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Feeding ten billion people is possible within four terrestrial planetary boundaries

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Global agriculture puts heavy pressure on planetary boundaries, posing the challenge to achieve future food security without compromising Earth system resilience. Based on process-detailed, spatially explicit representation of four interlinked planetary boundaries (biosphere integrity, land-system change, freshwater use, nitrogen flows) and agricultural systems in an internally consistent model framework, we here show that almost half of current global food production depends on planetary boundary transgressions. Hotspot regions, mainly in Asia, even face simultaneous transgression of multiple underlying local boundaries. If these boundaries were strictly respected, the present food system could provide a balanced diet (2,355 kcal cap^{-1} d^{-1}) for 3.4 bn people only. However, as we also demonstrate, transformation towards more sustainable production and consumption patterns could support 10.2 billion people within the planetary boundaries analysed. Key prerequisites are spatially redistributed cropland, improved water–nutrient management, food waste reduction, and dietary changes.

Adoption of the Sustainable Development Goals (SDGs) by all nations in 2015 is the first ever commitment to a world development path that safeguards the stability of the Earth system as a prerequisite for meeting universal human standards[1]. The long-standing challenge of achieving food security through sustainable agriculture is particularly acute in this context, as world agriculture is a leading cause for the current transgressions of multiple planetary boundaries (PBs) globally and regionally[2–5]. The PB framework is a comprehensive scientific attempt to synoptically define our planet's biogeophysical limits to anthropogenic interference. It suggests bounds to nine interacting processes that together delineate a Holocene-like Earth system state. The Holocene is chosen as reference state as it is the only period known to provide a safe operating space for a world population of several billion people, and according to a precautionary principle, the PBs are set in sufficient distance from processes that may critically undermine Earth system resilience and global sustainability. A challenging question thus is, whether human development goals such as food security can be met while maintaining multiple PBs along with their subglobal manifestations.

Further PB transgressions could jeopardize the chances of providing sufficient food for a world population projected to be wealthier and reach >9 billion by 2050. This conundrum portrays a tradeoff between Earth's biophysical carrying capacity and humankind's rising food demand, calling in response for radical rethinking of food production and consumption patterns[6–9]. Yield gap closures, avoidance of excessive input use, shifts towards less resource-demanding diets, food waste reductions and efficient international trade are crucial options for sustainably increasing food supply[10–15]. For example, enhancing water-use efficiency on irrigated and rainfed farms can triple or quadruple crop yields in low-performing systems, suggesting possible global gains of >20%[16]. Even higher gains appear feasible through globally optimized configurations of the land-use pattern[17]; and cutting food losses by half could generate food for another billion people[18]. Thus, collective large-scale implementation of such options could sustain food for a further growing world population[19]. Yet, achieving this within a safe operating space as defined by PBs requires not only a halt to, but actually a reversal of, existing PB transgressions. Previous studies suggest that such a reconciliation might be possible, yet these were based on aggregate representations of PBs (not accounting for the spatial patterns of limits, transgressions and interactions) or considered only one boundary in isolation[17,20–23].

Here, we systematically quantify to what extent current food production depends on local to global transgressions of the PBs for biosphere integrity, land-system change, freshwater use and nitrogen (N) flows, along with the potential of a range of solutions to avoid these transgressions and still increase food supply (Table 1). To this end, we configured an internally consistent process-based model of the terrestrial biosphere including agriculture (LPJmL) with multiple spatially distributed PBs and their interactions. LPJmL is among the longest established and best evaluated biosphere models, showing robust performance regarding simulation of e.g. carbon, water and crop yield dynamics (Supplementary Figs. 1, 2; Supplementary Table 1; see ref.[24] for a comprehensive benchmarking and Supplementary Methods for more detail on model evaluations). In principle following established definitions[4], we refine the computation of some PBs with respect to their regional patterns and interactions (Methods), providing globally gridded precautionary limits to human interference with the Earth system at a level of great detail. In particular, we account for the evidence that many PBs need to be represented spatially explicitly[4], to cover their interactions not only at an aggregate global scale but also at smaller (here, 0.5° grid cell) scales where concrete circumstances matter. This may imply, e.g., that a PB's status is critical in some areas even though its global status is considered safe, or that areas considered safe regarding one PB are critical regarding other PBs. Hence, the PB definitions applied here entail that multiple environmental limits be respected in any location, yet also indicate where there is still room for exploitation.

While accounting for carbon dynamics of land-system change in our modelling, we do not fully integrate the PB for climate change, as emissions from the fossil fuel sector are the primary determinant of its status. Effects of land-based measures to avoid further transgression of this PB (e.g. bioenergy plantations, afforestation) are also not explicitly addressed and have been studied elsewhere[25]; hence, we implicitly assume that climate change is mitigated primarily through decarbonisation and the reductions in land-use change emissions simulated here (Supplementary Methods). Thus, we do not account for possible future climate change impacts (but see Supplementary Methods for an analysis of such effects on results presented here).

Specifically, we first constrain kcal production by respecting the four PBs in focus and their corresponding local boundaries (Methods), thereby illustrating the extent to which current agriculture depends on transgression of either of them in any location. Second, we quantify how far global adoption of more sustainable agricultural systems – namely redistribution of agricultural land and optimized water and nutrient management – can increase food production in a manner respecting PBs. Additionally, we quantify potentials of lowered food losses and less resource-demanding consumption, based on a further model that represents such interventions in a spatially explicit way as well (see Supplementary Methods).

Our scenarios assume ambitious practices as elaborated in previous studies, aimed at estimating biophysically feasible potentials under the condition that the different PBs be respected (Table 1). Thus, we do not scale up the food system and its environmental impacts in response to prescribed demand patterns or other transient environmental–societal developments, but design new scenarios mapping a world in which the PBs are respected and currently available options to sustainably increase food supply is implemented. Such an approach is required as PBs are not represented in present-generation Integrated Assessment Models. Third, based on this food supply potential, we estimate the population size that Earth could sustain within the considered PBs assuming an egalitarian basic need of 2,355 kcal cap^{-1} d^{-1} (intake after accounting for food losses and waste) according to the Average Dietary Energy Requirement, ADER (FAOSTAT data, www.fao.org/economic/ess/ess-fs/ess-fadata). This is representative of the amount of dietary energy (including sufficient protein content) needed to ensure that, if properly distributed, hunger would be eliminated. For comparison, results are also evaluated against other supply benchmarks. Calculations are performed on a

0.5° global grid, while results are mainly shown for Food Producing Units (FPUs), i.e. hydropolitical units within which even distribution of food is assumed; hence, trade flows are not modelled.

Results

According to our analysis, redirecting global food production and consumption onto more sustainable pathways could not only overcome the current PB transgressions but also increase ADER food supply to a level sufficient for 10.2 billion people (Fig. 1).

Planetary boundary constraints on food production

If PBs were maintained *ceteris paribus*, i.e. without concurrent transition towards more sustainable production and consumption, present agricultural practices could sustain only 3.4 billion people. In this situation of far-reaching tradeoff between environmental protection and food security, total global food supply would be as low as $2.95 * 10^{15}$ kcal (net supply to households without consumption waste, compatible with the dietary energy requirement targets that define actual food intake). This is substantially below the simulated $5.74 * 10^{15}$ kcal net supply under actual (2005) land-use and management practices (Table 2).

Correspondingly, as much as 48.6% of food is currently grown under conditions that violate PBs (Table 2; Figs. 2, 3d; Supplementary Fig. 3a). This cumulative effect is composed of individual boundary transgressions (see Fig. 3 and freed areas in Extended Data Fig. 1 / Supplementary Fig. 4): Maintaining the PB for biosphere integrity – i.e. cropland abandonment in biodiversity and protection hotspots (Table 1, Fig. 2a) – would involve a reduction in global kcal production by 12.4% (Table 2). A further 6.9% reduction would occur if the PB for land-system change were to be maintained on top of this constraint, i.e. if cropland were abandoned to permit forest regrowth especially in tropical regions (Fig. 2b). Restricting local freshwater withdrawals to ensure rivers' environmental flow requirements (EFRs) would result in an additional 4.2% global reduction. This latter contribution is comparatively small since only part of present cropland is irrigated, but critical in irrigation hotspots like northern India and parts of the Near and Middle East (Extended Data Fig. 1b / Supplementary Fig. 4b, Supplementary Fig. 5c). Finally, respecting the PB for N flows would lower global kcal production by another 25.1%, as the heavy fertilizer use especially in India, China, Europe and the eastern US would be reduced. Note that while these individual contributions are additive, the isolated effects of each PB restriction – i.e. excluding interference with restrictions imposed by the respective other PBs – would be somewhat larger (Table 2, Supplementary Fig. 5).

Overall, reductions would affect the majority of FPUs (Fig. 3d), as one or more PBs are transgressed in many regions (Fig. 2, Extended Data Fig. 2 / Supplementary Fig. 6). Especially in main producer regions with intensified agricultural systems, i.e. in large parts of central and Southeast Asia, Europe and the Americas, more than half (regionally even >70%) of kcal production depends on such transgressions. This widespread impact results from the spatially rather distinct transgression patterns of the individual PBs adding up (Fig. 3a–d). The eastern US and Europe, for example, are affected primarily by excessive N use; the tropics are dominated by loss of biosphere integrity and land-system change; and many subtropical regions feature freshwater extractions in excess of EFRs. Countries such as India, Iran or Peru even face strong transgressions of three PBs simultaneously (Extended Data Fig. 2 / Supplementary Fig. 6).

Opportunities within the safe operating space

Our further simulations suggest that the global ~49% 'loss' of food production due to PB constraints can be re-established through transitions to more sustainable food production systems and demand patterns – eventually leading to a global net increase of ~53% above the current level (Fig. 3e–h, Table 2). Specifically, reallocation of cropland and its irrigated and N-fertilized fractions within the diverse PB constraints could compensate for more than half of the losses incurred, as such measures would increase kcal production by 29.3 percentage points (Table 2, Fig. 3e). This potential results from agricultural land expansion as far as allowed within the PBs for biosphere integrity and land-system change; from irrigation expansion into rainfed cropland within the freshwater PB; and from increased fertilizer use on areas where allowed within the nitrogen PB (see Extended Data Fig. 1 / Supplementary Fig. 4 for spatial patterns). These efforts – in combination with the above-discussed measures to restore the safe space (*cf.* Fig. 3d) – would result in a global net decrease of agricultural area by 16% (from currently 4,267 Mha to 3,605 Mha), of irrigation water use by 7% (from 2,498 to 2,333 km^3 yr^{-1}), and of organic and inorganic N fertilization by 38% (from 148 to 92 Mt N yr^{-1}), respectively. We stress that this scenario implies widespread changes of cropping areas and practices, e.g. abandonment of crop cultivation and irrigation in parts of Asia; irrigation expansion in Sub-Saharan Africa (SSA), the eastern US, Argentina and Central/East Europe; and restricted fertilizer use e.g. in eastern China, India and Central Europe as opposed to increased fertilization in SSA and the western US (Extended Data Fig. 1 / Supplementary Fig. 4).

An additional, even larger (35.4%) increase in kcal production appears practicable if sustainable water and nutrient management – upgraded irrigation systems, water harvesting, partially alleviated soil evaporation, restoration of degraded land, increased N use efficiency

(Table 1) – was realized on all (newly distributed) agricultural land (Fig. 3f). These measures combined with the gains attainable through the spatial reallocations would lift global net food supply to 6.67 $*10^{15}$ kcal yr^{-1}, which is 16% above the 2005 level (Table 2). Production declines simulated at this step for a few areas can be explained by process interactions such as higher irrigation water use in upstream areas lowering water availability and thus yields in downstream areas.

Finally, further substantial increases in kcal supply are simulated to be possible due to food system improvements, i.e. through reducing both food losses (16.8%) and livestock contributions to diets (19.9%) (Table 2). Concurrently, with all measures combined, a global net carbon sequestration of 75 GtC compared to current agricultural patterns and practices is achievable (see Methods, and Supplementary Fig. 7 for spatial patterns). This translates to a reduction of atmospheric CO_2 concentration by 35 ppm, offsetting the historical contribution of land-use change to transgressing the climate change PB. Besides, non-CO_2 greenhouse gas emissions are also strongly reduced (Supplementary Discussion).

Exploiting this full opportunity space would lift kcal supply above present levels especially in semiarid regions in SSA and Central Asia but also in many other areas across continents (Fig. 3h). Globally it would enable a net gain in food supply of 52.9% above the year 2005 level (reaching 8.78 $*10^{15}$ kcal yr^{-1}; Table 2), sufficient to provide 10.2 billion people with ADER. This would be enough vis-à-vis most medium Shared Socio-economic Pathway (SSP) peak population predictions, but fail to support larger world populations such as in SSP3 (Fig. 1b). Importantly, in some regions – e.g. the Middle East, the Indus Basin, Indonesia, parts of Europe – production declines implied by restoring the safe space cannot be compensated even if all considered technological and socio-cultural transformations were in place (Fig. 3h). This suggests that many regions will not reach self-sufficiency under any population scenario even in our ambitious intensification scenarios (Supplementary Fig. 8). Thus, for ensuring the suggested diet for all their inhabitants, they would remain dependent on international trade or on future innovations not quantified here (discussed below).

The estimated number of people who could be fed according to our end-scenario somewhat varies if another reference diet or another diet composition were preferred (Fig. 4). Applying continental averages of ADER (between ~2,200 kcal cap^{-1} d^{-1} in Africa and ~2,500 kcal cap^{-1} d^{-1} in North America and Europe) demonstrates a range of 9.6–10.9 bn people fed. Alternatively, ~13 bn (12.3–13.7 bn) people could be supported with the Minimum Dietary Energy Requirement of 1,846 (1,759–1,948) kcal cap^{-1} d^{-1}, but this low supply would be inadequate as it merely avoids undernourishment. Moreover, if e.g. the livestock sector was intensified towards western European conditions (Supplementary Discussion), the number of people supplied with ADER would increase to 10.7 (10.1–11.5) bn. This effect is moderate due to simulated complex interactions: more energy-efficient industrial livestock feeding may reduce total feed demand but also induce a relative shift from pasture grazing and crop residues toward concentrate feed, but the inputs required for the cultivation of such protein-rich feed on cropland are constrained by the N boundary.

Implications and caveats of findings

This study suggests that transitions toward more sustainable food production and consumption would enable food supply for ~10 billion people (or somewhat more or less depending on target diet and ambition level of solutions) without compromising multiple PBs as is currently the case. This positive prospect is remarkable in light of the fact that our analysis follows a rather strict precautionary approach assuming that subglobal boundaries be respected everywhere, in contrast to former studies suggesting that (global) boundary transgressions appear to be unavoidable in the future[22,25]. Complementary to a recent assessment based on a different methodological approach[22,23], our geographically explicit representation of constraints and development opportunities enables identification of regions where agriculture undermines natural capital and environmental processes by transgressing multiple PBs simultaneously (Fig. 3, Extended Data Fig. 2 / Supplementary Fig. 6); and where there are leverage points to revert these transgressions by employing specific technological or socio-cultural measures (such as appears possible by combining crop management improvements and dietary changes in many Asian countries; Fig. 3). The analysis thus may help identifying hotspot regions and crucial mechanisms suited to link multiple development targets across regions and globally. The here adopted grid cell scale of PB evaluation allows for capturing much of local to regional dynamics, but eventually a PB should be translated to, and complement, context and policies at local administrative scales. In general, systematic uncertainty analysis comparing datasets at different spatial resolution (especially on forest and cropland distribution), different models and estimation methods (e.g. regarding EFRs and biodiversity metrics) is required to more robustly define the PBs, assess their status and understand their interactions.

While we assess sustainable food supply options within the global limits set by four PBs directly relevant for agriculture, our supposition that the climate change PB can be concurrently maintained requires corroboration by more comprehensive assessments. This is particularly relevant since carbon sequestration to achieve ‘negative emissions’ through e.g. dedicated biomass plantations may exert substantial additional pressure on PBs[21,25], likely reducing the opportunity space suggested here. Likewise, a failure of the Paris Agreement – producing adverse climate change impacts on e.g. crop production, water availability or ecosystems – may compromise the here found possible reconciliation of global agriculture and PB maintenance. Furthermore, the PB for phosphorus flows (not studied here) may constrain food production to a similar extent than does the PB for N flows[26]; whether this could be compensated by respective opportunities remains to be studied. Such aspects require a yet more integrative analysis of spatially distributed biophysical PB constraints and food systems, e.g. by integrating such work as in ref.[22] with our Earth system modelling framework.

We emphasize the particular challenge that here quantified opportunities would require simultaneous implementation in order to achieve their full synergistic potential (*cf.* Table 2, Fig. 1), implying major transformations across sectors. That is, the number of people who could be fed within PBs depends on the extent to which these transformations can actually be realized *vis-à-vis* local socioeconomic circumstances[19,22]. This will require further in-depth analyses including exploration of feasible local to global pathways, e.g. by representing PBs in Integrated Assessment Models, which is currently not the case. For example, sustainable agricultural intensifications require investments supporting both ecosystem integrity and human well-being[27]; and achieving here simulated biophysical potentials of improved on-farm water use and irrigation expansion necessitates culturally appropriate and economically feasible local water technologies[5]. Similarly, the suggested large-scale shifts in land-use patterns require alignment with the livelihoods of rural populations (possibly including migrations), avoiding governmental–institutional, legal and financial obstacles[28]. Finally, even if enough food was produced sustainably at global level, improved access to food as well as fair food redistribution and trade will be of utmost importance – especially for regions that are not self-sufficient and where strong population growth is anticipated, such as in the Middle East and various African countries[29].

Theoretically, however, food supply could be increased to support even more people than suggested here, should further, hitherto unknown or underexplored potentials be unlocked in the future – such as novel technologies in agriculture, breeding, agroforestry, optimized water re-use in irrigation and desalination technologies. However, the potential of such modernizations may be limited due to both their possibly high resource and energy demand and socio-cultural barriers, requiring further analysis in more varied scenarios and in the context of other demanding sustainability goals[30]. Evidently, their prospect can be optimized if substantial sources of (protein-rich) nutrition become available that do not depend on precious land. Among other options such as usage of insect-based food or synthetic meat, the many novel forms of aquaculture might well contribute to food security. To prevent increased pressure on land and freshwater from related feed requirements, aquaculture (and also marine fisheries) strongly require sustainable management and good governance to help respect all nine PBs including those for the marine environment[31,32]. In any event, our analysis of both the food-related Earth system risks that humankind faces and the transformative opportunities it has puts out a major 21st century challenge: to master the tradeoff between Earth system resilience and food security through concerted implementation of sustainable strategies.

Methods

This section summarizes how the PBs considered in the main analysis and the opportunities for increasing food supply were modelled. The Supplementary Methods provide further information on the climate change PB, the diet and population scenarios, and the model used.

Definition and current status of planetary boundaries

This analysis explicitly considers four PBs, whose status is strongly influenced by global agriculture: biosphere integrity, land-system change, freshwater use, and biogeochemical flows (only nitrogen, N) (Table 1). As for their definition and calculation we basically follow the latest proposal[4] considering subglobal boundaries, positioned at the lower end of an uncertainty zone. As the PBs have been set according to a precautionary principle – in safe distance from potentially detrimental developments – based on current scientific knowledge, we here do not explore alternative definitions. However, to ensure consistency in the joint simulation of all PBs, to account for latest datasets, and to improve various aspects of the subglobal patterns, we made some modifications, thereby contributing to the ongoing process of improving PB definitions and quantifications. Subglobal boundaries are represented at 0.5° resolution (land-system change: continent-biome scale), pending availability of more detailed datasets with global coverage and conclusive knowledge about the best spatial scale to evaluate PBs at.

The status of the PB for biosphere integrity is taken from a global gridded dataset (here linearly aggregated from 1 km to 0.5° resolution) of the Biodiversity Intactness Index BII as a proxy for functional diversity[33]. It represents the average proportion of natural biodiversity (across a broad range of species) remaining in local ecosystems, expressed as the current abundance relative to that in undisturbed habitats. Novel species in agricultural landscapes are not considered, as they "biotically compromise" the system. The boundary is set at a precautionary level of 90%, i.e. a maximum 10% reduction in BII (due e.g. to anthropogenic land conversion) is tolerated in each grid cell. It is already beyond its boundary (<90%) in most biomes including biodiversity hotspots and wilderness areas, but still within it in high latitudes and parts of the tropics (Fig. 2a).

The PB for land-system change is determined to ensure that at least 50% of temperate forest biomes and 85% of boreal and tropical forest biomes be maintained[4]. The status of this PB – separately for each forest biome and continent – was derived by comparing contiguous areas potentially covered with natural forest with the current cropland and pasture distribution. The underlying areas were derived from simulations with the bio- and agrosphere model LPJmL used throughout this study (see Supplementary Methods). An equilibrium simulation of potential natural vegetation (based on current climate) was made to determine whether a grid cell belongs to any of the three forest biomes (which we assume if >60% of the cell is covered by either forest; savannahs not included – classification details in ref.[34], which also shows that the vegetation distribution is reproduced well). The current status of each continent-biome is then given as the sum of the remaining forest cover in cells belonging to that biome, i.e. after subtraction of the fractional coverages with cropland and pastures (from ref.[35] for year 2005; Supplementary Methods). Accordingly, the strength of transgression somewhat differs from that portrayed before[4], mirroring uncertainty in knowledge about the size of pristine forest area, current global agricultural area and remaining forest area, respectively. In our analysis, transgressions prevail in much of the tropics and the Eurasian boreal forest (Fig. 2b). This puts a stronger constraint on the Amazon compared to ref.[4] where this region was classified as safe, but the classification of the other continent-biomes as either safe or at risk is the same in the two approaches.

The PB for human freshwater use was calculated based on the amount of water needed to maintain riverine ecosystems in at least a fair status, i.e. the environmental flow requirements (EFRs), here calculated at grid cell level with the Variable Monthly Flow method[36]. Accordingly, in low-flow months (when long-term mean monthly streamflow MMF is ≤40% the long-term mean annual flow MAF), 60% of MMF are allocated to EFRs; in high-flow months (MMF >80% of MAF) the EFR share is 30% of MMF; else it is 45%. The EFR shares are varied by ±15% to represent an uncertainty zone for EFR estimation, with the lowest values representing the boundary for each cell (Table 1). The EFR targets are estimated as monthly averages for 1951–1980 under potential natural vegetation. Transgressions thus result from human water withdrawals (irrigation from LPJmL also considering reservoir storages[38]; domestic, manufacturing, thermoelectric and livestock water use from ref.[37]) including indirect effects from land use changes. Such transgressions are presently severe and widespread especially in the western US, the Mediterranean and MENA regions, Central and South Asia, and the North China Plains (Fig. 2c, where the uncertainty zone represents areas with an EFR transgression-to-uncertainty ratio between 5 and 75%, averaged over months with a transgression). EFR computation is omitted in cells where MAF is <1 $m^3 s^{-1}$.

The PB for nitrogen flows, also regionally distributed, limits leached N concentrations in surface waters to 1 mg N l^{-1} (upper end of uncertainty zone: 3 mg N l^{-1}) for preventing aquatic ecosystems from eutrophication[39]. In a post-processing analysis – as N flows are not explicitly modelled in LPJmL – we compute cell-specific N leaching based on N losses from soils and an N leaching and runoff fraction (as a function of precipitation and potential evapotranspiration)[40]. Subsequently we assume that 71% of the N in leaching and runoff reaches surface waters[41]. To ensure critical N concentrations in tributary rivers are captured, N concentrations are determined as N leached to surface water divided by the runoff in each cell. Runoff is computed by LPJmL dependent on the soil moisture status in different layers, also influenced by irrigation[24]. N losses from pastures and natural vegetation are calculated as the sum of atmospheric N deposition (NO_x, NH_x)[42] and biological N fixation, assuming a steady-state equilibrium between inputs and losses. Biological N fixation in natural ecosystems is calculated by linearly scaling global estimates of 58 Mt N per annum[43] with evapotranspiration under potential natural vegetation per grid cell[44]. The thus derived ratio between N fixation and evapotranspiration is also applied to determine biological N fixation on pastures. The N losses on cropland are calculated as the difference between N inputs and N yields. Modelled crop carbon yields are transformed into N yields using crop-specific C:N ratios[45,46] (see Supplementary Discussion for a sensitivity test), and N inputs are linearly downscaled to cells based on the ratio of total national N input and N yield, respectively[47]. This implies that high-N crops are favoured, but poor availability and quality of crop-specific fertilization data limits a more detailed representation.

Currently, N concentrations exceed the boundary's uncertainty zone in large parts of Asia, Europe and the US, as well as in parts of South America (Fig. 2d). Dearth of data does not permit spatially detailed validation of globally calculated N flows and concentration in rivers, yet comparison with independent large-scale estimates demonstrates overall good agreement (Supplementary Fig. 1d, Supplementary Table 1). N harvest tends to be underestimated e.g. because different land-use datasets are used (with our dataset exhibiting a smaller cropland or pasture area in some large countries) and multi-cropping systems or forage crops are not explicitly simulated. While representing more process details compared to previous approaches, the here used new method to determine a PB for N flows requires further improvement, e.g. regarding more detailed modelling of N leaching as influenced by soil depletion, crop residues removal or forest fires.

Respecting planetary boundaries

For regions where any subglobal PB is currently transgressed, we enforce a situation where that transgression is reverted, i.e. we simulate relieved pressure on the respective PBs with the goal to respect all regionalized PBs simultaneously (see Table 1).

Regarding the PB for biosphere integrity, we assume abandonment of agricultural land – and regrowth of natural vegetation – on protected areas[48] and in cells where >5% of present species are threatened (based on the ratio of threatened amphibians, birds and mammals to their respective species richness[49]), see Fig. 2a. This procedure acknowledges that areas with a BII<90% cannot all be restored, but that at least the pressure on biodiversity-rich regions is relaxed.

Regarding the PB for land-system change, we determine a reforestation target for each FPU situated in a biome that currently shows a transgression of its respective boundary. This target is defined as the FPU's fractional share of the total deforestation that has occurred in the biome it belongs to, multiplied with the reforestation needed to move the entire biome back into the safe space. We prioritize cells for (always complete) reforestation where other PBs are transgressed or where adjacent cells are forested, avoiding patchiness. Crop types and pasture on deforested areas are assumed to be reforested in proportion to their share of a cell until the respective FPU target is reached. To minimise fragmentation, this procedure starts in cells whose eight neighbouring cells have the highest fractional forest share and then continues iteratively for the cells with the next-highest share.

Regarding the PB for freshwater use, tapped EFR volumes are considered no longer available for human use; i.e., in each cell agricultural, industrial and domestic withdrawal is restricted as long as it would rely on EFRs[5]. In this calculation, industrial and domestic withdrawals are always prioritized over irrigation withdrawals (yet also reduced proportionally in case of EFR transgression).

In order to respect the PB for N flows, we assumed that the N input is reduced in cells where the critical concentration in surface waters is exceeded. Since fertilization impacts on yields are not captured by LPJmL, we used a parameter (Y_{max}) driven yield (Y) and N fertilization (F) relationship (units in N equivalents; N fertilization incl. inorganic and organic inputs): $Y = Y_{max} * F / (Y_{max} + F)$[47,50]. The function takes into account that increasing Y under given climate and management requires an over-proportional increase in F. Y_{max} was calibrated per cell with the current state, assuming an equal N use efficiency (NUE) within a country. The critical N input in line with the PB is calculated from the critical N leaching losses to surface water and the calibrated yield–fertilizer relationships. Reduced yields are calculated for the reduced N input via this relationship, with preindustrial N deposition as minimum N input per cell.

These restorations of the safe space are modelled in the described sequence, considering dynamic interactions among each other. For example, the reversal of EFR transgression is modelled using the land-use map newly generated from the two preceding steps. However, as the N flows are not fully coupled into LPJmL, we cannot consider that a fertilized plant may require more water to grow, while we do consider increasing N demand from yield increases due to irrigation.

Opportunities within the safe space

Departing from the (theoretical) situation that all PBs are respected *ceteris paribus*, we assess a variety of opportunities to revert the production losses from respecting the PBs and to increase food supply sustainably without leaving the safe space (Table 1). First, we assume that agricultural areas can still be expanded (keeping the relative proportions of crop types and pastures constant) where the PBs for biosphere integrity and land-system change permit, where the PB for N flows permits additional leaching losses to surface waters, and where the PB for freshwater use allows expansion of irrigated land. Per FPU, the expanded areas are re-cultivated proportionally to the production declines resulting from the various PB constraints; if further land use expansion potentials remain, additional cropland is allocated. Second, we explore the potentials of system (management) improvements on the – thus partly newly distributed – agricultural areas. Third, we explore the potentials of changes in consumption behaviour, i.e. diet changes and food loss reductions.

<u>Expansion within the safe operating space:</u> Regarding the first step, agricultural land expansion is allowed to take place outside the above-specified protected and threatened areas and where BII>90% – up to the extent that continental forest biomes are preserved as required by the PB for land-system change (Figs. 2b, 4a). We also preclude severely degraded soils (category 4 *cf.* ref.[51]), wetlands[52] and marginal lands from conversion. The latter are defined where at least half of the crop types and pasture coexisting in a cell would achieve potential rainfed or irrigated yields (calculated in an extra simulation) below the 0.2 quantile of the potential yield across all cells where the respective crop types grow. In cells with existing cropland, the criterion of marginal land is not applied.

Irrigated farmland is expanded in proportion to additionally available freshwater while respecting EFRs, first in cells with existing irrigation, then also in cells with only rainfed cropland if actual production there is <50% of potential production without water constraints (determined from an extra simulation). Irrigation expansion is applied proportionally to a cell's irrigation system and crop types under irrigation. If expanded into cells with purely rainfed cropland, we calculate the fraction of the existing crop mix that can be irrigated with the water volume available after accounting for EFRs. No irrigation is assumed north of 60°N and where MAF <1 m^3 s^{-1}. Withdrawals can affect discharge in downstream locations as cells are linked through river routing. Renewable groundwater is included in our simulations (baseflow entering discharge with some delay) and thus can be extracted, but due to lack of respective spatial datasets no water is allowed to be withdrawn from fossil groundwater; also long-distance water diversions are not considered. These omissions may lead to an underestimation of current water availability and use in some regions such as northern India and the western US and thus an overestimation of the pressure on river flows and EFRs; but it is a meaningful restriction for our opportunity scenarios as fossil groundwater extraction and water diversions can be considered unsustainable. Still, our estimates of irrigation water use are broadly in line with other reports (Supplementary Table 1).

In cells where the critical N concentration in surface water is currently not reached, we allow fertilization to increase up to that point, with associated yield increases calculated using the calibrated yield–fertilizer relationships. For cells where agricultural area was expanded as allowed by the land-use and biosphere integrity PBs, we assume a linear increase in N inputs. N inputs to cells without current agricultural land are interpolated from grid cells with similar yields in the respective country.

Generally, in FPUs where the crop mix is altered by the initial production losses from maintaining the PBs and these first expansion steps, we iteratively adopt the crop fractions of the resulting land-use pattern to approach the current crop production mix, to minimize implicit assumptions about diet change.

Water and nutrient management improvements: On top of these expansions, we account for enhancements in land, water and nutrient management: We assume that severely degraded land (in total 390 Mha) can be fully restored and thus converted to agricultural land – though other PB criteria effectively limit this to 26.4 Mha). Also we assume that a) half of the water that otherwise would contribute to surface runoff from cropland is stored for irrigation during dry-spells (assuming a stricter irrigation threshold compared to regular irrigation); b) half of unproductive soil evaporation is avoided (through e.g. mulching or conservation tillage); c) irrigation systems are upgraded with drip systems where crop suitability allows and sprinkler systems elsewhere (paddy rice: always surface systems). Achieving such improvements globally is ambitious but feasible from a technical and agronomic perspective as field studies indicate respective potentials locally[16].

Furthermore, we assume a minimum NUE of 75%, implying that simulated yields can be achieved using lower N inputs. Adopting well-proven and mostly low-cost measures could raise NUE above 70%[53]; with technological progress like precision farming and under inclusion of higher-cost options, reaching a scenario value of 75% NUE is plausible and has been assumed in other studies[54,55]. Accordingly, N inputs are reduced to maximally 1/0.75 of N yields and a new Y_{max} parameter is calibrated per cell. Yield increases from water management and irrigation improvements are shifting the cellular Y_{max} parameters upwards. As in the previous steps, we reduce (increase) fertilization if the critical N concentration in surface water is (not) reached, with associated yield increases calculated using the newly calibrated Y_{max}. Improving pasture fertilization and NUE (not examined here) may provide further opportunities. As N flows are not explicitly modelled, N management adaptations and related yield changes are not mutually coupled with effects of the water management options.

Changes in consumption behaviour: Subsequently, potentials of diet change and food loss reduction are evaluated. As currently ~25% of the total kcal produced is lost or wasted within the supply chain from primary production to final consumption[18], we applied a scenario in which loss and waste are halved in each step of the supply chain[14]. We account for country-level production and post-production losses/waste of crops and livestock products (Supplementary Methods). The selected scenario reflects the goal of e.g. the EU 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”[56].

To address the opportunity of increasing food supply by adopting a less resource-intensive diet, we analyse a scenario in which the share of animal-based foodstuffs is reduced. As the minimum protein supply, we chose the midpoint of the population-level protein content recommendation in WHO dietary guidelines, on average 12.5% of total dietary energy supply[57]. To represent a limited consumption of animal-based food, we capped the farmed animal protein share of total dietary protein at 25% in each FPU. Thereby we allow pastures to be replaced with the respective cell’s current crop mix (as climate conditions allow for its growth) if protein supply is sufficient, else with protein-rich pulses or soybean. As this analysis provides a lower-end estimate of livestock-related potentials, we also performed an analysis assuming additional intensification of the livestock sector (Supplementary Discussion). Analysing the effects of treating different livestock species separately is not possible within our framework, as the data used do not provide feed composition per animal species but only totals per crop type (Supplementary Methods).

The global maps portrayed in Figs. 2 & 3, Extended Data Figs. 1 & 2 as well as Supplementary Figs. 3–7, 9 & 11 were created with FPU outlines adapted from ref.[58].

Data Availability: Data supporting the main findings of this study are available via GFZ Data Services, https://doi.org/10.5880/PIK.2019.021[59]. Model code, analysis scripts and further supplementary data are available from the corresponding author upon request.

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Author contributions. D.G. designed the study and led the writing; V.H. and J.J. conducted the model simulations; B.L.B., I.F., M.J., M.K. and S.S. contributed specific parts of the concept and data analysis; W.L., J.R. and H.J.S. contributed to overall analysis design; all co-authors contributed to manuscript writing.

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References

[1] D. Griggs *et al.*, Sustainable development goals for people and planet. *Nature* **495**, 305–307 (2013).

[2] B. M. Campbell *et al.*, Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* **22(4)**, 8 (2017).

[3] J. Rockström *et al.*, A safe operating space for humanity. *Nature* **461**, 472–475 (2009).

[4] W. Steffen *et al.*, Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).

[5] J. Jägermeyr, A. Pastor, H. Biemans, D. Gerten, Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nat. Commun.* **8**, 15900 (2017).

[6] D. Tilman, C. Balzer, J. Hill, B. L. Befort, Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **108**, 20260–20264 (2011).

[7] J. Rockström *et al.*, Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* **46**, 4–17 (2017).

[8] T. Searchinger *et al.*, *Creating a Sustainable Food Future – a Menu of Solutions to Feed Nearly 10 Billion People by 2050.* (World Resources Institute, 2018).

[9] J. Foley *et al.*, Solutions for a cultivated planet. *Nature* **478**, 337–342 (2011).

[10] N. D. Mueller *et al.*, Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257 (2012).

[11] J. Poore, T. Nemecek, Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).

[12] W. Mauser *et al.*, Global biomass production potentials exceed expected future demand without the need for cropland expansion. *Nat. Commun.* **6**, 8946 (2015).

[13] K.-H. Erb *et al.*, Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.* **7**, 11382 (2016).

[14] M. Jalava *et al.*, Diet change and food loss reduction: what is their combined impact on global water use and scarcity? *Earth's Fut.* **4**, 62–78 (2016).

[15] P. C. West *et al.*, Leverage points for improving global food security and the environment. *Science* **345**, 325–328 (2014).

[16] J. Jägermeyr *et al.*, Integrated crop water management might sustainably halve the global food gap. *Environ. Res. Lett.* **11**, 025002 (2016).

[17] V. Heck, H. Hoff, S. Wirsenius, C. Meyer, H. Kreft, Land use options for staying within the Planetary Boundaries – synergies and trade-offs between global and local sustainability goals. *Global Environ. Change* **49**, 73–84 (2018).

[18] M. Kummu *et al.*, Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Sci. Total Environ.* **438**, 477–489 (2012).

[19] M. Kummu *et al.*, Bringing it all together: linking measures to secure nations' food supply. *Curr. Op. Environ. Sust.* **29**, 98–117 (2017).

[20] J. G. Conijn, P. S. Bindraban, J. J. Schröder, R. E. E. Jongschaap, Can our global food system meet food demand within planetary boundaries? *Agric. Ecos. Environ.* **251**, 244–256 (2018).

[21] R. C. Henry *et al.*, Food supply and bioenergy production within the global cropland planetary boundary. *PLoS ONE*, **13(3)**, e0194695. doi.org/10.1371/journal.pone.0194695 (2018).

[22] M. Springmann *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).

[23] W. Willet *et al.*, Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).

[24] S. Schaphoff *et al.*, LPJmL4 – a dynamic global vegetation model with managed land: part 2 – model evaluation. *Geosci. Model Dev.* **11**, 1377–1403 (2018).

[25] V. Heck, W. Lucht, D. Gerten, A. Popp, Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change* **8**, 151–155 (2018).

[26] H. Kahiluoto, M. Kuisma, A. Kuokkanen, M. Mikkilä, L. Linnanen, Taking planetary nutrient boundaries seriously: can we feed the people? *Global Food Sec.* **3**, 16–21 (2014).

[27] L. V. Rasmussen *et al.*, Social-ecological outcomes of agricultural intensification. *Nat. Sust.* **1**, 275–282 (2018).

[28] Fischer, G, Transforming the global food system. *Nature* **562**, 501–502 (2018).

[29] M. Fader, D. Gerten, M. Krause, W. Lucht, W. Cramer, Spatial decoupling of agricultural production and consumption: quantifying dependence of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* **8**, 014046 (2013).

[30] D. W. O'Neill, A. L. Fanning, W. F. Lamb, J. K. Steinberger, A good life for all within planetary boundaries. *Nat. Sust.* **1**, 88–95 (2018).

[31] German Advisory Council on Global Change, *World in Transition: Governing the Marine Heritage* (WBGU, 2013).

[32] K. L. Nash *et al.*, Planetary boundaries for a blue planet. *Nat. Ecol. Evol.* **1**, 1625–1634 (2017).

[33] T. Newbold *et al.*, Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* **353**, 288–291 (2016).

[34] S. Ostberg, S. Schaphoff, W. Lucht, D. Gerten, Three centuries of dual pressure from land use and climate change on the biosphere. *Environ. Res. Lett.* **10**, 044011 (2015).

[35] M. Fader, S. Rost, C. Müller, A. Bondeau, D. Gerten, Virtual water content of temperate cereals and maize: present and potential future patterns. *J. Hydrol.* **384**, 218–231 (2010).

[36] A. V. Pastor, F. Ludwig, H. Biemans, H. Hoff, P. Kabat, Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.* **18**, 5041–5059 (2014).

[37] M. Flörke *et al.*, Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. *Global Environ. Change* **23**, 144–156 (2013).

[38] H. Biemans *et al.*, Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water Resour. Res.* **47**, W03509 (2011).

[39] W. de Vries, J. Kros, J., C. Kroeze, S. P. Seitzinger, Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr. Op. Environ. Sust.* **5**, 392–402 (2013).

[40] G. L. Velthof, J. Mosquera Losada, *Calculation of Nitrous Oxide Emission from Agriculture in the Netherlands: Update of Emission Factors and Leaching Fraction.* Alterra Report 2251 (Alterra, 2011).

[41] A. F. Bouwman *et al.*, Global trends and uncertainties in terrestrial denitrification and N_2O emissions. *Phil. Trans. Roy. Soc. B* **368**, 20130112 (2013).

[42] J.-F. Lamarque *et al.*, Multi-model mean nitrogen and sulfur deposition from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): evaluation of historical and projected future changes. *Atmos. Chem. Phys.* **13**, 7997–8018 (2013).

[43] P. M. Vitousek, D. N. L. Menge, S. C. Reed, C.C. Cleveland, Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems. *Phil. Trans. Roy. Soc. B* **368**, 20130119 (2013).

[44] C. C. Cleveland *et al.*, Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochem. Cy.* **13**, 623–645 (1999).

[45] B. L. Bodirsky *et al.*, N_2O emissions of the global agricultural nitrogen cycle – current state and future scenarios. *Biogeosci.* **9**, 4169–4197 (2012).

[46] W. von Bloh *et al.*, Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geosci. Model Dev.* **11**, 2789–2812 (2018).

[47] L. Lassaletta, G. Billen, B. Grizzetti, J. Anglade, J. Garnier, 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* **9**, 105011 (2014).

[48] IUCN & UNEP-WCMC, *The World Database on Protected Areas (WDPA)* (2015). www.protectedplanet.net, retrieved 20 Oct 2015.

[49] S. L. Pimm *et al.*, The biodiversity of species and their rates of extinction, distribution, and protection. *Science* **344**, e1246752 (2014).

[50] B. L. Bodirsky, C. Müller, Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution. *Environ. Res. Lett.* **9**, 105011 (2014).

[51] L. R. Oldeman, T.R. Hakkeling, W. G. Sombroek, *GLASOD: World Map of Human-Induced Soil Degradation.* (International Soil Reference and Information Centre, Wageningen, 1991).

[52] B. Lehner, P. Döll, Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* **296**, 1–22 (2004).

[53] V. Smil, Nitrogen in crop production: an account of global flows. *Global Biogeochem. Cy.*, **1**3, 647–662 (1999).

[54] B. L. Bodirsky *et al.*, Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Commun*. **5**, 3858 (2014).

[55] X. Zhang *et al.*, Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).

[56] EC (European Commission), *Closing the Loop – an EU Action Plan for the Circular Economy* (EC, 2015).

[57] WHO (World Health Organization), *Diet, Nutrition and the Prevention of Chronic Diseases.* WHO Technical

Report Series No. 196 (WHO, 2003).

[58] M. Kummu, P. J. Ward, H. de Moel, O. Varis, Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ. Res Lett.* **5**, 034006 (2010).

[59] D. Gerten et al., Model output for: "Feeding ten billion people is possible within four terrestrial planetary boundaries". GFZ Data Services. https://doi.org/10.5880/PIK.2019.021/ (2020).

Planetary Boundary (uncertainty zone)	Respective boundary constraints	Opportunities for increased food supply within boundaries
Biosphere integrity (BII: 90–30%)	Abandon agricultural land in protected areas and areas with >5% threatened species.	Expand cropland/pastures where BII ≥90% and outside of protected areas and areas with >5% threatened species.
Land-system change (remaining tropical and boreal forest: 85–60%, temperate forest: 50–30%)	Preserve 85% of tropical/boreal forest and 50% of temperate forest on each continent; in continent-biomes with transgression, abandon agricultural land up to respective limit.	In continent-biomes without transgression, expand cropland and pastures up to respective limit; restore severely degraded land for agricultural use.
Human freshwater use (withdrawal: 25–55%, 40–70% and 55–85% of mean flow in low-, intermediate- and high-flow months)	Reduce agricultural and other human water withdrawal to the extent they tap environmental flow requirements (EFRs).	Expand irrigation as EFRs allow (in rainfed areas only where water gap >50%); improve farm water management: harvest 50% of surface runoff for supplemental irrigation, reduce 50% of soil evaporation, upgrade irrigation systems.
Nitrogen (N) flows (concentration in surface water: 1–3 mg N l^{-1})	Decrease cropland fertilization where N leaching leads to critical concentrations (>1mg NL^{-1}) in surface water.	Increase fertilization on cropland with uncritical leaching losses; increase N use efficiency to 75%.

Table 1. Criteria to constrain resource use, and thus food production, by restoring the safe operating space (i.e. respecting the planetary boundaries), and to sustainably increase food supply within it. Boundary values in brackets refer to the lower and upper end of the uncertainty zone, whereby the lower end represents the boundary. All constraints and opportunities are considered at 0.5° grid cell level except land-system change at continent-biome level. See Methods for details and datasets used.

Scenario	Percentage change in global net kcal supply			Global net food supply (10^{15} kcal yr^{-1})
	Cumulative partial effect (% relative to 2005)	**Respective incremental contribution** (% difference)	**Isolated effect** (% relative to 2005)	
Respecting boundaries:				
PB for biosphere integrity	–12.4	–12.4	–12.4	5.03
+ PB for land-system change	–19.3	–6.9	–9.3	4.64
+ PB for freshwater use	–23.4	–4.2	–6.4	4.40
+ PB for N flows	**–48.6**	–25.1	–29.6	2.95
Opportunities within PBs:				
Expansion of cropland, irrigation and fertilizer use	–19.3	+29.3	n.a.	4.63
+ Improved land, water and nutrient management	+16.1	+35.4	n.a.	6.67
+ Halved food loss	+33.0	+16.8	n.a.	7.63
+ Diet change	**+52.9**	+19.9	n.a.	8.78

Table 2. Food supply declines associated with a restoration of the safe operating space, and supply gains achievable by taking different opportunities. Shown are global decreases in net kcal supply (including sufficient protein content) when consecutively respecting each of the considered boundaries and exploring each management and socio-cultural opportunity within these constraints, respectively. Changes are detailed for the successive combined effects, the corresponding incremental effects of each measure in the multi-option scenario, and the isolated effects if each measure were implemented disregarding the constraints from the respective preceding measures (only for boundary restrictions). Respective absolute annual supply estimates are shown in the last column (estimate for baseline 2005: $5.74*10^{15}$ kcal yr^{-1}). Net food supply corresponds to the dietary energy requirement on the consumption side.

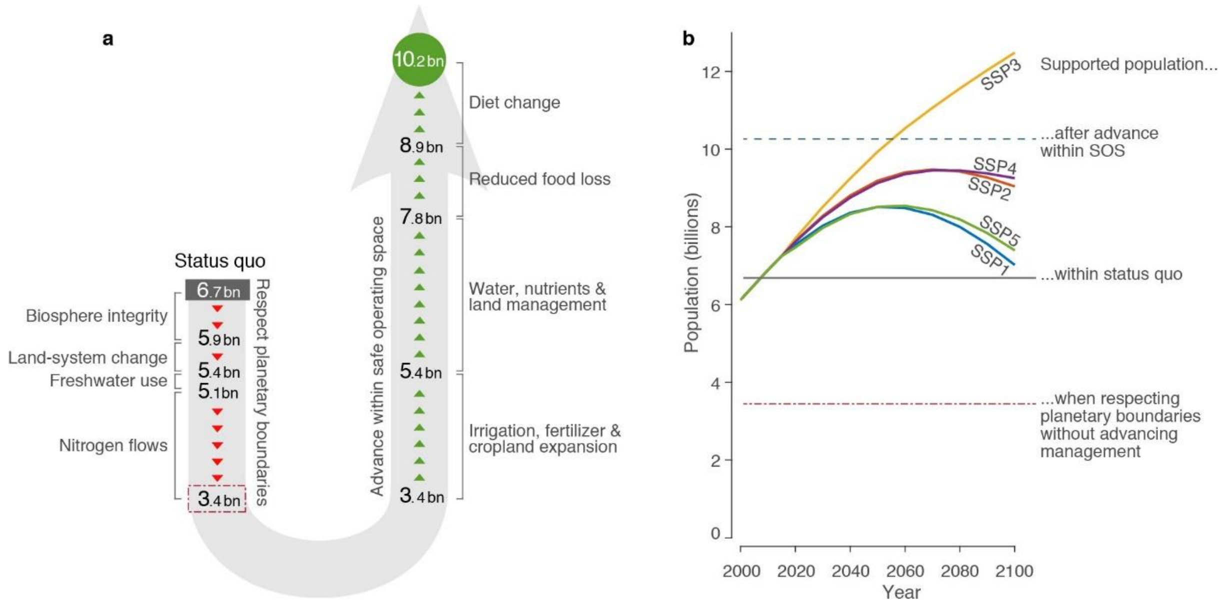

Fig. 1. Simulated technological-cultural 'U-turn' towards increasing global food supply within four planetary boundaries. Global population that can be provided with a global average net food supply of 2,355 kcal cap^{-1} d^{-1} (including sufficient protein content) when respecting the different planetary boundaries given unchanged current practices (left-hand side) and, respectively, when making use of opportunities of agricultural land expansion, management and socio-cultural changes within the safe operating space (SOS) (right-hand side) (**a**). Panel **b** illustrates population projections for the different Shared Socio-Economic Pathways benchmarked against the corresponding net food supply for the reference year 2005 (status quo, solid horizontal line), when respecting all boundaries (lower dotted line), and when implementing all opportunities within the SOS (upper dashed line), respectively. Note that an implementation of the opportunities does not necessarily have to follow the sequence shown; but due to synergistic effects their full potential calculated would be realized only if implemented in this order or in parallel.

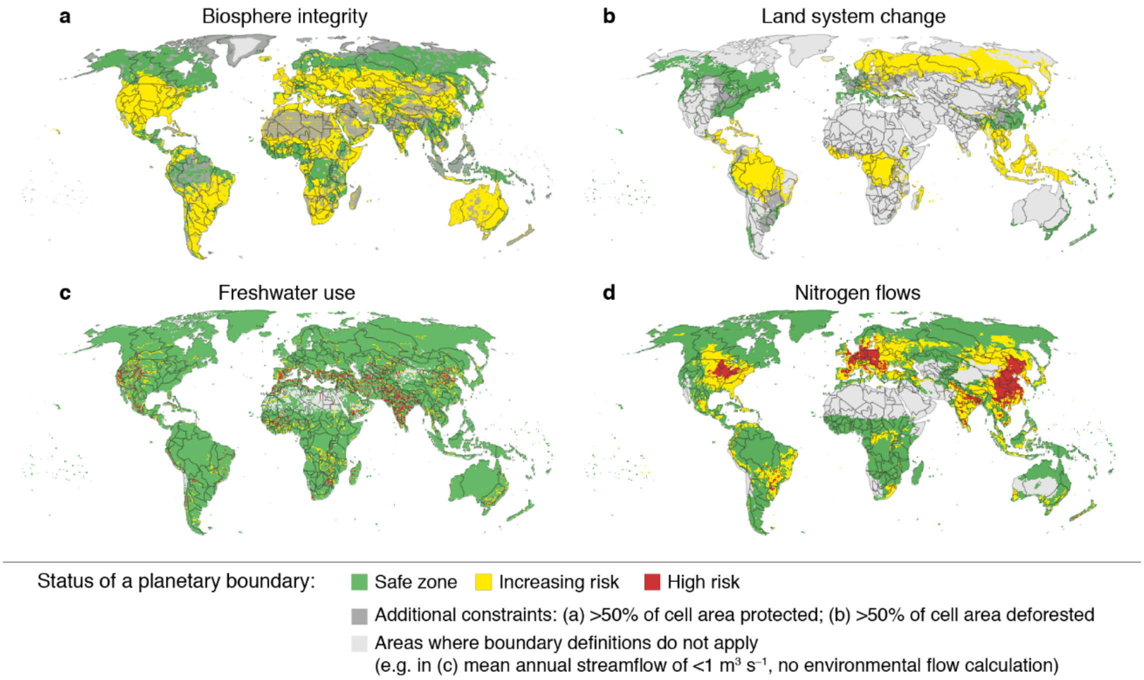

Fig. 2. Current status of the four planetary boundaries for biosphere integrity (**a**), land-system change (**b**), freshwater use (**c**), and nitrogen flows (**d**). In (**a**) and (**b**) additional constraints applied are highlighted in dark grey (if >50% of a cell's area is protected or a cell's deforested area is >50%, respectively); light grey indicates areas where no PB values are computed. All statuses are given as 1980–2009 averages except (**a**) for year 2005.

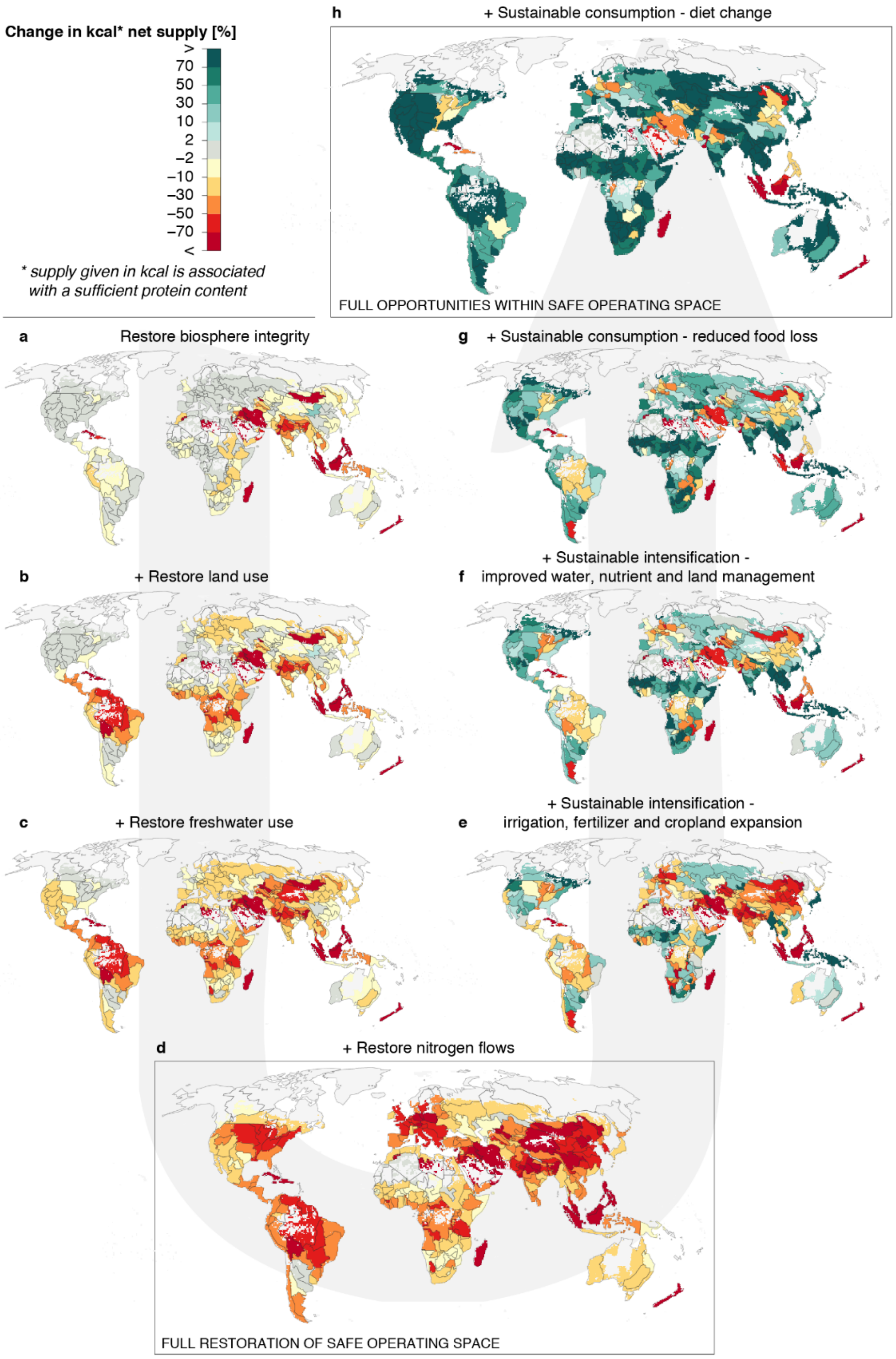

Fig. 3. Effects on kcal net supply per FPU for each step of the U-turn. Shown are percent changes relative to the 2005 baseline given consecutive restoration of the safe operating space (left) and, respectively, consecutive implementation of individual opportunities within it (right). Restorations: biosphere integrity only (**a**); additionally considering land-system change (**b**); additionally considering freshwater use (**c**); and all boundary dimensions including nitrogen flows (**d**). Opportunities: expansion of agricultural land, irrigation and nitrogen-fertilised areas as allowed within the boundaries (**e**); additionally improved water and nitrogen management as well as degraded land restoration (**f**); additionally food waste reduction (**g**); all opportunities including diet change (**h**). Light grey: currently no agricultural land or not suited for agricultural use in the scenarios.

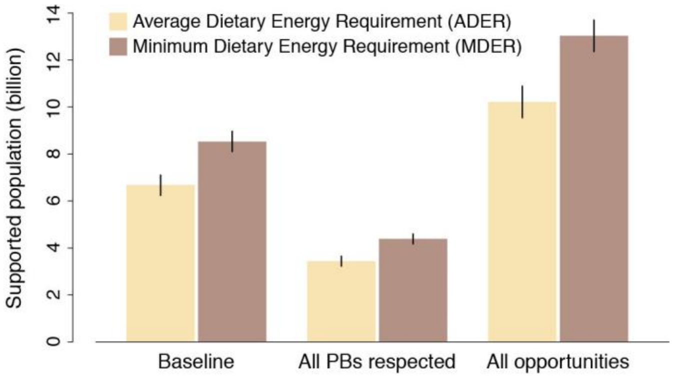

Fig. 4. Number of people that could be fed assuming alternative food supply targets. ADER, Average Dietary Energy Requirement (2,355 kcal cap^{-1} d^{-1}); MDER, Minimum Dietary Energy Requirement (1,846 kcal cap^{-1} d^{-1}), including sufficient protein content. Whiskers represent results for the lower and higher ends of world-region values. Results are shown for the 2005 baseline, the scenario in which all PBs are respected without any technological and socio-cultural changes (*cf.* Fig. 3d), and the scenario with all opportunities implemented (*cf.* Fig. 3h).