SCIENTIFIC ADVISORY COMMITTEE (SAC)

THEME 2: PLANETARY BOUNDARIES IN FOOD SYSTEMS TRANSFORMATION

TRANSFORMING FOOD SYSTEMS TO RETURN TO EARTH'S LIMITS

The global food system supports the livelihoods of over 1.2 billion people. Almost half of the world's population lives in households linked to agri-food systems[1], with agricultural households constituting up to two-thirds of people living in extreme poverty worldwide.[2] Since 1961, food supply per capita has increased by more than 30%, accompanied by greater use of nitrogen fertilizers (an increase of about 800%) and water resources for irrigation (an increase of more than 100%)[3], as well as increased consumption of animal proteins (41% of total proteins intake) and increased food loss and waste (25-30% of total food produced is lost or wasted). Still, an estimated 733 million people were chronically undernourished in 2023,[4] and 22% of children under five years were stunted (too short for their age), indicating long-term malnourishment. More than a third of the world's population could not afford a healthy diet in 2022,[5] and 30% adults and 6% of children were overweight or obese[6]. Suboptimal diet is an important preventable risk factor for non-communicable diseases[7]. In short, the global food system is in dire need of interventions for sustainable transformation.

Food systems encompass all the elements and activities related to the production, processing, distribution, preparation, and consumption of food, as well as the output of these activities, including socioeconomic and environmental outcomes. Food production and consumption significantly impact the environment, including land use, water use, biodiversity loss, and greenhouse gas (GHG) emissions.

Planetary boundaries are a concept developed by scientists to define the safe operating space for humanity on Earth[8]. They represent the environmental limits within which human civilization can

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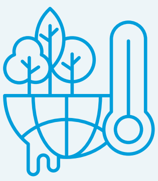
thrive. In such a state, global environmental functions and life-support systems remain similar to those experienced over the past approximately 10,000 years rather than shifting into a state without analogue in human history. The planetary boundaries have strong links to the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda, established by the United Nations. The SDGs address global challenges, including poverty, hunger, climate change, and environmental degradation. Environmental SDGs directly relate to the planetary boundaries, such as SDG 6 (Freshwater), SDG 13 (Climate Action), SDG 14 (Life Below Water) and SDG 15 (Life on Land). Science provides evidence that six of the nine planetary boundaries have been transgressed,[9] suggesting that Earth is well outside the safe operating space for humanity.

The global food system is a major driver of the transgression of five of these boundaries (Box 1): climate change, biosphere integrity, land use, freshwater use, and nitrogen and phosphorus flows. Unsustainable agricultural practices[10] and dietary preferences contribute to exceeding the planetary boundaries, thereby undermining the long-term sustainability of food systems. Between 2010 and 2050, because of projected increases in human population, diets and income levels, the environmental effects of global food systems are expected to increase by 50–90%, reaching levels that will cause the planetary boundaries.[11]

BOX 1. THE ROLE OF FOOD SYSTEMS IN THE SIX PLANETARY BOUNDARIES TRANSGRESSED

1. CLIMATE CHANGE



This boundary aims to limit the increase in global average temperature to well below 2 °C above pre-industrial levels. Food systems contribute to ca. **30%** of global anthropogenic GHG emissions[12]. This estimate includes emissions from crop and livestock activities within the farm gate (9–14%) as well as from land use and land-use change, including deforestation and peatland degradation (5–14%); the remainder (5–10%) is attributed to food processing, packaging, transportation, and retail activity, including GHG emissions from food loss and waste. Half of the total anthropogenic CH_4 emissions have been linked to livestock and paddy rice cultivation, while three-quarters of the total N_2O emissions are from nitrogen-fertilized agricultural soils. CO_2 emissions from deforestation and peatland degradation linked to agriculture contribute about 10% of the total anthropogenic emissions[13].

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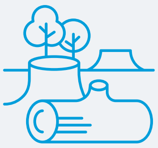
2. BIOSPHERE INTEGRITY

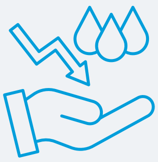
This boundary focuses on preventing biodiversity loss and species extinction. Food systems may contribute to approximately **two-thirds** of biosphere integrity loss, although a first estimate[10] suggested it could be as high as 80%. The intensification and expansion of agricultural activities lead to habitat destruction and fragmentation, directly impacting biodiversity. Agriculture, aquaculture, and fisheries are identified as threats to 63% of the 29,000 species, which IUCN has documented as at risk of extinction.[13] Over two-thirds of the human appropriation of net primary productivity (NPP), the total energy captured by photosynthesis on land, is caused by agriculture[14]. Farmed animal species (mainly cows and pigs) account for 60% of all mammal species by mass, compared to 4% for wild mammals[15].

3. LAND SYSTEM CHANGE



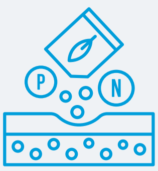
This boundary aims to maintain the integrity of ecosystems and prevent deforestation and soil degradation. Food systems induce **80-90%** of tropical deforestation and wetland loss. In the past decade, at least 90% of tropical deforested land occurred in landscapes where agriculture drove forest loss[16]. Agricultural development is a primary cause of wetland loss through drainage and infilling[17].

4. FRESHWATER USE



This boundary aims to ensure sustainable water use and prevent the depletion of freshwater resources. About **70%** of all freshwater withdrawals are currently used for agriculture, and about 85% of withdrawn resources are consumed in irrigated agricultural production[18]. Irrigation intensity is associated with reduced streamflow, wet soil moisture,[19] and groundwater decline[20].

5. NITROGEN (N) AND PHOSPHORUS (P) CYCLES



Excessive use of agricultural fertilizers and the resulting pollution of water bodies accounts for **85% and 95%** of the perturbation in N and P cycles[1], respectively. For phosphorus, the planetary boundary is set at one-third of the current global use of fertilizer-P to avert widespread eutrophication of freshwater ecosystems[1]. For nitrogen, the boundary is set at 55% of the current use of industrially fixed N in the agricultural system[1].

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6. NOVEL POLLUTANTS

This boundary focuses on preventing the release of novel chemicals and materials into the environment. The fraction of novel pollutants from food systems (e.g., plastics, pesticides, and antibiotics) is not known, but the use of pesticides and antibiotics in agriculture, as well as plastics[21] in packaging, have significant impacts on biodiversity[22,23] and food safety.[24,25,26]

Beyond planetary boundaries, significant harm to the environment, animal, human populations, and food systems results from natural and anthropogenic earth system changes[8]. Climate change is already affecting food security through increasing temperatures, changing precipitation patterns, and greater frequency of extreme events. About 500 million people live within areas undergoing desertification,[27] while around two billion people live within watersheds exposed to water scarcity. With climate change, the numbers could double by 2050.[28] Over half of the tropical forests worldwide have been destroyed since the 1960s, affecting the lives of one billion poor people whose livelihoods depend on forests.[29]

Concerns about justice across countries and communities, as well as across generations, are raised by increasing land and food-based challenges. Challenges related to undernourishment, soil degradation, land desertification, water scarcity, and the loss of biodiversity hot spots – partly linked to Earth system changes – are concentrated[30] in rural areas and countries with low levels of human development, as estimated from the Human Development Index.[31] The harm is likely to increase from one generation to the next, as the continuation of current trends will result[32,33], in substantial adverse outcomes for food security, biodiversity, water availability and quality, and human health, while exacerbating climate change. For instance, by 2050, soil degradation and climate change could reduce global crop yields by about 10%, with strong negative impacts in parts of Asia and sub-Saharan Africa, resulting in conflicts and the displacement of up to 700 million people.[34] Without intervention, food system emissions will likely increase by about 30–40% by 2050 due to increasing demand based on population, income growth, and dietary change[35].

Feeding the world's population by 2050 within planetary boundaries may be possible through a holistic transformation of global food systems. According to an initial modeling study,[36] if the biosphere integrity, land-system use, freshwater use, and nitrogen flow boundaries were strictly respected, the present food system could only provide a balanced diet for 3.4 billion people. Nevertheless, transformation towards more sustainable production and consumption patterns could support 10.2 billion people within these four planetary boundaries. A holistic transformation of the food system would be required, including spatially redistributed cropland, improved water–nutrient

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management, food waste reduction and dietary changes. A second study highlights the potential for carbon sequestration in soils and in agricultural biomass to keep the global food system within the climate change boundary,[37] with most of this potential located in low- and middle-income countries, especially in sub-Saharan Africa.

Carbon sequestration on agricultural land could provide producers worldwide with large additional revenues. However, many barriers to agricultural carbon sequestration exist, including deploying highly efficient institutions and carbon monitoring systems across world regions. Such studies provide some degree of hope that feeding the world population within the planetary boundaries is feasible. Still, they do not offer specific socio-economic policies and roadmaps for achieving these goals and they tend to ignore the increasingly negative impacts of climate change and environmental degradation on food systems and food security.

Numerous highly synergistic response options are already available to actors for sustainably managing food systems in relation to biodiversity, climate change, water, soil and health. When implemented at appropriate scales and in suitable contexts, these response options provide many benefits to different degrees across these interdependent dimensions, and many are low-cost.[38,39] For instance, several land management options have co-benefits across four land challenges[40] - food security, climate change adaptation and mitigation, soil degradation and land desertification. These options include enhanced food productivity, improved cropland and grazing land management, improved livestock management, agroforestry, improved forest management, increased soil organic carbon (SOC) content, fire management, and reduced post-harvest losses.

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In contrast, safeguards are required to ensure that expansion of energy crops does not impact natural systems and food security if applied at scales necessary to remove CO_2 from the atmosphere. Dietary change with less animal products (on a global average) and reduced food waste have potentially large benefits for all land challenges. Shifting from westernized diets to plant-based diets would open opportunities to significantly reduce agricultural land use, fertilizers, water and energy use, as well as GHG emissions.[41] However, as animals are excellent converters of waste streams into high-nutritious food products and can feed on non-arable land, the most efficient food systems are mixed, but with significantly fewer animal proteins than in current western diets.[42] A synergistic combination of changes in food demand and in food supply chains will be needed to sufficiently mitigate the projected increase in environmental pressures.[43]

The concept of a safe and just operating space (SJOS) for humanity integrates the planetary boundaries framework with human well-being.[44] In this 'doughnut' model'[45], the outer circle represents the planetary boundaries, whereas the social foundation (avoiding shortfalls e.g. in food, health, education, income and work) comprises the inner circle. The area between the two circles is the "safe and just space," where humanity should aim to live. The SJOS concept can enhance the policy relevance and effectiveness of the SDGs by translating global limits to regional scales,[46] as most governance occurs at regional levels and by helping the understanding of synergies and trade-offs across SDGs.[47] However, a clear and generalized way to achieve the application of this concept to food systems at local scale has not yet been achieved.[48] Indeed, several drivers of food systems are regional, national (e.g., governance) and sub-national (e.g., conflicts). At the same time, many are differentiated across geographies (e.g., poverty, demography, technologies, land degradation, water scarcity and water pollution). More than half of the world's population is living in areas experiencing the highest impacts from declines in food security, biodiversity, water availability and quality, and increases in health risks and negative effects of climate change. These burdens disproportionately affect developing countries, including small island developing states, indigenous peoples and local communities as well as humans in vulnerable situations in higher-income countries.[49]

Overcoming the food system polycrisis requires a systemic and participatory approach. Holistic approaches are essential, as scenarios that prioritize objectives for a single dimension – whether food, water, biodiversity, human health or climate change – without considering the others often result in trade-offs across these inter-related dimensions, which together form a nexus.[50] During the Stocktake two years after the UN Food Systems Summit,[51] the report of the UN Secretary-General underlined that a radical transformation of food systems was required to reach the goals of the 2030 Agenda, including SDG 2 (Zero Hunger), SDG 1 (No Poverty), SDG 3 (Good Health and Well-Being, given the critical role of nutrition for health), and SDG 6 (Clean Water and Sanitation, as agriculture manages most water resources). The report also underlined that food systems transformation must also reflect commitments on sustainable consumption and production in SDG 12, climate change adaptation and mitigation in SDG 13 and the protection, restoration and sustainable management of terrestrial ecosystems in SDG 15.

Since 2021, 126 countries have adopted national food systems transformation pathways that often aim to address multiple objectives, including food security, nutritional health, environmental sustainability, and social equity. For instance, the FABLE Consortium's approach[52] integrates global targets with country-specific scenarios, emphasizing the need for policy coherence and iterative participatory refinement to meet both national and international goals. Holistic frameworks and monitoring architectures have been developed. For example, the Food Systems Countdown Initiative[53] is intended to complement other global goals and monitoring efforts, notably the SDGs, to track food system transformations across various domains such as diets, environment, livelihoods, governance, and resilience.

Science should increasingly inform solutions and generate actionable[54] knowledge to transform food systems. Careful consideration of the trade-offs, externalities, and costs of not acting is needed to ensure that the changes will benefit all, especially the most vulnerable in society.

Translating global-scale scientific assessments into actionable knowledge at national and local levels is essential. Greater coordination among food systems stakeholders is crucial for greater inclusion, transparency, and accountability. Sharing lessons and experiences will enable adaptive learning and responsive actions. A participatory and holistic transformation process, informed by science, must be established at various scales, from global to national and local levels. Some pilot countries have already established national Science-Policy-Society Interfaces (SPSIs) for food systems transformation.[55] However, much more remains to be done to advance food systems transformation through science.[56]

We call upon decision-makers to meet the growing food demand while ensuring the integrity of all planetary boundaries. The 2nd UN Food Systems Summit Stocktake in July 2025 offers political momentum to all countries to update their national pathways for food systems transformation.

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This policy brief is developed under the thematic area Planetary Boundaries in Food Systems Transformation of the Scientific Advisory Committee (SAC) of the UN Food Systems Coordination Hub. This thematic area is led by Prof. Jean-François Soussana, one of the four Co-Chairs of the SAC. The brief reflects the personal perspectives of the author(s), and the views expressed herein do not necessarily represent the positions, policies, or viewpoints of any affiliated organizations, institutions, or entities.