Food system contributions to future planetary boundary transgressions: a multiscale modelling assessment of scenarios

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Summary

Background Food systems are important drivers of planetary boundary transgressions at both global and local scales. Growing evidence shows that when multiple planetary boundaries are transgressed simultaneously, such transgression can amplify their negative consequences on Earth system processes. Therefore, it is essential to scrutinise global boundary transgressions at the local scale.

Methods This study assessed future planetary boundary transgressions under different food system-transformation (EL2) and combined food system-transformation and climate mitigation (ELM) scenarios, both on global and local scales, by defining ten global and eight local boundary indicators and simulating them using the Integrated Model to Assess the Global Environment framework.

Findings Our results identified hotspots of local boundary transgressions across scenarios. Policies addressing the food system (such as dietary change, productivity increase, and halving food loss and waste) can help to reduce future transgressions. Dietary change results in the largest reductions in the land-system change (70%) and biosphere integrity (69%) domains. Policies with a focus on agricultural productivity improve the biogeochemical flows (phosphorus) domain (92%), and mitigation measures drive most of the improvements in freshwater change (62% blue, 82% green), climate change (67%), and aerosol loading (75%). On a global scale, there are no trade-offs between the EL2 and ELM scenarios, but trade-offs can occur on a local level, with large regional differences in boundary transgressions. Grid cells with six or more local boundary transgressions account for 6·1% of the total land area under business-as-usual, 4·5% under EL2, and 3·1% under ELM, as compared with 4·9% in the historical reference period 2020.

Interpretation Policies addressing both the food system and climate change can be effective in simultaneously reducing boundary transgressions across scenarios, although a multiscale approach can help to identify regional trade-offs that remain hidden at global scales.

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Introduction

Globally, food production is expected to grow substantially to meet the rising demand.[1] Environmental pressures from these agricultural activities include biodiversity loss, climate change, disturbance of natural cycles of nutrients and water, and introduction of all kinds of chemicals into the environment.[2–5] Consequently, food systems play a crucial role in the transgression of planetary boundaries.[6–9] Reducing these pressures requires policy interventions targeting both food production systems and consumption patterns.[7,10] Different policy options for a food system transformation have already been explored. For example, promoting more sustainable diets and lower meat consumption can provide environmental benefits.[6,11,12] Moreover, reducing food loss and waste (FLW) and improving agricultural and nitrogen-use efficiency,[7,10] in addition to expanding protected areas,[13] are key levers to reducing environmental pressures.

One way to evaluate environmental impacts is via the planetary boundary framework. This framework identifies nine key Earth system processes and their respective boundary thresholds that demarcate the safe operating space for humanity.[14,15] Some of the boundaries are also defined at regional scales, as boundary transgressions are often driven by local processes.[14,16] Assessments of the current state indicate that we are already transgressing six (biosphere integrity, climate change, land-system change, freshwater change, biogeochemical flows, and novel entities) of the global boundaries, with increased risk of irreversible environmental damage.[17] A 2025 study suggests that a seventh boundary (ocean acidification) is also transgressed now.[18] One powerful way of returning within planetary boundaries is by transforming our food system, as agriculture is a major driver of transgressions.[7,8] Recent multimodel assessments show that a shift towards a more sustainable diet is often an integral part of a food system

Research in context

Evidence before this study

We searched Scopus for studies between 2013 and 2025 using the search terms ("planetary boundar*" OR "safe operating space") AND ("food system transformation" OR "diet") AND ("transgression" OR "scenario") AND ("global" OR "regional" OR "local"). Most previous studies have assessed the planetary boundary framework in the context of its historical or current state, repeatedly showing that most boundaries are already transgressed. We found only one scenario-based modelling study that assessed the full planetary boundary framework at the global scale. At the local scale, previous work has used one or a smaller subset of boundary indicators. We found no previous modelling studies that attempted to link global and local scales using different scenarios.

Added value of this study

To our best knowledge, this study is the first scenario study that links global and local planetary boundary indicators within an integrated assessment modelling framework. We used different food system-transformation and climate change-mitigation scenarios to present interactions and the possible trade-offs between them. This assessment is important as the local scale can reveal regional hotspots of boundary transgressions that remain hidden at the global scale.

Implications of all the available evidence

Transforming the food system might reduce environmental pressures. A multiscale assessment is essential for designing policies at both the global and local scales.

transformation.[19,20] A well known example is the Planetary Health Diet, a largely plant-based reference diet developed by the EAT-*Lancet* Commission to keep food consumption within environmental limits.[21]

Earlier studies have assessed the impacts of food system transformation on the planetary boundary framework, focusing either on global boundaries[10,22,23] or a subset of regional boundaries.[7,24] For example, Gerten and colleagues[7] analysed how current food production can stay within four global and regional boundaries through adoption of different actions (eg, reduction of FLW, dietary shifts) while still meeting food demand. Heck and colleagues[24] showed that globally optimised land use can help to stay within the land-system change and freshwater change boundaries, but that these improvements can conflict with local policy objectives (such as food production and biodiversity protection). Schulte-Uebbing and colleagues[25] estimated the reduction in nitrogen inputs required to bring agriculture back within local and global boundaries for nitrogen surplus. Similarly, Porkka and colleagues[26] presented an improved representation of the planetary boundary on freshwater change, explicitly taking into account local changes in the water cycle (both for blue and green water).

In this study, we added to the existing literature by investigating the future development of planetary boundary transgressions both at the global and local scales, in one consistent model framework. All global planetary boundary domains (except novel entities) and eight local indicators are assessed under business-as-usual (BAU) and solution-oriented pathways. Combining climate change-mitigation measures with policies targeting the food system is essential to address transgressions in all domains.[22,23,27] We specifically investigated the contribution of a food system transformation to the reduction in planetary boundary transgressions, including its combined effects with stringent climate change-mitigation measures. By providing a multiscale (from global to local) analysis, we were able to explicitly analyse differences in the scale of assessment and identify regional hotspots of transgression. By also investigating climate and air pollution boundaries at the local scale, we moved beyond previous spatially explicit studies that focused only on land use-dominated boundaries.[7]

To achieve this aim we applied the Integrated Model to Assess the Global Environment (IMAGE) framework[28] and used a set of scenarios that were co-developed with multiple model teams as part of the EAT-*Lancet* Commission.[19,21] We analysed one pathway that largely continues the latest trends in human development (BAU), and two solution pathways outlining possible trajectories to keep human development within planetary boundaries. One pathway focuses on food system transformation only, whereas the second solution pathway also includes climate change-mitigation policies. To identify the environmental impact of food system transformation and climate change-mitigation policies, we quantified the impact on ten global indicators across eight domains and compared these global impacts to eight local boundaries. This approach allowed us to assess the extent to which these policy measures can address planetary boundaries at multiple scales and identify local hotspots of change. Such assessment is important, as evidence suggests that interactions between multiple boundary transgressions can amplify each other, and reduce their safe operating space.[29,30] The key question is—to what extent do policy measures addressing the food system and climate change contribute differently to restricting planetary boundary transgressions and how does this contribution affect regional and local hotspots of transgressions.

Methods

IMAGE

IMAGE is a framework for assessing future human development in relation to environmental impacts. IMAGE is a powerful tool to assess impacts on planetary boundaries, as it accounts for the complex interactions between socioeconomic drivers and biophysical processes. Specifically, IMAGE includes detailed descriptions of food and energy consumption and production. The modelling framework can quantify our food systems and their possible feedback on the environment. IMAGE combines models from various disciplines (eg, energy-system, agriculture, material flow, and policy) to explore long-term global changes and their effects on society and the environment.[31] The IMAGE framework produces outputs at both the global scale and up to 5-arcminute grid resolution. A more detailed description of IMAGE can be found in the appendix (pp 3–5).

Scenario setup

We used three main scenarios (appendix p 10) to analyse how a food system transformation and climate change-mitigation policies affect planetary boundaries at the local and global scales by 2050. These scenarios are also used in the EAT-*Lancet* Commission.[21] In all scenarios, the global population is expected to grow to 9·6 billion people in 2050, and global gross domestic product will increase by 127% between 2020 and 2050, according to the middle-of-the-road shared socioeconomic pathway (SSP)2 scenario.[32] Agricultural productivity continues to increase in line with historical development and areas for nature are assumed to be effectively protected but not to expand further.[33]

In the BAU scenario, dietary patterns, technological growth, and FLW follow current trajectories. Normally, IMAGE calculates yields endogenously using the LPJmL model. In this study, however, we build on the Inter-Sectoral Impact Model Intercomparison Project crop model ensemble in accordance with the study by Rockström and colleagues,[21] using data from the Earth System Model Institut Pierre-Simon Laplace[34] under Representative Concentration Pathway (RCP)7.0, representing high greenhouse gas emissions. Productivity shocks for both livestock and labour are based on heat stress due to increased temperatures under RCP7.0. We used the livestock productivity impacts from the study by Thornton and colleagues[35] and labour impacts from the one by Nelson and colleagues.[36]

In the food system-transformation scenario (EL2), a shift towards the Planetary Health Diet as described by Rockström and colleagues[21] is assumed. This diet consists primarily of plant-based foods and aligns human nutritional needs with improved health outcomes. Globally, uptake of this diet means a large reduction in the consumption of animal products, and an increased intake of, for example, fruits, vegetables, nuts, and legumes. In addition to dietary change, additional food system-transformation assumptions are included: agricultural productivity settings from SSP1 are adopted as per study by Stehfest and colleagues,[37] reflecting faster technological development and higher yields, as compared with those seen in BAU. In addition, FLW is halved by 2050, in line with the sustainable development goal 12.3, and optimistic assumptions on the adoption of improved agricultural management are included, with improved efficiency in fertiliser use, large-scale soil conservation measures, and high irrigation efficiency. In this scenario, there are no further policies on climate change mitigation. For climate change impacts, the same effects on crop, livestock, and labour productivity as those in BAU were used.

To disentangle the effects of different food system-transformation drivers in relation to climate change mitigation, a decomposition analysis was performed wherein the effect of each policy measure was isolated as a separate scenario relative to BAU. These scenarios are categorised as dietary change (BAU_DIET), agricultural productivity and management (BAU_PROD), FLW reduction (BAU_WAST), and climate change mitigation (BAU_MITI). BAU_DIET, BAU_PROD, and BAU_WAST together make-up the EL2, whereas ELM combines this transformation with the climate change-mitigation policies. This mitigation scenario reflects ambitious climate change-mitigation policies that align with restricting global warming to 1·5°C.[3] We also included policies that increase the protected terrestrial area, including targeted protection of high-carbon ecosystems. In line with these measures, climate impacts on crops, livestock, and labour are modelled using RCP2.6, wherein climate change is restricted to around 2°C in 2100.[35,36] We also included increased nitrogen-use efficiency measures, which help to further reduce emissions (see appendix p 10 for a detailed overview).

For detailed model descriptions, see www.pbl.nl/image

See Online for appendix

In IMAGE, planetary boundary indicators change dynamically in response to the measures taken in each scenario. A global shift towards a more plant-based diet reduces livestock and fertiliser inputs, which in turn lowers nitrogen and phosphorus losses, in addition to reducing pressures on land use (see appendix pp 3–5 for more details on model dynamics).

Planetary boundaries

The planetary boundaries assessed in this study are mostly based on the studies by Steffen and colleagues and Richardson and colleagues.[14,17] Owing to data and modelling limitations, some of the control variables were adjusted to assess the full range of planetary boundary domains using IMAGE, similar to earlier work.[22] Several indicators were adapted from the safe and just boundary framework,[16] applying a stricter health-related boundary. The selection of global and local boundary indicators is discussed in the appendix (pp 6–9). The ten global boundary indicators used in this study are given in the table. Following the study by van Vuuren and colleagues,[22] we included an upper-uncertainty zone and an undisturbed Earth reference in addition to the global boundary (appendix p 11). We calculated planetary boundary developments for BAU, EL2, and ELM scenarios and compared these developments to those in the historical reference period (2020).

In addition to the global boundaries, we defined eight local boundaries that are spatially explicit at a 0·5° resolution. Not all global scale boundaries can be translated

	Global control variable	Global boundary	Local control variable	Local boundary
Biosphere integrity	MSA[22]	90%	MSA[16]	72·5%
Climate change	Radiative forcing[22]	1·9 W/m^2	Wet-bulb temperature[38]	1 day >32°C
Land-system change	Forest area[22]	45 Gha	Natural area share[17]	75% of original natural cover
Freshwater change: Green water	Variation in soil moisture[26]	10·3%	Variation in soil moisture[26]	<5% and >95% deviations relative to those in the pre-industrial period
Freshwater change: Blue water	Variation in river discharge[26]	9·4%	Variation in river discharge[26]	<5% and >95% deviations relative to those in the pre-industrial period
Biogeochemical flows: N	Nitrogen surplus[25]	57 Tg N/year	Nitrogen exceedance[25]	2·5 mgN/L in surface water or 11·3 mgN/L in groundwater or landcover-specific critical N deposition
Biogeochemical flows: P	Phosphorus losses to surface water[39]	6·1 Tg P/year	Phosphorus exceedance to surface water[39]	0·075 mgP/L in surface water
Ocean acidification	pH[22]	8·01	Na	na
Stratospheric ozone depletion	O3 concentration 60°–90°[22]	276 DU	Na	na
Aerosol loading	Mean $PM_{2·5}$[22,40]	10 µg/m^3	Mean $PM_{2·5}$[22,40]	10 µg/m^3
Novel entities		No control variable currently defined		

MSA=mean species abundance. N=nitrogen. na=not available. P=phosphorus. The first column indicates the different Earth system processes, each of which has a global control variable and, wherever applicable, a local control variable, each with a boundary value used to identify transgression. More details on the planetary boundary selection can be found in the appendix (pp 6–9).

***Table:* Boundaries used in the global and local assessments**

directly to the local scale, so we adapted some boundaries to enable their assessment at the local scale (table). For biosphere integrity, we used the mean species abundance (MSA) indicator, which IMAGE calculates at the grid level.[41] We set the local boundary at 72·5%, reflecting the midpoint of the global planetary boundary of 90% and the subglobal ecosystem safe boundary of 55%, as given in the study by Rockström and colleagues.[16] Wet-bulb temperatures were used to assess local boundary transgressions in the climate change domain. We set the boundary at 32°C, which is the temperature threshold at which human wellbeing is affected.[38] For land-system change, we used the share of natural land area relative to the total area, and set the boundary at 75% of the original natural cover, similar to the global boundary for forest cover given in the study by Richardson and colleagues.[17]

We used the latest definition from the study by Porkka and colleagues[26] to assess the status of the freshwater change boundary, which adopts local monthly deviations from pre-industrial variability envelopes (5th and 95th percentiles) for both green and blue water. Green water deviations are represented by soil moisture (in LPJmL: root-zone soil moisture), and blue water deviations are represented by streamflow. The planetary boundary is set at 10·3% of the total land area transgressed for green water and 9·4% for blue water. Local boundaries for nitrogen pollution are calculated as per the study by Schulte-Uebbing and colleagues,[25] and the impacts of surface and groundwater pollution and nitrogen deposition on biodiversity and water quality are considered (appendix p 12). In addition, we used phosphorus losses to surface water for the biogeochemical flows domain. We set our local boundary at 0·075 mgP/L as a maximum surface water phosphorus concentration.[39] For aerosol loading, we calculated spatially explicit $PM_{2·5}$ concentrations. We set the local boundary at 10 µg/m^3, in line with WHO recommendation.[40] More details on the selection of global and local boundaries can be found in the appendix (pp 6–9). The Ocean acidification and stratospheric ozone depletion domains were not included in our local scale assessment. In this study, we did not explicitly analyse interactions between planetary boundaries.

Role of the funding source

The funders of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

In 2020, six of eight planetary boundary domains showed a transgression (figure 1). Under the BAU scenario (figure 1B), ocean acidification will additionally be transgressed. Most of the planetary boundary indicators show increased transgressions on a global scale by the year 2050. Only stratospheric ozone depletion and aerosol loading show slight improvements with the current policies. Climate change and biogeochemical flows (both nitrogen [N] and phosphorus [P]) show the largest increase in transgression across planetary boundary domains under the BAU scenario.

A food system transformation, including a global dietary shift (EL2) can help to reduce pressures on global planetary boundaries; however, it is not sufficient on its own to reduce the impacts to below the safe threshold levels by the year 2050 for all planetary boundaries (figure 1C). Compared with the historical reference period and BAU,

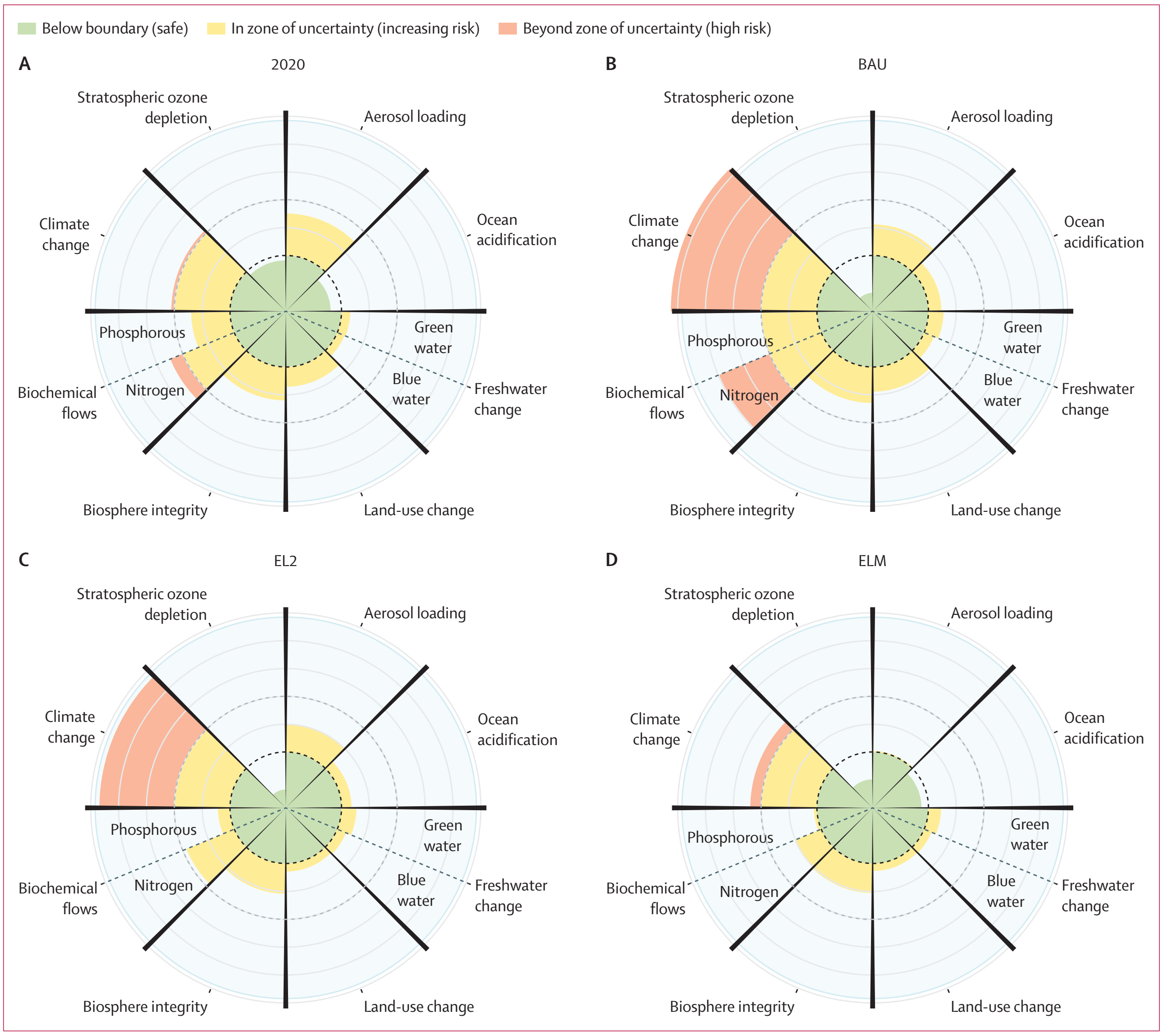
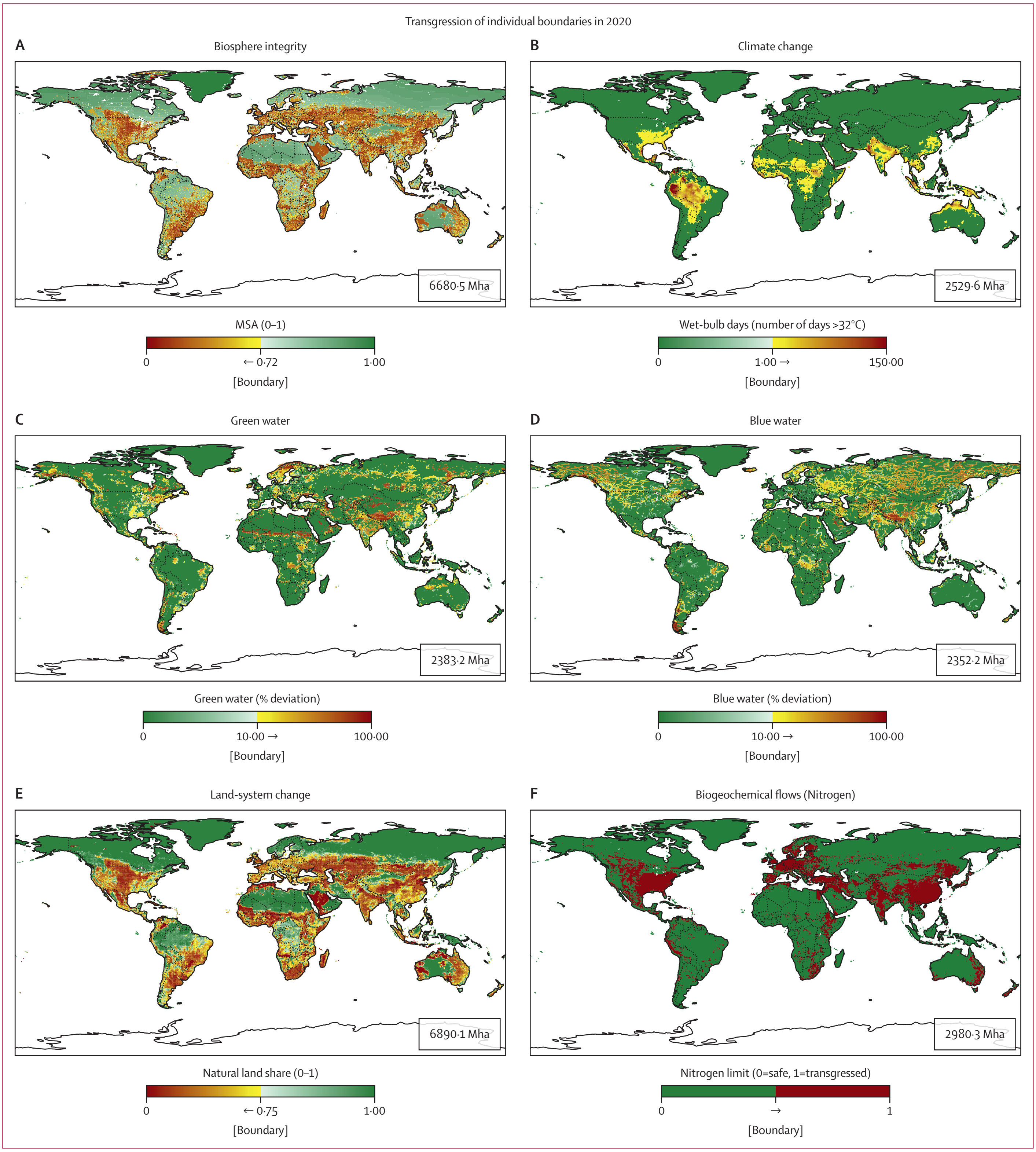


***Figure 1:* Planetary boundaries**

Planetary boundaries for the historical reference period (2020; A), and the BAU (B), food-system transformation (EL2) (C), and combined food system and climate mitigation (ELM; D) scenarios in 2050. Each boundary indicator is scaled using additional values for the upper end of the uncertainty zone, and a low end reference value (appendix p 11). The intersection between the green and yellow is the planetary boundary. Yellow colours indicate that the planetary boundary indicators are transgressed and red colour shows transgressions beyond the upper-end values. BAU=business-as-usual.

biogeochemical flows show the greatest reduction in transgression, as a result of lower livestock manure excretion and synthetic fertiliser application. Including mitigation policies (ELM) further alleviates impacts across some boundaries (figure 1D). In ELM, ocean acidification is now within the planetary safe thresholds. The reduction in ocean acidification pressure is mostly due to mitigation policies that target greenhouse gas emissions, with the strongest effect on the climate change and aerosol loading domains. Both aerosol loading and biogeochemical flows (P) are close to the safe thresholds, but biosphere integrity, land-system change, and biogeochemical flows (N) remain within the zone of increasing risk, whereas climate change remains in the high-risk zone. Overall, despite substantial reductions in planetary boundary transgressions from food system-transformation and climate change-mitigation policies, the policy measures in these scenarios are only sufficient for some of the boundaries.

The spatial distribution of individual local boundary transgressions in the historical reference period (2020) is presented across six boundary domains and eight boundaries, each represented by a local indicator (A–H) (figure 2). Biosphere integrity (figure 2A) and land-system change (figure 2E) show a similar pattern of transgression, as MSA loss often concentrates in regions where the share of natural land is low. Biosphere integrity is, however, also affected by climate change, implying that all locations globally are affected to some extent. Local transgressions of the climate change indicator wet-bulb days (figure 2B) are mostly found in humid regions near the equator. Highest values are found in the Amazon, although low population density means low exposure. High values in densely



(Figure 2 continues on next page)

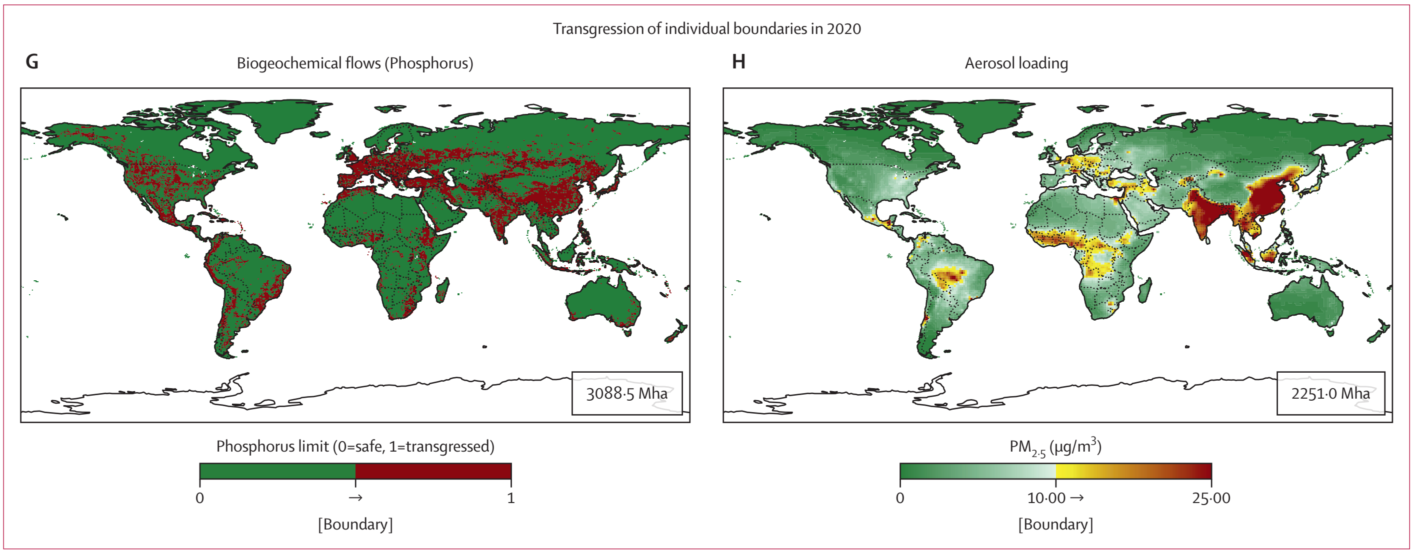


Figure 2: **Transgression of individual local boundaries in the historical reference period (2020)**
Yellow to red colours show the intensity of transgressions for each local grid, whereas green colours are still in the safe zone. Total transgressed area for each indicator is shown on the bottom right of the subplots. Boundaries for nitrogen and phosphorus have been calculated separately for each grid cell, and, therefore, depicted as binary, since their local thresholds are grid dependent.

populated areas are much more impactful, for example, in India and Pakistan. The biogeochemical flows domain, which includes nitrogen (figure 2F) and phosphorus (figure 2G), and to a lesser extent, freshwater change (figure 2C, 2D), often shows transgressions in regions with intensive agricultural activity or high population density, or both, such as south Asia and east Asia. Aerosol loading (figure 2H) shows high transgressions in densely populated and industrial regions, in addition to locations with high levels of land-system change, such as the Amazon, central Africa, and Indonesia.

The total number of transgressions based on all eight local boundaries in each 0·5° grid cell in the historical reference period and in 2050 in three scenarios (BAU, EL2, and ELM) are given in figure 3. In 2020, across 641 Mha, six or more local boundary indicators were transgressed (4·9% of the global terrestrial area). This area increased to 800 Mha under BAU (6·1% of the global terrestrial area), 589 Mha under EL2 (4·5%), and decreased to 404 Mha under ELM (3·1%). Also, the number of grid cells with zero, one, or two indicator transgressions increased under EL2 and ELM (appendix pp 17). This finding is important as increasing evidence suggests that interactions between Earth system processes might aggravate risk levels and further narrow down the safe operating space,[29,30] which implies that areas in which multiple planetary boundaries are crossed simultaneously might be at increased risk levels. Historically, the highest levels of transgressions are concentrated in India and China, with smaller hotspots in parts of EU and the USA (figure 3A).

Under the BAU scenario, transgressions intensify further, and more boundary transgressions emerge in various world regions, such as parts of Brazil and central Africa (figure 3E). In Brazil, increasing livestock numbers generate more N and P through manure, leading to spillovers into the environment, and increase transgressions in the biogeochemical flows domain. The transgressions in central Africa are driven by an increase in wet-bulb temperatures and increased $PM_{2.5}$ emissions from biomass burning. Globally, all boundary indicators have more grid cells transgressed than those in the historical reference period (2020), but some regions already show improvements. For example, parts of EU show a reduction of boundary transgressions under BAU, which are caused by improvements in the aerosol loading and biogeochemical flows (ie, N and P) domains (figure 4). For these regions, continuing historical trends under BAU already leads to reduced transgressions. Regions in the northern hemisphere that have permafrost thawing, such as Canada and Russia, show the largest increase in transgressions for the freshwater change domain. Higher evapotranspiration and changing precipitation patterns as a result of climate change strongly influence soil moisture (green water) and streamflow (blue water).

Compared with BAU, a food system transformation (EL2) reduces environmental impacts across all boundary domains (figures 3F, 4). The largest improvements are seen in the biosphere integrity and land-system change domains, which are closely interlinked, in addition to the biogeochemical flows (N and P) domain. Improvements in land-system change transgressions are largely caused by the decreased land requirements of livestock grazing and animal feed production, allowing more land to remain or revert to its natural state. This change also positively affects the MSA indicator that is used to capture the biosphere integrity domain. In addition, lower manure production in the livestock sector and reduced nitrogen application for animal feed crops lead to a decrease in nitrogen deposition,

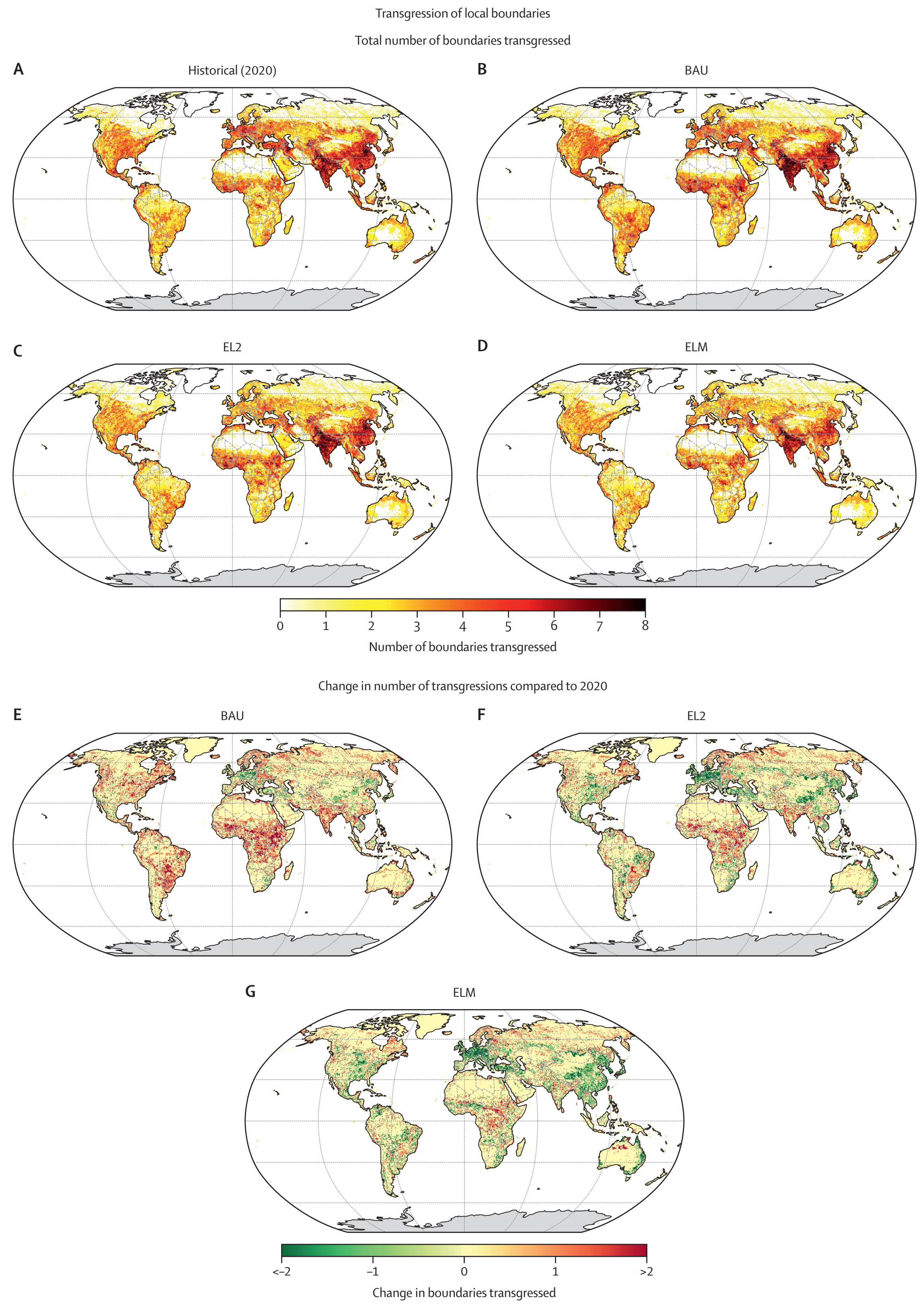

Transgression of local boundaries
Total number of boundaries transgressed
A
Historical (2020)
B
BAU
C
EL2
D
ELM
0
1
2
3
4
5
6
7
8
Number of boundaries transgressed
Change in number of transgressions compared to 2020
E
BAU
F
EL2
G
ELM
<–2
–1
0
1
>2
Change in boundaries transgressed

Figure 3: **Total number of transgressions and changes for eight local boundaries for each 0·5° grid cell**
The historical reference scenario (2020; A), BAU, food system-transformation (EL2), and combined food system and climate mitigation (ELM) scenarios in 2050 (B–D). (E–G) Change in total number of transgressions, as compared with the historical reference period (2020). Each grid cell shows the number of boundaries that are transgressed (A–D) or the change in boundaries transgressed in 2050 compared to those in 2020 (E–G) following the planetary boundary limits. BAU=business-as-usual.

positively affecting the MSA. Large improvements are seen in regions with current high livestock densities (eg, Brazil, Australia, and New Zealand), as agricultural land is restored to natural land, improving the biosphere integrity and land-system change domains. Other regions, such as southeast Asia and India, show only minimal improvements in these domains, as livestock populations remain stable in the EL2 scenario. Improvements in Europe and the USA are mainly driven by improvements in the biogeochemical flows (N and P) domain indicators (figure 4).

The decomposition of the four policy measure categories across the scenarios: dietary change, increased agricultural productivity, reduction of FLW, and climate mitigation is shown in figure 5. Transitioning towards a Planetary Health Diet plays the largest role in reducing pressures on the biosphere integrity (69%) and land-system change (70%) indicators, with smaller contributions from increased productivity and reduced FLW (figure 5). Improvements in the biogeochemical flows domain are also strongly influenced by policies associated with a transformation of the food system (ie, dietary change, increased productivity, and reduced FLW). Around 35% of the improvements of the biogeochemical flows (N) indicator can be attributed to a change in diets, which will lower the number of crops that need to be grown to feed livestock, resulting in less agricultural land use and lower nitrogen application to soils. Increased agricultural productivity (26%) leads to more efficient fertiliser use, lowering spillover into the environment (figure 5). Improvements in phosphorus are almost entirely driven by higher agricultural productivity (92%), as a result of lowered phosphorus application rates (based on SSP1) and increased soil conservation, which will lower phosphorus delivery to the surface water. The Planetary Health Diet improves all indicators except biogeochemical flows (P), which increases slightly because of changing land use patterns of crop production.

The other four indicators show small improvements that can be attributed to food system transformation. Dietary change, increased agricultural productivity, and reduction of FLW, all contribute to lowering agricultural emissions, leading to improvements in the climate change domain (figure 5). Blue water transgressions, and to a lesser extent, green water transgressions, improve under EL2 mainly because of reduced groundwater and surface water withdrawals resulting from improved irrigation efficiency. Aerosol loading transgressions decline under EL2, as a reduced livestock population lowers ammonia (NH_3) emissions, and consequently, the formation of ammonium nitrate, which contributes to $PM_{2·5}$. Lower black and organic carbon emissions from reduced waste burning and deforestation further decrease aerosol loading transgressions.

Including climate change measures on top of a food system transformation in the ELM scenario leads to further improvements in the local transgression status of all indicators, which shows that, on a global aggregate level, there are no trade-offs between a food system transformation and climate change-mitigation policies. On a regional level, there can be trade-offs between EL2 and ELM. For example, the expansion of bioenergy production in northern Australia leads to higher transgressions in the land-system change and biosphere integrity domains, as compared with that under EL2 (figure 3G). The largest improvements under ELM are in the aerosol loading (75%) and climate change (67%) domains, with large reductions in tropical regions (figure 3G). Global aggregate climate change transgressions are still increasing as compared with the historical reference (figure 4), primarily owing to the frequency of wet-bulb temperatures of more than 32°C, which continue to rise in some regions even under stringent climate change-mitigation policies. Cleaner energy carriers reduce $PM_{2·5}$ emissions from industry, energy, and biomass burning, leading to lower pollution in central Africa, India, and China, which are also regions with high population densities. Climate change mitigation shows large improvements for the green water (82%) and blue water (62%) indicators (figure 5), which reflects that transgressions in the freshwater change domain are largely driven by climate change, through impacts on the water cycle from changes in evaporation and precipitation. Additionally, the ELM scenario includes policies that keep the total irrigation area constant, further reducing green and blue water transgressions. In ELM, around 33% of the global improvements of the biogeochemical flows (N) can be attributed to climate change mitigation (figure 5), which includes additional measures to improve fertiliser efficiency to reduce N_2O emissions. There are large regional differences, with some regions (eg, USA, Europe) showing large improvements, and others (eg, Brazil) showing large increases in nitrogen transgressions, even under ELM. Climate change-mitigation policies also contribute to small improvements in the land-system change (18%) and biosphere integrity (20%) domains because of increased protection of high-carbon ecosystems.

Wherever multiple local boundaries are transgressed simultaneously, their effects are likely to amplify each other. Policies in the food system-transformation scenario, combined with climate change-mitigation policies, can drastically reduce these combined transgressions (figure 3B–D).

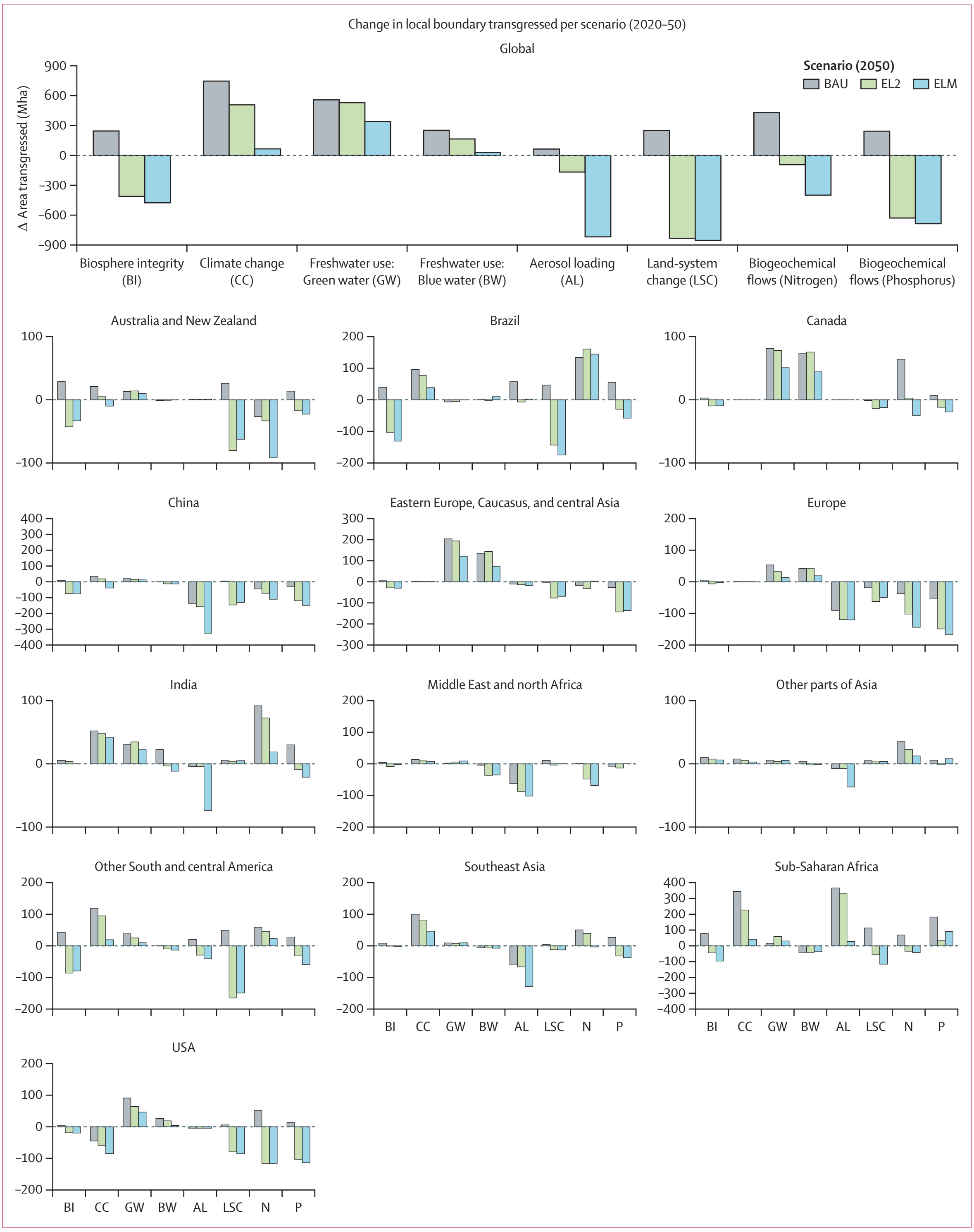


Figure 4: **Changes in local boundary transgressions aggregated to regional and global totals for eight boundaries**

Aggregate change of local boundary transgressions, as compared with the historical reference period (2020) for BAU, and the food system-transformation (EL2) and climate change-mitigation (ELM) scenarios across eight different local boundaries. The regions are mapped to the EAT-*Lancet* Commission 2.0 classification (appendix p 13). AL=aerosol landing. BAU=business-as-usual. BI=biosphere integrity. BW=blue water. CC=climate change. GW=green water. LSC=land-system change. N=nitrogen. P=phosphorus.

Discussion

Our results showed that the number of multiple (planetary boundary) transgressions were reduced under a food system transformation, with further reductions upon addition of climate change-mitigation measures. This finding is important as evidence suggests that multiple boundary transgressions have an amplifying effect on their safe operating space.[29,30] Policies targeting the food system appear to predominantly reduce transgressions in the biosphere integrity and land-system change domains. Dietary change is the most effective policy (in terms of reducing transgression rates) in regions with high livestock densities such as Brazil. This finding aligns with previous findings, which show that shifting away from animal-source diets frees up land used for pasture and feed, increasing the capacity to meet food demand within planetary boundaries.[7,20,42] However, dietary change makes a smaller contribution to reducing climate change transgressions than what similar studies suggest,[19,21] because our climate indicators respond to all greenhouse gas emissions (energy and industrial emissions, and land use-related emission). Increased agricultural productivity mainly drives improvements in the biogeochemical flows domain. Previous work shows that higher yields can raise nutrient flows because of additional fertilisation.[20] In our productivity scenario, however, we assumed increased nitrogen-use efficiencies and reduced phosphorus application rates, reducing biogeochemical flows transgressions. Halving FLW only contributes a few percentage in reducing local boundary transgressions, consistent with other work showing that FLW reductions yield smaller environmental benefits than dietary change.[19,20] These measures nonetheless remain important for keeping the food system affordable and fair.[19,21] This study illustrates a discrepancy between trade-off assessments at multiple scales: although no direct trade-offs between the EL2 and ELM scenarios appear at the global level, local transgressions reveal trade-offs in some regions, specifically in the biosphere integrity and land-system change domains. These trade-offs could result from regional competition for agricultural land (from biofuels) or the expansion of nature protection. This finding highlights the importance of adopting a multiscale approach to interpret and evaluate planetary boundary transgressions.

This study builds on previous scenario studies that primarily focus on the global perspective,[22,23] or uses only a subset of boundaries.[7,24] For example, Gerten and colleagues[7] only looked at four terrestrial planetary boundaries, whereas van Vuuren and colleagues[22] and Beier and colleagues[23] extended the domain coverage but stayed at the global scale. By combining a broader range of planetary boundary domains (eight of nine) with a local scale assessment, we could identify spatially heterogeneous patterns in indicator pressures and reveal local improvements from a food system transformation.

The different individual policy options for a food system transformation as presented in this study can partly mitigate future planetary boundary transgressions. A combination of policies, such as additional climate change-mitigation efforts, can further reduce these pressures on the Earth system, but such measures might not be sufficient for all boundary transgressions. Although previous work shows that staying within a subset of planetary boundaries might be possible with targeted policies,[7,24] our results show that challenges remain when we consider a broader set of boundaries. Both climate policies and food system transformations require broad societal acceptance,[21] suggesting that they could support each other as part of a broader transition towards global sustainability. We assume global adoption of the Planetary Health Diet by 2050. In reality, shifting diets can be challenging because of various cultural and socioeconomic factors.[43,44] Achieving dietary changes would require exploring a range of policy measures, such as informing consumers and increasing the visibility of plant-based foods.[45] Other policy incentives to transition towards such a diet include subsidies for healthy foods, and a combination of taxation and regulatory measures targeting unhealthy foods.[21]

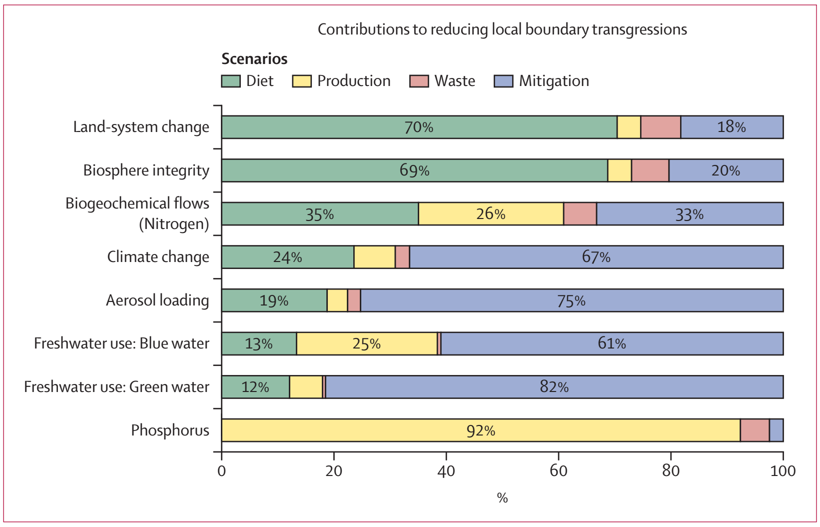


Figure 5: **Decomposition of local boundary transgression by individual driver**
Horizontal bars show the percentage change attributable to dietary change (green), productivity increase (yellow), losses and waste reduction (red), and climate change-mitigation measures (blue). The indicators are sorted from high to low contribution of dietary change.

This study has some limitations that should be noted. We used only one SSP2 baseline socioeconomic trajectory as an exogenous driver for all scenarios, to focus exclusively on the impacts of a food system transformation and climate change mitigation. This approach is in line with the multimodel assessment that was the basis for scenario development.[19] In IMAGE, consumer and producer prices, consumption of agricultural goods, and farmers' income are adjusted. However, gross domestic product does not respond dynamically, even though a full food system transformation would likely affect this aspect. Similarly, for the freshwater change domain, we applied the latest green and blue water definitions[26] but used a single model setup rather than a multimodel mean, because LPJmL is integrated in IMAGE as its only hydrological component, resulting in slightly different historical transgressions, as compared with those in the study by Porkka and colleagues.[26] Furthermore, we did not account for uncertainty when visualising our transgression maps, and they are reported as either transgressed or not. We acknowledge that other methodologies can capture these uncertainties, for example, the study by Hadjikakou and colleagues[20] instead expresses each boundary as a probability and reports the risk of exceeding the boundary.

Our global and local indicators are based on existing planetary boundary literature,[14,25,26] but due to model and data constraints, we made minor adjustments and adopted alternatives for our local climate change (wet-bulb temperatures) and land-system change (natural area shares) domains. Moreover, the global and local indicators used in this study were not always identical, making direct comparison between the two scales difficult. However, they could still provide complementary insights into the planetary boundary domains. Behrens and Poore[46] caution against attributing non-food impacts to the food system, which our decomposition addresses by separating food-specific effects from non-food drivers such as bioenergy.

This study also does not account for interactions between boundaries, which can amplify transgressions,[30] meaning our results are probably on the conservative side. For aerosol loading and climate change, we based the local limits on human health rather than the underlying Earth system process, following the study by Rockström and colleagues,[16] who highlight that these processes can also be harmful for human health and, therefore, include additional justice indicators. This approach means that for two local indicator domains (aerosol loading and climate change), the boundaries are more stringent than those for their Earth system counterparts. We applied the same logic in this study by including $PM_{2\cdot5}$ concentrations for aerosol loading, following WHO public health standards, rather than the atmospheric effects on monsoon variability, as proposed by Steffen and colleagues.[14] Using $PM_{2\cdot5}$ concentrations also enabled us to achieve global coverage. In a similar way, we included dangerous levels of wet-bulb temperatures as a regional boundary indicator for climate change. Two boundary domains were not included at the local level: ocean acidification and novel entities. Although ocean acidification can have region-specific impacts,[47] we focused our grid analysis on land-based indicators. Novel entities were not included due to high uncertainties with respect to chemical load impacts on the environment and human wellbeing,[16] in addition to severe data limitations. However, there are studies suggesting that we are already transgressing the novel entities boundary.[48] Further research is needed to establish control variables and boundary values for novel entities.

Further research could also explore the opportunities offered by novel foods, such as cultivated meat, which are also likely to further reduce environmental impacts.[49] Although this study primarily assessed the environmental impacts of a food system transformation, there are other benefits from a dietary shift, including health benefits from reducing the prevalence of non-communicable diseases,[50] and improvements in animal welfare.[51] Additionally, restructuring food systems can raise food prices and disrupt agricultural incomes in some regions.[19] Future work should analyse these trade-offs against national objectives, such as agricultural employment or food self-sufficiency.

Contributors
HL, JCD, ES, and DvV conceptualised this study. HL conducted the formal analysis, visualisation, and wrote the original draft. HL, JCD, HB, ABo, ABe, VD, AM, LS-U, StW, WJvZ, ES, and DvV worked on the methodology and development of the models. HL, JCD, Abe, and MS were responsible for data curation. HL and JCD directly accessed and verified the underlying data. All authors had full access to the data in the study and had final responsibility to submit for publication.

Declaration of interests
We declare no competing interests.

Data sharing
The model output data and code to reproduce the figures will be made available to researchers on reasonable request to the corresponding author, following publication.

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References
1 van Dijk M, Morley T, Rau ML, Saghai Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat Food* 2021; **2:** 494–501.
2 Jaureguiberry P, Titeux N, Wiemers M, et al. The direct drivers of recent global anthropogenic biodiversity loss. *Sci Adv* 2022; **8:** eabm9982.
3 Intergovernmental Panel on Climate Change. Climate Change 2022: impacts, adaptation, and vulnerability. In: Pörtner HO, Roberts DC, Tignor M, et al, eds. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2022.
4 Dupas R, Delmas M, Dorioz J-M, Garnier J, Moatar F, Gascuel-Odoux C. Assessing the impact of agricultural pressures on N and P loads and eutrophication risk. *Ecol Indic* 2015; **48:** 396–407.
5 Carvalho FP. Pesticides, environment, and food safety. *Food Energy Secur* 2017; **6:** 48–60.
6 Bowles N, Alexander S, Hadjikakou M. The livestock sector and planetary boundaries: a 'limits to growth' perspective with dietary implications. *Ecol Econ* 2019; **160:** 128–36.
7 Gerten D, Heck V, Jägermeyr J, et al. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat Sustain* 2020; **3:** 200–08.
8 Campbell BM, Beare DJ, Bennett EM, et al. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol Soc* 2017; **22.**

9 Te Wierik S, DeClerck F, Beusen A, et al. Identifying the safe operating space for food systems. *Nat Food* 2025; **6:** 1153–63.

10 Conijn JG, Bindraban PS, Schröder JJ, Jongschaap REE. Can our global food system meet food demand within planetary boundaries? *Agric Ecosyst Environ* 2018; **251:** 244–56.

11 Willett W, Rockström J, Loken B, et al. Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems. *Lancet* 2019; **393:** 447–92.

12 Springmann M, Clark M, Mason-D'Croz D, et al. Options for keeping the food system within environmental limits. *Nature* 2018; **562:** 519–25.

13 Watson JEM, Dudley N, Segan DB, Hockings M. The performance and potential of protected areas. *Nature* 2014; **515:** 67–73.

14 Steffen W, Richardson K, Rockström J, et al. Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science* 2015; **347:** 1259855.

15 Rockström J, Steffen W, Noone K, et al. Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc* 2009; **14.**

16 Rockström J, Gupta J, Qin D, et al. Safe and just Earth system boundaries. *Nature* 2023; **619:** 102–11.

17 Richardson K, Steffen W, Lucht W, et al. Earth beyond six of nine planetary boundaries. *Sci Adv* 2023; **9:** eadh2458.

18 Findlay HS, Feely RA, Jiang LQ, Pelletier G, Bednaršek N. Ocean acidification: another planetary boundary crossed. *Glob Change Biol* 2025; **31:** e70238.

19 Sundiang M, Diniz Oliveira T, Mason-D'Croz D, et al. Bundling measures for food systems transformation: a global, multimodel assessment. *Lancet Planet Health* 2025; **9:** 101339.

20 Hadjikakou M, Bowles NI, Geyik O, et al. Ambitious food system interventions required to mitigate the risk of exceeding Earth's environmental limits. *One Earth* 2025; **8:** 101351.

21 Rockström J, Thilsted SH, Willett WC, et al. The EAT-*Lancet* Commission on healthy, sustainable, and just food systems. *Lancet* 2025; **406:** 1625–700.

22 van Vuuren DP, Doelman JC, Schmidt Tagomori I, et al. Exploring pathways for world development within planetary boundaries. *Nature* 2025; **641:** 910–16.

23 Beier FD, Dietrich JP, Heinke J, et al. Planetary boundaries under a land-based climate change mitigation scenario with a food demand transformation: a modelling study. *Lancet Planet Health* 2025; **9:** 101249.

24 Heck V, Gerten D, Lucht W, Popp A. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat Clim Change* 2018; **8:** 151–55.

25 Schulte-Uebbing LF, Beusen AHW, Bouwman AF, de Vries W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* 2022; **610:** 507–12.

26 Porkka M, Virkki V, Wang-Erlandsson L, et al. Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change. *Nat Water* 2024; **2:** 262–73.

27 Humpenöder F, Popp A, Merfort L, et al. Food matters: dietary shifts increase the feasibility of 1.5°C pathways in line with the Paris Agreement. *Sci Adv* 2024; **10:** eadj3832.

28 PBL Netherlands Environmental Assessment Agency. Integrated assessment of global environmental change with IMAGE 3.0: model description and policy applications. 2014. https://www.pbl.nl/sites/default/files/downloads/pbl-2014-integrated_assessment_of_global_environmental_change_with_image30_735.pdf (accessed June 29, 2026).

29 Chrysafi A, Virkki V, Jalava M, et al. Quantifying Earth system interactions for sustainable food production via expert elicitation. *Nat Sustain* 2022; **5:** 830–42.

30 Lade SJ, Steffen W, de Vries W, et al. Human impacts on planetary boundaries amplified by Earth system interactions. *Nat Sustain* 2020; **3:** 119–28.

31 PBL Netherlands Environmental Assessment Agency. IMAGE documentation. https://models.pbl.nl/image/Welcome_to_IMAGE_3.3_Documentation (accessed June 29, 2026).

32 Riahi K, van Vuuren DP, Kriegler E, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob Environ Change* 2017; **42:** 153–68.

33 Doelman JC, Stehfest E, Tabeau A, et al. Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation. *Glob Environ Change* 2018; **48:** 119–35.

34 Jägermeyr J, Müller C, Ruane AC, et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat Food* 2021; **2:** 873–85.

35 Thornton P, Nelson G, Mayberry D, Herrero M. Increases in extreme heat stress in domesticated livestock species during the twenty-first century. *Glob Change Biol* 2021; **27:** 5762–72.

36 Nelson GC, Vanos J, Havenith G, Jay O, Ebi KL, Hijmans RJ. Global reductions in manual agricultural work capacity due to climate change. *Glob Change Biol* 2024; **30:** e17142.

37 Stehfest E, van Zeist W-J, Valin H, et al. Key determinants of global land-use projections. *Nat Commun* 2019; **10:** 2166.

38 Liang C, Zheng G, Zhu N, Tian Z, Lu S, Chen Y. A new environmental heat stress index for indoor hot and humid environments based on Cox regression. *Build Environ* 2011; **46:** 2472–79.

39 de Vries W, Schulte-Uebbing L, Beusen A, te Wierik S. Revisiting safe and just planetary boundaries for nitrogen and phosphorus. *Curr Opin Environ Sustain* 2026; **83:** 101685.

40 WHO. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Sept 22, 2021. https://www.who.int/publications/i/item/9789240034228 (accessed June 29, 2026).

41 Ambrósio G, Doelman JC, Schipper AM, Stehfest E, van Vuuren D. Global sustainability scenarios lead to regionally different outcomes for terrestrial biodiversity. *Environ Res Lett* 2024; **19:** 104055.

42 Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science* 2018; **360:** 987–92.

43 Stoll-Kleemann S, Schmidt UJ. Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors. *Reg Environ Change* 2017; **17:** 1261–77.

44 Hoek AC, Pearson D, James SW, Lawrence MA, Friel S. Shrinking the food-print: a qualitative study into consumer perceptions, experiences and attitudes towards healthy and environmentally friendly food behaviours. *Appetite* 2017; **108:** 117–31.

45 Kwasny T, Dobernig K, Riefler P. Towards reduced meat consumption: a systematic literature review of intervention effectiveness, 2001–2019. *Appetite* 2022; **168:** 105739.

46 Behrens P, Poore J. Food systems boundaries are currently poorly defined. *Nat Food* 2025; **6:** 1098–99.

47 Jiang LQ, Feely RA, Carter BR, Greeley DJ, Gledhill DK, Arzayus KM. Climatological distribution of aragonite saturation state in the global oceans. *Glob Biogeochem Cycles* 2015; **29:** 1656–73.

48 Persson L, Carney Almroth BM, Collins CD, et al. Outside the safe operating space of the planetary boundary for novel entities. *Environ Sci Technol* 2022; **56:** 1510–21.

49 Mazac R, Meinilä J, Korkalo L, Järviö N, Jalava M, Tuomisto HL. Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80%. *Nat Food* 2022; **3:** 286–93.

50 Wang DD, Li Y, Afshin A, et al. Global improvement in dietary quality could lead to substantial reduction in premature death. *J Nutr* 2019; **149:** 1065–74.

51 van Marle-Köster E, Visser C. Unintended consequences of selection for increased production on the health and welfare of livestock. *Arch Anim Breed* 2021; **64:** 177–85.