situation has been examined through forward looking studies as well. Using model projections, van der Esch et al. (2017) analyze the future land degradation dynamics by 2050, and estimate for instance that 27 Gt of additional soil organic carbon would be lost globally, compared to 2010. Exposure to degraded land would also increase, with 40-50% more population living in drylands, a growth rate twice higher than in the rest of the world. They also find that by 2050 an additional 5% increase in land expansion globally would be attributable to the effect of decreased land productivity due to soil fertility loss and land management. Mitigation measures against arable land degradation are therefore crucial. In the case of soil management, these include in particular conservation agriculture, integrated nutrient management, continuous vegetative cover as well as more sustainable practices in the livestock sector, such as lower stocking rates to avoid overgrazing (Lal, 2015). Strong synergies can be found in these areas with climate change mitigation (Frank et al., 2017; Smith et al., 2019).

### 4.6. Fisheries and marine life conservation (SDG14)

Fish is an essential food source in many regions and is rich in micronutrients. However, overfishing is putting important pressure on marine fish population and reduces catches in low-income food deficit countries by around 15% (Srinivasan et al., 2010). Falling fish catches therefore pose serious risk of malnutrition for vulnerable populations and are essential to address (Golden et al., 2016). Protecting life in the oceans is also at the center of the SDGs (SDG14). There is a fear that marine conservation could conflict with food security along a similar trade-off dynamic as for land. Ocean wilderness area represent approximately 13% of the ocean area but only 4.9% of this area is protected (Jones et al., 2018a). Furthermore, the vast majority of the top 10% priority areas for biodiversity protection are located within the exclusive economic zones of coastal nations and therefore conflict with potential fishing activities (Sala et al., 2021). However, assessments converge on the fact that marine protected areas could bring win-win solutions to both biodiversity and fisheries by reconstituting fish stocks in overfished areas, and benefitting yields of adjacent fish zones (Cabral et al., 2020; Kerwath et al., 2013; Roberts et al., 2005). Sala et al. (2021) estimate that optimizing conservation strategies would allow to increase fish catches by 6 Mt annually, protect 28% of the ocean and secure 35% of biodiversity simultaneously. It would even be possible to protect up to 71% of the ocean and 91% of the biodiversity without any reduction in catches. This highlights the strong potential for win-win solutions between food security and ocean conservation with well-tailored strategies.

### 4.7. Competition for land with urbanization and infrastructure needs (SDG9 & 11)

The expansion of food systems will put pressure on land use, as highlighted in Section 2.3. However, these expansion needs will also face the development of cities and peri-urban areas. Even though SDG9 and SDG11 are aimed at supporting a sustainable integration of the urban and rural worlds, development of cities will increase the level of food demand due to higher consumption of transformed products, and also trigger expansion of infrastructure and land uptake for urban areas. According to Bren d'Amour et al. (2016), urban areas are expected to triple during the period 2000-2030, and could take between 1.8 and 2.4% of global cropland, mostly in Asia and Africa, and 3–4% of crop production due to the higher productivity of that land. This area lost to agriculture could be three times higher than those figures if peri-urban and village systems expansion were also considered (van Vliet et al., 2017). Due to urban encroachment into cropland, indirect effects of land displacements are to be expected (Barthel et al., 2019). van Vliet et al. (2017) project for instance 35 Mha of additional indirect cropland expansion by 2040. FAO (2018) assume in their most recent foresight a decrease of land suitable for crop cultivation of 1.6–3.3 Mha/yr in the coming decades, based on estimates from Lambin and Meyfroidt (2011). These pressures required by the growth of cities, peri-urban areas and overall infrastructure need to be considered in the nexus of future tensions around land.

## 5. Towards sustainable pathways: transforming the food system for the Agenda 2030

With all the impacts and challenges highlighted above, there is a consensus that the global food system needs deep changes in the 21st century to support achievement of the Agenda 2030 (Food and Land Use Coalition, 2019; Schmidt-Traub et al., 2019; Smith et al., 2019). Large-scale transformations will be required, both on the supply and demand sides (Smith et al., 2013). We highlight in this section the role of some key enablers – the first ones already integrated to SDG2 with the targets 2.a, 2.b/2.c, but also other transformation options on the demand side. These specific enablers complement the more general ones, already embedded in the socioeconomic

SDGs covered in Section 3 – in particular SDG1 on poverty elimination, and SDG 16 and 17 highlighting the role of governance and international partnership. We summarize the main findings from modelling studies combining these various transformation options into ambitious transformation scenarios leading to sustainable pathways.

### 5.1. Investment, research, and innovation for sustainable agriculture (Target 2.a)

We have seen that agricultural productivity gains are crucial to the attainment of SDG2 (Section 2.4) and for mitigation of adverse impacts on other SDGs. Significant investments and technology transfers will be required for this purpose, as highlighted by Target 2.a, in sectors such as market infrastructure, irrigation, and research and development (R&D) -- the latter being crucial for technical progress. Public spending on agricultural R&D has tripled in developing countries between 1981 and 2011 and now equals those of developed countries at more than $22 bn per year (in 2011 PPP$, Fuglie et al. (2019)). However, budgets remain very uneven depending on the region. In Sub-Saharan Africa, R&D spending ($1.9 bn) is declining as a share of agricultural output and expenditure per farmer represents only 10% of the level in Latin America, a region where $7 bn were invested in 2011. Furthermore, the effectiveness of R&D investments in generating real productivity gains varies widely across regions and is often significantly lower in poorer regions such as Sub-Saharan Africa (Fuglie, 2017). Private R&D investment, at $13 bn in 2011, represents only a quarter of total research investments at a global level but up to three quarters of spending in developed countries like the US (Fuglie and Toole, 2014). Private investments stimulate new forms of public-private partnerships but remain focused on some particular sectors and technologies (e.g. crop technologies) and remain very limited in the least advanced regions (Fuglie et al., 2019). Increasing public investments could ensure important productivity gains in the future, but need to be sustained over time as their effects typically materialize on time frames of 11 to 30 years (Alston et al., 2011; Baldos et al., 2018). Innovations should in addition be examined under the broader perspective of their impacts across the full SDG spectrum, to ensure food benefits do no induce some other adverse environmental or socioeconomic trade-offs (Herrero et al., 2021).

Global analyses have compared the costs and benefits of different investment strategies. Rosegrant et al. (2017) compare a wide range of scenario of investment in R&D, as well as water and market infrastructures. They anticipate a need of $8.1 bn per year for R&D investment in developing regions – complemented by $11 bn for water and $23 bn for market infrastructure - to bring population at risk of hunger down from its current level to 361 million in 2050. Examining more ambitious scenarios of investment, they find that with $2–3 bn extra expenditure in R&D, a further 20–25% decrease in undernourishment could be reached at horizon 2030-2050, compared to 6% maximum under more costly investments focused on irrigation or infrastructure. Hertel et al. (2020) compares food security impacts at the horizon 2050 for Africa depending on the level of technological spill-ins versus domestic R&D investment and trade integration (virtual technology import). They find that trade would be the most promising strategy for food security, and spill-ins would remain superior to domestic R&D efforts due to the slow pace of investment and poor performance of R&D institutions in Africa compared to other regions. This scenario would however only stand if other regions kept using their productivity gains to provide more food instead of sparing natural resources. On the other hand, Burney et al. (2010) estimated that past investments in yield were among the cheapest climate mitigation technology ($4/t$CO_2$ avoided between 1971 and 2005). Looking into the future, Lobell et al. (2013) find that R&D investments targeting adaptation to climate change would also deliver mitigation co-benefits at $11–22/t$CO_2$, thanks to 61 Mha of land conversion savings by 2050. Implementing a similar strategy, Havlík et al. (2013) find that such approach would be three times more cost-efficient than a carbon tax, also thanks to co-benefits from productivity gains in the livestock sector. A win-win strategy for SDG2 and other environmental goals will therefore depend on the balance found between the different co-benefits accruing from productivity increases.

### 5.2. International trade and food markets (Target 2.b and 2.c)

The role of market integration and international collaboration on market information is also well acknowledged in SDG2 through Targets 2.b and 2.c. Trade integration can support food security by lowering agricultural product prices and providing easier access to food products (Anderson, 2016; Smith and Glauber, 2019). This is even more important in the context of increased production variability under the threat of climate change extreme events. Examining the role of trade for adaptation, Baldos and Hertel (2015) find for instance that integrating markets could lower undernourishment by up to 100 million by 2050, in the most unfavorable climate scenario. Gouel and Laborde (2021) calculate on their side that welfare losses from climate change are significantly larger (by 30%) when trade adjustments are disabled. Similarly, Janssens et al. (2020) find that undernourishment would increase by 73 million by 2050 under the same assumption of no trade adjustments. Removing tariffs and structural barriers to trade would in contrast reduce undernourishment by 64% compared to the baseline. These benefits hold in general for generic scenarios of trade liberalization, but need of course to be evaluated in the context of each policy situation and trade arrangements, as all scenarios may not be beneficial to all partners without accompanying measures (Bouët et al., 2005; Bureau et al., 2006). Furthermore, benefits of trade cooperation are well recognized in situation of price volatility (Gouel, 2016). Policies like export taxes are particularly detrimental to food security, leading to world price increases and more difficult access to food for importing regions (Bouët and Debucquet, 2011).

On the other hand, international trade could increase environmental pressure if production is relocated to less sustainable areas. Schmitz et al. (2012) finds that increasing trade leads to more deforestation and higher GHG emissions globally, shifting crop production to tropical regions and livestock production to less efficient world regions. And even though international trade could reduce water scarcity globally, it would lead to higher water scarcity in some world regions (Biewald et al., 2014). To limit the environmental impacts of trade liberalization, consistent environmental standards are needed across regions or border-tax adjustments would have to be added in trade agreements to correct for the different emission-intensities and displaced externalities between trading countries.

### 5.3. Shifting diets

In addition to Targets 2.a-2.c, other impactful measures can also be taken on the demand side to support the transformation of the food systems. Changing our consumption patterns has been recognized for its potential to leverage considerable benefits on SDG outcomes, both by relieving pressure on natural resources as identified in Section 2.2 and fostering the health co-benefits discussed in Section 3.2. Even though no SDG target explicitly calls for dietary changes, Target 12.8 within SDG12 on Responsible production and consumption points to the need to raise awareness for all people about sustainable development and lifestyle in harmony with nature.

Quantification of the impact of dietary shifts has been achieved in many studies to date, some also discussed in Section 3.2. These were initially focusing on the benefits of moving away from meat consumption (Popp et al., 2010; Stehfest et al., 2009; Wirsenius et al., 2010), already highlighting substantial gains in terms of land savings (100 Mha of cropland and 1.1 to 3.2 Gha of pasture land depending on the scenarios for Stehfest et al. and Wirsenius et al.) and for GHG emissions (from 4.8 Gt $CO_2$e in Popp et al. with non-$CO_2$ emissions to 10 Gt $CO_2$e for Stehfest with also land use emissions). These scenarios are often assuming replacing animal proteins by vegetal ones, but a shift from meat towards aquaculture would also bring substantial land sparing effects (Froehlich et al., 2018). More recent studies examined more realistic diet variations: Stehfest et al. (2013) focused on WHO recommendations, Tilman and Clark (2014) distinguished transitions to pescatarian, Mediterranean and vegetarian diets, Ranganathan et al. (2016) compared a broader set of typical diets with different levels of meat cuts and overconsumption reduction, similarly to Springmann et al. (2016a); (2018b) who also consider a healthy or flexitarian option. Beckman et al. (2011) identified in total 83 studies mostly published on the period 2005-2015 assessing environmental benefits of healthy diets. The most influential recent publication on the topic from the EAT-Lancet Commission (Willett et al., 2019) assesses that shifting to a healthier and more sustainable (flexitarian) diet would reduce global emissions by 4.8 Gt $CO_2$e, but do not find any saving in cropland and water consumption due to the extra needs for some specific crops. They however also identify that a pescatarian, vegetarian or vegan diet would bring higher benefits including up to 500 Mha land savings. However, as emphasized in Section 3.2, these diets would increase costs for households and would not be affordable for the poorest, indicating the need to move SDG2 together with SDG1.

In addition to shifts to other traditional products, an increasing interest also relates to the potential of "future foods" – composed of products not widely consumed until now, such as insects, algae, cultured meat – to bring new sustainable and healthy options (Parodi et al., 2018). Alexander et al. (2017a) compare the impacts of some of these options for land use and find that the largest benefits would come from the pastureland savings, whereas cultured meat and insects would still require levels of crop inputs similar to chicken eggs. Imitation meat based on vegetal proteins appears the most promising of the options studied and constitute particularly cost-competitive alternatives. Next to food, new products could also be used as feed – likely achieving more rapid acceptance and faster implementation (van Zanten et al., 2015). Pikaar et al. (2018) show a high potential of using microbial protein to substitute protein feeds like soybean cake or cereals, sparing 0 to 13% of cropland, reducing nitrogen losses by 3-8% and land system greenhouse gases by 6–9% depending on the microbial technology. The production is however rather energy intensive and may shift emissions from the land system to the energy system. More exploratory scenarios based on feed crops replacement by microalgae have also been examined and could lead to large mitigation benefits when the technology becomes mature (Walsh et al., 2015).

### 5.4. Reducing food waste and losses

Also aligned with SDG12 objectives, reducing inefficiencies along the food supply chain as well as in households and restaurants represent an additional lever for sustainable transformation, explicitly identified in Target 12.3 with the objective of halving food waste per capita and reducing food losses by 2030. The common assumption has been over the past decade that one third of food lost or wasted (Gustavsson et al., 2011). More recent refinements allowed to estimate the extent of global food losses at 14%, whereas consumer waste would range from 2–17% for cereals to 14–33% for meat and animal products (FAO, 2019). Top-down estimates comparing food caloric supply with population dietary energy needs found global food waste in households to be 20–25% in 2010 (Bodirsky et al., 2020; Hic et al., 2016). Alexander et al. (2017b) also highlight that a large share of the harvested agricultural biomass is also lost in the livestock sector production chain and evaluate that 50% of the energy harvested for food is lost in the food system. Beside food losses, they estimate that overconsumption would be of similar magnitude to consumer waste in terms of inefficiency. van den Bos Verma et al. (2020) also find that waste would be higher than usually assumed and highlight the substantial impact of economic growth on waste rate. Testing for the influence of future economic growth on food waste, Barrera and Hertel (2020) project that it could nearly double at the horizon 2050 without further interventions, while Bodirsky et al. (2020) estimate it will increase by 85% from 2010 till 2050. Considering only a scenario of stabilization of waste at 2020 level would decrease global cropland use by 5% and reduce undernourishment in Sub-Saharan Africa by close to 12% according to their analysis. Hasegawa et al. (2019) – already studied in Section 3.2 for their findings on overconsumption – found similar results from removing food waste, with about 7% for the food calorie savings compared to a reduction of 6% in overconsumption.

### 5.5. Transformative pathways for the world's food systems

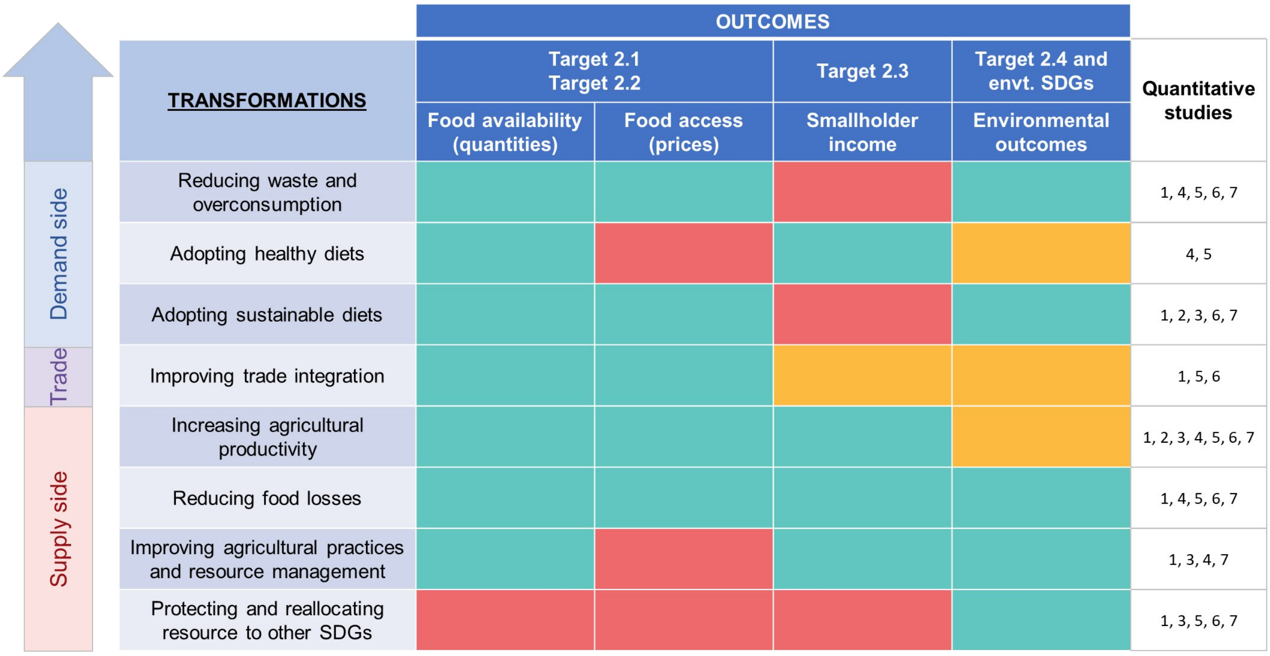
How much could these interventions help to bring food systems onto a sustainable path for SDG2 and the Agenda 2030 in general? We emphasized above the most emblematic transformative actions related to the food systems. There are also more specific mitigation measures are also identified in Section 4. For instance, Smith et al. (2019) present a set of 40 practices that could allow to deliver food security, climate mitigation and adaptation, and limit land degradation and desertification – ranging from increased food productivity or improved cropland or livestock management to demand measures as highlighted above. More general socioeconomic enablers from other SDGs, as identified in Section 3.3, are also key to support the achievement of SDG2.

Combining a large set of these options has usually been presented as the best way – if not the only one – to succeed bringing back the food systems within a safe operating space and providing sustainable food to all while supporting the other SDGs. Table 1 provides an illustration of such comprehensive strategies for the food systems as proposed through policy-oriented reports produced by agencies or expert groups – ranging from the Five strategies for the Great Food Transformation from the EAT-Lancet Commission (Willett et al., 2019), to the Priority actions from the Global Panel on Agriculture Food Systems for Nutrition (2020). These series of propositions are not similar but contain common recommendations, such as the need to adopt healthier diets or cutting food waste and losses.

Quantification of transformational agendas has been attempted recently through several global modelling studies. In contrast to most studies presented in previous sections, these typically model in a forward-looking approach the combination of many different simultaneous interventions into the food systems, to see to what extent these can together help achieve the various sustainable development dimensions. We identified here seven studies corresponding to this description: four based on integrated assessment models (Deppermann et al., 2019; Obersteiner et al., 2016; Springmann et al., 2018a; van Vuuren et al., 2015), two land systems analyses (Erb et al., 2016; Gerten et al., 2020) and one model ensemble study, with a stronger emphasis on biodiversity (Leclère et al., 2020).

Figure 5 below provides an overview of the typical transformations which have been modelled across these different studies. For each of these transformations, we highlight whether these would enhance specific indicators supporting the different SDG2 targets. All the measures for instance improve food availability except for the supply side interventions aimed at allocating more resources to other SDGs. In contrast, adopting healthy diets may increase the cost of food, and therefore complicate food access, whereas sustainable diet based on moving away from meat proteins can be done at low price by using vegetal proteins. Food access may also be challenged by more sustainable management practices, which may also come with extra production costs. When looking at smallholder income, approaches leading to lower food demand through efficiency gains in the supply chain may paradoxically decrease producer prices and smallholder revenues. Last, some transformation may also be ambiguous for the environment: trade integration for the reasons discussed above (Section 5.2), agricultural productivity gains due to the Jevons paradox, and healthy diets due to their increased demand in specific nutrient-rich products such as fruits, vegetables and nuts, dairy, etc. As can be seen, not many transformations are win-wins across all dimensions. Reducing food losses is one of them when harvest losses are included and avoidable at low cost for the producer. Some options can be combined, e.g. sustainable and healthy diets could be designed to deliver positive outcomes across all dimensions.

These studies of food system transformation highlight the need for combining a large number of options on both the supply and demand sides in order to achieve sustainable pathways. The challenge for the food systems modelling community in the future will be to enrich these analyses of alternative sustainable pathways and implement these in a national and local context (Schmidt-Traub et al., 2019). This endeavor will be even more important now that the COVID-19 crisis has brought new social and economic challenges that could undermine the achievement of SDGs and limit progress towards long-term sustainability. Revisiting the current frameworks and analyzing how to overcome these challenges in an integrative manner should be high priority for the years to come, while also paying greater attention to questions of vulnerability and resilience.



|  |  | OUTCOMES |  |  |  |  |
|---|---|---|---|---|---|---|
|  | **TRANSFORMATIONS** | **Target 2.1**<br>**Target 2.2** |  | **Target 2.3** | **Target 2.4 and envt. SDGs** | **Quantitative studies** |
|  |  | **Food availability (quantities)** | **Food access (prices)** | **Smallholder income** | **Environmental outcomes** |  |
| Demand side | Reducing waste and overconsumption | 🟩 | 🟩 | 🟥 | 🟩 | 1, 4, 5, 6, 7 |
|  | Adopting healthy diets | 🟩 | 🟥 | 🟩 | 🟧 | 4, 5 |
|  | Adopting sustainable diets | 🟩 | 🟩 | 🟥 | 🟩 | 1, 2, 3, 6, 7 |
| Trade | Improving trade integration | 🟩 | 🟩 | 🟧 | 🟧 | 1, 5, 6 |
| Supply side | Increasing agricultural productivity | 🟩 | 🟩 | 🟩 | 🟧 | 1, 2, 3, 4, 5, 6, 7 |
|  | Reducing food losses | 🟩 | 🟩 | 🟩 | 🟩 | 1, 4, 5, 6, 7 |
|  | Improving agricultural practices and resource management | 🟩 | 🟥 | 🟩 | 🟩 | 1, 3, 4, 7 |
|  | Protecting and reallocating resource to other SDGs | 🟥 | 🟥 | 🟥 | 🟩 | 1, 3, 5, 6, 7 |

***Figure 5.*** *Key transformations implemented in global analyses and their typical impact for relevant indicators: green = positive impact, red = negative impact, orange = ambiguous impact. The impacts are based on typical impact of the market equilibrium model responses, but the measures are not tested separately in each of the studies. For smallholder income, the impact is based on the anticipated average farm income effect.*

*Study references: 1 - Vuuren et al. (2015); 2 - Erb et al. (2016); 3 - Obersteiner et al. (2016); 4 - Willet et al. (2019) / Springmann et al. (2018); 5 – Deppermann et al. (2019); 6 - Leclere et al. (2020); 7 - Gerten et al. (2020)*

***Table 1.*** *Main measures proposed for the food and land systems transformations in selected policy reports*

| **EAT-Lancet Commission (Willet et al., 2019)** | **Food and Land Use Coalition**<br>**(FOLU, 2019)** | **CGIAR CCAFS (Steiner et al., 2020)** | **Global Panel on Agriculture and Food Systems for Nutrition (2020)** |
|---|---|---|---|
| *"Five strategies for a Great Food Transformation"* | *"Ten critical transitions"* | *"Actions to transforms food systems"* | *"Priority policy actions to transition food systems towards sustainable healthy diets"* * |
| | | | |
| 1. seek international and national commitments to shift towards healthy diets | 1. healthy diets | 1. no ag land expansion into high carbon land | 1a. rebalance agricultural subsidies |
| 2. reorient agricultural priorities from producing large quantities of food to producing healthy food | 2. productive and regenerative agriculture | 2. support development of climate-resilient and low emissions practices | 1b. rebalance agricultural R&D |
| 3. sustainably intensify food production, generating high-quality output | 3. protecting and restoring nature | 3. support prosperity through rural reinvigoration | 1c. promote production of a wide range of nutrient-rich food |
| 4. strong and coordinated governance of land and oceans | 4. healthy and productive ocean | 4. early warning and safety nets | 2a. coopt levers of trade |
| 5. Halve food loss and waste, in line with global SDGs | 5. diversifying protein chain | 5. help farmers make better choice | 2b. cut food loss and waste |
| | 6. reducing food losses and waste | 6. shift to heathy and sustainable diets | 2c. support job growth across the food system |
| | 7. local loops and linkages | 7. reduce food losses and waste | 2d. support technology and financial innovation along food supply chains |
| | 8. digital revolution | 8. implement policy and institutional change for transformations | 3a. implement safety nets |
| | 9. stronger rural livelihoods | 9. unlock billions in sustainable finance | 3b. promote pro-poor growth |
| | 10. gender and demography | 10. drive social change to more sustainable decisions | 3c. reduce costs through tech and innovation |
| | | 11. transform innovation systems | 3d. adjust tax and subsidies on key foods |
| | | | 4a. define principles of engagement between public and private sector |
| | | | 4b. upgrade dietary guidelines and promote enhanced knowledge about implication of dietary choices |
| | | | 4c. better regulate advertising and marketing |
| | | | 4d. implement behavioral nudges via carefully designed taxes and subsidies |

* For the Global Panel on Agriculture Food Security and Nutrition's report, the actions are structured around 4 axes, identified here with the following numbering: 1 – availability; 2 – accessibility; 3 – affordability; 4 – desirability (see report Figure 9.2).

# 6. References

Afshin, A., Sur, P.J., Fay, K.A., Cornaby, L., Ferrara, G., Salama, J.S., Mullany, E.C., ..., Murray, C.J.L. (2019) Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet 393, 1958-1972.

Agarwal, B. (2018) Gender equality, food security and the sustainable development goals. Current Opinion in Environmental Sustainability 34, 26-32.

Ahmed, N., Thompson, S., Glaser, M. (2018) Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability. Environmental Management 63, 159-172.

Alavanja, M.C.R., Hoppin, J.A., Kamel, F. (2004) Health effects of chronic pesticide exposure: cancer and neurotoxicity. Annu. Rev. Public Health 25, 155-197.

Alcott, B. (2005) Jevons' paradox. Ecological Economics 54, 9 - 21.

Alderman, H., Headey, D.D. (2017) How Important is Parental Education for Child Nutrition? World Development 94, 448-464.

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M.D.A. (2017a) Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? Global Food Security 15, 22-32.

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., Rounsevell, M.D.A. (2017b) Losses, inefficiencies and waste in the global food system. Agricultural Systems 153, 190-200.

Alexandratos, N., Bruinsma, J., (2012) World Agriculture Towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations, Rome.

Alston, J.M., Andersen, M.A., James, J.S., Pardey, P.G. (2011) The Economic Returns to U.S. Public Agricultural Research. American Journal of Agricultural Economics 93, 1257-1277.

Anderson, K. (2016) Agricultural trade, policy reforms, and global food security. Springer.

Baldos, U.L.C., Hertel, T.W. (2014) Global food security in 2050: the role of agricultural productivity and climate change. Australian Journal of Agricultural and Resource Economics 58, 554-570.

Baldos, U.L.C., Hertel, T.W. (2015) The role of international trade in managing food security risks from climate change. Food Security 7, 275-290.

Baldos, U.L.C., Viens, F.G., Hertel, T.W., Fuglie, K.O. (2018) R&D Spending, Knowledge Capital, and Agricultural Productivity Growth: A Bayesian Approach. American Journal of Agricultural Economics 101, 291-310.

Balmford, A., Green, R.E., Scharlemann, J.P.W. (2005) Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biology 11, 1594-1605.

Barbier, E.B., Hochard, J.P. (2018) Land degradation and poverty. Nature Sustainability 1, 623-631.

Barrera, E.L., Hertel, T. (2020) Global food waste across the income spectrum: Implications for food prices, production and resource use. Food Policy, 101874.

Barrett, C., Reardon, T., Swinnen, J., Zilberman, D., (2019) Structural transformation and economic development: insights from the agri-food value chain revolution. Cornell University.

Barthel, S., Isendahl, C., Vis, B.N., Drescher, A., Evans, D.L., van Timmeren, A. (2019) Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. The Anthropocene Review 6, 71-97.

Beach, R.H., Sulser, T.B., Crimmins, A., Cenacchi, N., Cole, J., Fukagawa, N.K., Mason-DCroz, D., Myers, S., Sarofim, M.C., Smith, M., Ziska, L.H. (2019) Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. The Lancet Planetary Health 3, e307-e317.

Beckman, J., Jones, C.A., Sands, R. (2011) A global general equilibrium analysis of biofuel mandates and greenhouse gas emissions. American Journal of Agricultural Economics 93, 334-341.

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., Williams, M. (2015) Feeding 9 billion by 2050 } Putting fish back on the menu. Food Security 7, 261-274.

Biewald, A., Rolinski, S., Lotze-Campen, H., Schmitz, C., Dietrich, J.P. (2014) Valuing the impact of trade on local blue water. Ecological Economics 101, 43-53.

Bijl, D.L., Bogaart, P.W., Dekker, S.C., Stehfest, E., de Vries, B.J.M., van Vuuren, D.P. (2017) A physically-based model of long-term food demand. Global Environmental Change 45, 47 - 62.

Black, R.E., Victora, C.G., Walker, S.P., Bhutta, Z.A., Christian, P., de Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R., Uauy, R. (2013) Maternal and child undernutrition and overweight in low-income and middle-income countries. The Lancet 382, 427-451.

Bodirsky, B.L., Dietrich, J.P., Martinelli, E., Stenstad, A., Pradhan, P., Gabrysch, S., Mishra, A., Weindl, I., Mouël, C.L., Rolinski, S., Baumstark, L., Wang, X., Waid, J.L., Lotze-Campen, H., Popp, A. (2020) The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Scientific Reports 10.

Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A., Stevanovic, M. (2014) Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. Nature Communications 5, -.

Bodirsky, B.L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., Lotze-Campen, H. (2015) Global Food Demand Scenarios for the 21<italic><sup>st</sup></italic> Century. PLoS ONE 10, e0139201.

Böhringer, C., Löschel, A. (2006) Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. Ecological Economics 60, 49-64.

Bonsch, M., Popp, A., Biewald, A., Rolinski, S., Schmitz, C., Weindl, I., Stevanovic, M., Högner, K., Heinke, J., Ostberg, S., Dietrich, J.P., Bodirsky, B., Lotze-Campen, H., Humpenöder, F. (2015) Environmental flow provision: Implications for agricultural water and land-use at the global scale. Global Environmental Change 30, 113-132.

Borlaug, N.E. (2002) Feeding a world of 10 billion people: the miracle ahead. In Vitro Cellular & Developmental Biology. Plant 38, 221-228.

Bouët, A., Bureau, J.-C., Decreux, Y., Jean, S. (2005) Multilateral Agricultural Trade Liberalisation: The Contrasting Fortunes of Developing Countries in the Doha Round. The World Economy 28, 1329-1354.

Bouët, A., Debucquet, D.L. (2011) Food crisis and export taxation: the cost of non-cooperative trade policies. Review of World Economics 148, 209-233.

Bouwman, L., Goldewijk, K.K., Hoek, K.W.V.D., Beusen, A.H.W., Vuuren, D.P.V., Willems, J., Rufino, M.C., Stehfest, E. (2011) Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proceedings of the National Academy of Sciences 110, 20882-20887.

Brauman, K.A., Siebert, S., Foley, J.A. (2013) Improvements in crop water productivity increase water sustainability and food security}a global analysis. Environmental Research Letters 8, 024030.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C. (2016) Future urban land expansion and implications for global croplands. Proceedings of the National Academy of Sciences 114, 8939-8944.

Burchi, F., Fanzo, J., Frison, E. (2011) The Role of Food and Nutrition System Approaches in Tackling Hidden Hunger. International Journal of Environmental Research and Public Health 8, 358-373.

Bureau, J.-C., Jean, S., Matthews, A. (2006) The consequences of agricultural trade liberalization for developing countries: distinguishing between genuine benefits and false hopes. World Trade Review 5, 225-249.

Burney, J.A., Davis, S.J., Lobell, D.B. (2010) Greenhouse gas mitigation by agricultural intensification. Proceedings of the National Academy of Sciences 107, 12052-12057.

Busch, J., Ferretti-Gallon, K. (2017) What drives deforestation and what stops it? A meta-analysis. Review of Environmental Economics and Policy 11, 3-23.

Byerlee, D., Stevenson, J., Villoria, N. (2014) Does intensification slow crop land expansion or encourage deforestation? Global Food Security 3, 92-98.

Byers, E., Gidden, M., Leclre, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., Parkinson, S., Rao, N.D., Rogelj, J., Satoh, Y., Wada, Y., Willaarts, B., Riahi, K. (2018) Global exposure and vulnerability to multi-sector development and climate change hotspots. Environmental Research Letters 13, 055012.

Cabral, R.B., Bradley, D., Mayorga, J., Goodell, W., Friedlander, A.M., Sala, E., Costello, C., Gaines, S.D. (2020) A global network of marine protected areas for food. Proceedings of the National Academy of Sciences 117, 28134-28139.

Cafiero, C., Melgar-Quinonez, H.R., Ballard, T.J., Kepple, A.W. (2014) Validity and reliability of food security measures. Annals of the New York Academy of Sciences 1331, 230-248.

Carpenter, S.R., Bennett, E.M. (2011) Reconsideration of the planetary boundary for phosphorus. Environmental Research Letters 6, 014009.

Chaudhary, A., Kastner, T. (2016) Land use biodiversity impacts embodied in international food trade. Global Environmental Change 38, 195-204.

Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., Hill, J.D. (2020) Global food system emissions could preclude achieving the 1.5} and 2}C climate change targets. Science 370, 705-708.

Coker, R., Rushton, J., Mounier-Jack, S., Karimuribo, E., Lutumba, P., Kambarage, D., Pfeiffer, D.U., Stärk, K., Rweyemamu, M. (2011) Towards a conceptual framework to support one-health research for policy on emerging zoonoses. The Lancet Infectious Diseases 11, 326-331.

Creutzig, F., d'Amour, C.B., Weddige, U., Fuss, S., Beringer, T., Gläser, A., Kalkuhl, M., Steckel, J.C., Radebach, A., Edenhofer, O. (2019) Assessing human and environmental pressures of global land-use change 2000-2010. Global Sustainability 2.

Creutzig, F., Popp, A., Plevin, R., Luderer, G., Minx, J., Edenhofer, O. (2012) Reconciling top-down and bottom-up modelling on future bioenergy deployment. Nature Climate Change 2, 320-327.

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

Cunningham, S.A., Attwood, S.J., Bawa, K.S., Benton, T.G., Broadhurst, L.M., Didham, R.K., McIntyre, S., Perfecto, I., Samways, M.J., Tscharntke, T., Vandermeer, J., Villard, M.-A.e., ,, Young, A.G., Lindenmayer, D.B. (2013) To close the yield-gap while saving biodiversity will require multiple locally relevant strategies. Agriculture, Ecosystems & Environment 173, 20-27.

de Lima, C.Z., Buzan, J.R., Moore, F.C., Baldos, U.L.C., Huber, M., Hertel, T.W. (2021) Heat stress on agricultural workers exacerbates crop impacts of climate change. Environmental Research Letters 16, 044020.

de Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P. (2013) Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability 5, 392-402.

Deguines, N., Jono, C., Baude, M., Henry, M., Julliard, R., Fontaine, C. (2014) Large-scale trade-off between agricultural intensification and crop pollination services. Frontiers in Ecology and the Environment 12, 212-217.

Deppermann, A., Valin, H., Gusti, M., Sperling, F., Batka, M., Chang, J., Frank, S., Havlik, P., Lauri, P., Leclere, D., Palazzo, A., Thomson, M., Obersteiner, M., (2019) Towards sustainable food and land-use systems: Insights from integrated scenarios of the Global Biosphere Management Model (GLOBIOM). International Institute for Applied Systems Analysis, Laxenburg, Austria.

Dixon, P.B., Parmenter, B.R., (1996) Chapter 1 Computable general equilibrium modelling for policy analysis and forecasting, Handbook of Computational Economics. Elsevier, pp. 3-85.

Donald, P.F., Green, R.E., Heath, M.F. (2001) Agricultural intensification and the collapse of Europe}s farmland bird populations. Proceedings of the Royal Society of London. Series B: Biological Sciences 268, 25-29.

Eickhout, B., Bouwman, A., Vanzeijts, H. (2006) The role of nitrogen in world food production and environmental sustainability. Agriculture, Ecosystems & Environment 116, 4-14.

Eitelberg, D.A., Vliet, J., Verburg, P.H. (2014) A review of global potentially available cropland estimates and their consequences for model-based assessments. Global Change Biology 21, 1236-1248.

Endo, A., Tsurita, I., Burnett, K., Orencio, P.M. (2015) A review of the current state of research on the water, energy, and food nexus. Journal of Hydrology: Regional Studies.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H. (2016) Exploring the biophysical option space for feeding the world without deforestation. Nature Communications.

Ericksen, P.J. (2008) Conceptualizing food systems for global environmental change research. Global Environmental Change 18, 234-245.

Evans, A.E.V., Mateo-Sagasta, J., Qadir, M., Boelee, E., Ippolito, A. (2019) Agricultural water pollution: key knowledge gaps and research needs. Current Opinion in Environmental Sustainability 36, 20-27.

Ewers, R.M., Scharlemann, J.P.W., Balmford, A., Green, R.E. (2009) Do increases in agricultural yield spare land for nature? Global Change Biology 15, 1716-1726.

Ewing, M., Msangi, S. (2009) Biofuels production in developing countries: assessing tradeoffs in welfare and food security. Environmental Science & Policy 12, 520-528.

FAO (1996) Rome Declaration on World Food Security and World Food Summit Plan of Action. Food and Agriculture Organization of the United Nations.

FAO (2011) The State of Food and Agriculture: Women in Agriculture Closing the gender gap for development. Food and Agriculture Organization of The United Nations, Roma.

FAO (2018) The Future of Food and Agriculture 2018: Alternative Pathways to 2050. Food and Agriculture Food and Agriculture Organization of the United Nations.

FAO (2019) The State of Food and Agriculture: Moving Forward on Food Loss and Waste Reduction. Food and Agriculture Organization of the United Nations, Rome.

FAO (2020a) The State of Food and Agriculture: Overcoming water challenges in agriculture. Food and Agriculture Organization of the United Nations, Rome.

FAO (2020b) The State of World Fisheries and Aquaculture 2020. Sustainability in Action. Food and Agriculture Organization of The United Nations, Rome.

FAO, IFAD, UNICEF, WFP, WHO (2017) The State of Food Security and Nutrition in the World 2017: Building Resilience for Peace and Food Security. Food and Agriculture Organization of the United Nations, Rome.

FAO, IFAD, UNICEF, WFP, WHO, (2020) The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets. Food and Agriculture Organization of the United Nations.

Field, C.B., Mach, K.J. (2017) Rightsizing carbon dioxide removal. Science 356, 706-707.

Fischer, R.A., Byerlee, D., Edmeades, G.O., (2009) Can Technology Deliver on the Yield Challenge to 2050? Food and Agriculture Organization of the United Nations.

Fitton, N., Alexander, P., Arnell, N., Bajzelj, B., Calvin, K., Doelman, J., Gerber, J.S., Havlik, P., Hasegawa, T., Herrero, M., Krisztin, T., van Meijl, H., Powell, T., Sands, R., Stehfest, E., West, P.C., Smith, P. (2019) The vulnerabilities of agricultural land and food production to future water scarcity. Global Environmental Change 58, 101944.

Folberth, C., Khabarov, N., Balkovic, J., Skalsky, R., Visconti, P., Ciais, P., Janssens, I.A., Penuelas, J., Obersteiner, M. (2020) The global cropland-sparing potential of high-yield farming. Nature Sustainability 3, 281-289.

Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltine, A. (1996) An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. Global Biogeochemical Cycles 10, 603-628.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., others (2011) Solutions for a cultivated planet. Nature 478, 337-342.

Food and Land Use Coalition (2019) Growing Better: Ten Critical Transformations to Transform Food and Land Use. Food and Land Use Coalition.

Frank, S., Beach, R., Havlik, P., Valin, H., Herrero, M., Mosnier, A., Hasegawa, T., Creason, J., Ragnauth, S., Obersteiner, M. (2018a) Structural change as a key component for agricultural non-CO2 mitigation efforts. Nature Communications 9.

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., Obersteiner, M. (2017) Reducing greenhouse gas emissions in agriculture without compromising food security? Environmental Research Letters.

Frank, S., Havlik, P., Stehfest, E., van Meijl, H., Witzke, P., Perez-Dominguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H. (2018b) Agricultural non-CO2 emission reduction potential in the context of the 1.5 C target. Nature Climate Change.

Fritz, S., See, L., van der Velde, M., Nalepa, R.A., Perger, C., Schill, C., McCallum, I., Schepaschenko, D., Kraxner, F., Cai, X., Zhang, X., Ortner, S., Hazarika, R., Cipriani, A., Di Bella, C., Rabia, A.H., Garcia, A., Vakolyuk, M.y., Singha, K., Beget, M.E., Erasmi, S., Albrecht, F., Shaw, B., Obersteiner, M. (2013) Downgrading Recent Estimates of Land Available for Biofuel Production. Environmental science & technology 47, 1688-1694.

Froehlich, H.E., Runge, C.A., Gentry, R.R., Gaines, S.D., Halpern, B.S. (2018) Comparative terrestrial feed and land use of an aquaculture-dominant world. Proceedings of the National Academy of Sciences 115, 5295-5300.

Fuglie, K. (2017) R&D Capital, R&D Spillovers, and Productivity Growth in World Agriculture. Applied Economic Perspectives and Policy 40, 421-444.

Fuglie, K., Gautam, M., Goyal, A., Maloney, W.F. (2019) Harvesting prosperity: Technology and productivity growth in agriculture. The World Bank.

Fuglie, K.O., (2010) Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data, in: Alston, J.M., Babcock, B.A., Pardey, P.G. (Eds.), The Shifting Patterns of Agricultural Production and Productivity Worldwide. Midwest Agribusiness Trade Research and Iowa State University, Ames, IA, pp. 63-95.

Fuglie, K.O., Toole, A.A. (2014) The Evolving Institutional Structure of Public and Private Agricultural Research. American Journal of Agricultural Economics 96, 862-883.

Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B.L., Bosetti, V., Callen, J., Despres, J., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Havlik, P., Humpenöder, F., Koopman, J.F.L., van Meijl, H., Ochi, Y., Popp, A., Schmitz, A., Takahashi, K., van Vuuren, D. (2019) A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability 2, 386-396.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., Schellnhuber, H.J. (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability 3, 200-208.

Giannadaki, D., Giannakis, E., Pozzer, A., Lelieveld, J. (2018) Estimating health and economic benefits of reductions in air pollution from agriculture. Science of The Total Environment 622-623, 1304-1316.

Gibb, R., Redding, D.W., Chin, K.Q., Donnelly, C.A., Blackburn, T.M., Newbold, T., Jones, K.E. (2020) Zoonotic host diversity increases in human-dominated ecosystems. Nature 584, 398-402.

Global Panel on Agriculture Food Systems for Nutrition (2020) Future Food Systems: For people, our planet, and prosperity.

Golden, C.D., Allison, E.H., Cheung, W.W.L., Dey, M.M., Halpern, B.S., McCauley, D.J., Smith, M., Vaitla, B., Zeller, D., Myers, S.S. (2016) Nutrition: Fall in fish catch threatens human health. Nature 534, 317-320.

Golub, A., Hertel, T., Lee, H.-L., Rose, S., Sohngen, B. (2009) The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. Resource and Energy Economics 31, 299 - 319.

Golub, A.A., Henderson, B.B., Hertel, T.W., Gerber, P.J., Rose, S.K., Sohngen, B. (2012) Global climate policy impacts on livestock, land use, livelihoods, and food security. Proceedings of the National Academy of Sciences.

Gomez, M.I., Barrett, C.B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., Carisma, B., Thompson, B. (2013) Post-green revolution food systems and the triple burden of malnutrition. Food Policy 42, 129-138.

Gouel, C. (2016) Trade policy coordination and food price volatility. American Journal of Agricultural Economics 98, 1018-1037.

Gouel, C., Guimbard, H. (2018) Nutrition Transition and the Structure of Global Food Demand. American Journal of Agricultural Economics 101, 383-403.

Gouel, C., Laborde, D. (2021) The crucial role of domestic and international market-mediated adaptation to climate change. Journal of Environmental Economics and Management 106, 102408.

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G. (2018) The paradox of irrigation efficiency. Science 361, 748-750.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S.D., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlk, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H. (2018) A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. Nature Energy 3, 515-527.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., (2011) Global food losses and food waste. Food and Agriculture Organization of the United Nations.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M. (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 104, 12942-12947.

Hallegatte, S., Rozenberg, J. (2017) Climate change through a poverty lens. Nature Climate Change 7, 250-256.

Hasegawa, T., Fujimori, S., Havlik, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Dominguez, I.P., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K., Witzke, P. (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change 8, 699-703.

Hasegawa, T., Fujimori, S., Takahashi, K., Masui, T. (2015) Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. Environmental Research Letters 10, 014010.

Hasegawa, T., Fujimori, S., Takahashi, K., Yokohata, T., Masui, T. (2016) Economic implications of climate change impacts on human health through undernourishment. Climatic Change 136, 189-202.

Hasegawa, T., Havlik, P., Frank, S., Palazzo, A., Valin, H. (2019) Tackling food consumption inequality to fight hunger without pressuring the environment. Nature Sustainability 2, 826-833.

Hasegawa, T., Sands, R.D., Brunelle, T., Cui, Y., Frank, S., Fujimori, S., Popp, A. (2020) Food security under high bioenergy demand toward long-term climate goals. Climatic Change 163, 1587-1601.

Havlík, P., Valin, H., Gusti, M., Schmid, E., Leclère, D., Forsell, N., Herrero, M., Khabarov, N., Mosnier, A., Cantele, M., Obersteiner, M., (2015) Climate change impacts and mitigation in the developing world: An integrated assessment of the agriculture and forestry sectors. World Bank.

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A. (2014) Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences 111, 3709-3714.

Havlík, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J.S., Herrero, M., Rufino, M.C., Schmid, E. (2013) Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. American Journal of Agricultural Economics 95, 442-448.

Headey, D.D., Martin, W.J. (2016) The Impact of Food Prices on Poverty and Food Security. Annual Review of Resource Economics 8, 329-351.

Heinke, J., Lannerstad, M., Gerten, D., Havlik, P., Herrero, M., Notenbaert, A.M.O., Hoff, H., Müller, C. (2020) Water Use in Global Livestock Production}Opportunities and Constraints for Increasing Water Productivity. Water Resources Research 56.

Henders, S., Persson, U.M., Kastner, T. (2015) Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Environmental Research Letters 10, 125012.

Henderson, B., Golub, A., Pambudi, D., Hertel, T., Godde, C., Herrero, M., Cacho, O., Gerber, P. (2017) The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production. Mitigation and Adaptation Strategies for Global Change 23, 349-369.

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

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C. (2020) Innovation can accelerate the transition towards a sustainable food system. Nature Food 1, 266-272.

Herrero, M., Thornton, P.K., Mason-DCroz, D., Palmer, J., Bodirsky, B.L., Pradhan, P., Barrett, C.B., Benton, T.G., Hall, A., Pikaar, I., Bogard, J.R., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Fanzo, J., Godde, C.M., Jarvis, A., Loboguerrero, A.M., Mathys, A., McIntyre, C.L., Naylor, R.L., Nelson, R., Obersteiner, M., Parodi, A., Popp, A., Ricketts, K., Smith, P., Valin, H., Vermeulen, S.J., Vervoort, J., van Wijk, M., van Zanten, H.H.E., West, P.C., Wood, S.A., Rockström, J. (2021) Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health 5, e50-e62.

Hertel, T., (2012a) Global Applied General Equilibrium Analysis using the GTAP Framework. Global Trade Analysis Project (GTAP), Department of Agricultural Economics, Purdue University, West Lafayette, IN.

Hertel, T.W. (1997) Global Trade Analysis: modeling and applications. Cambridge University Press.

Hertel, T.W., (2012b) Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug vs. Jevons. Global Trade Analysis Project Center.

Hertel, T.W. (2015) Food security under climate change. Nature Climate Change 6, 10-13.

Hertel, T.W., Baldos, U.L.C., van der Mensbrugghe, D. (2016) Predicting Long-Term Food Demand, Cropland Use, and Prices. Annual Review of Resource Economics 8, 417-441.

Hertel, T.W., Burke, M.B., Lobell, D.B. (2010) The poverty implications of climate-induced crop yield changes by 2030. Global Environmental Change 20, 577-585.

Hertel, T.W., Ramankutty, N., Baldos, U.L.C. (2014) Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. Proceedings of the National Academy of Sciences 111, 13799-13804.

Hertel, T.W., Rose, S.K., Tol, R.S.J. (2009) Economic Analysis of Land Use in Global Climate Change Policy. Routledge.

Hertel, T.W., Steinbuks, J., Baldos, U.L.C., (2012) Competition for Land in the Global Bioeconomy, 2012 Conference, August 18-24, 2012, Foz do Iguacu, Brazil.

Hic, C., Pradhan, P., Rybski, D., Kropp, J.P. (2016) Food Surplus and Its Climate Burdens. Environmental science & technology 50, 4269-4277.

Hicks, C.C., Cohen, P.J., Graham, N.A.J., Nash, K.L., Allison, E.H., D'Lima, C., Mills, D.J., Roscher, M., Thilsted, S.H., Thorne-Lyman, A.L., MacNeil, M.A. (2019) Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574, 95-98.

Hirvonen, K., Bai, Y., Headey, D., Masters, W.A. (2019) Affordability of the EAT}Lancet reference diet: a global analysis. The Lancet Global Health.

Hiza, H.A.B., Casavale, K.O., Guenther, P.M., Davis, C.A. (2013) Diet Quality of Americans Differs by Age, Sex, Race/Ethnicity, Income, and Education Level. Journal of the Academy of Nutrition and Dietetics 113, 297-306.

HLPE (2017) Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.

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 Insecurity.

IAASTD (2009) International assessment of agricultural knowledge, science and technology for development (IAASTD).

Ingram, J. (2011) A food systems approach to researching food security and its interactions with global environmental change. Food Security 3, 417-431.

IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.

IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC, Switzerland.

IPCC (2019) 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. IPCC, Switzerland.

IRENA, (2020) Global Renewable Energy Outlook: Energy Transformations 2050. International Renewable Energy Agency.

ISC (2017) A Guide to SDG Interactions: from Science to Implementation. International Council for Science, Paris.

Ivanic, M., Martin, W., (2014) Short-and long-run impacts of food price changes on poverty.

Ivanic, M., Martin, W., Zaman, H. (2012) Estimating the Short-Run Poverty Impacts of the 2010–11 Surge in Food Prices. World Development 40, 2302 - 2317.

Janssens, C., Havlik, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclere, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Lipzig, N.V., Maertens, M. (2020) Global hunger and climate change adaptation through international trade. Nature Climate Change.

Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J., Said, M.Y., McKeever, D., Mutua, F., Young, J., McDermott, J., Pfeiffer, D.U. (2013) Zoonosis emergence linked to agricultural intensification and environmental change. Proceedings of the National Academy of Sciences 110, 8399-8404.

Jung, M., Rowhani, P., Scharlemann, J.P.W. (2019) Impacts of past abrupt land change on local biodiversity globally. Nature Communications 10.

Kanter, D.R., Winiwarter, W., Bodirsky, B.L., Bouwman, L., Boyer, E., Buckle, S., Compton, J.E., Dalgaard, T., de Vries, W., Lecl\`e, re, David, Leip, A., Müller, C., Popp, A., Raghuram, N., Rao, S., Sutton, M.A., Tian, H., Westhoek, H., Zhang, X., Zurek, M. (2020) A framework for nitrogen futures in the shared socioeconomic pathways. Global Environmental Change 61, 102029.

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S. (2012) Global changes in diets and the consequences for land requirements for food. Proceedings of the National Academy of Sciences 109, 6868-6872.

Kearney, J. (2010) Food consumption trends and drivers. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2793-2807.

Kerwath, S.E., Winker, H., Götz, A., Attwood, C.G. (2013) Marine protected area improves yield without disadvantaging fishers. Nature Communications 4.

Keyzer, M.A., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F.A. (2005) Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecological Economics 55, 187-202.

Kim, H., Rosa, I.M.D., Alkemade, R., Leadley, P., Hurtt, G., Popp, A., van Vuuren, D.P., Anthoni, P., Arneth, A., Baisero, D., Caton, E., Chaplin-Kramer, R., Chini, L., Palma, A.D., Fulvio, F.D., Marco, M.D., Espinoza, F., Ferrier, S., Fujimori, S., Gonzalez, R.E., Gueguen, M., Guerra, C., Harfoot, M., Harwood, T.D., Hasegawa, T., Haverd, V., Havl\'\i, k, Petr, Hellweg, S., Hill, S.L.L., Hirata, A., Hoskins, A.J., Janse, J.H., Jetz, W., Johnson, J.A., Krause, A., Lecl\`e, re, David, Martins, I.S., Matsui, T., Merow, C., Obersteiner, M., Ohashi, H., Poulter, B., Purvis, A., Quesada, B., Rondinini, C., Schipper, A.M., Sharp, R., Takahashi, K., Thuiller, W., Titeux, N., Visconti, P., Ware, C., Wolf, F., Pereira, H.M. (2018) A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios. Geoscientific Model Development 11, 4537-4562.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., Beach, R. (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America 105, 10302-10307.

Kreidenweis, U., Humpenöder, F., Stevanovic, M., Bodirsky, B.L., Kriegler, E., Lotze-Campen, H., Popp, A. (2016) Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. Environmental Research Letters 11, 085001.

Laborde, D., Martin, W., Swinnen, J., Vos, R. (2020) COVID-19 risks to global food security. Science 369, 500-502.

Laborde Debucquet, D., Martin, W. (2018) Implications of the global growth slowdown for rural poverty. Agricultural Economics 49, 325-338.

Lal, R. (2009) Soil degradation as a reason for inadequate human nutrition. Food Security 1, 45-57.

Lal, R. (2010) Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Security 2, 169-177.

Lal, R. (2015) Restoring Soil Quality to Mitigate Soil Degradation. Sustainability 7, 5875-5895.

Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D.C., Rudel, T.K., Gasparri, I., Munger, J. (2013) Estimating the world's potentially available cropland using a bottom-up approach. Global Environmental Change, -.

Lambin, E.F., Meyfroidt, P. (2011) Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108, 3465-3472.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Bald, A.B., Bertollini, R., Bose-OReilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potonik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M. (2018) The Lancet Commission on pollution and health. The Lancet 391, 462-512.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J. (2014) 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters 9, 105011.

Law, E.A., Wilson, K.A. (2015) Providing Context for the Land-Sharing and Land-Sparing Debate. Conservation Letters 8, 404-413.

Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N., Obersteiner, M. (2014) Climate change induced transformations of agricultural systems: insights from a global model. Environmental Research Letters 9, 1748-9326.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., Palma, A.D., DeClerck, F.A.J., Marco, M.D., Doelman, J.C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J.P., Hill, S.L.L., Humpenöder, F., Jennings, N., Krisztin, T., Mace, G.M., Ohashi, H., Popp, A., Purvis, A., Schipper, A.M., Tabeau, A., Valin, H., van Meijl, H., van Zeist, W.-J., Visconti, P., Alkemade, R., Almond, R., Bunting, G., Burgess, N.D., Cornell, S.E., Fulvio, F.D., Ferrier, S., Fritz, S., Fujimori, S., Grooten, M., Harwood, T., Havlik, P., Herrero, M., Hoskins, A.J., Jung, M., Kram, T., Lotze-Campen, H., Matsui, T., Meyer, C., Nel, D., Newbold, T., Schmidt-Traub, G., Stehfest, E., Strassburg, B.B.N., van Vuuren, D.P., Ware, C., Watson, J.E.M., Wu, W., Young, L. (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585, 551–556.

Licker, R., Johnston, M., Foley, J.A., Barford, C.C., Kucharik, C.J., Monfreda, C., Ramankutty, N. (2010) Mind the gap: how do climate and agricultural management explain the `yield gap' of croplands around the world? Global Ecology and Biogeography 19, 769-782.

Liu, J., Hertel, T.W., Lammers, R.B., Prusevich, A., Baldos, U.L.C., Grogan, D.S., Frolking, S. (2017) Achieving sustainable irrigation water withdrawals: global impacts on food security and land use. Environmental Research Letters 12, 104009.

Lloyd, S.J., Bangalore, M., Chalabi, Z., Kovats, R.S., Hallegatte, S., Rozenberg, J., Valin, H., Havlik, P. (2018) A Global-Level Model of the Potential Impacts of Climate Change on Child Stunting via Income and Food Price in 2030. Environmental Health Perspectives 126, 097007.

Lobell, D.B., Baldos, U.L.C., Hertel, T.W. (2013) Climate adaptation as mitigation: the case of agricultural investments. Environmental Research Letters 8, 015012.

Lotze-Campen, H., Lucht, W., Müller, C., Bondeau, A., Smith, P. (2005) How tight are the limits to land and water use? - Combined impacts of food demand and climate change. Advances in Geosciences 4, 23-28.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W. (2008) Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agricultural Economics 39, 325-338.

Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., Hasegawa, T., Popp, A., Schmitz, C., Tabeau, A., Valin, H., Willenbockel, D., Wise, M. (2014) Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. Agricultural Economics 45, 103-116.

Ludena, C.E., Hertel, T.W., Preckel, P.V., Foster, K., Nin, A. (2007) Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. Agricultural Economics 37, 1-17.

Lun, F., Liu, J., Ciais, P., Nesme, T., Chang, J., Wang, R., Goll, D., Sardans, J., Peuelas, J., Obersteiner, M. (2018) Global and regional phosphorus budgets in agricultural systems and their implications for phosphorus-use efficiency. Earth System Science Data 10, 1-18.

MacDonald, G.K., Bennett, E.M., Potter, P.A., Ramankutty, N. (2011) Agronomic phosphorus imbalances across the world}s croplands. Proceedings of the National Academy of Sciences 108, 3086-3091.

Malthus, T. (1798) An Essay on the Principle of Population. J. Johnson.

Matson, P.A. (1997) Agricultural Intensification and Ecosystem Properties. Science 277, 504-509.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M. (2016) Biodiversity: The ravages of guns, nets and bulldozers. Nature 536, 143-145.

Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.-G., Sapkota, T., others, (2019) Food Security, 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., pp. 437-550.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, I., William W. (1972) The limits to growth. A report for the Club of Rome's project on the predicament of mankind. Universe Books.

Mehrabi, Z., Ellis, E.C., Ramankutty, N. (2018) The challenge of feeding the world while conserving half the planet. Nature Sustainability 1, 409-412.

Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being : Scenarios, Volume 2. Island Press.

Mogollon, J.M., Beusen, A.H.W., van Grinsven, H.J.M., Westhoek, H., Bouwman, A.F. (2018a) Future agricultural phosphorus demand according to the shared socioeconomic pathways. Global Environmental Change 50, 149-163.

Mogollon, J.M., Lassaletta, L., Beusen, A.H.W., van Grinsven, H.J.M., Westhoek, H., Bouwman, A.F. (2018b) Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways. Environmental Research Letters 13, 044008.

Möhring, N., Ingold, K., Kudsk, P., Martin-Laurent, F., Niggli, U., Siegrist, M., Studer, B., Walter, A., Finger, R. (2020) Pathways for advancing pesticide policies. Nature Food 1, 535-540.

Morse, S.S., Mazet, J.A.K., Woolhouse, M., Parrish, C.R., Carroll, D., Karesh, W.B., Zambrana-Torrelio, C., Lipkin, W.I., Daszak, P. (2012) Prediction and prevention of the next pandemic zoonosis. The Lancet 380, 1956-1965.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A. (2012) Closing yield gaps through nutrient and water management. Nature 490, 254-257.

Mueller, N.D., West, P.C., Gerber, J.S., MacDonald, G.K., Polasky, S., Foley, J.A. (2014) A tradeoff frontier for global nitrogen use and cereal production. Environmental Research Letters 9, 054002.

Müller, B., Hoffmann, F., Heckelei, T., Müller, C., Hertel, T.W., Polhill, J.G., van Wijk, M., Achterbosch, T., Alexander, P., Brown, C., Kreuer, D., Ewert, F., Ge, J., Millington, J.D.A., Seppelt, R., Verburg, P.H., Webber, H. (2020) Modelling food security: Bridging the gap between the micro and the macro scale. Global Environmental Change 63, 102085.

Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., Hasegawa, T., others (2014) Increasing CO2 threatens human nutrition. Nature 510, 139-142.

Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T.B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., Rosegrant, M. (2018) Income growth and climate change effects on global nutrition security to mid-century. Nature Sustainability 1, 773-781.

Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., von Lampe, M., Lotze-Campen, H., Mason D'Croz, D., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., Willenbockel, D. (2014) Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences 111, 3274-3279.

Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., Palma, A.D., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., Burton, V.J., Chng, C.W.T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B.I., Whitmee, S., Zhang, H., Scharlemann, J.P.W., Purvis, A. (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353, 288-291.

Newbold, T., Hudson, L.N., Hill, S.L.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., Day, J., Palma, A.D., D\'\i, az, Sandra, Echeverria-Londo\~n, o, Susy, Edgar, M.J., Feldman, A., Garon, M., Harrison, M.L.K., Alhusseini, T., Ingram, D.J., Itescu, Y., Kattge, J., Kemp, V., Kirkpatrick, L., Kleyer, M., Correia, D.L.P., Martin, C.D., Meiri, S., Novosolov, M., Pan, Y., Phillips, H.R.P., Purves, D.W., Robinson, A., Simpson, J., Tuck, S.L., Weiher, E., White, H.J., Ewers, R.M., Mace, G.M., Scharlemann, J.P.W., Purvis, A. (2015) Global effects of land use on local terrestrial biodiversity. Nature 520, 45-50.

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P., Hens, L. (2016) Chemical Pesticides and Human Health: The Urgent Need for a New Concept in Agriculture. Frontiers in Public Health 4.

Nkonya, E., Mirzabaev, A., Von Braun, J. (2016) Economics of land degradation and improvement--A global assessment for sustainable development. Springer Nature.

Nougadère, A., Sirot, V., Kadar, A., Fastier, A., Truchot, E., Vergnet, C., Hommet, F., Bayl, J., Gros, P., Leblanc, J.-C. (2012) Total diet study on pesticide residues in France: Levels in food as consumed and chronic dietary risk to consumers. Environment International 45, 135-150.

O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., van Ruijven, B.J., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, T., Leininger, J., Monteith, S., Pichs-Madruga, R. (2020) Achievements and needs for the climate change scenario framework. Nature Climate Change 10, 1074-1084.

O’Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R., Vuuren, D. (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122, 387-400.

Obersteiner, M., Walsh, B., Frank, S., Havlik, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S., van Vuuren, D. (2016) Assessing the land resource-food price nexus of the Sustainable Development Goals. Science Advances 2, e1501499-e1501499.

OECD (2012) OECD Environmental Outlook to 2050. OECD Publishing.

OECD (2016) Alternative Futures for Global Food and Agriculture. OECD Publishing, Paris.

OECD, (2019) The Heavy Burden of Obesity: The Economics of Prevention. OECD Publishing.

OECD, IIASA (2020) Systemic Thinking for Policy Making: The Potential of Systems Analysis for Addressing Global Policy Challenges in the 21st Century. OECD.

Palazzo, A., Valin, H., Batka, M., Havlik, P., (2019) Investment needs for irrigation infrastructure along different socio-economic pathways. World Bank, Washington DC.

Parodi, A., Leip, A., Boer, I.J.M.D., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tuomisto, H., Valin, H., Middelaar, C.E.V., Loon, J.J.A.V., Zanten, H.H.E.V. (2018) The potential of future foods for sustainable and healthy diets. Nature Sustainability 1, 782-789.

Parson, E.A., Fisher-Vanden, K. (1997) Integrated Assessment Models of Global Climate Change. Annual Review of Energy and the Environment 22, 589-628.

Pastor, A.V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P., Ludwig, F. (2019) The global nexus of food}trade}water sustaining environmental flows by 2050. Nature Sustainability.

Patz, J.A., Daszak, P., Tabor, G.M., Aguirre, A.A., Pearl, M., Epstein, J., Wolfe, N.D., Kilpatrick, A.M., Foufopoulos, J., Molyneux, D., Bradley, D.J. (2004) Unhealthy Landscapes: Policy Recommendations on Land Use Change and Infectious Disease Emergence. Environmental Health Perspectives 112, 1092-1098.

Persson, U.M. (2015) The impact of biofuel demand on agricultural commodity prices: a systematic review. Wiley Interdisciplinary Reviews: Energy and Environment 4, 410-428.

Phalan, B., Green, R.E., Dicks, L.V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B.B.N., Williams, D.R., z. Ermgassen, E.K.H.J., Balmford, A. (2016) How can higher-yield farming help to spare nature? Science 351, 450-451.

Phalan, B., Onial, M., Balmford, A., Green, R.E. (2011) Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333, 1289-1291.

Pikaar, I., Matassa, S., Bodirsky, B.L., Weindl, I., Humpenoder, F., Rabaey, K., Boon, N., Bruschi, M., Yuan, Z., van Zanten, H., others (2018) Decoupling livestock from land use through industrial feed production pathways. Environmental Science \& Technology 52, 7351-7359.

Popp, A., Calvin, K., Fujimori, S., Havlík, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., van Vuuren, D.P. (2017) Land-use futures in the shared socio-economic pathways. Global Environmental Change 42, 331-345.

Popp, A., Lotze-Campen, H., Bodirsky, B. (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Global Environmental Change 20, 451-462.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., Kropp, J.P. (2017) A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth{\textquotesingle}s Future 5, 1169-1179.

Pravalie, R., Patriche, C., Borrelli, P., Panagos, P., Ro?ca, B., Dumitracu, M., Nita, I.-A., Svulescu, I., Birsan, M.-V., Bandoc, G. (2021) Arable lands under the pressure of multiple land degradation processes. A global perspective. Environmental Research 194, 110697.

Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., Searchinger, T.I.M., Authors, G.-W.M., (2016) Shifting diets for a sustainable food future. World Resources Institute, pp. 831878447-1548317259.

Roberts, C.M., Hawkins, J.P., Gell, F.R. (2005) The role of marine reserves in achieving sustainable fisheries. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 123-132.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A. (2009) A safe operating space for humanity. Nature 461, 472-475.

Rosegrant, M.W., Sulser, T.B., Mason-D'Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., Zhu, T., Ringler, C., Wiebe, K.D., Robinson, S., others (2017) Quantitative foresight modeling to inform the CGIAR research portfolio. International Food Policy Research Institute.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W. (2014)

Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences 111, 3268-3273.

Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M. (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology 170, 166-182.

Ruel, M.T., Alderman, H. (2013) Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? The Lancet 382, 536-551.

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., Rockström, J. (2019) Six Transformations to achieve the Sustainable Development Goals. Nature Sustainability 2, 805-814.

Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Morgan, L.E., Mouillot, D., Palacios-Abrantes, J., Possingham, H.P., Rechberger, K.D., Worm, B., Lubchenco, J. (2021) Protecting the global ocean for biodiversity, food and climate. Nature 592, 397-402.

Sala, O.E. (2000) Global Biodiversity Scenarios for the Year 2100&nbsp$$. Science 287, 1770-1774.

Sattari, S.Z., Bouwman, A.F., Giller, K.E., van Ittersum, M.K. (2012) Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences 109, 6348-6353.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Coln-Gonzlez, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P. (2013) Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences 111, 3245-3250.

Schleicher, J., Zaehringer, J.G., Fastre, C., Vira, B., Visconti, P., Sandbrook, C. (2019) Protecting half of the planet could directly affect over one billion people. Nature Sustainability.

Schmidt-Traub, G., Obersteiner, M., Mosnier, A. (2019) Fix the broken food system in three steps. Nature 569, 181-183.

Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M., Weindl, I. (2012) Trading more food: Implications for land use, greenhouse gas emissions, and the food system. Global Environmental Change 22, 189 - 209.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlík, P., Heyhoe, E., D'Croz, D.M., Popp, A., Sands, R.D., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H. (2014) Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. Agricultural Economics 45, 69-84.

Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., von Gunten, U., Wehrli, B. (2010) Global Water Pollution and Human Health. Annual Review of Environment and Resources 35, 109-136.

Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R., Plevin, R. (2015) Do biofuel policies seek to cut emissions by cutting food? Science 347, 1420-1422.

Seppelt, R., Arndt, C., Beckmann, M., Martin, E.A., Hertel, T.W. (2020) Deciphering the Biodiversity}Production Mutualism in the Global Food Security Debate. Trends in Ecology {\&} Evolution 35, 1011-1020.

Sinha, E., Michalak, A.M., Calvin, K.V., Lawrence, P.J. (2019) Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century. Nature Communications 10.

Sloat, L.L., Davis, S.J., Gerber, J.S., Moore, F.C., Ray, D.K., West, P.C., Mueller, N.D. (2020) Climate adaptation by crop migration. Nature Communications 11.

Smith, L.C., Haddad, L.J. (2000) Explaining child malnutrition in developing countries: A cross-country analysis. International Food Policy Research International Food Policy Research Institute.

Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Hoang, A.L., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M.A., Manning, F.C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., Roe, S., Cowie, A., Rounsevell, M., Arneth, A. (2019) Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology 26, 1532-1575.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C. (2015) Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6, 42-50.

Smith, P., Gregory, P.J., van Vuuren, D.P., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J. (2010) Competition for land. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2941-2957.

Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S. (2013) How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biology 19, 2285-2302.

Smith, V.H., Glauber, J.W. (2019) Trade, policy, and food security. Agricultural Economics 51, 159-171.

Soergel, B., Kriegler, E., Bodirsky, B.L., Bauer, N., Leimbach, M., Popp, A. (2021) Combining Ambitious Climate Policies with Efforts to Eradicate Poverty. Nature Communications.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W. (2018a) Options for keeping the food system within environmental limits. Nature.

Springmann, M., Godfray, H.C.J., Rayner, M., Scarborough, P. (2016a) Analysis and valuation of the health and climate change cobenefits of dietary change. Proceedings of the National Academy of Sciences 113, 4146-4151.

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.C.J., Gollin, D., Rayner, M., Ballon, P., Scarborough, P. (2016b) Global and regional health effects of future food production under climate change: a modelling study. The Lancet 387, 1937 - 1946.

Springmann, M., Wiebe, K., Mason-D\textquotesingle, C., Daniel, Sulser, T.B., Rayner, M., Scarborough, P. (2018b) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. The Lancet Planetary Health 2, e451-e461.

Srinivasan, U.T., Cheung, W.W.L., Watson, R., Sumaila, U.R. (2010) Food security implications of global marine catch losses due to overfishing. Journal of Bioeconomics 12, 183-200.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S. (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855-1259855.

Stehfest, E., Bouwman, A.F., van Vuuren, D.P., den Elzen, M., Eickhout, B., Kabat, P. (2009) Climate benefits of changing diet. Climatic Change 95, 83-102.

Stehfest, E., van den Berg, M., Woltjer, G., Msangi, S., Westhoek, H. (2013) Options to reduce the environmental effects of livestock production – Comparison of two economic models. Agricultural Systems 114, 38 - 53.

Stehfest, E., van Zeist, W.-J., Valin, H., Havlik, P., Popp, A., Kyle, P., Tabeau, A., Mason-D'Croz, D., Hasegawa, T., Bodirsky, B.L., Calvin, K., Doelman, J.C., Fujimori, S., Humpenöder, F., Lotze-Campen, H., van Meijl, H., Wiebe, K. (2019) Key determinants of global land-use projections. Nature Communications 10.

Steiner, A., Aguilar, G., Bomba, K., Bonilla, J.P., Campbell, A., Echeverria, R., Gandhi, R., Hedegaard, C., Holdorf, D., Ishii, N., Quinn, K., Ruter, B., Sunga, I., Sukhdev, P., Verghese, S., Voegele, J., Winters, P., Campbell, B., Dinesh, D., Huyer, S., Jarvis, A., Loboguerrero Rodriguez, A.M., Millan, A., Thornton, P., Wollenberg, L., Zebiak, S., (2020) Actions to transform food systems under climate change. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Steinfeld, H., Gerber, P.J., Wassenaar, T.D., Castel, V., de Haan, C. (2006) Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations.

Stokstad, E. (2014) Ammonia Pollution From Farming May Exact Hefty Health Costs. Science 343, 238-238.

Strzepek, K., Boehlert, B. (2010) Competition for water for the food system. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2927-2940.

Swinburn, B.A., Sacks, G., Hall, K.D., McPherson, K., Finegood, D.T., Moodie, M.L., Gortmaker, S.L. (2011) The global obesity pandemic: shaped by global drivers and local environments. The Lancet 378, 804-814.

Swinnen, J., McDermott, J. (2020) COVID-19 and global food security. International Food Policy Research Institute (IFPRI).

Swinnen, J., Squicciarini, P. (2012) Mixed Messages on Prices and Food Security. Science 335, 405-406.

Tabeau, A., van Meijl, H., Overmars, K.P., Stehfest, E. (2017) REDD policy impacts on the agri-food sector and food security. Food Policy 66, 73-87.

Tilman, D., Balzer, C., Hill, J., Befort, B.L. (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108, 20260-20264.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S. (2002) Agricultural sustainability and intensive production practices. Nature 418, 671-677.

Tilman, D., Clark, M. (2014) Global diets link environmental sustainability and human health. Nature 515, 518-522.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D. (2001) Forecasting Agriculturally Driven Global Environmental Change. Science 292, 281-284.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R. (2009) Beneficial Biofuels--The Food, Energy, and Environment Trilemma. Science 325, 270-271.

Tongeren, F., Meijl, H., Surry, Y. (2001) Global models applied to agricultural and trade policies: a review and assessment. Agricultural Economics 26, 149-172.

UN (1996) Rome Declaration on World Food Security United Nations.

UN (2015) Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., Obersteiner, M. (2013) Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? Environmental Research Letters 8, 035019.

Valin, H., Sands, R.D., van der Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Manson-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., van Meijl, H., von Lampe, M., Willenbockel, D. (2014) The Future of Food Demand: Understanding Differences in Global Economic Models. Agricultural Economics 45, 51-67.

van den Bos Verma, M., de Vreede, L., Achterbosch, T., Rutten, M.M. (2020) Consumers discard a lot more food than widely believed: Estimates of global food~waste using an energy gap approach and~affluence elasticity of food waste. {PLOS} {ONE} 15, e0228369.

van der Esch, S., ten Brink, B., Stehfest, E., Bakkenes, M., Sewell, A., Bouwman, A., Meijer, J., Westhoek, H., van den Berg, M., van den Born, G.J., others (2017) Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: scenarios for the UNCCD Global Land Outlook.

van der Velde, M., See, L., You, L., Balkovic, J., Juraj, Fritz, S., Khabarov, N., Obersteiner, M., Wood, S. (2013) Affordable Nutrient Solutions for Improved Food Security as Evidenced by Crop Trials. PLoS ONE 8, e60075.

van Dijk, M., Morley, T., Rau, M.L., Saghai, Y. (2021) Systematic review and meta-analysis of global food security projections to 2050. Nature Food (in press).

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. (2013) Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4 - 17.

van Meijl, H., Shutes, L., Valin, H., Stehfest, E., van Dijk, M., Kuiper, M., Tabeau, A., van Zeist, W.-J., Hasegawa, T., Havlik, P. (2020a) Modelling alternative futures of global food security: Insights from FOODSECURE. Global Food Security 25, 100358.

van Meijl, H., Tabeau, A., Stehfest, E., Doelman, J., Lucas, P. (2020b) How food secure are the green, rocky and middle roads: food security effects in different world development paths. Environmental Research Communications 2, 031002.

van Vliet, J., Eitelberg, D.A., Verburg, P.H. (2017) A global analysis of land take in cropland areas and production displacement from urbanization. Global Environmental Change 43, 107-115.

van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W. (2010) Phosphorus demand for the 1970}2100 period: A scenario analysis of resource depletion. Global Environmental Change 20, 428-439.

van Vuuren, D.P., Bouwman, L.F., Smith, S.J., Dentener, F. (2011a) Global projections for anthropogenic reactive nitrogen emissions to the atmosphere: an assessment of scenarios in the scientific literature. Current Opinion in Environmental Sustainability 3, 359-369.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S.K. (2011b) The representative concentration pathways: an overview. Climatic Change 109, 5-31.

van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Weyant, J. (2011c) A special issue on the RCPs. Climatic Change 109, 1-4.

van Vuuren, D.P., Kok, M., Lucas, P.L., Prins, A.G., Alkemade, R., van den Berg, M., Bouwman, L., van der Esch, S., Jeuken, M., Kram, T., Stehfest, E. (2015) Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. Technological Forecasting and Social Change 98, 303-323.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E. (2018) Alternative pathways to the 1.50.167em}C target reduce the need for negative emission technologies. Nature Climate Change 8, 391-397.

van Wijk, M.T. (2014) From global economic modelling to household level analyses of food security and sustainability: How big is the gap and can we bridge it? Food Policy 49, 378-388.

van Wijk, M.T., Rufino, M.C., Enahoro, D., Parsons, D., Silvestri, S., Valdivia, R.O., Herrero, M. (2014) Farm household models to analyse food security in a changing climate: A review. Global Food Security 3, 77-84.

van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G., de Boer, I.J.M. (2015) From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. Journal of Cleaner Production 102, 362-369.

van Zeist, W.-J., Stehfest, E., Doelman, J.C., Valin, H., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Humpenöder, F., Kyle, P., Lotze-Campen, H., Mason-D\textquotesingle, C., Daniel, van Meijl, H., Popp, A., Sulser, T.B., Tabeau, A., Verhagen, W., Wiebe, K. (2020) Are scenario projections overly optimistic about future yield progress? Global Environmental Change 64, 102120.

Villoria, N.B., Byerlee, D., Stevenson, J., (2013) The Effects of Agricultural Technological Progress on Deforestation: What do we really know? Purdue University.

von Braun, J., Zamagni, S., Sorondo, M.S. (2020) The moment to see the poor. Science 368, 214-214.

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason D.'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H. (2014) Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics 45, 3-20.

Wada, Y., Bierkens, M.F.P. (2014) Sustainability of global water use: past reconstruction and future projections. Environmental Research Letters 9, 104003.

Waite, R., Beveridge, M., Brummett, R., Castine, S., Chaiyawannakarn, N., Kaushik, S., Mungkung, R., Nawapakpilai, S., Phillips, M., (2014) Improving productivity and environmental performance of aquaculture. World Resources Institute.

Walsh, B.J., Rydzak, F., Palazzo, A., Kraxner, F., Herrero, M., Schenk, P.M., Ciais, P., Janssens, I.A., Peuelas, J., Niederl-Schmidinger, A., Obersteiner, M. (2015) New feed sources key to ambitious climate targets. Carbon Balance and Management 10.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J. (2013) The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. Proceedings of the National Academy of Sciences.

Weindl, I., Lotze-Campen, H., Popp, A., Müller, C., Havlík, P., Herrero, M., Schmitz, C., Rolinski, S. (2015) Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environmental Research Letters 10, 094021.

Wheeler, T., von Braun, J. (2013) Climate Change Impacts on Global Food Security. Science 341, 508-513.

Wicke, B., van der Hilst, F., Daioglou, V., Banse, M., Beringer, T., Gerssen-Gondelach, S., Heijnen, S., Karssenberg, D., Laborde, D., Lippe, M., van Meijl, H., Nassar, A.M., Powell, J., Prins, A.G., Rose, S.K., Smeets, E.M.W., Stehfest, E., Tyner, W.E., Verstegen, J.A., Valin, H., van Vuuren, D.P., Yeh, S., Faaij, A.P.C. (2014) Model collaboration for the improved assessment of biomass supply, demand and impacts. GCB Bioenergy in press.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W.D., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L. (2019) Food in the Anthropocene: the EAT}Lancet Commission on healthy diets from sustainable food systems. The Lancet 393, 447-492.

Wilson, E.O. (2016) Half-earth: our planet's fight for life. WW Norton \& Company.

Wirsenius, S., Azar, C., Berndes, G. (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems 103, 621-638.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M. (2016) Reducing emissions from agriculture to meet the 2 °C target. Global Change Biology, n/a-n/a.

Yu, W., Hertel, T.W., Preckel, P., Eales, J. (2004) Projecting World Food Demand Using Alternative Demand Systems. Economic Modelling 21, 99-129.

Zabel, F., Putzenlechner, B., Mauser, W. (2014) Global Agricultural Land Resources: A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions. {PLOS} {ONE} 9, e107522.

Zhang, J., Beusen, A.H.W., Apeldoorn, D.F.V., Mogollon, J.M., Yu, C., Bouwman, A.F. (2017) Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century. Biogeosciences 14, 2055-2068.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y. (2015) Managing nitrogen for sustainable development. Nature.

Zurek, M., Hebinck, A., Selomane, O. (2021) Looking across diverse food system futures: Implications for climate change and the environment. Q Open 1.

# 7. APPENDIX. Sustainable Development Goal 2

The Agenda 2030 for Sustainable Development (UN, 2015) defines SDG2 as follows:

**Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture**

- **Target 2.1.** By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round
- **Target 2.2.** By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons
- **Target 2.3.** By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
- **Target 2.4.** By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
- **Target 2.5.** By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed
- **Target 2.a.** Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries
- **Target 2.b.** Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round
- **Target 2.c.** Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility

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For further information about the Scientific Group,

visit **https://sc-fss2021.org** or

contact **info@sc-fss2021.org**

**@sc_fss2021**