nature
SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41586-018-0594-0
In the format provided by the authors and unedited.

Options for keeping the food system within environmental limits

Marco Springmann[1,2*], Michael Clark[3], Daniel Mason-D'Croz[4,5], Keith Wiebe[4], Benjamin Leon Bodirsky[6], Luis Lassaletta[7], Wim de Vries[8], Sonja J. Vermeulen[9,10], Mario Herrero[5], Kimberly M. Carlson[11], Malin Jonell[12], Max Troell[12,13], Fabrice DeClerck[14,15], Line J. Gordon[12], Rami Zurayk[16], Peter Scarborough[2], Mike Rayner[2], Brent Loken[12,14], Jess Fanzo[17,18], H. Charles J. Godfray[1,19], David Tilman[20,21], Johan Rockström[6,12] & Walter Willett[22]

[1]Oxford Martin Programme on the Future of Food, Oxford Martin School, University of Oxford, Oxford, UK. [2]Centre on Population Approaches for Non-Communicable Disease Prevention, Nuffield Department of Population Health, University of Oxford, Oxford, UK. [3]Natural Resources Science and Management, University of Minnesota, St Paul, MN, USA. [4]Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), Washington, DC, USA. [5]CSIRO Agriculture and Food, Commonwealth Scientific and Industrial Research Organisation, St Lucia, Brisbane, Australia. [6]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [7]CEIGRAM/Agricultural Production, Universidad Politécnica de Madrid, Madrid, Spain. [8]Environmental Systems Analysis Group, Wageningen University, Wageningen, The Netherlands. [9]WWF International, Gland, Switzerland. [10]Hoffmann Centre for Sustainable Resource Economy, Chatham House, London, UK. [11]Department of Natural Resources and Environmental Management, University of Hawai'i at Manoa, Honolulu, HI, USA. [12]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. [13]Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden. [14]EAT, Oslo, Norway. [15]Agricultural Biodiversity and Ecosystem Services, Bioversity International, Rome, Italy. [16]Department of Landscape Design and Ecosystem Management, Faculty of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon. [17]Nitze School of Advanced International Studies (SAIS), Berman Institute of Bioethics, Johns Hopkins University, Baltimore, MD, USA. [18]Department of International Health of the Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA. [19]Department of Zoology, University of Oxford, Oxford, UK. [20]Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, MN, USA. [21]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA. [22]Department of Epidemiology and Department of Nutrition, Harvard T. H. Chan School of Public Health, Boston, MA, USA. *e-mail: marco.springmann@dph.ox.ac.uk

Supplementary Information to

“Options for keeping the food system within environmental limits”

Contents

Food systems model

For our analysis, we constructed a food systems model that connects food consumption and production across regions. The model is based on the database and model equations of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) [1]. The IMPACT model projects food production and demand until 2050 for 62 agricultural commodities and 159 countries. Because we were interested in analysing the environmental impacts associated with specific dietary scenarios, we reformulated the IMPACT model such that food demand is an input parameter and food production is an output. For that purpose, we distinguished several steps along the food chain, starting from trade in processed commodities and animals, feed demand for animals, demand of primary commodities to process oils and refined sugar, trade in primary commodities, and primary production, including non-food uses, e.g. in industry. Below we summarise the main model equations. A full description of the IMPACT-related parameters is provided elsewhere [1].

Starting from final consumption demand ($QD_{c,r}^{cns}$) for commodity *c* in region *r*, we first add demands other than food demand, in particular stock variation, seed demand, and demand for industrial use ($QD_{c,r}^{oth}$), as well as demand for biofuels ($QBF_{c,r}$):

$$QD_{c,r}^{cns+oth} = QD_{c,r}^{cns} + QD_{c,r}^{oth} + QBF_{c,r}$$

Then we calculate the feed demand that supports the consumption of animal-based foods in the specific dietary scenarios. Because feed requirements differ by region, we first estimate where livestock is produced by accounting for trade flows ($QL_{c,r}^{trd} = QL_{c,r} - QL_{c,r}^{imp} + QL_{c,r}^{exp}$). For that purpose, we use import-to-demand fractions ($FI_{c,r} = \frac{QI_{c,r}}{QD_{c,r}^{cns+oth}}$) to calculate the percentage of livestock that is imported ($QL_{c,r}^{imp}$), and balance imports with exports ($QL_{c,r}^{\exp}$) in line with projected imports and exports ($QI_{c,r}$, $QE_{c,r}$) by using the ratio of regional exports to all exports ($FE_{c,r} = \frac{QE_{c,r}}{\sum_r QE_{c,r}}$), a method that implicitly assumes that in each dietary scenarios, current exporters stay exports, and current importers stay importers. Feed demand ($QF_{c,r}$) is then calculated in relation to regional feed requirements ($FR_{c,r}$):

$$QL_{c,r}^{imp} = FI_{c,r} \cdot QL_{c,r}$$

$$QL_{c,r}^{\exp} = FE_{c,r} \cdot \sum_r QL_{c,r}^{imp}$$

$$QF_{c,r} = FR_{c,r} \cdot QL_{c,r}^{trd}$$

Next we calculate the intermediate demand for primary commodities that supports the consumption of processed goods (vegetable oils, oil meals, refined sugar) in the dietary scenarios. For that purpose, we first adjust the mix of intermediate processed commodities for trade ($P_{c,r}^{trd} = QP_{c,r} - QP_{c,r}^{imp} + QP_{c,r}^{exp}$), and then use region-specific processing factors for oils and sugar ($PF_{c,r}$) to calculate the demand for primary commodities (oil crops, sugar crops):

$$QInt_{c,r} = PF_{c,r} \cdot QP_{c,r}^{trd}$$

Finally, we account for trade in those primary commodities that satisfy the demand for processing ($QInt_{c,r}^{trd} = QInt_{c,r} - QInt_{c,r}^{imp} + QInt_{c,r}^{exp}$), in feed that consists of primary commodities ($QF_{c,r}^{trd} = QF_{c,r} - QF_{c,r}^{imp} + QF_{c,r}^{exp}$), and in the primary commodities that are demanded in unprocessed form ($QD_{c,r}^{cns+oth,trd} = QD_{c,r}^{cns+oth} - QD_{c,r}^{cns+oth,imp} + QD_{c,r}^{cns+oth,exp}$). The production of primary commodities is then given by the sum of:

$$QS_{c,r} = QD_{c,r}^{cns+oth,trd} + QF_{c,r}^{trd} + QInt_{c,r}^{trd} - QL_{c,r} - QP_{c,r}$$

An overview of the consumption and production accounts in 2010 and 2050 is provided in Supplementary Table 1.

Nitrogen budget model

In our main analysis, we focus on nitrogen application as our control variable. This focus is in line with the focus of the planetary boundary framework on anthropogenic disruptions of the Earth system. However, as the surplus of reactive nitrogen is often more closely related to regional environmental impacts than nitrogen application rates, we also constructed a country-specific nitrogen budget module and linked it to the food system model.

Following the method outlined by Lassaletta and colleagues [2], we calculated the nitrogen surplus in each region by subtracting nitrogen offtake by crops from nitrogen inputs related to synthetic fertilization, symbiotic nitrogen fixation, manure application, human excretion, and atmospheric deposition. Data on the nitrogen content of crops, symbiotic fixation rates, animal excretion rates and the ratio of applied manure were adapted from Lassaletta and colleagues [2,3], and data on atmospheric deposition were adapted from Lamargue and colleagues [4].

To calculate the boundary value for nitrogen surplus, we followed the same method as described in the Methods sections. We used global risk values for eutrophication derived by De Vries and colleagues [5] and an upper value in line with a scenario that rebalanced nitrogen application between over and under-applying regions [6]. This results in a planetary boundary for nitrogen surplus of (90, 67-146 TgN of nitrogen surplus).

Our results indicate a nitrogen surplus of 134 TgN in 2010, composed of a nitrogen offtake by crops of 73 TgN, synthetic fertilization of 104 TgN, symbiotic nitrogen fixation of 28 TgN, manure application of 24 TgN, nitrogen content in diets that re-enter the environment by excretion of 41 TgN, and atmospheric deposition of 11 TgN. That estimate is comparable to estimates in the literature that used the same budget components and estimated a current nitrogen surplus of 116-138 TgN [2,7,8].

The percentage changes in the counterfactual scenarios for nitrogen surplus are similar to those for nitrogen application. We project increases in nitrogen surplus along the business-as-usual pathway to 2050 of 49% (47-51) compared to 50% (49-51) for nitrogen application. Reducing food loss and waste by 75% results in reductions of 18% in nitrogen surplus compared to 19-24% in nitrogen application; ambitious levels of technological change result in reductions of 31% in nitrogen surplus compared to 32% in nitrogen application; and dietary changes towards more plant-based, flexitarian diets result in reductions of 14-21% in nitrogen surplus compared to 17-22% in nitrogen application. The planetary option space is similar as well (Extended Data Figure 3).

Planetary boundary for phosphorus

(adapted from Wim De Vries, *in prep.*)

Unlike nitrogen (N), phosphorus (P) is adsorbed in the soil and P concentrations in solution are governed by soil P contents/pools. Changes in P pools are thus the cause of changes in P leaching and P runoff to surface water and P losses to surface water are reacting with a large delay time to changes in P input. An input of P above P uptake by crop removal (often denoted as offtake) thus leads first to soil P accumulation. As long as a soil is P deficient, this is profitable as it increases soil fertility and does not lead to environmental problems, as long as a critical soil P concentration, in view of surface water impacts, is not exceeded. Inversely, when the current soil P concentration exceeds a critical value, there is a need for mining the soil P pool to avoid surface water impacts. In long-term critical load calculations, the acceptable P accumulation or needed P mining (from a current P level tot a critical P level) can, however, be neglected, as done by Carpenter and Bennet [10]. The drawback of that model approach is, however, that it (implicitly) assumes that soil erosion is the principal source of P to surface freshwaters. Internal P pathways related to crop uptake followed by animal and human consumption and P inputs to surface water by manure and human waste are thus neglected. This may cause an overestimate of the planetary P boundary and furthermore, the potential for improvements in P use efficiency by P recycling, reducing point source P loads and thereby increasing the P boundary, are not accounted for.

A more appropriate approximation of the P flows is to include P intake by humans and account for a P fraction that is recycled to land, where it can be stored in soil and sediment, and a remaining P fraction that is not recycled to land which can only be stored in sediment. The flow diagram shown in Extended Data Figure 2 illustrates that the external acceptable P input is determined by the long term (thousands of years) acceptable accumulation of P in soil and sediments at a P concentration in surface waters that equals a critical threshold. The P boundary is affected by the fraction of P that is taken up by humans (frP_{uptake} being the P use efficiency, PUE, of the complete food chain, from mined P to P intake or food chain PUE) and the fraction of human excreted P that is not recycled to land ($1- frP_{rec}$), thus becoming a point source for water pollution. This P can only be stored in sediment at a given sediment P retention fraction ($frP_{ret,sed}$), while the recycled P can additionally be stored in soil at a given soil P retention fraction ($frP_{ret,soil}$). The critical P input ($P_{in(crit)}$) can then be calculated as the sum of a critical soil P retention and critical sediment P retention and a critical input to surface water (oceans) due to runoff and leaching according to:

$P_{in,mine(crit)} = P_{in,water(crit)}/(1- frP_{ret,sed})/((1-frP_{ret,soil}) \times (1 - (1-frP_{rec}) \times frP_{uptake}) + frP_{uptake} \times (1-frP_{rec}))$

The critical input to water, $P_{in,water(crit)}$, is determined by the global water flux from land to water, Q, multiplied by a critical P concentration in surface water, $[P]_{crit}$. Using this approach, and applying mean values of 0.25 for frP_{uptake} [11], 0.8 for $frP_{ret,soil}$ [8,12], 0.2 for $frP_{ret,sed}$ [13], 38 x 10^{12} m^3 yr^{-1} for Q and 50-100 mg P m^{-3} for $[P]_{crit}$ [14] leads to a long-term P boundary of approximately 6-12 Tg P yr^{-1} assuming no waste recycling. A higher long-term P boundary of approximately 8-16 Tg P yr^{-1} is derived when assuming 50% waste recycling (current situation).

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