



United Nations Food Systems Summit 2021
Scientific Group
<https://sc-fss2021.org/>

A paper from the Scientific Group of the UN Food Systems Summit
26 May 2021

Achieving Zero Hunger by 2030

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

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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, 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

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.

Socioeconomic needs

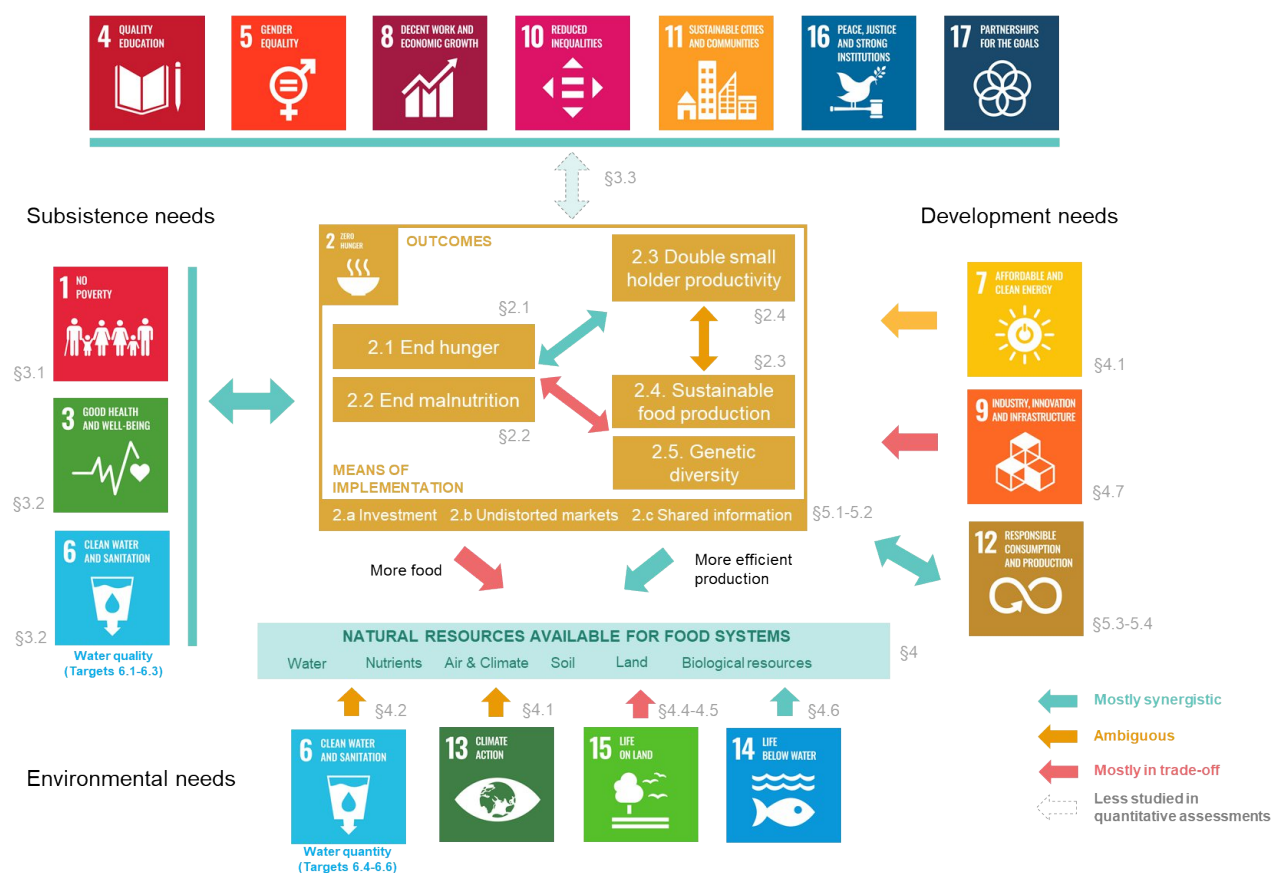


Figure 1. SDG2, its targets and relations to other SDGs, as analyzed in this paper. Colored arrows represent direction and nature of main SDG relations (mostly synergistic or in trade-off). Relations less studies are marked with pale colors/dashed arrow outlines. References to specific sections of the 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>.

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 IASA, 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 envelopes 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,

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%) underweight⁶ 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

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 CO₂ 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.

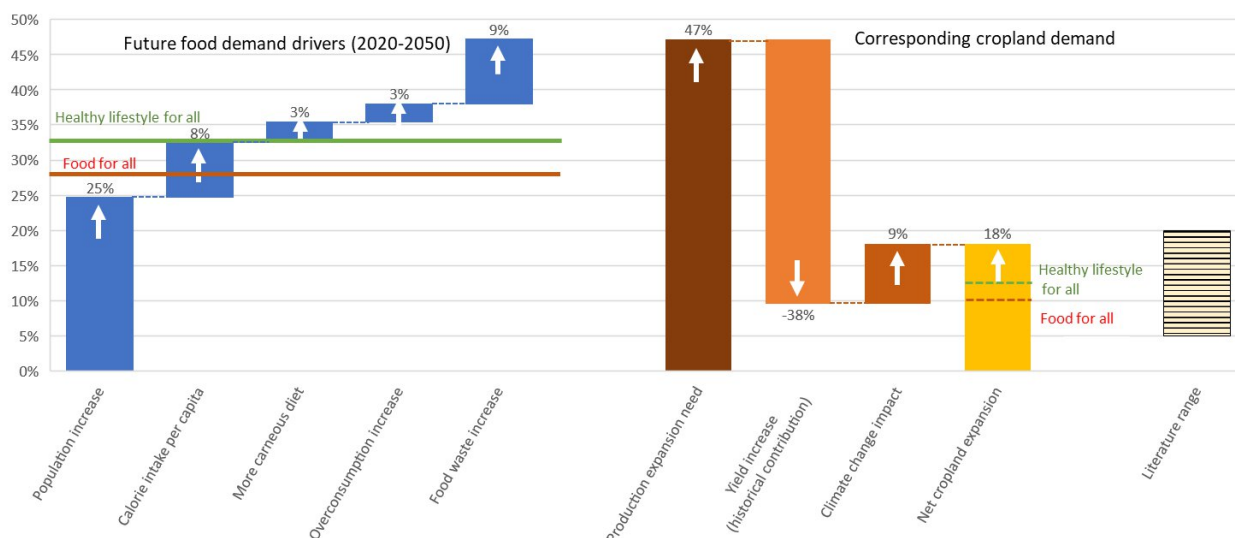


Figure 2. Decomposition of future food demand from 2020 to 2050 (left-hand side, blue bars) and potential implications for cropland expansion based on stylized assumptions (right-hand side, warm colors). Total food demand increase (sum of blue bars – 47%) is the cumulated effect from population increase, 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](#)).

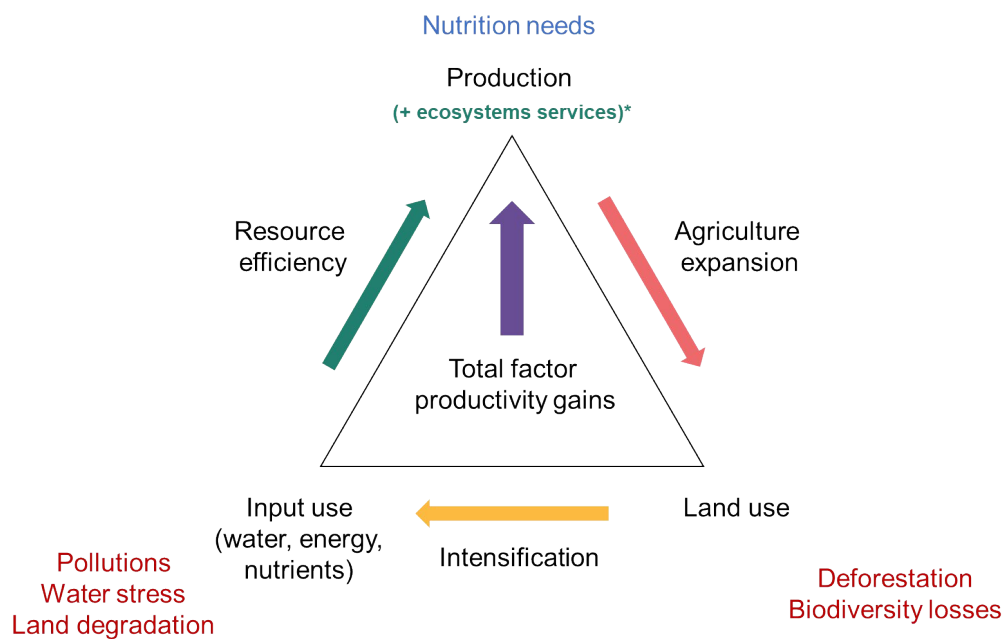


Figure 3. The role of total factor productivity (TFP) gains to limit impact of agricultural production on the environment (in red).

* 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 GtCO₂e 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 been 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.

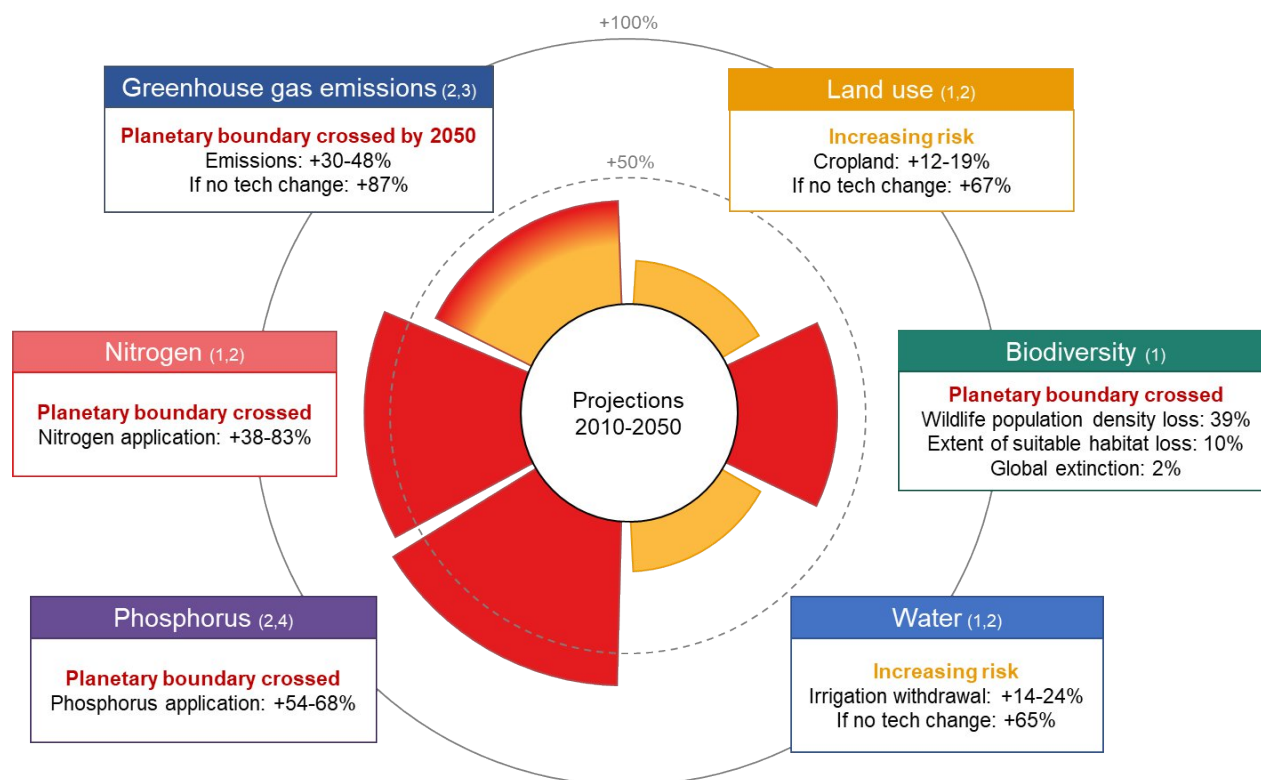


Figure 4. Projections of the food systems pressure along selected environmental dimensions (Visual representation inspired from the planetary boundaries, Steffen et al., 2015). Colors of the sectors indicate the status for each planetary boundary: green = no risk (none); orange = at risk of crossing 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-CO₂ 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 CH₄ and N₂O 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 CO₂ abatement in the land using sector ([Golub et al., 2009](#); [Kindermann et al., 2008](#)). Non-CO₂ 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-third ([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; N₂O climate-warming emissions; air pollution through ozone formation; groundwater contamination from nitrate; and stratospheric ozone depletion induced by N₂O 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](#);

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 not 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/tCO₂ 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/tCO₂, 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 CO₂e in Popp et al. with non-CO₂ emissions to 10 Gt CO₂e 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 CO₂e, 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.

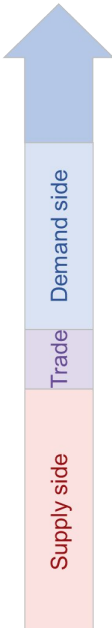
Combining a large set of these options has usually been presented as the best way – if not the only one – to succeed bringing back the food systems within a safe operating space and providing sustainable food to all while supporting the other SDGs. Table 1 provides an illustration of such comprehensive 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.



	TRANSFORMATIONS	OUTCOMES				Quantitative studies
		Target 2.1 Target 2.2		Target 2.3	Target 2.4 and envt. SDGs	
		Food availability (quantities)	Food access (prices)	Smallholder income	Environmental outcomes	
Demand side	Reducing waste and overconsumption	Green	Green	Red	Green	1, 4, 5, 6, 7
	Adopting healthy diets	Green	Red	Green	Orange	4, 5
	Adopting sustainable diets	Green	Green	Red	Green	1, 2, 3, 6, 7
Trade	Improving trade integration	Green	Green	Orange	Orange	1, 5, 6
Supply side	Increasing agricultural productivity	Green	Green	Green	Orange	1, 2, 3, 4, 5, 6, 7
	Reducing food losses	Green	Green	Green	Green	1, 4, 5, 6, 7
	Improving agricultural practices and resource management	Green	Red	Green	Green	1, 3, 4, 7
	Protecting and reallocating resource to other SDGs	Red	Red	Red	Green	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 - Leclerc 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 (FOLU, 2019)	CGIAR (Steiner et al., 2020)	CCAFS (Steiner et al., 2020)	Global Panel on Agriculture and Food Systems for Nutrition (2020)
<i>“Five strategies for a Great Food Transformation”</i>	<i>“Ten critical transitions”</i>	<i>“Actions to transforms food systems”</i>		<i>“Priority policy actions to transition food systems towards sustainable healthy diets” *</i>
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 healthy 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

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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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Helpful comments on an earlier draft by five external peer reviewers, by colleagues in the Scientific Group are gratefully acknowledged.

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