nature food

Article

https://doi.org/10.1038/s43016-025-01252-6

Identifying the safe operating space for food systems

Received: 9 February 2025

Accepted: 30 September 2025

Published online: 31 October 2025

Check for updates

Sofie te Wierik[1,2] ✉, Fabrice DeClerck[3,4], Arthur Beusen[2,5], Dieter Gerten[1,6], Federico Maggi[7], Anna Norberg[1], Kevin Noone[8], Lena Schulte-Uebbing[2], Marco Springmann[9], Fiona H. M. Tang[10], Wim de Vries[11], Detlef van Vuuren[2,12], Sonja Vermeulen[13] & Johan Rockström[1,14,15]

Global environmental pressures from food systems threaten biodiversity and the stability of the Earth system, yet the safe operating space for food systems is unknown. Here we calculate food system boundaries as shares of planetary boundaries, proposing budgets for the food system across nine boundaries. Our results indicate that food systems are a critical driver of planetary boundary transgressions, dominating at least four transgressed boundaries (that is, biosphere integrity, land system change, freshwater change and biogeochemical flows) while strongly contributing to the transgression of two more (that is, climate change and novel entities). Moreover, global food systems are currently beyond all nine food system boundaries; moving to the safe operating space requires reducing related greenhouse gas emissions substantially, halting the conversion of intact nature to agriculture, redistributing fertilizer inputs, limiting pesticide and antibiotic use, and preserving critical freshwater flows without negatively affecting yields.

The planetary boundary (PB) framework[1] aims to define and quantify a safe operating space for humanity based on environmental thresholds, within which human activities can unfold without threatening the stability of the Earth system[1]. As of now, six of nine PBs are being transgressed[2]. There is ample evidence that food systems are a dominant driver of global environmental change[3–5], mainly from agricultural production[6]. Several studies quantifying the impacts of agricultural production[6,7] and food systems[5] across the PBs concordantly show that agricultural production alone is responsible for the current transgression of the biosphere integrity and biogeochemical flows PBs[6] and contributes strongly to the transgression of other PBs, thereby pushing the Earth system further into a zone of increasing risk. Dietary shifts, changes in production systems, improved land governance, and reduction in food loss and waste can help bring such systems back to the safe operating space defined by PBs for freshwater, biogeochemical flows, land-system change, biosphere integrity and climate change, while still producing sufficient food to feed around 10 billion people in 2050[5,7]. Yet, estimating the full potential of food systems to move back into this safe operating space is a complex exercise which, so far, remains limited to a subset of the boundaries[7–9] or uses global proxy indicators for PB domains[5,6]. In addition, some of these studies lack the regional detail necessary to assess transgression risks for local ecosystems[10]. In other words, a framework to navigate food systems back into their safe operating space is needed, but a comprehensive assessment of the boundaries for the food system is still lacking.

[1]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany. [2]PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands. [3]EAT, Oslo, Norway. [4]Alliance of Biodiversity and CIAT, CGIAR, Montpellier, France. [5]Department of Earth Sciences-Geochemistry, Utrecht University, Utrecht, Netherlands. [6]Geography Department, Humboldt-Universität zu Berlin, Berlin, Germany. [7]The University of Sydney, Sydney, New South Wales, Australia. [8]Stockholm University, Stockholm, Sweden. [9]Institute for Global Health, University College London, London, UK. [10]Department of Civil Engineering, Monash University, Clayton, Victoria, Australia. [11]Wageningen University and Research, Wageningen, Netherlands. [12]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands. [13]Senior Advisor at Clim-Eat. Agro Business Park 10, Wageningen, Netherlands. [14]Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany. [15]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. ✉e-mail: sofietewierik@gmail.com

In this study, we consolidate scientific evidence on the impact of food systems across all nine planetary boundaries, proposing a set of food system boundaries (FSBs) that may serve as a guideline to ensure that food systems operate within their safe operating space (Table 1). FSBs correspond to shares of PBs estimated specifically for food systems, calculated as scenario-based budgets for the food system. We account for the impacts of food production (consistent with the 'agriculture, forestry and land use' (AFOLU) category used in IPCC reports) and pre- and postprocessing stages, although our calculations are sometimes limited by data granularity (for example, we were not always able to disaggregate food versus non-food agricultural production) or availability (for example, no estimates were available for pre- and postprocessing impacts). First, we quantified the present-day contribution of food systems to the PBs, updating existing calculations[6] based on a consistent methodological approach across all PB domains (see Methods) and guided by the most recent advances in PB science[2,11], thereby aiming to use robust evidence from multimodel ensembles. Despite the data limitations mentioned above, evidence suggests that the non-food contribution of agricultural production to each boundary is minor at the global level (Fig. 1). Second, we identified FSBs by allocating a share of the safe operating space to food systems based on available scientific evidence. In contrast to the PBs—which are based on quantified levels of risk associated with global change[1]—FSBs are based on several principles adopted in current scientific assessments, ranging from (economically) optimized allocations of emission reductions using integrated assessment models (for example, as for the climate change FSB), to proportional reductions based on their current contributions to boundary transgressions (for example, for freshwater and biogeochemical flow FSBs, assuming similar efforts across sectors to enable a return to the safe operating space), to effects emerging from boundary interactions (for example, for ozone depletion and aerosol loading FSBs, responding to reductions in nitrogen surplus under the biogeochemical flow FSBs). There is no single, uniform approach available to quantify the FSBs across the current literature; for transparency, a full overview of studies included is provided in Supplementary Table 1.

In summary, this study aims to provide an integrated assessment of the safe operating space for food systems (Fig. 2). Because food systems impact multiple planetary boundaries through local-to-regional practices on land and in marine systems, we opted to retain the biogeophysical and global character of the PB framework while also considering more explicitly regional-scale processes and impacts across the different PBs.

Results

Climate change

Food is responsible for around 30% of current greenhouse gas (GHG) emissions. AFOLU emissions amount to 11.9 $GtCO_2e\ yr^{-1}$ (21% of total emissions), comprising CO_2 emissions from land conversion (5.9 $GtCO_2e\ yr^{-1}$), methane (CH_4) emissions (4.2 $GtCO_2e\ yr^{-1}$) and nitrous oxide (N_2O) emissions (1.8 $GtCO_2e\ yr^{-1}$). Other emissions (energy use on-farm and post-farmgate, transport, cold storage, processing, retail, catering, food management in homes, and waste) amount 5.8 $GtCO_2e\ yr^{-1}$ (ref. 12) (Supplementary Table 2 and Supplementary Text 1). These emissions have added an estimated ±1 W m^{-2} of positive radiative forcing with respect to preindustrial levels. They are partly offset by negative forcing from agricultural-induced aerosol emissions and land use change, suggesting a contribution to the net radiative forcing effect of 24% (although large uncertainties for some forcers exist) (Supplementary Table 4). Various studies—including top-down economically optimized allocation modelling using integrated assessment models (IAMs), and bottom-up sectoral mitigation potential assessments—confirm that AFOLU emissions should be reduced to around 5 $GtCO_2e\ yr^{-1}$ (Supplementary Table 3), comprising solely non-CO_2 emissions from food systems that are hard to abate, to remain within 1.5 °C of warming if combined with carbon removal strategies[13]. We therefore adhere to 5 $GtCO_2e\ yr^{-1}$ as the FSB for climate change. Note that, in addition, negative CO_2 emissions from AFOLU are critical across all 1.5 °C scenarios by 2050[13], which are not included in the FSB as defined here.

Land system change

Agricultural land covers 48 Mkm^2, which is 37% of the global land area. A third of agricultural land is used for crop production (16 Mkm^2), while the remaining 32 Mkm^2 comprises permanent meadows and pastures[14]. Continuing agricultural expansion predominantly occurs at the expense of tropical forest[15,16], making food systems the most important driver of deforestation and loss of intact nature[17]. Various studies confirm that 50–60% of land must remain intact to protect biodiversity and its contributions to climate mitigation and hydrological cycles[11,18,19]. We adopt this (lower) bound of 50% of remaining intactness as boundaries at both the global and ecoregion level, with particular attention to forest biomes for climate regulation[2]. Distribution of agricultural land and remaining intactness is irregular across ecoregions (Fig. 3) and forest biomes (Supplementary Fig. 1). In 5% of the ecoregions, croplands alone breach the 50% intactness boundary. When including grazing lands, 34% of ecoregions are transgressed (Supplementary Text 2). Staying within the land system PB requires zero conversion of remaining intact ecosystems, while restoring intactness in areas with substantial losses (Fig. 3).

Biosphere integrity

Land conversion, freshwater drawdown, and pollution from chemical and nutrient overloads[20] in agriculture are the main drivers of biodiversity loss. They affect the supporting functions across agricultural ecosystems (that is, ecosystem integrity, expressed as the embedded natural habitat on agricultural lands) and the global energy balance of the biosphere (that is, biosphere integrity, expressed as the human-appropriated net primary productivity (HANPP)). Ecosystem functional integrity requires (semi)natural habitat embedded in agricultural lands (for example, hedgerows, buffer strips) to preserve fine-scaled ecosystem functions (for example, pollination, pest control, sediment and nutrient capture functions). Recent analyses support 10–25% (semi)natural habitat per km^2 as a critical minimum value below which such functions are lost[11,21,22], which we adopt as a boundary for all agricultural lands (of which 88% are used to produce food)[4]. Between 33% and 60% of agricultural lands are currently below the boundary[22].

The PB for biosphere integrity (HANPP) suggests that 90% of Holocene NPP (in total 55 GtC yr^{-1}), plus the climate resilience response of the biosphere (>15 GtC yr^{-1} additional uptake from CO_2 fertilization), should remain available for ecosystems[2], implying that around 10% of Holocene NPP (5.5 GtC yr^{-1}) can be safely appropriated. Food systems appropriate NPP via land conversion and harvesting of biomass, in total amounting to 9.9–11.7 GtC yr^{-1} (72–85% of total HANPP; Supplementary Table 4)[2,23,24]. Considering the dominant food system share, we propose that the FSB is placed at the PB (<10% HANPP, or 5.5 GtC yr^{-1}), while ensuring that the Earth system does not exceed the upper end of the zone of increasing risk (20% HANPP)[2] when including additional land uses (for example, urbanization, industrial use).

Freshwater change

Most human freshwater consumption from water withdrawals is for irrigating crops. Process-based models estimate irrigation consumptive use at around 1,200 $km^3\ yr^{-1}$ (of which 545 $km^3\ yr^{-1}$ is sourced from groundwater)[25], while water footprint assessments appear to be at the higher end of the range (1,800 $km^3\ yr^{-1}$)[5] (Supplementary Table 6). However, as the majority of agricultural lands is rainfed, accounting for consumption of green water (plant-available soil moisture) in addition to blue water consumption adds another ~7,000 $km^3\ yr^{-1}$ (refs. 26–28). The PB for freshwater was initially expressed only in terms of a blue water consumptive use limit to preserve ecological flow requirements

https://doi.org/10.1038/s43016-025-01252-6

Table 1 | Overview of the state of food systems and FSBs across planetary boundaries

Earth system domain	Control variable	PB	Current state	Contribution of the food system (% of total)	FSB	FSB status
Climate change	Atmospheric CO_2 concentration (ppm CO_2)	350 ppm	419 ppm	16–17.7 $GtCO_2e\,yr^{-1}$ (~30% of total emissions)	<5 $GtCO_2e\,yr^{-1}$ of remaining emissions	Transgressed
	Total anthropogenic radiative forcing at top-of-atmosphere ($W\,m^{-2}$)	+1.2 $W\,m^{-2}$	+2.91 $W\,m^{-2}$	+0.69 $W\,m^{-2}$ (2% of total radiative forcing)		
Land system change	Global: Area of intact land as the percentage of original cover [a]	Global: 50–60% remaining intactness	Global: 50% remaining intactness	Global: 48 Mkm^2 (37% of total land area)	Agricultural land <48 Mkm^2 (halting conversion of intact land); <40–50% agricultural land at ecoregion level; restoring 8.5 Mkm^2 in forest ecoregions	Partly transgressed
	Forest biome: Area of forested land as the percentage of potential forest (% area remaining)	Forest biomes: Tropical, 85%; temperate, 50%; boreal, 85%	Forest biomes: Tropical, 37.5–83.9%; temperate, 34.2–51.2%; boreal, 56.6–70.3%	Forest biomes: Agricultural area covers 25–50% of tropical forest, 20–65% of temperate forest and 3% of boreal forest		
	Ecoregions: Area of intact land as a percentage of the original cover by ecoregion[a]	Ecoregions: 50–60% remaining intact across all ecoregions	Ecoregions: 10–95% remaining intact	Ecoregions: 34% of ecoregions below the intactness threshold (50%) due to agriculture alone		
Biosphere integrity	Ecosystem functional integrity[a]	>20–25% habitat per km^2 for supporting agroecosystem functioning	30–60% of agricultural lands below boundary	88% of agricultural lands used for food production	100% of agricultural lands for food production within boundary	Transgressed
	Biosphere functional integrity	HANPP [1] <10% of Holocene NPP, that is, remaining >90% for the biosphere	13–16.8 $GtC\,yr^{-1}$ (25–30% of Holocene NPP)	9.9–11.7 $GtC\,yr^{-1}$ (72–85% of total HANPP)	<5.5 $GtC\,yr^{-1}$	Transgressed
Freshwater use	Consumptive blue water use ($km^3\,yr^{-1}$)[d]	2,800 $km^3\,yr^{-1}$	1,800–2,600 $km^3\,yr^{-1}$	>1,200–1,800 $km^3\,yr^{-1}$ (70% of consumptive use)	< 2,000 $km^3\,yr^{-1}$	Regionally transgressed
	Green water (% of ice-free land area beyond 5–95th variability envelope)	11.1% of ice-free land area with local deviations	15.8% of ice-free land area with local deviations	16.8% of agricultural land is beyond local variability envelope	Agricultural land remains within global soil moisture variability envelopes (11.1% of ice-free land area beyond variability envelope)	Transgressed
Biogeochemical glows	Nitrogen surplus ($TgN\,yr^{-1}$)[b]	57 $TgN\,yr^{-1}$	119 $TgN\,yr^{-1}$	50%, 70% and 80% to deposition, surface water load, and groundwater leaching, respectively	<57 $TgN\,yr^{-1}$ (corresponding to agricultural nitrogen input <134 $TgN\,yr^{-1}$ based on current NUE)	Transgressed
	Phosphorus loss to surface water ($TgP\,yr^{-1}$)[c]	6.1 $TgP\,yr^{-1}$	9.7 $TgP\,yr^{-1}$	7.2 $TgP\,yr^{-1}$ (75% of total phosphorus delivery)	<4.6 $TgP\,yr^{-1}$	Transgressed
Stratospheric ozone depletion	Stratospheric O_3 concentration (global average) (Dobson unit, DU)	<5% reduction from preindustrial level assessed by latitude (~276 DU)	284 DU	3.9–4.2 $TgN\,yr^{-1}$ agricultural N_2O emissions as main ozone-depleting substance (54–69% of total N_2O emissions)	<1.8 $TgN\,yr^{-1}$	Transgressed although globally within boundary

https://doi.org/10.1038/s43016-025-01252-6

Table 1 (continued) | Overview of the state of food systems and FSBs across planetary boundaries

Earth system domain	Control variable	PB	Current state	Contribution of the food system (% of total)	FSB	FSB status
Aerosol loading	Interhemispheric difference in AOD	<0.1 (mean annual interhemispheric difference)	0.076	Northern hemisphere: >80% of NH_3 emissions forming secondary PM2.5 concentrations Southern hemisphere: >50% of PM2.5 from biomass burning due to food system	Northern hemisphere: <20 $TgNH_3$ (45% reduction in global NH_3 emissions compared with current emissions) Southern hemisphere: halting biomass burning emissions from land conversion	Transgressed
Ocean acidification	Average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% of the preindustrial averaged global Ω_{arag} of 3.4	2.8	25% of CO_2 emissions as main driver of change in Ω_{arag}	Zero net CO_2 emissions from land use change and fossil emissions in the food chain	Transgressed
Novel entities	Percentage of synthetic chemicals released to the environment without adequate safety testing[e,f]	-	-	PAS application ($Tg\,yr^{-1}$): 3.3–3.7 (85–90% of total pesticide use)	<1 $TgPAS\,yr^{-1}$ (>70% reduction of current application) to avoid high pollution risk; <0.2 $TgPAS\,yr^{-1}$ (>90% reduction of current application) to remain below low pollution risk	Transgressed
		-	-	Antimicrobial use in food animals ($t\,yr^{-1}$): 73–130 $kt\,yr^{-1}$ (73% of total antimicrobial use)	Halting prophylactic use and reducing overall use by >50% (max. 36,500-75,000 $t\,yr^{-1}$)	Transgressed

The current contributions of the food system to the PBs are provided in absolute numbers and relative contributions (in brackets). The control variable, PB and current state are provided primarily based on the most recent assessments by ref. 2, unless indicated otherwise: [a]ref. 11, [b]ref. 10, [c]ref. 35, [d]ref. 9, [e]ref. 57, [f]ref. 59. Note that atmospheric CO_2 concentration control variable under the climate change boundary is expressed in CO_2e for the food system contribution and the FSB (including non-CO_2 gasses of CH_4 and N_2O). 'Partly transgressed' under 'FSB status' suggests either that at least one out of several control variables is transgressed; or that thresholds are breached regionally but remain within PBs globally.

(EFRs)[1,29]. Recent scientific updates recognize green water and express the PB based on the global land area (as a percentage) that experiences significant wet or dry soil moisture (green water) or streamflow (blue water) events compared with preindustrial variability baselines[2,30,31]. Currently 18.2% (15.8%) of ice-free land is experiencing such local blue (green) deviations from preindustrial conditions, compared with 10.2% (11.1%) in the preindustrial period, indicating strong transgression of the freshwater change PB.

Quantifying the contributions of food systems and defining a FSB for blue and green water using this novel freshwater PB is challenging (Supplementary Text 4). We propose that food systems remain within local EFR boundaries for blue water, with a global budget of 2,000 $km^3\,yr^{-1}$ (Supplementary Text 4), including groundwater[11], while remaining within the global green water deviation variability envelope across all agricultural lands (11.1%; Supplementary Fig. 3). Although this suggests we are within the PB for blue water, irrigation alone is transgressing regional EFR limits at river basin level, summing up to a global water withdrawal overshoot of ~1,000 $km^3\,yr^{-1}$ (ref. 32). In addition, 16.8% of agricultural land is beyond local variability envelopes for green water, and well above the global preindustrial value of 11.1% (Supplementary Fig. 3)

Biogeochemical flows

Nitrogen and phosphorus are key nutrients for crop growth and limited availability has adverse effects on crop yields. However, elevated nitrogen and phosphorus inputs in agriculture increase their losses to surface water, affecting aquatic biodiversity, causing harmful algal blooms and, in extreme cases, creating dead zones in coastal waters. Nitrogen losses to air cause terrestrial biodiversity loss from enhanced nitrogen deposition[33,34], and add climatic forcing through N_2O emissions. For nitrogen, we use regional nitrogen surplus boundaries derived by ref. 10, aggregated to a planetary nitrogen surplus, instead of the human-induced biological and chemical nitrogen fixation[2]. For phosphorus, we propose to use the phosphorus delivery (input) to surface water from agriculture, aquaculture and wastewater, with the losses from agriculture being dominated by soil phosphorus erosion (see Supplementary Text 5 for details on the control variables).

Nitrogen

The nitrogen input on agricultural lands (in total 233 $TgN\,yr^{-1}$ in 2010) derives from fertilizer, biological nitrogen fixation, manure and nitrogen (NH_3 and NO_x) deposition. Around half of the input is taken up by plants, while 119 $TgN\,yr^{-1}$ remains as agricultural surplus which, together with other nitrogen sources, ends up in surface water (70 $TgN\,yr^{-1}$), leaches to groundwater (56 $TgN\,yr^{-1}$) and is deposited on terrestrial ecosystems (20 $TgN\,yr^{-1}$). Food systems (including agriculture, aquaculture and nitrogen from wastewater) contribute around 70%, 80% and 50% to these processes, respectively (Supplementary Table 8), exceeding critical nitrogen surplus levels in two-thirds of the land area (Fig. 4). Respecting local nitrogen thresholds for surface water concentrations, groundwater leaching and deposition on terrestrial ecosystems, while allowing increased nitrogen input in nitrogen-deficient regions, leads to a nitrogen surplus boundary of 57 $TgN\,yr^{-1}$. Proportional reduction (that is, assuming proportional reductions across sectors) suggests that agricultural nitrogen surplus is brought back from 119 $TgN\,yr^{-1}$ to the PB value of 57 $TgN\,yr^{-1}$, associated with an agricultural nitrogen input reduction from 233 to 134 $TgN\,yr^{-1}$ (assuming a global mean current nitrogen use efficiency (NUE) of 50%). Improvements in NUE could

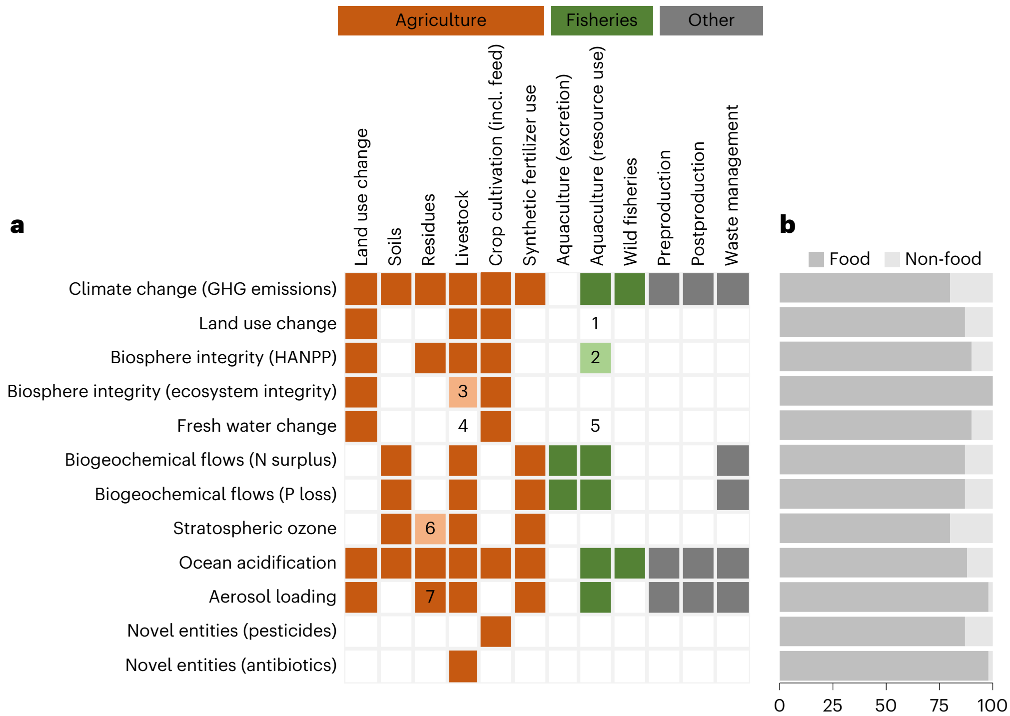

Fig. 1 | Definition of the food system and inclusion of food system elements and non-food agricultural production. a, Elements (columns) of the food system that are included in our estimate of the contribution of the food system to the PBs (rows). A further breakdown of elements is given in Supplementary Table 12. Elements within 'Agriculture' (orange) are equal to IPCC AFOLU accounting. Light shaded boxes represent elements that are partly included. Box numbers: 1, excludes surface area of ponds (only covers 0.055 Mkm^2 (ref. 82); 2, includes crop feed but excludes wild fish feed; 3, includes pasture lands but excludes seminatural extensive grazing land; 4, excludes livestock drinking water (only 2% of livestock water use)[83]; 5, evaporation from ponds is excluded (no data); 6, higher end of range includes biomass burning; 7, includes biomass burning from vegetation clearance in forest and peatlands. **b**, Estimated percentage share of non-food agricultural production (that is, crop and animal production for fibre, fuel or other industrial uses) included in our presented food system contribution estimates in Table 1. See Supplementary Table 1 and the data repository for Fig. 1 for details.

increase this critical nitrogen input limit without crossing the nitrogen surplus boundary[10] (Supplementary Text 5).

Phosphorus

Phosphorus losses to surface water are largely determined by physical soil erosion rates and the build-up of soil phosphorus content. Annual phosphorus delivery to surface water amounts to 9.7 TgP yr^{-1} (ref. 35), which is approximately 40% higher than the globally acceptable phosphorus delivery loss (6.1 TgP yr^{-1}) based on critical phosphorus surface water concentrations[36]. Food systems (including agriculture, aquaculture and phosphorus from wastewater; Fig. 3) contribute around 75% to these phosphorus losses[35] (Supplementary Table 8). Therefore, phosphorus loss from agricultural land should be reduced proportional to its 75% share (that is, from 7.2 to 4.6 TgP yr^{-1} from agricultural soils), reducing both the risk of surface water eutrophication and soil fertility loss.

Stratospheric ozone

Stratospheric ozone depletion has historically been dominated by the release of chlorofluorocarbons, but since the strict regulation imposed via the Montreal Protocol, the ozone layer has mostly recovered[2]. Currently, N_2O is the single most important ozone-depleting substance[37], and food systems are the dominant driver of N_2O emissions, mainly via fertilizer and manure application. Food systems are responsible for 54–69% (excluding or including biomass burning, respectively) of the anthropogenic N_2O emissions[38] (Supplementary Table 9). However, the contribution of N_2O to stratospheric ozone depletion remains small, and the concentration of stratospheric ozone is expected to return to historical values by the end of this century even without any further N_2O reductions[39]. We therefore restate the existing boundary for nitrogen surplus (57 TgN yr^{-1}), which simultaneously reduces the N_2O emissions (from 3.9 to 1.8 TgN$_2$O-N yr^{-1}) associated with exceeding the nitrogen surplus levels[10].

Ocean acidification

Ocean acidification has planetary-wide impacts through the loss of marine species dependent on calcium carbonate, and changes to marine carbon storage[40]. Acidification also amplifies threats to marine life deriving from climate change, such as ocean warming and associated thermal stress[41], and nutrient pollution in coastal zones[42]. Ocean acidification is strongly linked to CO_2 emissions, one-quarter of which is absorbed by the ocean[43,44], resulting in lower pH and hence affecting the aragonite saturation state. Food systems now contribute around 25% of the total CO_2 emissions[12,43,45] (and a similar rate of cumulative emissions from 1750 from land conversion; Supplementary Text 7), which following the climate change boundary, is set at zero CO_2 emission by 2050 through limiting emissions from land use change (5.9 GtCO$_2$ yr^{-1}) and other emissions from pre- and postproduction (4.3 GtCO$_2$ yr^{-1}) (Supplementary Table 2).

Aerosol loading

Increasing atmospheric aerosol loading—particular interhemispheric difference in aerosol optical depth (AOD), a measure of aerosol concentration blocking incoming solar radiation[2]—can have critical impacts on atmospheric circulation patterns (that is, monsoon patterns) and the ocean (that is, Atlantic meridional overturning circulation[46]). Overall, anthropogenic aerosol loading is highest in the northern hemisphere[47,48] where most of the land mass and associated human activities are concentrated, increasing the interhemispheric difference of AOD to 0.076 (ref. 2). Sources of aerosols are both natural (dust,

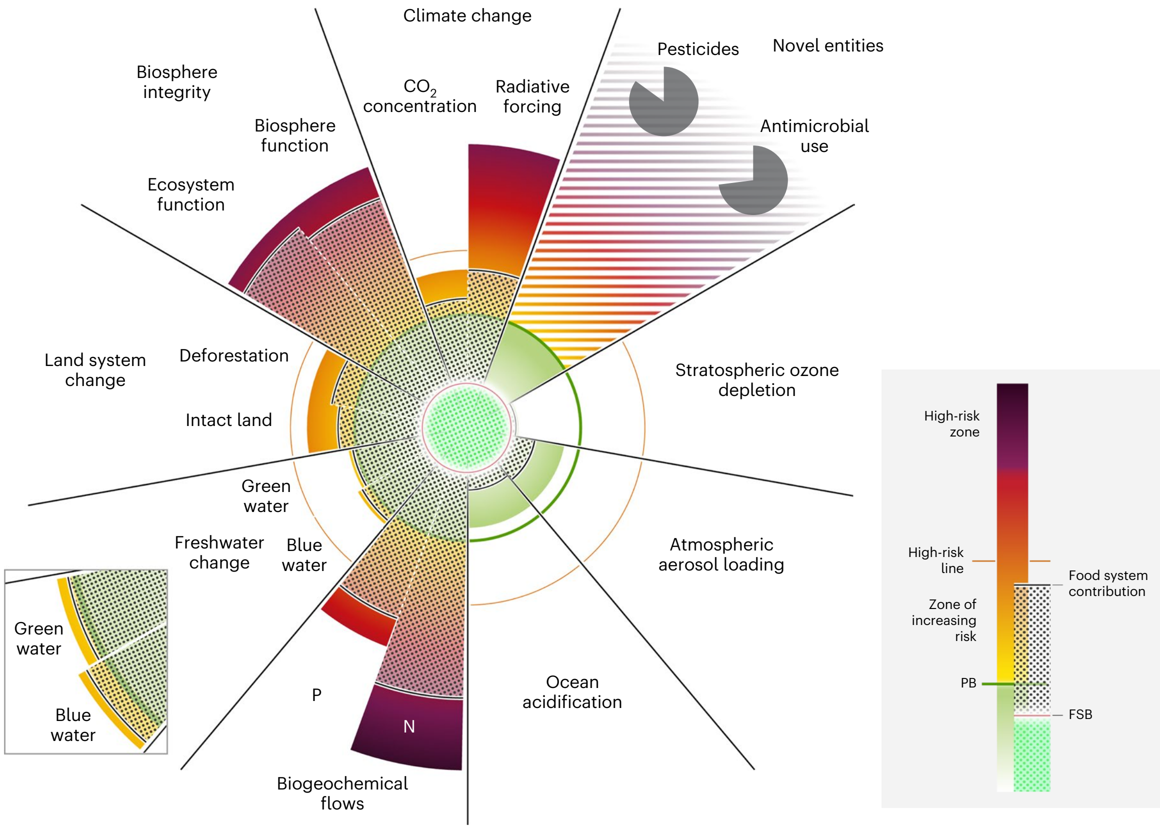

Fig. 2 | Status of the food system across PBs and the FSBs. FSBs (pink line) are represented in a stylized and uniform radius within the safe operating space (green sphere). The radar plot is adapted from ref. 2 (data) and ref. 11 (visualization). The contribution of the food system (in percentages, see Table 1 and Supplementary Table 11, indicated by the black dotted pattern) is projected based on the length of each wedge starting from the PB (for all transgressed boundaries) and the FSB (for the other three boundaries). The components representing novel entities (pesticides and antimicrobial use) are shown as pie charts within the largest set of all (up to now unquantified) novel entities. Note that CO_2 concentration is provided here in terms of CO_2, in contrast to the CO_2e in Table 1. Credit: Azote.

sand and wildfire contribute >75% of total PM2.5 mass globally) and anthropogenic (combustion, livestock, energy and industrial production, which contribute ~25% of PM2.5 mass) but predominant sources can regionally vary[49].

Food systems are a major contributor to anthropogenic aerosol loading by emitting direct particulate matter (PM2.5; that is, black and organic carbon from biomass burning from land clearance and agricultural waste burning) and secondary particle emissions from fertilizer use and livestock (NH_3) and energy-related processes in the food supply chain (SO_2)[50] (Supplementary Fig. 4). In the northern hemisphere, anthropogenic PM2.5 derives predominantly from fossil fuel combustion[51] and NH_3 emissions[49,52] from animal-based agriculture[50,52–54]. In the southern hemisphere, biomass burning is the main constituent of anthropogenic PM2.5, and is regionally responsible for up to 90% of the PM2.5 concentration[49]. Some estimates suggest that around half of global biomass burning-based PM2.5 (32 Mt yr^{-1}) derives from land conversion for agricultural production (14 Mt yr^{-1})[55]. In addition, agricultural waste burning emits another 6.8 Mt yr^{-1}. In the southern hemisphere, where land conversion is concentrated (in the tropical forests of Amazon, Congo and Indonesia), the contribution of food systems to PM2.5 concentration may even be higher. Remaining within the PB for aerosol loading requires aerosol emissions to be reduced in both the northern and southern hemisphere simultaneously, to protect local climate functioning, and human health and crop production[46,49,50,54]. We propose that northern hemisphere reductions in PM2.5 concentration can effectively be obtained through reducing NH_3 emissions in line with the nitrogen surplus boundary (global reduction of NH_3 emissions from 37 to 20 TgN yr^{-1}); while southern hemisphere reductions should be obtained from halting land conversion and associated emissions from biomass burning, in line with the land system change boundary.

Novel entities

Food systems are responsible for the release of a wide range of novel entities in the environment, such as plastics in food packaging and on-field use[56]; pesticides for crop protection[57]; antimicrobial use in animal husbandry[58,59]; and the introduction of (hybrid) varieties of genetically modified crops. Here, we consider pesticides and antibiotic use as key components of food system-sourced novel entities, considering their wide-spread use for food production and the availability of global data.

Pesticides. More than 3 Tg of pesticide active substances (PASs) are used in food production each year[60] (Supplementary Fig. 6). Around 82% of PASs subsequently degrade into a cascade of compounds; 10% remains as soil residues; 7.2% leaches below the root zone; and 0.1% enters river systems. These residue concentrations in surface water are exceeding safe exposure levels for aquatic biodiversity along 13,000 km of the world's major rivers[57]; 75% of agricultural land area is at risk of pesticide pollution by at least one active ingredient, while 64% is at risk of more than one active ingredient[61]. Bioaccumulation in organisms, legacy effects and cumulative cocktail loads[62] pose uncertainties on defining the safe exposure levels for biodiversity, and frustrate the setting of local and global boundaries for pesticide application. We therefore argue for a precautionary approach and propose that the residue concentration of pesticides in the environment should remain within local safe exposure levels for biodiversity, requiring a global

https://doi.org/10.1038/s43016-025-01252-6

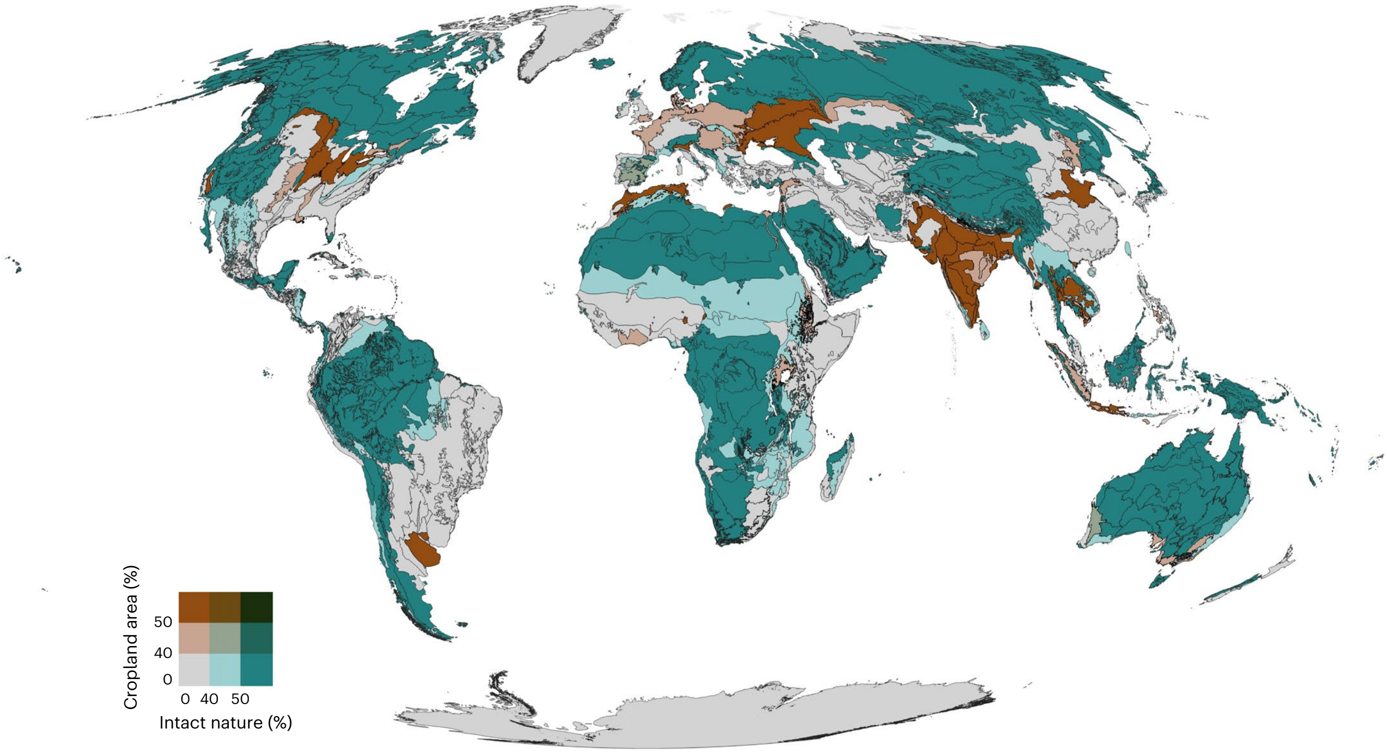

Fig. 3 | Exceedance of intact nature by cropland. Intactness data (blue) represents the land where natural processes predominate[11,18]. Cropland (brown) data are based on HYDE3.2 for 2017[84]. In 10% of the ecoregions, cropland alone is already covering >40% of the land area. Including grazing land increases the number of ecoregions that are in the zone of increasing risk from 10% to 43% (Supplementary Fig. 2).

reduction in pesticide application of 70% to minimize the area with high pesticide pollution risk, and a reduction of more than 90% to avoid introducing additional pollution risks to the environment (for details see Supplementary Text 9a and Supplementary Fig. 7) compared with the current PAS application rates.

Antimicrobial use. Global antimicrobial use for livestock and aquaculture amounts 73–130 kt yr^{-1} (refs. 58,59,63,64) and is projected to further increase with the growing demand for animal-sourced foods and the shift towards intensive production. Most of the antimicrobial use is for food animals (73%); around a quarter is for human consumption[64]. Antibiotics accumulate in soils via application of animal manure, increasing antimicrobial resistance risk in soil biota[65]. The subsequent impact on genetic diversity and abundance of soil biota through selection pressure can undermine crucial soil functions that enable biogeochemical cycles of nitrogen and carbon[66], through which they affect other PB domains. Considering uncertainties regarding the development of antimicrobial resistance across species, and subsequent risks for human and environmental health more broadly[67], we propose halting prophylactic use of antibiotics in agriculture (that is, preventive use of antimicrobials in healthy animals) in line with World Health Organization recommendations[68], and halving the overall current average application rates (from 50 to 25 mg kg^{-1} of animal) while retaining the productive capacity of livestock systems (Supplementary Text 9b).

Discussion

Our results show that food systems are the single-largest pressure across Earth system processes and that all proposed FSBs are currently transgressed. It is critical for food systems to operate within a safe space to preserve Earth system stability. Operating outside FSBs is simultaneously putting human health at risk[54] and undermining the capability for food production itself by polluting the environment[50,61,69], ultimately increasing the exposure of agricultural land to extreme weather events and driving the loss of biodiversity fundamental for food production (for example, soil microbiomes, and pollinating and pest-regulating organisms). The economic costs of food systems now outweigh benefits, and climate change is expected to further increase economic losses, and to increase food prices and the occurrence of hunger[70]. Without mitigation actions, food systems will contribute up to an additional 0.9 °C of warming by the end of this century[71].

The FSBs proposed here provide an integrated framework for measuring progress of the performance of global food systems against the PB framework. Since FSBs respond to changes in mitigation cost and many other societal developments, they should be considered dynamic sectoral shares (aligned with the PB framework, albeit fundamentally different from the biophysical thresholds represented by PBs or targets derived from stakeholder negotiation or policy deliberation processes).

This is a first attempt to operationalize the PB framework for food systems across all planetary boundaries; moving towards the safe operating space requires parallel action and transformation across sectors, including moving to carbon-neutral energy and transportation systems.

Our assessment highlights important knowledge gaps: the lack of uniform approaches to defining food systems (that is, what is included and excluded) across different fields of Earth system science, leading to different estimates of the impacts of food systems. Agricultural production data often provide limited granularity for the discard effects of non-food products (for example, biofuel, fibre and timber production), and probably overestimate the impacts of food systems across the PBs. However, available evidence suggests that this component is relatively small (suggesting a mean ~10% error margin; Fig. 1b). Efforts to ensure internally consistent data collection on the impacts of food systems, following a unified definition and systematic disaggregation of food and non-food agriculture, can make important contributions to addressing these knowledge gaps. Moreover, there is no consistent approach to quantify the FSBs. Some FSBs (that is, climate, and indirectly, ocean acidification and aerosol loading) are partially derived from IAMs[72],

https://doi.org/10.1038/s43016-025-01252-6

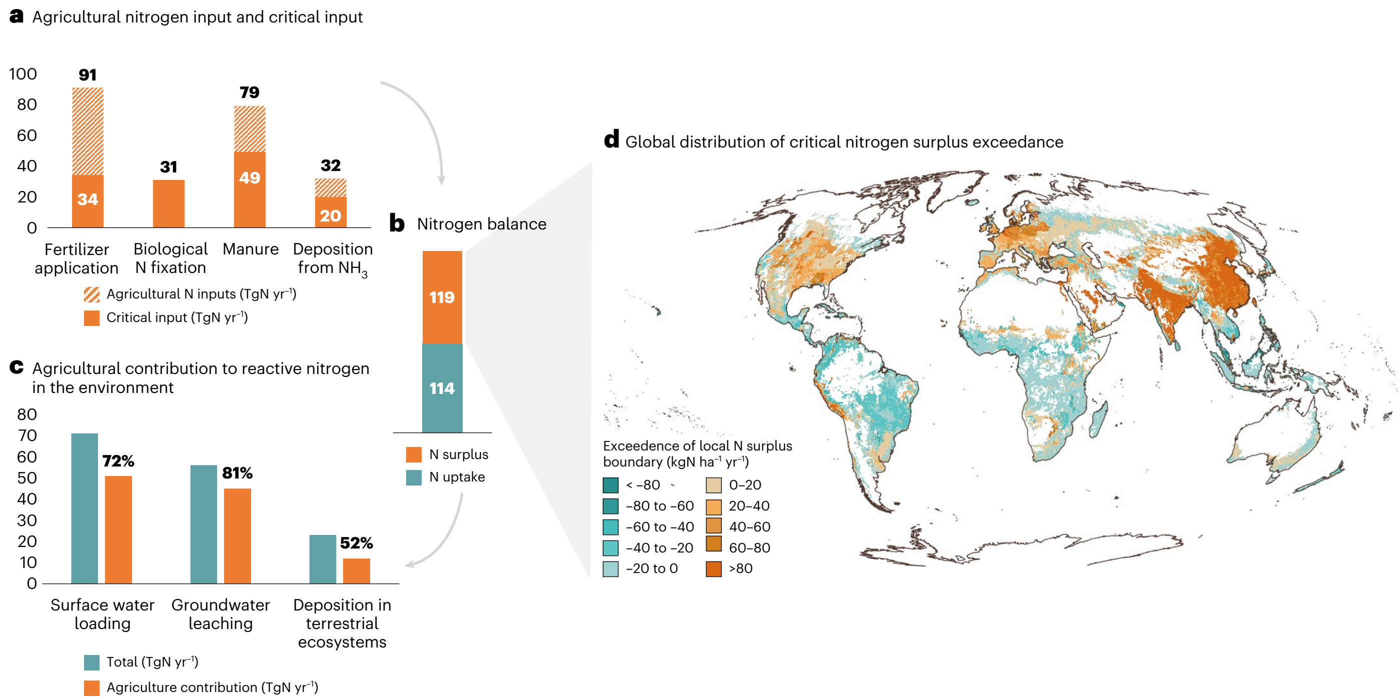

Fig. 4 | Agricultural nitrogen surplus. a–d, Global nitrogen input and critical input levels (where current input exceeds local thresholds) (**a**) and associated nitrogen uptake and surplus (**b**) that lead to exceedance of critical surplus value based on surface water loading, groundwater leaching and deposition in terrestrial ecosystems (**c**), and the spatial distribution of the critical nitrogen surplus exceedance (**d**). Agricultural inputs in **a** are provided for fertilizer application, biological nitrogen fixation, manure, and deposition from NH_3. Numbers on top of the bars in **a** represent current inputs; the solid parts of the bars represent the required input reductions considering critical input values, assuming other nitrogen inputs will not change. Of the total inputs (233 TgN yr^{-1}), 114 TgN yr^{-1} is taken up by plants while 119 TgN yr^{-1} is surplus. Data from refs. 10,85. See Supplementary Table 8 for details.

which have been critiqued for their limited capacity to model behavioural systems in relation to the cost-optimization objective, leading to biases towards technological solutions (for example, carbon dioxide removal (CDR)[73]). More ambitious IAM scenarios that assume greater demand-side shifts (for example, dietary changes) may bring emissions closer to zero. However, such behavioural demand-side changes are usually exogenously prescribed in IAMs[74], implying that models may underestimate demand-side mitigation potential and favour techno-optimist solutions over societal transformation (for example, new technologies for emission efficiencies in meat production, rather than contract-and-converge pathways for per-capita meat consumption). This emphasizes that the 5 $GtCO_2e\ y^{-1}$ and other FBSs proposed here will be dynamic because there are diverse and emerging combinations of behavioural and technical options to stay within boundaries[75].

Our integrated framework identifies critical interventions that can tackle multiple issues at once: halting further agricultural expansion is critical to safeguarding biodiversity, sequestering carbon, reducing PM2.5 emissions, maintaining biogeochemical cycles, and retaining blue and green water; restricting nitrogen surplus reduces water and soil pollution, while limiting further ozone depletion and radiative forcing from associated N_2O emissions[10]; bringing CO_2 emissions to zero to limit further global warming and further ocean acidification to protect ocean life and aquatic food supply. These interactions underline the cross-cutting nature of food systems, and strongly suggest the need to align mitigation efforts for the food system with existing global governance frameworks, such as under the Convention for Biological Diversity to protect land and biodiversity; and the UN Framework Convention on Climate Change, bringing food front and centre in biodiversity and climate policy.

Existing studies stipulate the potential of food system transformations to bring food systems from the problem to the solution side for the environment, the economy[70] and human health, through a range of actions including dietary shifts, reductions in food loss and waste, and improved production practices. Further research is urgently needed into how we can transform both the demand and supply side of food systems to move back into the safe space. This research should address how effective policy measures can support such transformative actions, while simultaneously preserving the capacity to produce sufficient, healthy and affordable food for a growing population.

Methods

Identifying control variables and present-day food systems' contributions

The Earth system domains and associated control variables adopted in this study are in principle based on the most recent PB assessment[2]. In addition, we identify recent studies that propose alternative control variables that we consider better adapted to capture food system impacts, or to express the FSB. For biogeochemical flows, we adopted the proposed 'nitrogen surplus (TgN yr^{-1})' control variable[10] rather than the 'industrial and intentional fixation of nitrogen (TgN yr^{-1})'[2], and adopt phosphorus loss from soils to surface waters, based on ref. 36. For novel entities, we propose two control variables that capture the contributions of food systems to the release of novel entities in the environment (pesticide application and antimicrobial use)[61,64].

Next, we quantify the present-day contribution of food systems to PB transgressions through a scoping review of recent PB studies and global food systems impacts (Supplementary Table 1). In principle, we consider food systems to comprise both the production part and the processing, distribution and consumption parts (that is, from farm to fork), in line with the 'agrifood system' defined by refs. 76–78; however, we are sometimes limited by data availability, which implies some elements of the processing part are excluded (Fig. 1a) or not based on recent data (for example, nitrogen surplus estimates are based on 2010 nitrogen data). Although agriculture comprises more than food (also including, for example, crop production for bioenergy and fibres), most production (in terms of mass) is used for human consumption (direct consumption or indirect via fodder production)[4] which we therefore consider a good proxy for food systems, and comparable to approaches adopted in similar assessments[12]. Equally so, the environmental impacts aligned with the PBs following from agricultural production also appear dominated by food over other uses of agricultural production (Fig. 1b). However, as there is no unified approach to define and quantify the impacts of food systems across the PB domains, the presented numbers in the literature strongly depend on what is included.

Defining FSBs

We define FSBs as a specific global share of the PB budget. In contrast to PBs, FSBs do not reflect biophysical thresholds; rather, they are a set of science-based shares of food systems consistent with the PB framework. We identified several approaches to define these shares for the food system from the available literature (Supplementary Table 1) that broadly follow three main principles. First, based on the estimated required reduction of food systems only to ensure moving back within the PBs (that is, assuming that the pressure from other sectors remains constant, such as biosphere integrity, freshwater change and novel entities), or assuming proportional reduction across sectors based on current contributions to PB transgressions (for phosphorus, nitrogen, blue water and land use)[5,9]. Second, using top-down economic optimization models to estimate cost-effective mitigation potentials across sectors (that is, for climate change)[72,79]. Third, by considering cross-boundary interactions that provide multiple benefits to various Earth systems (that is, for ozone depletion, aerosol loading and ocean acidification). There is no single framework available to allocate the PB budget within the safe operating space across sectors, and no approach is without limitations: assuming proportional mitigation across sectors may not represent the most cost-effective target, while mitigation estimates from top-down economic optimization models can be dependent on a selection of mitigation options considered and on the assumed carbon price (that is, for the climate change FSB). This means that FSBs also can be adjusted over time based on new insights on reduction potentials per sector. Detailed approaches for defining the FSB are provided in the Supplementary Information for each Earth system domain. Alternative methods used in the literature to define FSBs are based on mitigation potentials, such as the mitigation options from dietary change[54], or on bottom-up approaches that identify per-capita budgets and aggregate those to the global level to derive a global estimate of minimum requirements (as adopted in ref. 80, which adopted a human-rights approach to define Earth system boundaries). Such approaches depend strongly on the assumptions made to derive per-capita budgets (including population trajectories), and on subsequent aggregation methods. For example, per-capita GHG emissions depend largely on the composition of food intake and can vary regionally depending on where the food is sourced.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data used for the generation of the food system status presented in Fig. 2 and Table 1 were obtained from the literature (Supplementary Table 1). The data needed to reproduce Figs. 1, 3 and 4 and Supplementary Figs. 1–6 are available via Zenodo at https://doi.org/10.5281/zenodo.17397894 (ref. 81).

Code availability

The code needed to reproduce Figs. 1, 3 and 4 and Supplementary Figs. 1–6 is available via Zenodo at https://doi.org/10.5281/zenodo.17397894 (ref. 81).

References

1. Rockström, J. et al. Planetary boundaries: exploring the safe operating space for humanity. *Ecol. Soc.* **14**, 32 (2009).
2. Richardson, K. et al. Earth beyond six of nine planetary boundaries. *Sci. Adv.* **9**, eadh2458 (2023).
3. Halpern, B. S. et al. The environmental footprint of global food production. *Nat. Sustain.* **5**, 1027–1039 (2022).
4. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
5. Springmann, M. et al. Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
6. Campbell, B. M. et al. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* **22**, (2017).
7. Gerten, D. et al. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustain.* **3**, 200–208 (2020).
8. van Vuuren, D. P. et al. Exploring pathways for world development within planetary boundaries. *Nature* **641**, 910–916 (2025).
9. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
10. Schulte-Uebbing, L. F., Beusen, A. H. W., Bouwman, A. F. & de Vries, W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* **610**, 507–512 (2022).
11. Rockström, J. et al. Safe and just Earth system boundaries. *Nature* **619**, 102–111 (2023).
12. Tubiello, F. N. et al. Greenhouse gas emissions from food systems: building the evidence base. *Environ. Res. Lett.* **16**, 065007 (2021).
13. Roe, S. et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change* **9**, 817–828 (2019).
14. *Land Statistics 2001–2022* (FAO, 2024).
15. Gibbs, H. K. et al. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc. Natl Acad. Sci. USA* **107**, 16732–16737 (2010).
16. Potapov, P. et al. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat. Food* **3**, 19–28 (2022).
17. Pendrill, F. et al. Disentangling the numbers behind agriculture-driven tropical deforestation. *Science* **377**, eabm9267 (2022).
18. DeClerck, F. A. J. et al. in *Science and Innovations for Food Systems Transformation* (eds von Braun, J., Afsana, K., Fresco, L. O. & Hassan, M. H. A.) 469–496 https://doi.org/10.1007/978-3-031-15703-5_25 (Springer, 2023).
19. Gupta, J. et al. Earth system justice needed to identify and live within Earth system boundaries. *Nat. Sustain*. https://doi.org/10.1038/s41893-023-01064-1 (2023).
20. Jaureguiberry, P. et al. The direct drivers of recent global anthropogenic biodiversity loss. *Sci. Adv.* **8**, eabm9982 (2022).
21. Garibaldi, L. A. et al. Working landscapes need at least 20% native habitat. *Conserv. Lett.* **14**, e12773 (2021).
22. Mohamed, A. et al. Securing nature's contributions to people requires at least 20%–25% (semi-)natural habitat in human-modified landscapes. *One Earth* **7**, 59–71 (2024).
23. Haberl, H. et al. Quantifying and mapping the human appropriation of net primary production in Earth's terrestrial ecosystems. *Proc. Natl Acad. Sci.USA* **104**, 12942–12947 (2007).
24. Stenzel, F. et al. biospheremetrics v1.0.2: an R package to calculate two complementary terrestrial biosphere integrity indicators—human colonization of the biosphere (BioCol) and risk of ecosystem destabilization (EcoRisk). *Geosci. Model Dev.* **17**, 3235–3258 (2024).
25. McDermid, S. et al. Irrigation in the Earth system. *Nat. Rev. Earth Environ*. https://doi.org/10.1038/s43017-023-00438-5 (2023).
26. Heinke, J. et al. Water use in global livestock production—opportunities and constraints for increasing water productivity. *Water Resour. Res.* **56**, e2019WR026995 (2020).

27. Rost, S. et al. Agricultural green and blue water consumption and its influence on the global water system. *Water Resour. Res.* **44**, (2008).
28. Schyns, J. F., Hoekstra, A. Y., Booij, M. J., Hogeboom, R. J. & Mekonnen, M. M. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proc. Natl Acad. Sci. USA* **116**, 4893–4898 (2019).
29. Gerten, D. et al. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. *Curr. Opin. Environ. Sustain.* **5**, 551–558 (2013).
30. Porkka, M. et al. Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change. *Nat. Water* **2**, 262–273 (2024).
31. Wang-Erlandsson, L. et al. A planetary boundary for green water. *Nat. Rev. Earth Environ.* **3**, 380–392 (2022).
32. Jägermeyr, J., Pastor, A., Biemans, H. & Gerten, D. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nat. Commun.* **8**, 15900 (2017).
33. de Vries, W. et al. Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: a review. *Earth-Sci. Rev.* **253**, 104789 (2024).
34. Erisman, J. W. et al. Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. B* **368**, 20130116 (2013).
35. Beusen, A. H. W. et al. Exploring river nitrogen and phosphorus loading and export to global coastal waters in the shared socio-economic pathways. *Glob. Environ. Change* **72**, 102426 (2022).
36. De Vries, W., Schulte-Uebbing, L. F., Beusen, A. H. W. & Te Wierik, S. A. Revisiting planetary boundaries for nitrogen and phosphorus. *Curr. Opin. Environ. Sustain.* (in the press).
37. Ravishankara, A. R., Daniel, J. S. & Portmann, R. W. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. *Science* **326**, 123–125 (2009).
38. Tian, H. et al. Global nitrous oxide budget (1980–2020). *Earth Syst. Sci. Data* **16**, 2543–2604 (2024).
39. Butler, A. H. et al. Diverse policy implications for future ozone and surface UV in a changing climate. *Environ. Res. Lett.* **11**, 064017 (2016).
40. Nash, K. L. et al. Planetary boundaries for a blue planet. *Nat. Ecol. Evol.* **1**, 1625–1634 (2017).
41. Gruber, N. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **369**, 1980–1996 (2011).
42. Kessouri, F. et al. Coastal eutrophication drives acidification, oxygen loss, and ecosystem change in a major oceanic upwelling system. *Proc. Natl Acad. Sci. USA* **118**, e2018856118 (2021).
43. Friedlingstein, P. et al. Global Carbon Budget 2023. *Earth Syst. Sci. Data* **15**, 5301–5369 (2023).
44. Gruber, N. et al. Trends and variability in the ocean carbon sink. *Nat. Rev. Earth Environ.* **4**, 119–134 (2023).
45. Dhakal, S. et al. in *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 215–294 (Cambridge Univ. Press, 2023); https://doi.org/10.1017/9781009157926.004
46. Liu, F. et al. Increased Asian aerosols drive a slowdown of Atlantic Meridional Overturning Circulation. *Nat. Commun.* **15**, 18 (2024).
47. Stevens, B. et al. MACv2-SP: a parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6. *Geosci. Model Dev.* **10**, 433–452 (2017).
48. Vogel, A. et al. Uncertainty in aerosol optical depth from modern aerosol-climate models, reanalyses, and satellite products. *J. Geophys. Res. Atmospheres* **127**, e2021JD035483 (2022).
49. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. & Pozzer, A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **525**, 367–371 (2015).
50. Crippa, M., Solazzo, E., Guizzardi, D., Van Dingenen, R. & Leip, A. Air pollutant emissions from global food systems are responsible for environmental impacts, crop losses and mortality. *Nat. Food* **3**, 942–956 (2022).
51. McDuffie, E. E. et al. Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. *Nat. Commun.* **12**, 3594 (2021).
52. Bauer, S. E., Tsigaridis, K. & Miller, R. Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.* **43**, 5394–5400 (2016).
53. Pozzer, A., Tsimpidi, A. P., Karydis, V. A., de Meij, A. & Lelieveld, J. Impact of agricultural emission reductions on fine-particulate matter and public health. *Atmos. Chem. Phys.* **17**, 12813–12826 (2017).
54. Springmann, M. et al. The global and regional air quality impacts of dietary change. *Nat. Commun.* **14**, 6227 (2023).
55. Balasubramanian, S. et al. The food we eat, the air we breathe: a review of the fine particulate matter-induced air quality health impacts of the global food system. *Environ. Res. Lett.* **16**, 103004 (2021).
56. He, L., Li, Z., Jia, Q. & Xu, Z. Soil microplastics pollution in agriculture. *Science* **379**, 547–547 (2023).
57. Maggi, F., Tang, F. H. M. & Tubiello, F. N. Agricultural pesticide land budget and river discharge to oceans. *Nature* **620**, 1013–1017 (2023).
58. Schar, D., Klein, E. Y., Laxminarayan, R., Gilbert, M. & Van Boeckel, T. P. Global trends in antimicrobial use in aquaculture. *Sci. Rep.* **10**, 21878 (2020).
59. Van Boeckel, T. P. et al. Global trends in antimicrobial use in food animals. *Proc. Natl Acad. Sci.* **112**, 5649–5654 (2015).
60. *Pesticides Use, Pesticides Trade and Pesticides Indicators* https://doi.org/10.4060/cc0918en (FAO, 2022).
61. Tang, F. H. M., Lenzen, M., McBratney, A. & Maggi, F. Risk of pesticide pollution at the global scale. *Nat. Geosci.* **14**, 206–210 (2021).
62. Geissen, V. et al. Cocktails of pesticide residues in conventional and organic farming systems in Europe—legacy of the past and turning point for the future. *Environ. Pollut.* **278**, 116827 (2021).
63. Acosta, A. et al. The future of antibiotic use in livestock. *Nat. Commun.* **16**, 2469 (2025).
64. Van Boeckel, T. P. et al. Reducing antimicrobial use in food animals. *Science* **357**, 1350–1352 (2017).
65. Zheng, D. et al. Global biogeography and projection of soil antibiotic resistance genes. *Sci. Adv.* **8**, eabq8015 (2022).
66. Toth, J. D., Feng, Y. & Dou, Z. Veterinary antibiotics at environmentally relevant concentrations inhibit soil iron reduction and nitrification. *Soil Biol. Biochem.* **43**, 2470–2472 (2011).
67. Larsson, D. G. J., Gaze, W. H., Laxminarayan, R. & Topp, E. AMR, One Health and the environment. *Nat. Microbiol.* **8**, 754–755 (2023).
68. Aidara-Kane, A. et al. World Health Organization (WHO) guidelines on use of medically important antimicrobials in food-producing animals. *Antimicrob. Resist. Infect. Control* **7**, 7 (2018).
69. Wang, M. et al. A triple increase in global river basins with water scarcity due to future pollution. *Nat. Commun.* **15**, 880 (2024).
70. Ruggeri Laderchi, C. et al. *The Economics of the Food System Transformation. Global Policy Report*. https://foodsystemeconomics.org/wp-content/uploads/FSEC-Global_Policy_Report.pdf (Food System Economics Commission, 2024).
71. Ivanovich, C. C., Sun, T., Gordon, D. R. & Ocko, I. B. Future warming from global food consumption. *Nat. Clim. Change* **13**, 297–302 (2023).

72. Nabuurs, G.-J. et al. in *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 747–860 https://doi.org/10.1017/9781009157926.009 (Cambridge Univer. Press, 2022).
73. Hollnaicher, S. On economic modeling of carbon dioxide removal: values, bias, and norms for good policy-advising modeling. *Glob. Sustain.* **5**, e18 (2022).
74. Gambhir, A., Butnar, I., Pei-Hao, L., Smith, P. & Strachan, N. A Review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies* **12**, 1747 (2019).
75. van den Berg, N. J. et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change* **162**, 1805–1822 (2020).
76. *The State of Food and Agriculture 2023* (FAO, 2023).
77. Foley, J. A. et al. Solutions for a cultivated planet. *Nature* **478**, 337 (2011).
78. Wang, S. et al. The booming non-food bioeconomy drives large share of global land-use emissions. *Glob. Environ. Change* **83**, 102760 (2023).
79. Frank, S. et al. Agricultural non-CO_2 emission reduction potential in the context of the 1.5 °C target. *Nat. Clim. Change* **9**, 66–72 (2019).
80. Gupta, J. et al. A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations. *Lancet Planet. Health* https://doi.org/10.1016/s2542-5196(24)00042-1 (2024).
81. te Wierik, S. Underlying data to support figures for te Wierik et al. Identifying the safe operating space for food systems (Version 5). *Zenodo* https://doi.org/10.5281/zenodo.17397894 (2025).
82. Wang, Z. et al. Global mapping of the landside clustering of aquaculture ponds from dense time-series 10 m Sentinel-2 images on Google Earth Engine. *Int. J. Appl. Earth Obs. Geoinformation* **115**, 103100 (2022).
83. Hoekstra, A. Y. & Mekonnen, M. M. The water footprint of humanity. *Proc. Natl Acad. Sci. USA* **109**, 3232–3237 (2012).
84. Klein Goldewijk, K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene—HYDE 3.2. *Earth Syst. Sci. Data* **9**, 927–953 (2017).
85. Schwede, D. B. et al. Spatial variation of modelled total, dry and wet nitrogen deposition to forests at global scale. *Environ. Pollut.* **243**, 1287–1301 (2018).

Acknowledgements

The authors acknowledge colleagues from the EAT-Lancet Commission 2.0 for their contributions to the conceptual development of this work, and J. Braun for supporting the green water boundary assessment. This research was supported by the IKEA Foundation and Novo Nordisk Foundation. The funders had no role in the study design, data collection, analysis and conclusions presented here. M.S. acknowledges funding from the Wellcome Trust through a Career Development Award (award number 225318/Z/22/Z), and the EU Horizon Programme through the CATALYSE project (grant agreement number 101057131), the BrightSpace project (grant agreement number 101060075) and the ACT4CAP project (grant agreement number 101134874).

Author contributions

S.t.W., F.D.C., A.N., M.S., W.d.V., D.v.V., S.V. and J.R. conceptualized and designed the study. S.t.W. developed and executed the literature and data analysis, with support from F.D.C., F.M., F.H.M.T. and L.S.-U. F.D.C., A.B., D.G., F.M., K.N., L.S.-U., M.S., W.d.V., D.v.V. and S.V. supported the interpretation of data. S.t.W. led the writing of the paper with support from F.D.C., J.R., S.V., A.N., W.d.V., K.N., D.G., L.S.-U. and F.H.M.T.

Funding

Open access funding provided by Potsdam-Institut für Klimafolgenforschung (PIK) e.V.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-025-01252-6.

Correspondence and requests for materials should be addressed to Sofie te Wierik.

Peer review information *Nature Food* thanks the anonymous reviewers for their contribution to the peer review of this work.

nature portfolio

Corresponding author(s): Sofie te Wierik

Last updated by author(s): 26-09-2025

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
[x]	[ ]	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
[x]	[ ]	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
[x]	[ ]	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
[x]	[ ]	A description of all covariates tested
[x]	[ ]	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
[x]	[ ]	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
[x]	[ ]	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
[x]	[ ]	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
[x]	[ ]	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
[x]	[ ]	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No new data was created for this study. The data used to reproduce the figures in this manuscript are provided in https://zenodo.org/records/17131021, as mentioned in the Data Availability statement in the manuscript.
Data analysis	Existing data was analyzed using Python v 3.12 and R v 4.3.2.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data availability
The data to derive the food system status presented in Figure 2 and Table 1 are obtained from existing literature and collected in Supplementary Table 1, including references to the sources of these data files. All data to reproduce the figures in the Main text and Supplementary Information are furthermore collected and

available via https://zenodo.org/records/17131021.
Additional Information
Supplementary Table 1. Excel file with overview of the scientific evidence (full references, approach and evidence to support Table 1 and Figure 1) to derive the current state of food systems and the food system boundaries.
Supplementary Information
Supplementary Information including Supplementary Text S1-S10, Supplementary Figures S1-S8 and Supplementary Tables S2- S12.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	*Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design; whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data, where this information has been collected, and if consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.*
Reporting on race, ethnicity, or other socially relevant groupings	*Please specify the socially constructed or socially relevant categorization variable(s) used in your manuscript and explain why they were used. Please note that such variables should not be used as proxies for other socially constructed/relevant variables (for example, race or ethnicity should not be used as a proxy for socioeconomic status). Provide clear definitions of the relevant terms used, how they were provided (by the participants/respondents, the researchers, or third parties), and the method(s) used to classify people into the different categories (e.g. self-report, census or administrative data, social media data, etc.) Please provide details about how you controlled for confounding variables in your analyses.*
Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*
Recruitment	*Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.*
Ethics oversight	*Identify the organization(s) that approved the study protocol.*

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Literature review to quantify the contribution of food systems to planetary boundary transgressions and identify global budgets (food system boundaries) for the food system. The food system boundaries in the study also derived from existing literature that used different modeling approaches, including IAM-based studies.
Research sample	*Describe the research sample (e.g. a group of tagged Passer domesticus, all Stenocereus thurberi within Organ Pipe Cactus National Monument), and provide a rationale for the sample choice. When relevant, describe the organism taxa, source, sex, age range and any manipulations. State what population the sample is meant to represent when applicable. For studies involving existing datasets, describe the data and its source.*
Sampling strategy	Literature was collected through a scoping review which is provided in Supplementary Table 1.
Data collection	*Describe the data collection procedure, including who recorded the data and how.*
Timing and spatial scale	Literature was collected between October 2023- June 2025.
Data exclusions	*If no data were excluded from the analyses, state so OR if data were excluded, describe the exclusions and the rationale behind them, indicating whether exclusion criteria were pre-established.*

Reproducibility

Describe the measures taken to verify the reproducibility of experimental findings. For each experiment, note whether any attempts to repeat the experiment failed OR state that all attempts to repeat the experiment were successful.

Randomization

Describe how samples/organisms/participants were allocated into groups. If allocation was not random, describe how covariates were controlled. If this is not relevant to your study, explain why.

Blinding

Describe the extent of blinding used during data acquisition and analysis. If blinding was not possible, describe why OR explain why blinding was not relevant to your study.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks

Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.

Novel plant genotypes

Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor was applied.

Authentication

Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosiacism, off-target gene editing) were examined.