Kummu, Matti; Fader, Marianela; Gerten, Dieter; Guillaume, Joseph HA; Jalava, Mika; Jägermeyr, Jonas; Pfister, Stephan; Porkka, Miina; Siebert, Stefan; Varis, Olli

Bringing it all together : linking measures to secure nations' food supply

Published in:
Current Opinion in Environmental Sustainability

DOI:
10.1016/j.cosust.2018.01.006

Published: 01/12/2017

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Bringing it all together: linking measures to secure nations' food supply

Matti Kummu[1*], Marianela Fader[2], Dieter Gerten[3,4], Joseph H.A. Guillaume[1,5], Mika Jalava[1], Jonas Jägermeyr[3], Stephan Pfister[6], Miina Porkka[1,8], Stefan Siebert[7], Olli Varis[1]

1 Water & Development Research Group (WDRG), Aalto University, Tietotie 1E, 02150 Espoo, Finland
2 International Centre for Water Resources and Global Change (UNESCO), hosted by the Federal Federal Institute of Hydrology, P.O. Box 200253, 56002 Koblenz, Germany.
3 Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A62, D-14473 Potsdam, Germany
4 Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
5 The Fenner School of Environment and Society, The Australian National University, Building 48A, Linnaeus Way, Canberra ACT 0200, Australia
6 Institute of Environmental Engineering, Chair of Ecological System Design, ETH Zurich, 8039 Zurich, Switzerland
7 Department of Crop Sciences, University of Göttingen, Von-Siebold-Strasse 8, 37075 Göttingen, Germany
8 School of Energy Systems, Lappeenranta University of Technology (LUT), Saimaankatu 11, 15140 Lahti, Finland

** corresponding author: matti.kummu@aalto.fi, +358 50 407 5171*

Abstract: A growing human population and changing consumption patterns threaten adequate food supply globally by increasing pressure on already scarce land and water resources. Various measures have been suggested to sustainably secure future food supply: diet change, food loss reduction and closing the yield gap of nutrients as well as water. As yet, they have been assessed separately or, if combined, at a global or macro-region level only. In this paper, we carry out a review and integration of this literature to provide a first estimate of the combined potential of these measures at country level. The overall potential increase in global food supply was estimated to be 111% and 223% at moderate and high implementation levels, respectively. Projected global food demand in 2050 could thus be met, but deficiencies in various countries in Africa and the Middle East appear inevitable without changes to trade or adapting future innovations. Further, this analysis highlights country-level management opportunities for each intervention studied. Several potential future research opportunities are proposed to improve integration of measures.

Introduction

Over 800 million people (11% of world total) are currently undernourished [1]. In the most critical hunger areas, South Asia and Sub-Saharan Africa, the population is growing rapidly [2] and natural resources for food production are already scarce [3-5]. The global population is projected to surpass nine or even ten billion by the year 2050 [2,6], with particularly rapid growth in these critical regions. It is estimated that food production would need to increase globally by 50-100% by 2050 [7,8] to satisfy the growing demand, while more recent analysis estimates this to be 25-70% above 2014 levels [9]. The large variation of these estimates mainly derives from the large uncertainty in future population growth (global population estimates for year 2050 vary from 9.2 to 10.2 billion with 95% prediction interval) [10] as well as future diet composition (meat intensive diets would require more feed to be produced, for example) [11].

At the same time, environmental degradation intensifies the challenge of producing adequate food supply in many regions [12,13] and literature widely agrees that humanity cannot sustainably increase the use of land and water resources, the key resources for food production, for much longer [14-18]. Various countries have already reached their limits in harnessing water and land resources [4,19,20], which has deepened their dependency on international trade to secure adequate food supply [21-23]. Further, climate change introduces a large uncertainty regarding the growing conditions of the majority of crops [24-26].

To allow the world to meet future dietary requirements with essentially less pressure on resources than today, we argue that there is a need for *improved understanding of the spatially varying effect of combined demand and production-side opportunities*. This is consistent with Foley et al. [27] and Rockström et al. [28], who argue that in order to achieve future food supply, we need to shift away from emphasis on single ultimate solution as well as away from increased production through increased resource use.

Securing food supply while limiting pressure on resources can be achieved by cutting excess food production per capita through avoiding overconsumption of food [29,30], eating less animal products [29,31-33], and reducing food losses and waste throughout the food supply chain [30,34,35]. It also means finding more resource-efficient ways for food production, for example by increasing cropping efficiency and closing the yield gap in underperforming areas [21,27,36-38] or intensifying food production particularly in areas where additional water use has low environmental impact [39]. These actions are also promoted through the Sustainable Development Goals (SDGs), in which all countries are now committed to a transformative agenda aiming for sustainable food production systems.

The potential of these proposed measures has often been highlighted [24,27]. In addition to explicit quantitative analyses of potential futures (focussing either on resource efficiency or productivity), there are historical analyses [40], meta-analyses of alternative measures [41], and qualitative discussions [24,42]. Most quantitative studies fall, however, short on three key points:

i) they include all the measures to the analysis but do not provide results of the combined potential at national or finer scale but either at global [27,39,43-46] or macro-region level [47-50],
ii) they assess only a subset of measures at global or macro-region level [51-54] or
iii) they assess only a subset of measures at national or finer scale [20,21,29,33,35-37,55-57] without estimating their combined impact.

As exceptions, the effect of diet change and food loss reduction on resource efficiency is assessed in a combined manner at country-scale by Jalava et al. [34], while Pradhan et al. [38] combine yield gap closure with dietary changes (improving nutrition in low income countries at grid scale). All studies reporting results in a spatially disaggregated manner illustrate well that food availability potentials exhibit strong geographic gradients. Further, the combined work by Jalava et al. [34] shows that there are synergies between the measures: loss reductions are found to be more effective under a changed diet. The scope and spatial scale of an extensive list of relevant studies, based on our literature review, is summarised in Table 1.

Thus, spatially explicit information on these measures in a combined assessment is urgently needed to understand the suite of most suitable, resource-efficient management opportunities for each geographic area. Here we aim to provide an analysis towards this goal using recent datasets at country scale. Although our approach lacks the full integration of these measures, it provides a first global and spatially explicit (national level) assessment that integrates all these future food system opportunities and delivers combined estimates of their impact on the food availability. Through compiling such a management portfolio this study also leads to open research challenges that still need to be addressed to obtain more rigorous results as well as a fully integrated estimate of overall potentials.

Methods: analysis of combined measures

To estimate the combined potential of selected measures to increase food supply, we consider two scenarios reflecting moderate and high levels of implementation of each measure (Table 2). All estimates are on country or finer scale. In the case of diet change and food loss reduction, the implementation level refers to the degree of change towards less meat-intensive diets and lower food waste (Table 2). In the case of yield gap closure, we used output from two different simulation models representing the degree to which agricultural intensification is pursued [21,36,37]. The selected estimates are drawn from recent spatially explicit studies that represent the state of the art, and cover a broad range of assumptions about implementation. However, the analysis is not intended as a complete meta-analysis. In more detail, we chose to use the selected studies due to following reasons:

- *Diet change*: Jalava et al. [29,34] are the only national level studies that i) take into account detailed diet recommendations (food supply energy, proteins, fats, fruits & vegetables, and sugar) as well as ii) include different levels of decrease in animal protein content in the diet, which is replaced by vegetable food stuff protein to meet the diet recommendations
- *Food loss reduction*: the method from Jalava et al. [34], based on Kummu et al. [35], is the state-of-the-art food loss reduction study at national level, taking into account losses and waste in all the food supply chain stages
- *Yield gap closure*: the selected studies are spatially explicit (grid level) state-of-the-art studies that take into account both water and nutrient yield gap closures either in combined manner [36], or separately but using the same global model without double-counting the impacts of the two yield gap closure measures [21,37].

As shown in Fig. 1, the combined potential is estimated by compounding the food supply increases from each measure along the food supply chain. In other words, the measures are multiplicative (i.e. applied on top of increased food supply potential of a previous measure) and thus, the total effect exceeds the sum of the individual measures (see hypothetical example in Fig. 1). The effect of food loss reductions and resource efficiency savings from diet change can both be considered proportional to total production, and the effect of closing the yield gap by reducing one stress factor is typically dependent on the level of other stress factors. Multiplication is still a simplification, but seems reasonable as a means of obtaining a first estimate. Given that we are interested in country-scale estimates, we also separate production-side from consumption-side measures. Production-side measures are applied to local production, based on FAOSTAT [58], while the consumption-side measures are applied to total food supply (Fig. 1), after accounting for the current levels of trade as reported in FAOSTAT [58]. We assume trade volumes stay at current levels also in the scenarios, such that increases in local food supply are not passed on to others in the trade network.

Analysed measures to provide sustainable food supply

The datasets we used for the combined assessment, and the assumptions of each individual measure are described in the following, for both moderate and high levels of implementation.

Diet change: while animal foodstuffs provide important sources of protein to humankind, they also typically require more natural resources than equivalent plant-based nutrition. We adopted a two-fold diet change scenario based on Jalava et al. [29] to illustrate the potential of decreasing the resources use. Both scenarios, moderate and high levels of implementation, first introduce a diet based on recommendations by FAO [59] on food supply intake and by WHO [60] on proteins, fats and other macronutrients (which does increase food supply in under-nourished countries). The second part of the scenario introduces a cap on animal protein intake to 25% (moderate level of implementation) and 12.5% (high level of implementation) of the total protein intake in relation to nutritional recommendations, and replaces that with protein sources from plant-based foodstuffs to meet the WHO recommendations of protein intake. We then calculated the potential additional food production with the saved 'green' (i.e. naturally infiltrated rain, attached to soil particles and accessible by roots) and 'blue' (i.e. freshwater in rivers and aquifers) water resources.

Assuming full use of the available resource, resource use and food supply are inversely related, for example, if resource use decreases to 50%, then food supply potential is 200% of the original, or a 100% increase. In general, if x% of resources were saved, the food production would potentially be increased by a percentage of $p = 100\%/(100\% – x) – 100\%$.

Reduced food losses and waste: currently ~25% of the total food produced is lost or wasted (in terms of calories) within the food supply chain, i.e. from field to fork [35]. We adopted a scenario where food loss and waste is reduced by 25% (moderate level of implementation) or 50% (high level of implementation) in each step of the supply chain [35]. In the calculations, we considered in which part (either production or consumption) of the supply chain the loss occurred (see below 'Combined potential calculations'). The scenarios reflect the goals, for example, of the European Union which has a target to "*halve per capita food waste at the retail and consumer level by 2030, and reduce food losses along the food production and supply chains*" [61].

Yield gap closure: the current crop yields are, for example, much lower in Sub-Saharan Africa compared to other parts of the world [36]. From a water perspective, in Europe and North America a sufficient and healthy diet can be produced with less than 650 m^3/cap/yr of green-blue water resources, while in large parts of Africa and Asia the requirements are four-fold [4,19]. Thus, by enhancing cropping efficiency, improving agricultural management practices and nutrient supply as well as water management and irrigation practices, food production could be increased considerably. We developed two different datasets to represent the two assessed implementation levels:

For the *moderate implementation level*, we used the 95% yield gap closure scenario by Mueller et al. [36] (available at a 5 arc-min resolution from www.earthstat.org) who combine improved nutrient supply and irrigation expansion to reach attainable yields for 16 most important crops. Their study can be considered a moderate level of implementation since they compute potential production by observing similar regions in terms of climate and growing-degree-days (i.e. "climate bins"). Hence, their production potentials can be considered conservative, especially in regions where the reference is currently characterized with managed deficiencies. It should be noted that expansion of irrigated areas are simulated irrespective of local water availability, and overall water use is not considered a constraining factor [36].

For the *high implementation level*, we adopted an agricultural management scenario based on calculations by Fader et al. [21] and scenarios of farm water management based on Jägermeyr et al. [37]. Both measures were simulated with the LPJmL global bio- and agrosphere model. Fader et al. [21] compute potential production by optimizing agricultural management, allowing potential yields with only biological and climatic constraints and it can thus be considered a high-level scenario. In this study, increases in yields are based in a combination of high harvest indexes (assuming that countries will use the highest yielding breeds), high homogeneity of fields (assuming that management will avoid factors that promote heterogeneity like erosion areas and pests), and a high maximum leaf area index (assuming that plants will have the opportunity of reaching it by appropriate nutrient supply, adequate tillage, etc.). While Fader et al. [18] presented the combination of these measures with and without cropland expansion, in this study we only use the scenario without cropland expansion. A higher productivity of plants has effects on soil evaporation (normally a decrease) and crop transpiration (normally an increase). Thus, reaching optimal management increases water consumption slightly (1.8%).

In Jägermeyr et al. [37], improved water use efficiency to increase global food production (kcal) is systematically assessed through different ambition levels of integrated farm water management combining irrigation upgrades and different rainwater management opportunities; complementary to the Fader et al. [21] simulations. Irrigation efficiency improvements - mechanistically represented [56] – lead to reductions in consumptive water losses that are in turn used to expand irrigation into neighbouring rainfed cropland (return-flows stay untouched for downstream users). The total cropland remains constant and overall irrigation withdrawals decrease while consumptive water use slightly increases at global scale. Rainwater management includes water harvesting for supplemental irrigation during dry spells and reduced non-beneficial soil evaporation through e.g. mulching techniques. The high-end scenario employed here refers to an ambitious yet feasible implementation of integrated irrigated and rainfed farm water management, as detailed in Jägermeyr et al. [37].

Calculations on combined potential

Consistent with the compounding approach summarised in Fig. 1, the combined potential for each country was calculated with the following equations for the two levels of implementation. The food supply increases from each measure (expressed as percentage of current food supply) are multiplied. Production-side measures (YieldGapComb, YieldGapMgmt, YieldGapWater, $FoodLoss_{production}$; see definition of the variables in Table 3) are only applied to the locally produced portion of food supply. Net exports are then subtracted and consumption side measures (DietChange, $FoodLoss_{consumption}$; see definition of the variables in Table 3) are applied to both imported food and locally produced (non-exported) food. Food supply is in terms of energy consumed (kcal), i.e. after accounting for consumption side losses, but represented in indexed units relative to current locally produced food supply. The food and feed production was converted crop-specifically into kcals, while non-food crops were not included in the analysis. Consumption loss rates are assumed to be equal for local production and imported goods. The current trade flows from FAO statistics [58] are used, assuming that net export is kept constant. This means that increases in local food supply are not passed on to others in the trade network. When summed over all countries, the effect of this trade assumption cancels out.

Moderate level of implementation: (Eq. 1)

$$FoodSupply = [(100\%+YieldGapComb) * (100\%+FoodLoss_{production}) * LocalProduction - NetExport] * [(100\%+DietChange) * (100\%+FoodLoss_{consumption})]$$

High level of implementation: (Eq. 2)

$$FoodSupply = [(100\%+YieldGapMgmt) * (100\%+YieldGapWater) * (100\%+FoodLoss_{production}) * LocalProduction - NetExport] * [(100\%+DietChange) * (100\%+FoodLoss_{consumption})]$$

Where the variables are as defined in Table 3.

Potential to increase food supply vs population growth

We used country specific population projections based on the medium variant of the United Nations Population Prospect from the year 2015 [6]. When relating the food supply potential to population, we simply subtracted the percent population change (in relation to the year 2015) from the percent potential to increase food supply relative to current food supply.

Results and discussion: potential varies greatly across countries

At the global scale, our estimated increase in food availability of 111–223% for the moderate and high levels of implementation, respectively, is in line with previous findings, which ranged between 100 and 180% [27,38,39] (Table 2). Importantly, these scenarios would keep the exploitation of water and land resources at approximately the present level (depending on the scenario, see Methods) and if food availability is sufficient for the respective country population, the scenarios meet both FAO calorie intake recommendations [59] and WHO global dietary recommendations [60] for proteins and other macronutrients. The conclusion remains that feeding the future population – on a global scale – would be possible. The largest improvements stem from closing the yield gap, reaching +57% in the moderate scenario and +113% for the high implementation level (Table 2), while diet change and reduced food losses also have substantial potential to increase food availability (+28-36% and +7-14%, respectively) (Table 2). There is, however, large spatial variability in the combined potential as well as potential of each management opportunity, both across 12 macro-regions (defined by UN [62] and modified by Kummu et al. [63]) and countries (Fig. 2; Fig. 3).

Depending on the macro-region, the total potential to increase food availability ranges between 59% and 272% (125-527%) for the moderate (high) level of implementation (Fig. 2) while at country scale, the range is even larger (Fig. 3). The greatest local potential lies in Eastern Europe and the Central Asia region, as well as in Australia and Oceania, and Sub-Saharan Africa where food availability could be increased by >160% under moderate and >320% under high implementation level (Fig. 2, Fig. 3). Potential is also high in the Middle East and Latin America, reaching 120% (300%), while it is lowest in Western Europe, North Africa and South Asia. The composition of measures varies depending on the region, but can be separated into three clusters, summarised in Fig. 2. The clusters are notably differentiated by the impact of yield gap closure and diet change on food availability.

Considering future population growth, it appears that food supply satisfying WHO diet recommendations could be met globally and regionally in 2050 with the moderate implementation. In the year 2100, Sub-Saharan Africa could not meet the supply needed in either scenario. At a national level, not all countries would meet food requirements in 2050 even with a high implementation; and the situation would be even more critical in 2100 (Fig. 4). Many countries would, however, have potential to produce excess food, which could allow increased exports or reduced pressure on resources. The greatest 'excess potential' lies in Eastern Europe and Central Asia, Australia, South America, and East Asia (Fig. 4), where even under moderate implementation, there would be over 70% of excess food supply in the year 2050.

One important factor not considered in our estimations is the impact of climate change on food production. We intentionally left it outside the scope of this study due to: i) the Paris Agreement in December 2015 paves the way for limiting global warming below 2°C with the intention of restricting impacts of climate change, perhaps with the exception of sensitive crops and areas with very low adaptive capacity; ii) the CO_2-fertilization effect is likely to increase the water use efficiency of plants and the biomass production rate [64,65], partially counteracting the negative effects of heat and drought stress; and iii) several studies indicate that climate change has a smaller effect compared to management measures and to the effect of population growth [26,66]. Interestingly, agriculture is not only being impacted by climate change but is also, as a sector, one of the largest greenhouse gas (GHG) emitters [67]. Technological dissemination and large scale transformation of crop and livestock production systems are proposed to cut the emissions, but these need to supplemented with additional methods, in order to keep warming below 2 °C [68]. Integrating climate change into the combined assessment was thus left for future studies, as outlined in the last section.

It needs to be further noted that the adopted measures would limit increases in land and water resource use, but closing the yield gap by conventional farming techniques would require additional inputs of fertilizer and other agrochemicals [38], which may lead to unsustainable practices and environmental damage. Crop transpiration also increases due to enhanced irrigation efficiency, reducing soil evaporation and return flows that do not contribute to plant growth. Another important aspect is expansion of irrigation, which has especially high potential for increasing yields in Sub-Saharan Africa [69,70]. For this estimate, expansion is only addressed through saved consumptive losses from upgrades of the existing system (high implementation scenario). Finally, even the sustainable implementation of all the discussed options in every country would not necessarily result in food security for all people, as that would require additional work towards poverty alleviation, equal access to production resources and markets, good governance, improvements of infrastructure of smallholders, among other factors.

Way forward: towards fully integrated assessment

Our analysis based on compounding of contributions of the selected measures provides promising results, but also highlights several knowledge gaps in respect to the combined impact of identified measures. While our estimate goes beyond the literature cited in Introduction and Table 1, it still shares many of the same limitations. There are a variety of methodological developments that can be taken as next steps to obtain a more accurate, process-based, understanding of how the proposed measures would ease the pressure on natural resources used for food production. We have grouped these potential improvements into three categories (see also Fig. 5): i) the *core developments* that are essential for understanding the potential, ii) the *supportive developments* that provide important context to make sense of the potential, and iii) the *linking developments* that would deepen knowledge in specific fields and provide linkages with other disciplines.

Core developments: the quantitative representation of the food and resource system in our estimates is based on a simple conceptualisation of the supply chain (see Fig. 1). Integrated frameworks do exist to jointly consider consumption and production, notably using economic models [48]. However, they have typically not been applied at country scale, and their underlying assumptions usually represent one dominant view of decision making and resource use, e.g. focussed on optimization of economic variables. The full integration of measures (CA1; core action 1), including dynamic feedbacks, is thus a key action to understand how measures impact on each other and assess whether the integrated combined potential will be lower or higher than presented here. As discussed above, climate change will potentially also introduce uncertainty regarding the growing conditions across the globe. Thus, it is important to integrate climate change in the assessment, as well potential increase in climate variability and the effects of higher CO_2 concentrations in the atmosphere for plant growth (CA2), as has been partially done in some of the cited studies [25,39]. For each measure it is also crucial to use consistent scenarios (CA3) with harmonised assumptions, about climate change and population growth [71], amongst other key drivers. The measures are now concentrated on the main agricultural production and value chain steps. The assessment would thus benefit from inclusion of non-agricultural food sources (CA4), such as fish [72,73], as well as from filling gaps in the value chain (CA5). Little global data exists on the multiple steps in food processing and distribution, including re-use of "losses" elsewhere in the food chain [74].

Supportive developments: at country rather than global scale, agricultural trade plays a crucial role in supply chains, resource use efficiency, and food security [75,76]. The importance of trade raises questions about food sovereignty and purchasing power, including impacts of sub-national disparities, particularly in segments of populations affected by poverty and malnutrition. There is a need for broadened exploration of trade scenarios (SA1), as here we assumed current trade volumes, and other studies have projected changes in trade patterns due to changes in demand, land use patterns and/or policies (e.g. liberalization) [e.g. 77]. The political and practical feasibility of implementing (SA2) specific measures, including trade configurations, is a question which also requires further elaboration. The current practices used in this analysis could be expanded to include future innovations (SA3) affecting yield and resource use, including breeding and genetic manipulation [78], precision farming, and improved land use allocation [44], as well as emerging technologies such as vertical farming [79], artificial meat [51,80], and aquaponics [81]. Finally, feedbacks with non-food agriculture [82] could be integrated in the model rather than treated as external scenarios, capturing existing competition with food production, as well as possibility for re-use of by-products for food production (SA4), e.g. competition with fibre production biofuels [e.g. 33,39].

Linking developments: We approached sustainability from the perspective of available water and land resources but additional environmental sustainability and equity criteria are still missing (LA1) [38]. In addition to water quality and soil erosion, an important example is – as a precondition for attaining the SDGs related to water and the environment - that current violations of environmental flows need to be reallocated to safeguard life-supporting aquatic ecosystems. A recent study highlights that 40% of global irrigation water use occurs at the expense of environmental flows, affecting 10-30% of national food production across many producer regions [20]. Such trade-offs underpin the pivotal role of management interventions and are important to more comprehensive assessments.

Further, there is a need to bridge scales and conduct finer-scale implementation-level analyses of potential to increase yields [16,83], for example with case studies and analysis of local crops and cultivars (LA2). Finally, to put measures into action and to anticipate responses, there is a need to know what implementation agencies would take the lead in this, and why they would do so. Thus, system processes need to be tied to specific (types of) actors (LA3) and their preferences. One key issue is to consider the risk strategies that actors prefer when dealing with variability in climate and markets in their profession, as well as other risks related to conflict and geopolitics (LA4). This also requires the inclusion within this type of analysis of other research communities from socio-economic and political sciences to complement the quantitative, geographic perspectives in much of the cited literature.

To conclude, our spatially explicit results reinforce previous findings about potentials that theoretically it would be possible to meet the growing nutritional needs of humanity in 2050 with the current level, or even lower use of land and water resources. As we demonstrate, tackling this tremendous challenge would require the simultaneous implementation of a location-specific mix of measures as they – either in isolation or in combination – perform differently in specific regions. Our results based on a simple conceptualisation of the supply chain are, however, only indicative. To reliably provide country-level information, there are still substantial research gaps and problems that need to be addressed so that measures to sustainably secure food supply can be assessed in combination, not just in parallel.

Acknowledgements

The work was financially supported by Academy of Finland funded projects SCART (grant no. 267463) and WASCO (grant no. 305471), Emil Aaltonen Foundation funded project 'eat-less-water', *Maa- ja vesitekniikan tuki ry*, and Academy of Finland SRC project 'Winland'. Additionally, M. Fader was partially supported by the EU FP7 for funding through project LUC4C (GA603542), S. Pfister by the SNF project 'Sustainability evaluation of biorefinery systems for fuel and commodity chemical generation from plant residues', S. Siebert by the BMBF-project GlobeDrought (02WGR1457A) through the Programme Global Resource Water (GROW) and J. Jägermeyr was supported within the framework of the Leibniz Competition (SAW-2013-PIK-5).

Author Contributions

M.K., M.F., J.H.A.G., J.J. designed this study in consultation with D.G., M.J., S.P. and S.S. The modelling was conducted by M.F., M.J. and J.J. supported by M.K., J.H.A.G. and D.G. Analyses were conducted by M.K. in consultation with all co-authors. M.K., M.F., D.G., J.H.A.G., J.J., S.P. and O.V. wrote the article, with contributions from all co-authors.

Competing Financial Interests statement

The authors declare no competing financial interests.

References

1. FAO, WFP and IFAD: *The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition*; 2014.

2. Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, et al.: **World population stabilization unlikely this century**. *Science* 2014, **346**:234-237.

3. Fader M, Rulli MC, Carr J, Dell'Angelo J, D'Odorico P, Gephart JA, Kummu M, Magliocca N, Porkka M, Prell C, et al.: **Past and present biophysical redundancy of countries as a buffer to changes in food supply**. *Environmental Research Letters* 2016, **11**:055008.

4. Gerten D, Heinke J, Hoff H, Biemans H, Fader M, Waha K: **Global water availability and requirements for future food production**. *Journal of Hydrometeorology* 2011, **12**:885–899.

5. Kummu M, Guillaume JHA, de Moel H, Eisner S, Flörke M, Porkka M, Siebert S, Veldkamp TIE, Ward PJ: **The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability**. *Scientific Reports* 2016, **6**:38495.

6. United Nations: **World Population Prospects: The 2015 Revision**. Edited by: United Nations, Department of Economic and Social Affairs, Population Division; 2015.

7. Alexandratos N, Bruinsma J: **World agriculture towards 2030/2050: the 2012 revision**. In *ESA Working paper No. 12-03*. Edited by. Rome: FAO; 2012.

8. Tilman D, Balzer C, Hill J, Befort BL: **Global food demand and the sustainable intensification of agriculture**. *Proceedings of the National Academy of Sciences* 2011, **108**:20260-20264.

9. Hunter MC, Smith RG, Schipanski ME, Atwood LW, Mortensen DA: **Agriculture in 2050: Recalibrating Targets for Sustainable Intensification**. *BioScience* 2017:bix010.

10. United Nations: **World Population Prospects: The 2017 Revision**. Edited by: United Nations, Department of Economic and Social Affairs, Population Division; 2017.

11. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, et al.: **The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century**. *Global Environmental Change* 2017, **42**:169-180.

12. FAO: *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk*: Food and Agriculture Organization of the United Nations (FAO), Rome and Earthscan, London; 2011.

13. Pimentel D, Burgess M: **Soil Erosion Threatens Food Production**. *Agriculture* 2013, **3**:443.

14. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, et al.: **Planetary boundaries: Guiding human development on a changing planet**. *Science* 2015, **347**:6223.

    ** *the revised and updated framework for planetary boundaries, highlighting the need to consider certain thresholds in harnessing the planet for example for food production. They further introduce cross-scale interactions and regional-level heterogeneity of the boundaries and underlying processes.*

15. Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M, Pastor AV: **Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements**. *Current Opinion in Environmental Sustainability* 2013, **5**:551-558.

16. Rockström J, Falkenmark M, Allan T, Folke C, Gordon L, Jägerskog A, Kummu M, Lannerstad M, Meybeck M, Molden D, et al.: **The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability**. *Ecohydrology* 2014, **7**:1249-1261.

17. DeFries R, Fanzo J, Remans R, Palm C, Wood S, Anderman TL: **Metrics for land-scarce agriculture**. *Science* 2015, **349**:238-240.

18. de Fraiture C, Molden D, Wichelns D: **Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture**. *Agricultural Water Management* 2010, **97**:495-501.

19. Kummu M, Gerten D, Heinke J, Konzmann M, Varis O: **Climate-driven interannual variability of water scarcity in food production potential: a global analysis**. *Hydrol. Earth Syst. Sci.* 2014, **18**:447-461.

20. Jägermeyr J, Pastor A, Biemans H, Gerten D: **Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation**. *Nature Communications* 2017, **8**:15900.

21. Fader M, Gerten D, Krause M, Lucht W, Cramer W: **Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints**. *Environmental Research Letters* 2013, **8**:014046.

22. Porkka M, Kummu M, Siebert S, Varis O: **From food insufficiency towards trade-dependency: a historical analysis of global food availability**. *PLoS ONE* 2013, **8**:e82714.

23. Porkka M, Guillaume J, Siebert S, Schaphoff S, Kummu M: **The use of food imports to overcome local limits to growth**. *Earth's Future* 2017, **5**:393–407

24. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C: **Food Security: The Challenge of Feeding 9 Billion People**. *Science* 2010, **327**:812-818.

25. Schmidhuber J, Tubiello FN: **Global food security under climate change**. *Proceedings of the National Academy of Sciences* 2007, **104**:19703-19708.

26. Vörösmarty CJ, Green P, Salisbury J, Lammers RB: **Global Water Resources: Vulnerability from Climate Change and Population Growth**. *Science* 2000, **289**:284-288.

27. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, et al.: **Solutions for a cultivated planet**. *Nature* 2011, **478**:337-342.

28. Rockström J, Williams J, Daily G, Noble A, Matthews N, Gordon L, Wetterstrand H, DeClerck F, Shah M, Steduto P, et al.: **Sustainable intensification of agriculture for human prosperity and global sustainability**. *Ambio* 2016:1-14.

    *** highlights the importance of achieving both, environmental sustainability and human prosperity in future. The introduced paradigm shift aims to shift agriculture from largest driver of environmental change to key contributor towards sustainable world within planetary boundaries.*

29. Jalava M, Kummu M, Porkka M, Siebert S, Varis O: **Diet change – a solution to reduce water use?** *Environmental Research Letters* 2014, **9**:074016.

30. Alexander P, Brown C, Arneth A, Finnigan J, Moran D, Rounsevell MDA: **Losses, inefficiencies and waste in the global food system**. *Agricultural Systems* 2017, **153**:190-200.

31. Pradhan P, Reusser DE, Kropp JP: **Embodied Greenhouse Gas Emissions in Diets**. *PLOS ONE* 2013, **8**:e62228.

32. Vanham D, Hoekstra AY, Bidoglio G: **Potential water saving through changes in European diets**. *Environment International* 2013, **61**:45-56.

33. Cassidy ES, West PC, Gerber JS, Foley JA: **Redefining agricultural yields: from tonnes to people nourished per hectare**. *Environmental Research Letters* 2013, **8**:034015.

34. Jalava M, Guillaume JHA, Kummu M, Porkka M, Siebert S, Varis O: **Diet change and food loss reduction: What is their combined impact on global water use and scarcity?** *Earth's Future* 2016, **4**:62–78.

    ** demonstrates the synergies in combined impact of two measures, diet change and food loss reduction. Combining the measures would reduce water consumption by 23-28%.*

35. Kummu M, de Moel H, Porkka M, Siebert S, Varis O, Ward PJ: **Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use**. *Science of the Total Environment* 2012, **438**:477-489.

36. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA: **Closing yield gaps through nutrient and water management**. *Nature* 2012, **490**:254-257. *10.1038/nature11420*

37. Jägermeyr J, Gerten D, Schaphoff S, Heinke J, Lucht W, Rockström J: **Integrated crop water management might sustainably halve the global food gap**. *Environmental Research Letters* 2016, **11**:025002.

    ** comprehensive analysis of the water yield gap closure on a global scale. Integrated water management strategies could increase global production by 41%.*

38. Pradhan P, Fischer G, van Velthuizen H, Reusser DE, Kropp JP: **Closing Yield Gaps: How Sustainable Can We Be?** *PLoS ONE* 2015, **10**:e0129487.

** analysis of the yield gap closure, taking into account the location specific population growth and dietary habits. They found that production could be greatly enhanced by closing the yield gaps, but careful attention should be paid on how the strategies for closing yield gaps are chosen.*

39. Pfister S, Bayer P, Koehler A, Hellweg S: **Projected water consumption in future global agriculture: Scenarios and related impacts**. *Science of The Total Environment* 2011, **409**:4206-4216.

40. Kastner T, Rivas MJI, Koch W, Nonhebel S: **Global changes in diets and the consequences for land requirements for food**. *Proceedings of the National Academy of Sciences* 2012, **109**:6868-6872.

41. Clark M, Tilman D: **Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice**. *Environmental Research Letters* 2017, **12**:064016.

42. Wada Y, Gleeson T, Esnault L: **Wedge approach to water stress**. *Nature Geosci* 2014, **7**:615-617.

43. Keating BA, Herrero M, Carberry PS, Gardner J, Cole MB: **Food wedges: Framing the global food demand and supply challenge towards 2050**. *Global Food Security* 2014, **3**:125-132.

44. Mauser W, Klepper G, Zabel F, Delzeit R, Hank T, Putzenlechner B, Calzadilla A: **Global biomass production potentials exceed expected future demand without the need for cropland expansion**. *Nature Communications* 2015, **6**.

** comprehensive analysis of the potential to increase global biomass production without expanding the cropland expansion. Both, cropping intensification and spatial reallocation of crops would have considerable potential to increase food production.*

45. Conijn JG, Bindraban PS, Schröder JJ, Jongschaap REE: **Can our global food system meet food demand within planetary boundaries?** *Agriculture, Ecosystems & Environment* 2018, **251**:244-256.

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

47. Billen G, Lassaletta L, Garnier J: **A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade**. *Environmental Research Letters* 2015, **10**:025001.

** important analysis of range of opportunities to feed the world. They identify the areas in where performance potential is largest and show that global protein requirements could be met without increasing the trade or nitrogen environmental contamination.*

48. Springer NP, Duchin F: **Feeding Nine Billion People Sustainably: Conserving Land and Water through Shifting Diets and Changes in Technologies**. *Environmental Science & Technology* 2014, **48**:4444-4451.

49. Bajželj B, Richards KS, Allwood JM, Smith P, Dennis JS, Curmi E, Gilligan CA: **Importance of food-demand management for climate mitigation**. *Nature Climate Change* 2014, **4**:924.

50. Odegard IYR, van der Voet E: **The future of food — Scenarios and the effect on natural resource use in agriculture in 2050**. *Ecological Economics* 2014, **97**:51-59.

51. Alexander P, Brown C, Arneth A, Dias C, Finnigan J, Moran D, Rounsevell MDA: **Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?** *Global Food Security* 2017.

52. Bodirsky BL, Rolinski S, Biewald A, Weindl I, Popp A, Lotze-Campen H: **Global Food Demand Scenarios for the 21st Century**. *PLOS ONE* 2015, **10**:e0139201.

53. Muller A, Schader C, El-Hage Scialabba N, Brüggemann J, Isensee A, Erb K-H, Smith P, Klocke P, Leiber F, Stolze M, et al.: **Strategies for feeding the world more sustainably with organic agriculture**. *Nature Communications* 2017, **8**:1290.

54. Erb K-H, Lauk C, Kastner T, Mayer A, Theurl MC, Haberl H: **Exploring the biophysical option space for feeding the world without deforestation**. *Nature Communications* 2016, **7**:11382.

55. West PC, Gerber JS, Engstrom PM, Mueller ND, Brauman KA, Carlson KM, Cassidy ES, Johnston M, MacDonald GK, Ray DK, et al.: **Leverage points for improving global food security and the environment**. *Science* 2014, **345**:325-328.

56. Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W: **Water savings potentials of irrigation systems: global simulation of processes and linkages**. *Hydrology and Earth System Sciences* 2015, **19**:3073-3091.

57. Alexander P, Brown C, Arneth A, Finnigan J, Rounsevell MDA: **Human appropriation of land for food: The role of diet**. *Global Environmental Change* 2016, **41**:88-98.

58. FAO: *FAOSTAT – database for food and agriculture*. Rome: Food and agriculture Organisation of United Nations – FAO; 2015.

59. FAO: **Food security indicators, October 2015 release**. Edited by. Rome: Food and agriculture Organisation of United Nations (FAO), Available from: http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/ (Accessed Nov 2015); 2015.

60. WHO: *Diet, nutrition and the prevention of chronic diseases*. Geneva, Switzerland: World Health Organisation – WHO; 2003.

61. European Commission: **Closing the loop - An EU action plan for the Circular Economy**. Edited by. Brussels: European Commission; 2015.

62. UN: **United Nations World Macro Regions and Components. Available at unstats.un.org/unsd/methods/m49/m49regin.htm** In *UN Map Library*. Edited by. United Nations; 2000.

63. Kummu M, Ward PJ, de Moel H, Varis O: **Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia**. *Environmental Research Letters* 2010, **5**:034006.

64. Ackerman F, Stanton EA: **Climate Impacts on Agriculture: A Challenge to Complacency?** Edited by: Global Development and Environment Institute; 2013.

65. Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D, Thomson AM, Wolfe D: **Climate Impacts on Agriculture: Implications for Crop Production**. *Agronomy Journal* 2011, **103**:351-370.

66. Fader M, Shi S, von Bloh W, Bondeau A, Cramer W: **Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements**. *Hydrol. Earth Syst. Sci.* 2016, **20**:953-973.

67. Tubiello FN, Salvatore M, Golec RDCn, Ferrara A, Rossi S, Biancalani R, Federici S, Jacobs H, Flammini A: **Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks - 1990 – 2011 Analysis**. Edited by. Rome: Food and Agriculture Organization of the United Nations (FAO); 2014.

68. Wollenberg E, Richards M, Smith P, Havlík P, Obersteiner M, Tubiello FN, Herold M, Gerber P, Carter S, Reisinger A, et al.: **Reducing emissions from agriculture to meet the 2 °C target**. *Global Change Biology* 2016, **22**:3859-3864.

69. You L, Ringler C, Wood-Sichra U, Robertson R, Wood S, Zhu T, Nelson G, Guo Z, Sun Y: **What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach**. *Food Policy* 2011, **36**:770-782.

70. Burney JA, Naylor RL, Postel SL: **The case for distributed irrigation as a development priority in sub-Saharan Africa**. *Proceedings of the National Academy of Sciences* 2013, **110**:12513-12517.

71. Kaack LH, Katul GG: **Fifty years to prove Malthus right**. *Proceedings of the National Academy of Sciences* 2013, **110**:4161-4162.

72. Thilsted SH, Thorne-Lyman A, Webb P, Bogard JR, Subasinghe R, Phillips MJ, Allison EH: **Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era**. *Food Policy* 2016, **61**:126-131.

73. Gephart JA, Troell M, Henriksson PJG, Beveridge MCM, Verdegem M, Metian M, Mateos LD, Deutsch L: **The `seafood gap' in the food-water nexus literature—issues surrounding freshwater use in seafood production chains**. *Advances in Water Resources* 2017.

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

75. Puma MJ, Bose S, Chon SY, Cook BI: **Assessing the evolving fragility of the global food system**. *Environmental Research Letters* 2015, **10**:024007.

76. Suweis S, Carr JA, Maritan A, Rinaldo A, D'Odorico P: **Resilience and reactivity of global food security**. *Proceedings of the National Academy of Sciences* 2015, **112**:6902-6907.

77. Schmitz C, Lotze-Campen H, Gerten D, Dietrich JP, Bodirsky B, Biewald A, Popp A: **Blue water scarcity and the economic impacts of future agricultural trade and demand**. *Water Resources Research* 2013, **49**:3601-3617.

78. Tester M, Langridge P: **Breeding Technologies to Increase Crop Production in a Changing World**. *Science* 2010, **327**:818-822.

79. Despommier D: *The Vertical Farm: Feeding the World in the 21st Century*: St. Martin's Press; 2010.

80. Bonny SPF, Gardner GE, Pethick DW, Hocquette J-F: **What is artificial meat and what does it mean for the future of the meat industry?** *Journal of Integrative Agriculture* 2015, **14**:255-263.

81. Goddek S, Delaide B, Mankasingh U, Ragnarsdottir K, Jijakli H, Thorarinsdottir R: **Challenges of Sustainable and Commercial Aquaponics**. *Sustainability* 2015, **7**:4199.

82. Eitelberg DA, van Vliet J, Verburg PH: **A review of global potentially available cropland estimates and their consequences for model-based assessments**. *Global Change Biology* 2015, **21**:1236-1248.

83. Young OR, Berkhout F, Gallopin GC, Janssen MA, Ostrom E, van der Leeuw S: **The globalization of socio-ecological systems: An agenda for scientific research**. *Global Environmental Change* 2006, **16**:304-316.

Tables and table captions

Table 1 Summary of studies analysing food supply resource efficiency or productivity changes globally. Focus is on the scenarios, if scenarios not applied, the used measure is given in brackets.

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Alexander et al. [57]	global	country	Current diets from commodity profile, alternative diets for global population set to diet of individual countries (USA and India).	None (*historical global production efficiencies + FAO commodity balance consumer waste*)	None (*historical productivity used*)	Focus on changes in cropland use.
Alexander et al. [30]	global	global	None (*diets from FAO commodity balance used, over-consumption of food quantified as part of food waste*)	Current food loss and waste quantified, including losses and waste in food supply chain as well as over-consumption. No scenario for improvement applied	None (*FAO production used*)	Focus on changes in cropland use.
Alexander et al. [51]	global	global	Alternative diets including imitation meat (e.g. Tofu), cultured meat, alternative animal product scenarios, and insects	Food waste reduction from Alexander et al. [30] used	None (*FAO production used*)	Focus on changes in cropland use.
Bajželj et al. [49]	global	12 macro-regions	Healthy diets, i.e. average consumption of sugar, oil, meat and dairy is limited according to expert health recommendations	50% reduction of food and agricultural waste	Two yield gap scenarios used: Current Trends scenario assumes yields in each region will continue to increase at current rates until year 2050, while Yield Gap scenario assumes that sustainable intensification will achieve the current potentially attainable yields for their agro-ecological zone in all regions	Measures the change in cropland, pasture, forest covers, GHG emissions, fertilizer use as well as irrigation water use
Billen et al. [47]	global	12 macro-regions	An “equitable diet” was generated by finding the most protein rich and highest animal protein content feasible diet for 2050 that could be consumed by global population except for India, which limited to 20% animal products.	None (*current losses used*)	Increased crop fertilisation intensity (nitrogen)	Focus on nitrogen transfers and contamination. Trade modelled and extensively discussed.

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Bodirsky et al. [52]	global	10 macro-regions	Long term future scenarios using regression on i) total calorie demand and income, and ii) animal calorie share and income	None (*current losses in food supply of FAOSTAT*)	None	Focus on future food demand scenarios
Cassidy et al. [33]	global	gridded	Current energy and protein of crops consumed by humans directly rather than as livestock products or as biofuels.	None (*study estimates for food availability are pre-waste*)	None (*current productivity of cropland, excluding grassland*)	Focus on number of people fed per hectare of cropland (directly vs considering livestock and biofuel). Extensive analysis of biofuel.
Clark and Tilman [41]	global	global	None (*comparison of environmental impact of different food products; no assessment of diets per se*)	None (*current productivity*)	None (*comparison of production systems, e.g. organic vs non-organic, rather than yield per se*)	Meta-analysis of life-cycle assessments
Conijn et al. [45]	global	global	50% reduction in the supply shares of animal-based products in the human diet. Study uses a higher consumption of plant-based products to compensate the decreased energy supply due to the reduction of animal-based products.	50% reduction in the fractions of wastes in households and food balance chains for all food items	50% increase in the biomass yields for all crops and grassland, 25% improvement in the feed conversion ratios for all animal products.	Measures change in cropland and pasture areas, N and P losses from agricultural land and reduction of ammonia (NH3) volatilization, as well as effect on planetary boundaries
Erb et al. [54]	global	11 macro-regions & global	Diets converge until 2050, i.e. end result is a "model diet" approach not adjusted to take into account differences in the national diets. Five scenarios: RICH - diet of North America in 2000; BAU – FAO forecast for 2050; MEAT - considerable fraction of livestock meat; VEGETARIAN – diet without meat but with eggs, and milk; and VEGAN – diet without livestock products	None (*current losses and waste considered and kept static for projections*)	Four scenarios: FAO - based on FAO projections; HIGH – in line with the Global Orchestration scenario by the Millennium Ecosystem Assessment; YIELDGAP – yield gap to be closed to an attainable maximum; and ORGANIC – lower yields in industrialized systems and reflects yield losses due to organic farming	Measures the impact on cropland and grazing land. Includes both feasible and unfeasible scenarios. Also cropland expansion as one of the scenarios.
Fader et al. [21]	global	gridded	None (*current diets were calculated by observing resource use, food production and trade patterns. These diets were assumed to be maintained in future*.)	None	Yield gap closure is based on higher harvest indexes, higher homogenization of fields (by i.e. avoiding erosion areas and controlling pests), and a higher maximum leaf area index (by e.g. nutrient supply and adequate tillage).	*Used in this study*

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Foley et al. [27]	global	gridded & global	Crops used for animal feed transferred directly to human food.	Included in the portfolio of measures and current food waste figures discussed, but no detail scenario used.	Bringing yields to within 95% of their potential.	Also considers water savings, reduction in fertilizer use. Although some measures at gridded scale, combined results in global scale.
Godfray et al. [24]	global	global	None (*Included in the portfolio of measures, current situation discussed but scenarios are not quantified*)	None (*Included in the portfolio of measures, current situation discussed but scenarios are not quantified*)	None (*Included in the portfolio of measures, current situation discussed but scenarios are not quantified*)	Qualitative analysis of opportunities
Jalava et al. [29]	global	country	Two main scenarios: i) Recommended diet – WHO recommendations for protein, fat, fruits & vegetables, and sugar, and FAO set average dietary energy requirement; and ii) Cap on animal based protein and meat – four diet scenarios with 50%, 25%, 12.5%, and 0% cap on animal based protein, of which one third can be from meat. Decreased animal protein intake replaced with culturally adapted vegetable foodstuff so that diet recommendations are met.	None	None	Focus on water use efficiency
Jalava et al. [34]	global	country	As in Jalava et al. [29]; see row above	Two scenarios: i) HalfLoss – loss percentages reduced by half in all food supply chain phases; and ii) MinLoss – Smallest loss percentage among regions, of each food group, applied globally	None	*Used in this study.* Focus on water use efficiency. Combined impact measured and analysed
Jägermeyr et al. [56]	global	gridded	None	None	Irrigation improvements and expansion using thus saved water, modelled with mechanistic representation of irrigation transition scenarios	

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Jägermeyr et al. [37]	global	gridded	None	None	Food production potentials related to irrigation improvements and expansion as well as to rainwater management (water harvesting, mulching, conservation tillage), using mechanistic representation of integrated farm water management scenarios (irrigation transition and rainwater management)	*Used in this study*
Jägermeyr et al. [20]	global	gridded	None	None	Food production constraints through maintaining environmental flows can be compensated by improved water management in irrigated and rainfed farming. Uses mechanistic estimates of environmental flows and integrated farm water management	
Kastner et al. [40]	global	17 macro-regions	None (*historical data used, based on processing of FAOSTAT*)	None (*historical data used, based on processing of FAOSTAT*)	None (*historical data used, based on processing of FAOSTAT*)	Historical analysis of the impact of three drivers (i.e. changes in population, agricultural technology, and diet) on food supply and land requirements.
Keating et al. [43]	global	global	Proportional improvement (compared to combined impact of all the measures) estimated by survey of experts	Proportional improvement (compared to combined impact of all the measures) estimated by survey of experts	Proportional improvement (compared to combined impact of all the measures) estimated by survey of experts	Proportional importance of each measure, based on expert opinion. Focus on improvement, not current state
Kummu et al. [35]	global	country	None	Minimum loss scenario: smallest loss percentage among regions, of each food group, applied globally.	None (*current production based on FAOSTAT*)	*Used in this study.* Focus on water use efficiency
Mauser et al. [44]	global	gridded	None	None	Two measures, various scenarios: i) increased cropping intensity, and ii) an economically more efficient spatial allocation of crops	Focus on biomass production. Crop-allocation has implications for trade

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Mueller et al. [36]	global	gridded	None	None	Nutrient and water yield gap closures, by using climate-specific attainable yields to quantify the yield gap. Various yield-gap closure scenarios (50%, 75%, 90% and 100%).	*Used in this study*
Muller et al. [53]	global	global	Share of animal product decreased from 38% to 11%, compensated by increased usage of legumes.	Wastage reduction scenarios assume 25% and 50% less wastage	None (*current yields obtained from FAOSTAT, in future conditions those were assumed to increase everywhere. Yield gap for organic agriculture introduced*)	Concentrates on organic agriculture, and scenarios applied on top of shift to 100% organic agriculture
Odegard and van der Voet [50]	global	global & macro-regional	Four different scenarios, where base diets are FAO futures projections for 2030 or 2050. Eliminates undernutrition and in some scenarios following diet recommendations while in others assuming current western composition. Various scenarios for meat consumption dependent on level of economic development. Includes also vegetarian scenario and halving of meat consumption.	Two scenarios: i) 1995 USA levels, and ii) halving the waste	Varying closure of yield gap, and intensity of management, depending on the scenario. Also improvements in feeding efficiency as well as irrigation efficiency are taken into account.	Focus on alternative future scenarios, quantifying global land use, water use and fertilizer use
Pfister et al. [39]	global	gridded & global	None (*model assumes additional energy demand met by Wheat/corn as a proxy for increased food supply*)	Either halved or no change to current level, depending on scenario.	Yield gap closure by full irrigation. Fertilization is assumed but not modelled. Crop production expansion to pasture in some scenarios.	Focus on water consumption efficiency and land use efficiency (trade-off analysis). Global model that does not account national measures.
Pradhan et al. [31]	global	macro-regional	A number of patterns were observed in global diets using data for 1961-2007. Scenarios for future changes were projected using these. No healthy diet recommendation considered.	None	None	Focus on GHGs – how to intensify agriculture to reduce emissions. Regions defined not by geography, but by diet.

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Pradhan et al. [38]	global	gridded & national	No diet change as a sustainability strategy, a more energy-heavy diet was presented as a future scenario. No healthy diet recommendation.	None	Yield gap quantified from Global Agro-ecological Zones (GAEZv3.0) data. Various agricultural input and management strategies considered, including i) adequate fertilizer application, ii) soil quality management, iii) managing accessibility to markets, vi) weather induced yield variability management, and v) management of pests, diseases, and weeds.	Focus on crop calories produced.
Springer & Duchin [48]	global	10 macro-regions	Sustainable diet scenario: food supply energy demand target is set to 3000 kcal/cap/d, with no more than 20% of the calories from animal products.	None	Yield gap closure in Africa and Latin America: improved crop-water management and the availability of mixed pastoral and industrial livestock technologies.	Scenarios focus on land use and management. Economic model reallocates production instead of assuming current production areas. Trade is modelled using World Trade Model.
Tilman et al. [8]	global	7 economic groups	Future dietary requirements based on projected income levels. Relationship based on regression analysis using historical data.	None	Two measures considered: soil fertility enhancement (statistical model) and technology improvement (trend analysis)	Quantified impacts on land clearing, GHG emissions, and nitrogen fertilization.
Tilman and Clark [46]	global	7 economic groups	Four diet change scenarios: i) 2050 global income-dependent, ii) Mediterranean, iii) pescatarian, and iv) vegetarian.	Three scenarios: i) waste not reduced, ii) waste reduced by 15%, and iii) waste reduced by 30%.	Three scenarios: i) crop yields will continue increasing along the linear trajectory fitted to the past 25 years, and ii) yields increase from 2009 values linearly through the years such that by 2050 they have closed 15% more of the 2009 yield gap between an economic group and the highest-yielding economic group than would have been closed by following their historic yield trends, and iii) same than previous but with 30% closure	Quantified impacts on human health, GHG emissions, cropland area.

Paper	Extent	Unit of analysis	Diet change scenarios (*or diet*)	Food loss and waste scenarios (*or food loss and waste*)	Yield gap closure scenarios (*or yield*)	Notes
Vanham et al. [32]	Europe	national	Two scenarios: i) healthy diet where specific Food-Based Dietary Guidelines were produced for four sub-regions in Europe, and ii) vegetarian diet including fish, where meat is substituted by pulses and soy to meet the Food-Based Dietary Guidelines.	None (*current waste taken into account in calculations*)	None	Macro-regional study of Europe. Very extensive handling of diets through Food-Based Dietary Guidelines.
Wada et al. [42]	global	global	None	None	None (*identification of areas where enhanced agricultural productivity and improved irrigation efficiency would ease water scarcity.*)	Commentary about water stress mitigation strategies. Measures not quantified.
West et al. [55]	global	gridded, national & global	Diet methodology is from Cassidy et al. [33], calculating people fed by using energy/protein directly	Food waste and its reduction quantified in three countries, namely China, India, and the United States.	Increasing yields to 50% of the potential yield in all low-performing areas. Yield gap quantified by using 100 equal-area climate "bins".	Focus on food calorie gain with these measures. Additionally, focus on water savings and reduction in fertilizer use. To estimate combined effect, the impact of individual measures just summed up.

Table 2. Summary of the individual measures and the potential improvement of food production at the global level for two scenarios. Changes in food supply / production at regional or national level are presented in Figs. 2-4. See Methods and Fig. 1 for more detailed description of the measures and method of calculating the multiplicative impact of all measures together.

Measure	Improvement on food supply / production [c]		Description	References
	Moderate level of implementation	**High-level of implementation**		
Diet change	+28% (*reduction of animal protein intake to 25% of total protein intake)*	+36% (*reduction of animal protein intake to 12.5% of total protein intake*)	Recommended diet based on WHO + reduction of animal protein intake, which replaced with vegetable foodstuff based protein	Jalava et al. [29,34]
Reduced food losses	+7% (*25% loss reduction*)	+14% (*50% loss reduction*)	Reduction of food losses over the food supply chain	Jalava et al. [34], method based on Kummu et al. [35]
Yield gap closure a) *nutrient supply and management*	+56% (*both a and b measures of yield gap closure*)	+51% [b]	Improvement of agricultural management for reaching potential yields	*Nutrient supply and management*: Fader et al. [21] (high level of implementation) *Both measures*: Mueller et al. [36] (moderate level of implementation)
b) Integrated farm water management: *Enhanced irrigation efficiency & rainwater management*		+41% [b]	Irrigation upgrade and expansion into neighbouring rainfed cropland using "saved" consumptive losses; rainwater harvesting for supplemental irrigation, reduced soil evaporation	*Enhanced irrigation efficiency & rainwater management*: Jägermeyr et al. [37] (high level of implementation)
TOTAL [a]	**+111%**	**+223%**		

[a] Total potential is calculated with equations that consider the multiplicative nature of the measures and differentiate the impact of specific measures to production (reduced food losses in production, yield gap closure) or national food supply (diet change, reduced food losses at consumption end) (see Methods). Therefore, the individual potentials shown in table do not sum to the total.

[b] Combined potential of the two yield gap closure measures at a high implementation level is 113% (multiplicative effect), see Methods.

[c] Assumptions shown in brackets

Table 3. List and definitions of the variables used in calculations.

Variable	**Definition**
FoodSupply	Increased annual food energy supply (Index value relative to LocalProduction) [kcal/kcal]
DietChange	% increase in food supply from diet change (negative for decreases) (see Table 1)
$FoodLoss_{consumption}$	% increase in food supply from decrease in consumption-side food losses (see Table 1)
$FoodLoss_{production}$	% increase in food supply from decrease in production-side food losses (see Table 1)
YieldGapComb	% increase in food supply from yield gap closure using both improved nutrient supply and management, and integrated farm water management (see Table 1)
YieldGapMgmt	% increase in food supply from yield gap closure using improved nutrient supply and management (see Table 1)
YieldGapWater	% increase in food supply from yield gap closure using integrated farm water management (see Table 1)
LocalProduction	Food energy supply from local production (after food losses) based on FAO statistics (baseline=1) [kcal/kcal].
NetExport	Proportion of LocalProduction that is exported minus imported products based on FAO statistics [kcal/kcal].

Figures and figure captions

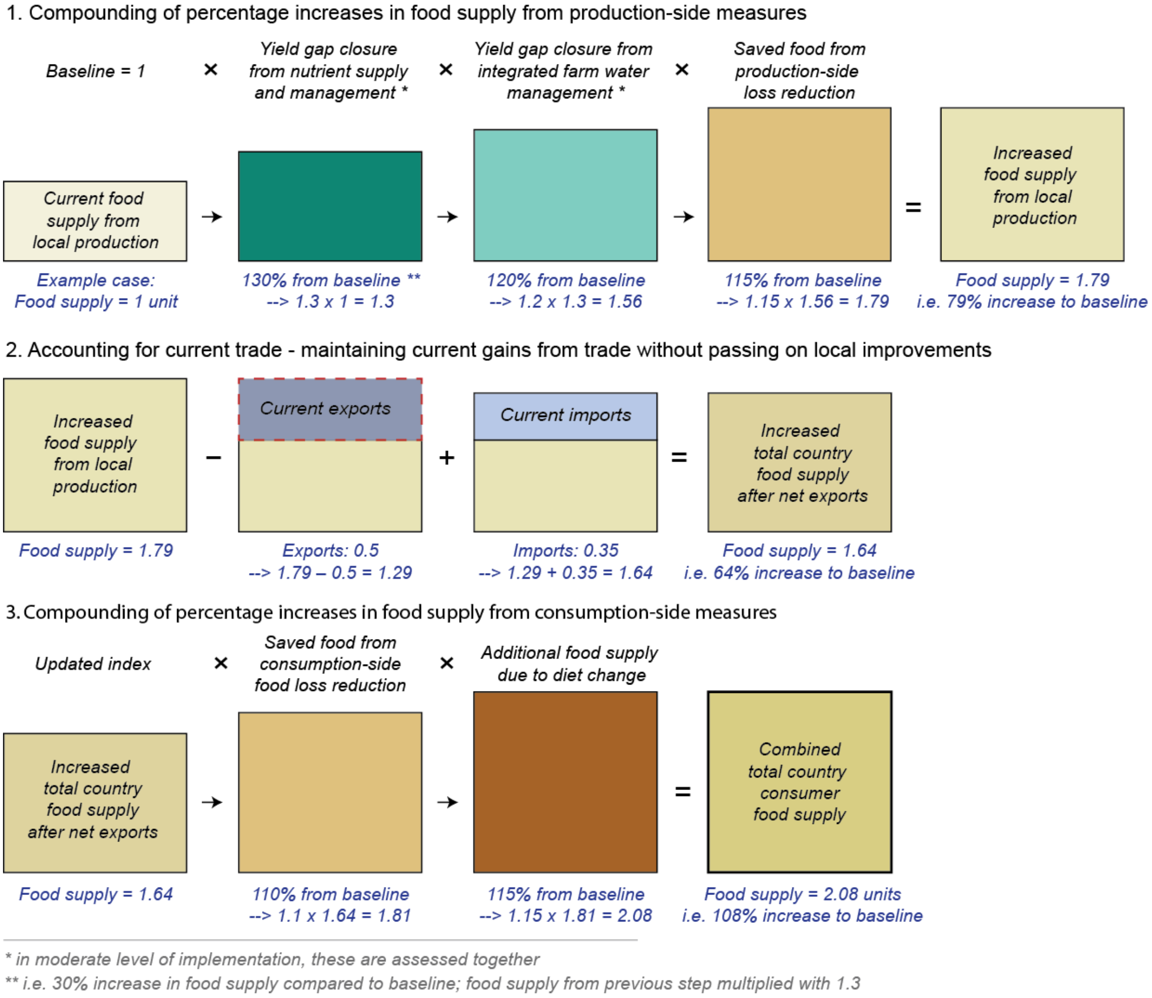

Figure 1. Schematic illustration of the combined measure calculations with an example case of a hypothetical country (see 'Calculations on combined potential' section).

Figure 2. Regional potential to increase food production under two scenarios, divided into individual actions. Regions are divided into four clusters, depending on the relative potential of different actions. A: diet change dominant measure, supported well with yield gap closure; B: balanced between diet change and yield gap closure; and C: dominated by yield gap closure.

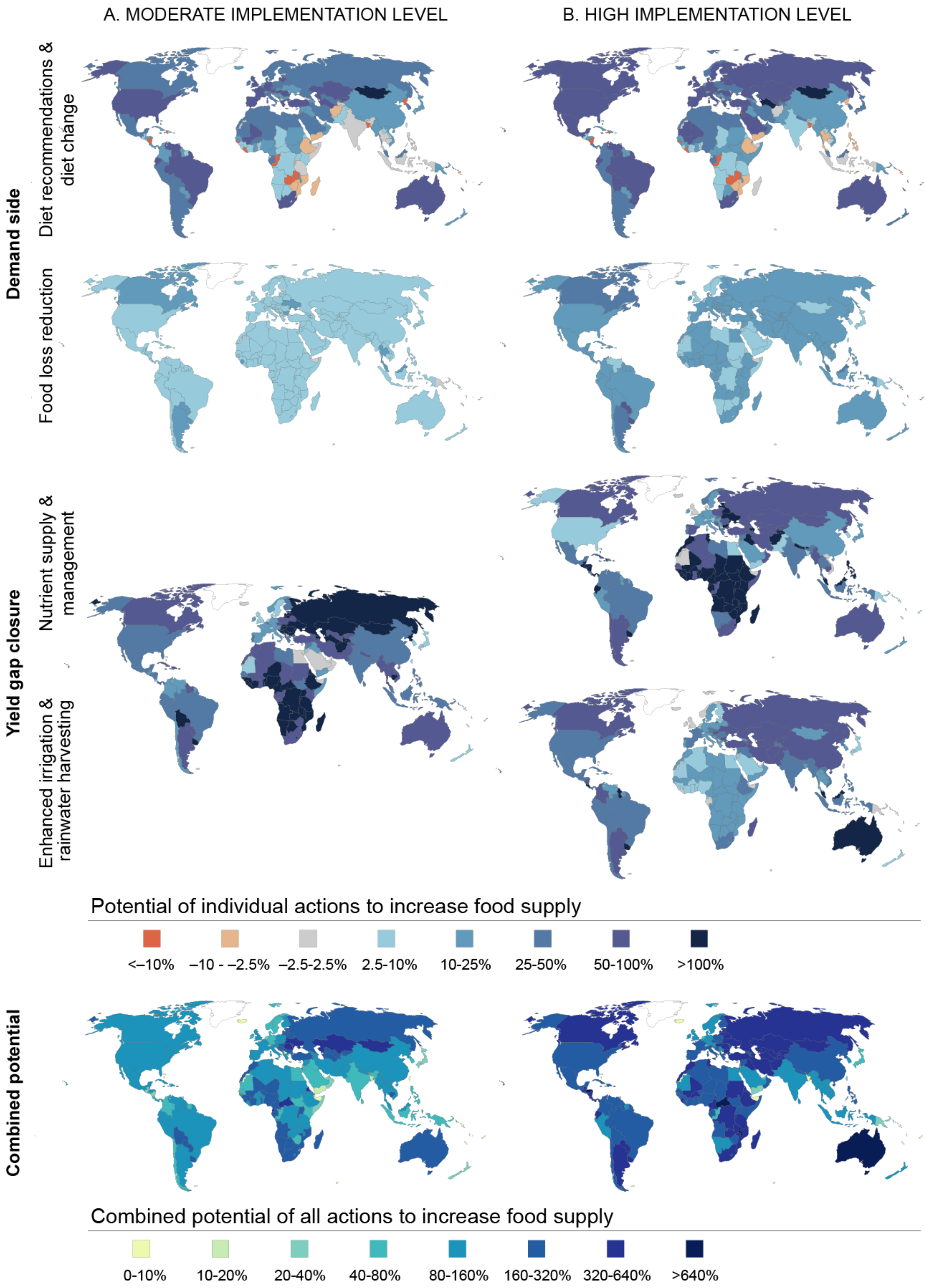

Figure 3. Spatially explicit values for potential to increase food availability with individual measures and combined potential under moderate (A) and high (B) levels of implementation. Note: negative values for some countries in 'Diet recommendations & diet change' are due to the need to increase the food supply in these countries to meet the WHO recommendations[60].

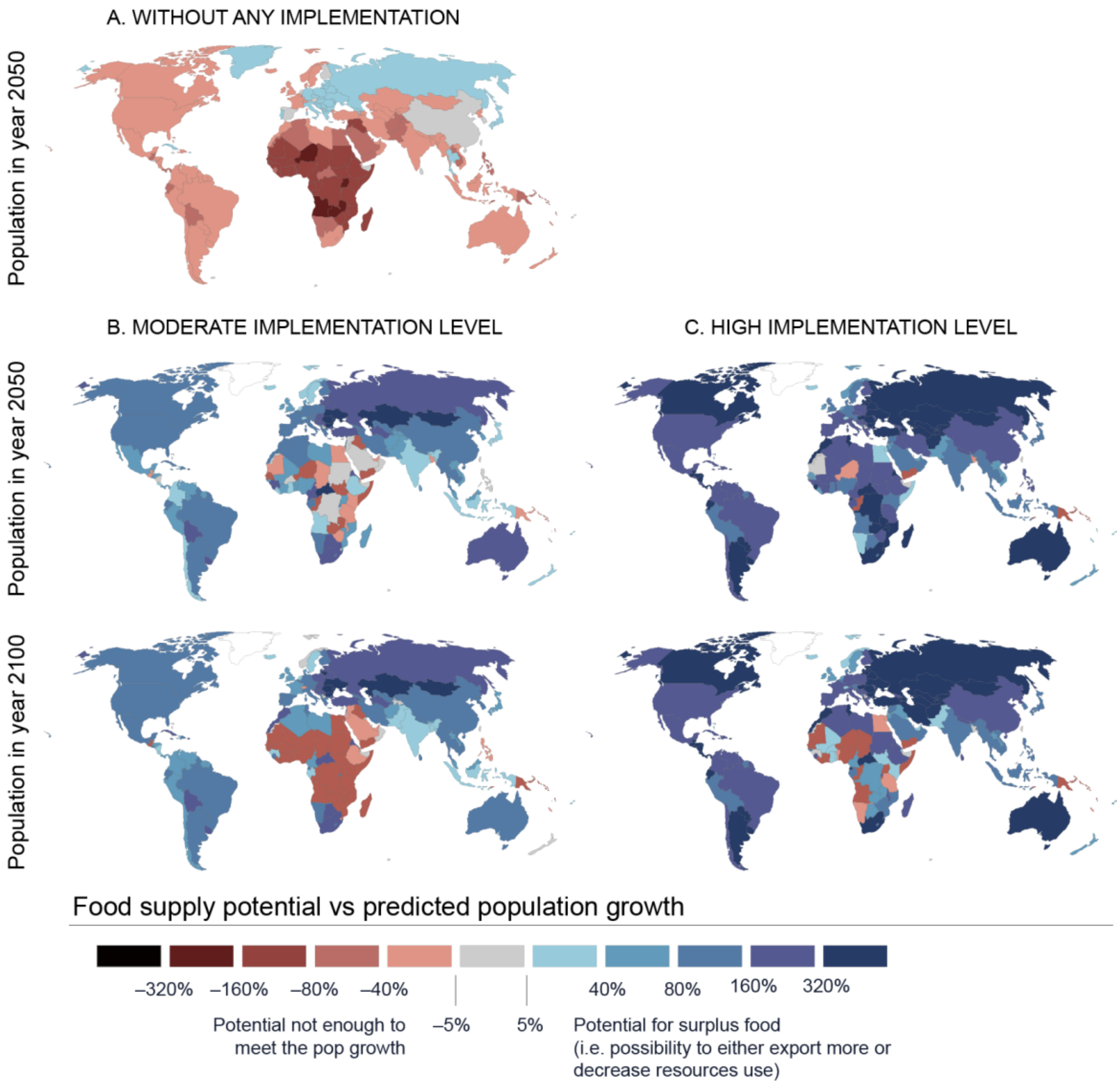

Figure 4. Potential to increase food supply in comparison with predicted population growth in 2050 (two upper rows) and 2100 (lower row) under no implementation (A), moderate implementation level (B), and high implementation level (C). Population growth is based on the medium variant of the population prospects of United Nations[6]. Note: 'No implementation' scenario is based on current diet, while in other scenarios the recommended diet is followed (see methods).

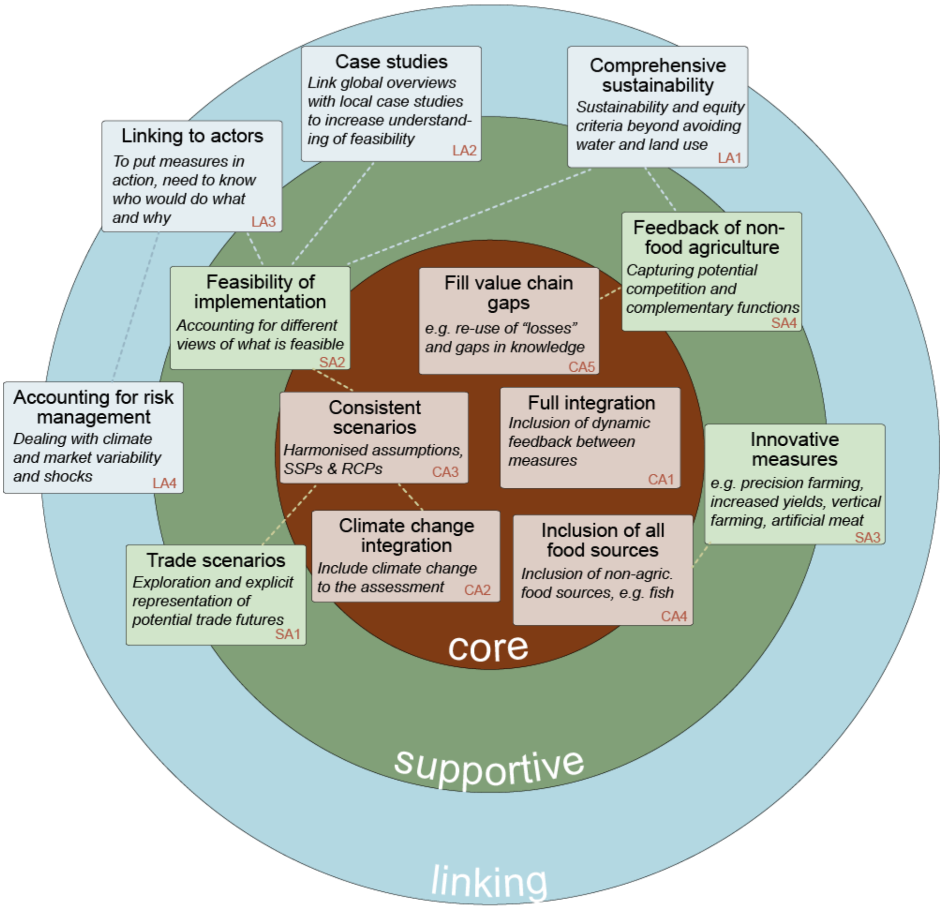

Figure 5. Methodological improvements suggested to obtain a more reliable understanding of the combined potential at country-scale to sustainably secure food supply, divided into three categories: core actions (CA1-CA5), supportive actions (SA1-SA4) and linking actions (LA1-LA4). The main linkages of these actions are shown as dashed lines.