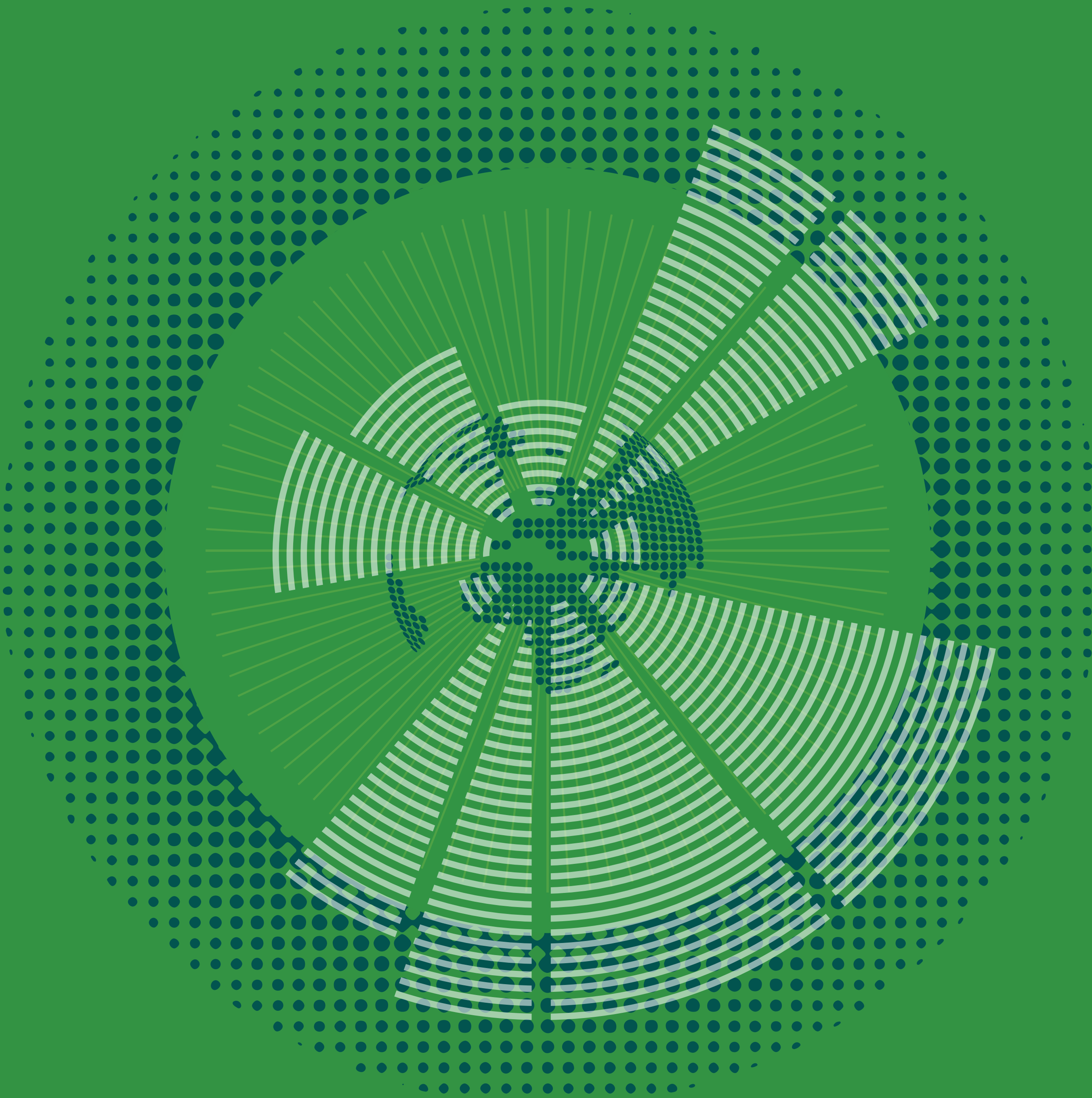
Slovenian Environment Agency



Planetary boundaries

Different approaches to their assessment and consideration in the green transition

Planetary boundaries: Different approaches to their assessment and consideration in the green transition

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SLOVENIAN ENVIRONMENT AGENCY

Planetary boundaries

Different approaches to their assessment and consideration in the green transition

8th Environment Action Programme (8th EAP)

Article 2, Paragraph 1 / Long-term Priority Goal

By 2050 at the latest, people live well, within the planetary boundaries in a well-being economy where nothing is wasted, growth is regenerative, climate neutrality in the Union has been achieved and inequalities have been significantly reduced.

A healthy environment underpins the well-being of all people and is an environment in which biodiversity is conserved, ecosystems thrive, and nature is protected and restored, leading to increased resilience to climate change, weather- and climate-related disasters and other environmental risks. The Union sets the pace for ensuring the prosperity of present and future generations globally, guided by a sense of intergenerational responsibility.

Figure: Are We on Track to Meet Environmental Goals by 2050?

Yes · Maybe · Maybe not · No · It is unclear

* Enabling conditions refer to the establishment of all necessary factors that support the successful implementation of specific activities or the achievement of goals. These include legal and regulatory changes, financial and technical support, and cooperation among stakeholders.

Figure source: Eighth EAP, 2022.

Introduction

In the framework of the **8th Environment Action Programme by 2030**, the European Union has set ambitious goals for sustainable development, including achieving climate neutrality, renewable growth, and a waste-free economy. The concept of planetary boundaries, which defines limits for key processes in the Earth system to prevent unacceptable global environmental changes, plays an important role in this. Despite some positive shifts, results indicate a severe environmental crisis, as six out of nine boundaries have already been crossed. While Slovenia exceeds some planetary boundaries, it still ranks better compared to the EU average. Successfully transitioning to a sustainable future requires systems thinking, innovation, and transformative actions that address both environmental and socio-economic challenges.

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The age of the Anthropocene, the concept of planetary boundaries, and the Earth4All initiative

The impact of humanity on Earth's natural systems, including the climate, has been so significant since the mid-20th century that scientists are calling this period the Anthropocene—**a new geological epoch** in which humans are a key force affecting nature. The concept of planetary boundaries defines limits for key processes within the Earth system that should not be crossed to prevent unacceptable global environmental changes. Six of the nine boundaries have already been exceeded. The goal of the **Earth4All*** initiative is to find the right path for humanity to maintain a balance on Earth between limited natural systems and sustainable economic and social development. Scientists caution that this balance could be disrupted if humanity fails to make a significant "Giant Leap" in turning around its relationship with natural systems.

* Earth4All, Dixson-Declève et al., 2022

Historical introduction to the Anthropocene and key frameworks of the Earth4All initiative

The Earth4All project and book build on insights from the "Limits to Growth" report and the planetary boundaries framework, integrating the Doughnut Economics model. A historical review of "Limits to Growth" (Meadows et al., 1972) is essential, given its prescient BAU (business-as-usual) scenarios and pioneering systems-based methodology (World3 model). In Earth for All, it is highlighted that only one scientific concept has truly transformed our understanding of the last fifty years since 1972: the recognition of the Anthropocene. Nobel laureate Paul Crutzen proposed in 2000 that Earth had entered a new epoch dominated by a single species—Homo sapiens. This idea quickly gained traction among scientists, who now recognize humans as the main driver of Earth system change.

The previous epoch, the Holocene, provided a stable climate that facilitated the development of human civilization around 11,700 years ago. This stability, particularly in climate, was crucial to the rise of agriculture and the first complex societies. However, rapid industrial growth, particularly after 1950, has moved Earth out of the Holocene's stable conditions, resulting in unprecedented environmental shifts. "The Great Acceleration" charts show how this explosive growth impacts Earth's systems. Scientists warn of significant risks if we cross tipping points, such as rainforest deforestation, Antarctic ice thinning, coral reef collapse, and Arctic sea ice melt. Breaching these boundaries could lead to irreversible ecosystem changes, threatening climate stability, biodiversity, and life as we know it, possibly triggering cascading effects with severe environmental, social, and economic repercussions.

The Earth4All initiative presents two scenarios and five exceptional turnarounds in the "Giant Leap" scenario

The book "Earth for All" presents two scenarios exploring how, based on decisions made in this decade, population, economies, resource use, pollution, well-being, and social tensions could change over this century. The Earth4All initiative was established to create a network of scientists, economists, and thought leaders to explore pathways to the Sustainable Development Goals (SDGs). Supported by system dynamics models, the book explores ways out of emergencies and delivers humanitarian, social, environmental, and economic benefits.

The project was conducted by the Club of Rome, Potsdam Institute for Climate Impact Research, Stockholm Resilience Centre, and Norway's BI Norwegian Business School, with the collaboration of leading economists, scientists, and sustainability advocates. The core message of Earth for All is clear: "Without addressing rising inequalities, societies may become dysfunctional. However, the world still has a chance to stabilize global temperatures below 2°C above pre-industrial levels and eradicate poverty by 2050."

Figure 1.1: The five turnarounds are interconnected, enabling a comprehensive transformation of the system.

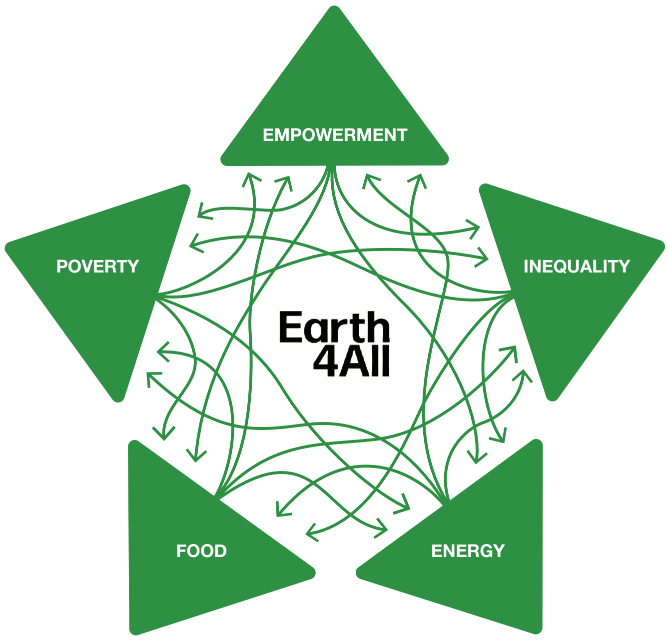


Figure 1.1 – Source: Dixson-Declève et al., 2022.

Scenarios to 2100

The two scenarios, beginning in 1980 and ending in 2100, are called "**Too Little, Too Late**" and "**The Giant Leap**." They explore how global population, economies, resource use, pollution, well-being, and social tensions might change over this century based on decisions made in this decade.

Too Little, Too Late:

In the first scenario, global temperatures are projected to rise by about 2.5°C by 2100, a dangerously high level that significantly exceeds the targets set by the Paris Agreement.

The anticipated consequences of this scenario include:
- The most vulnerable economies will bear the brunt, facing significant challenges in adapting to climate impacts. Many people will live in areas close to the limits of human survival.
- All societies will confront persistent crises driven by extreme climate events, such as heatwaves, droughts, and floods.

The model indicates that in this scenario, the risk of regional social breakdowns will increase significantly due to escalating social tensions, food insecurity, and worsening environmental degradation.

The Giant Leap toward sustainable development

Planetary boundaries represent clear limits within which humanity can operate without jeopardizing the stability of life-supporting ecosystems on Earth. The Earth4All initiative provides a strategic framework to address the greatest challenges of our time—from eliminating poverty and inequality to transforming the food system and transitioning to sustainable energy sources.

It highlights five critical areas where turnarounds are urgently needed to achieve sustainable development:
1. **Poverty:** Strategies to eradicate poverty include new economic growth models, trade reforms, and expansion of the political space. Globally, this means re-regionalizing trade and fairer distribution systems.
2. **Inequality:** Reducing inequality involves progressive tax reforms, strengthening trade unions, and introducing a universal basic dividend to ensure a fairer distribution of resources.
3. **Empowerment:** Empowerment goals include universal education, fair retirement, and increased gender equality, particularly in leadership roles.
4. **Food:** Transforming the food system through greater efficiency, sustainable agriculture, and reducing food poverty.
5. **Energy:** Transitioning to renewable energy sources, electrification, and increasing energy efficiency to achieve net-zero emissions by 2050.

These essential turnarounds involve reforming the financial system, reducing global inequalities, empowering women, overhauling the food system, and adopting clean energy—enabling global temperature stabilization and reducing poverty. Implementing these turnarounds requires a fundamental restructuring of our global economic system, redesigning it to serve both people and the planet.

TOO LITTLE, TOO LATE

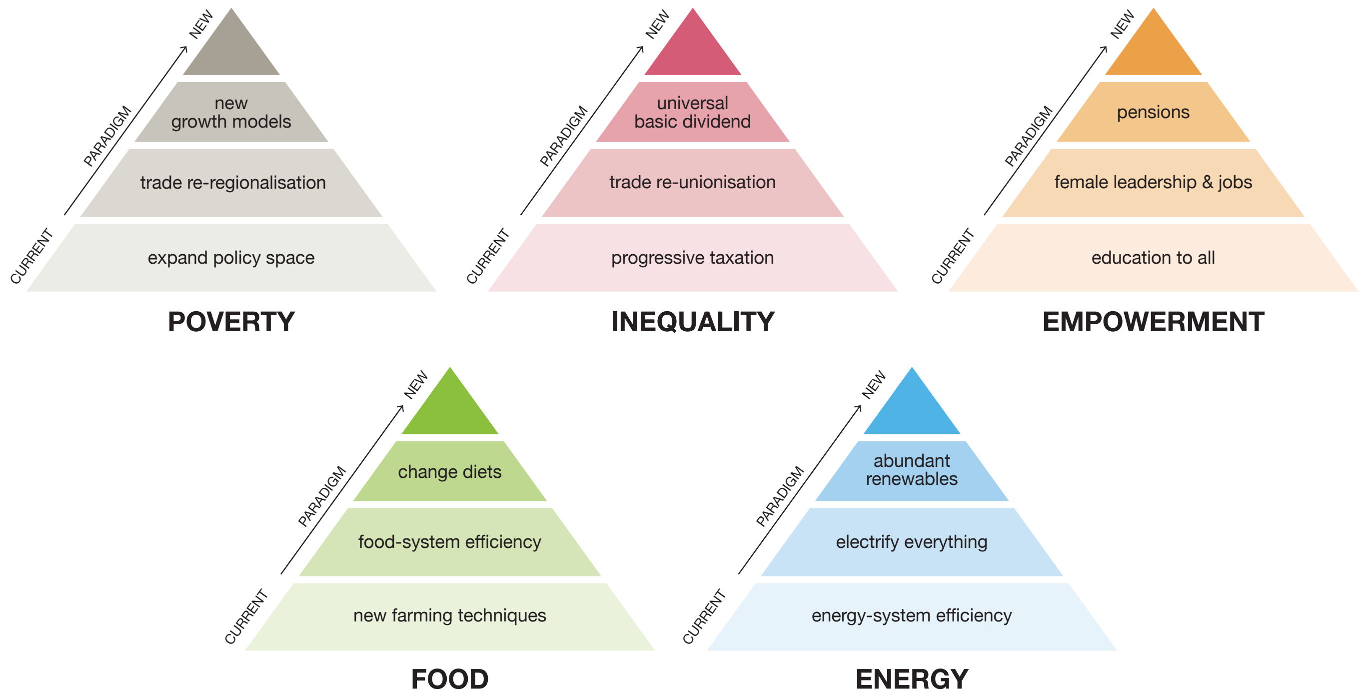
Global temperatures are expected to rise by

2.5°C

by year

2100

Figure 1.2: The Earth4All paradigm shift is illustrated by five triangles, each representing one of the turnarounds. Each contains critical levers with a disproportionate impact. Moving from the bottom up in each triangle begins with economic solutions within the current paradigm, while the top represents transformative proposals that drive a giant leap into a new paradigm.



Key actions for achieving the giant leap scenario necessary for social and ecological balance and address major global challenges

1. **Eradicating poverty** by reforming the international financial system, lifting 3-4 billion people out of poverty.
2. **Reducing inequality** by ensuring the top 10% of earners receive less than 40% of national income.
3. **Empowering women** to achieve complete gender equality by 2050.
4. **Transforming the food system** to ensure a healthy diet for both people and the planet.
5. **Transitioning to clean energy** to achieve net-zero emissions by 2050.

Figure 1.2 – Source: Dixson-Declève et al., 2022

Comparing the Earth4All initiative with development scenarios for a sustainable low-carbon society in Slovenia

Over a decade ago, a methodology similar to the Earth4All initiative was applied in Slovenia, forming a foundation for identifying sustainable solutions to climate change. The project "Scenarios for Slovenia's Development by 2035" (Piciga, 2010) created a new development strategy focused on a low-carbon society, with three development scenarios by 2035—Green Oasis, Chameleon, and No Ideas. Sixty experts participated in the Slovenia´s Development Scenario for 2035.

60 experts were involved in designing the scenario of Slovenia's development up to 2035.

What does the Green Oasis scenario entail?

- Best results with early action, technological changes, and shifts in attitudes.
- Implementation of GDH (Gross Domestic Happiness) instead of GDP.
- High energy efficiency and a shift to organic food production.

What do the other two scenarios entail?

The No Ideas scenario represents a situation where climate change is ignored or even denied. In this scenario, society and decision-makers do not respond to climate challenges, leading to stagnation in addressing environmental issues and an inability to develop appropriate sustainable policies.

The Chameleon scenario reflects an approach where responses to climate change are implemented too late or on too small a scale. Society adapts to changes, but adaptation is slow and limited insufficient, meaning that there are no early and proactive measures to prevent major impacts of climate change.

Vision: A mutually interconnected and inclusive low-carbon society with a thriving economy and high quality of life, land use space, and natural environment.

The scenario analyses from this project and the subsequent targeted research project (CRP) SINODA (Slovenia, Low-Carbon Society, CRP 2008-2011), using the International Futures system dynamics model, contributed to the foundational expertise for a comprehensive long-term climate strategy in 2011 (Government Climate Change Office, 2012). Slovenia was among the first countries globally to develop such a strategy, which today aligns closely with the "Giant Leap" scenario in the Earth4All report by the Club of Rome. The draft climate strategy also incorporated various other expert foundations and proposals arising from public and stakeholder discussions; more than 250 experts participated across eleven workshops to prepare the strategy in 2011.

Current development in Slovenia and prospects for a sustainable future

Based on scenarios set over a decade ago and the latest scientific findings, the question arises: What is Slovenia's current trajectory? Indicators such as greenhouse gas emissions and ecological footprint are well above planetary boundaries, pointing to serious challenges. Slovenia's ecological overshoot day was reached on April 25, 2024, signaling that it had already consumed all its allocated natural resources for the year.

Although the set target is climate neutrality by 2050, current emissions exceed the threshold by more than three times. After the 2008 economic crisis, changes were observed—indicators like GDP and HDI continued to rise, while emissions and ecological footprint declined. Slovenia is on a path toward emissions reduction, having decreased them by 16% by 2020, demonstrating the potential for achieving carbon neutrality by 2050 (Figure 1).

Two possible future scenarios for Slovenia are: "The Giant Leap" or "Too Little, Too Late." Efforts such as energy efficiency, phasing out fossil fuels, and electrification are already underway but must be intensified. Should these processes stall, Slovenia risks falling behind in economic development and facing greater negative impacts from climate change and global security issues.

Figure 1.3: Selected sustainability indicators over recent decades: total greenhouse gas emissions, ecological footprint per capita, energy supply per capita, gross domestic product per capita, and Human Development Index (HDI). The time series range depends on available data. The ecological footprint is based on actual data up to 2019 and projections from 2020 to 2022. HDI is shown in tenfold magnitude for clarity (adapted from Stritih, 2023b).

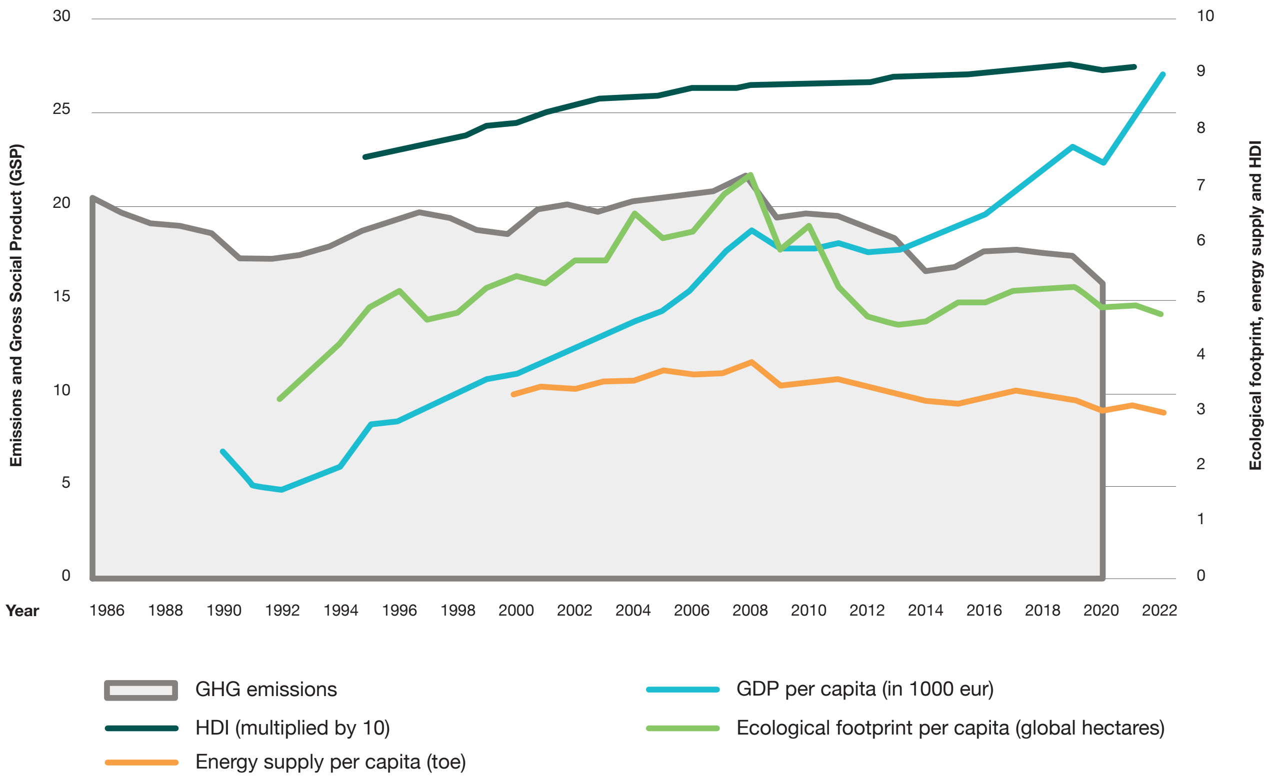


Figure 1.3 – Source: ARSO 2023, Global Footprint Network 2023, SURS 2023, UNDP 2023

2

A brief overview of the original concept of planetary boundaries and its evolution

The concept of planetary boundaries, first introduced in 2009, provided a framework for understanding Earth's safe operating space. Over the years, researchers have expanded this concept, analyzing the dynamic relationships between boundaries and the importance of respecting them to maintain Earth system resilience. Join us as we explore the evolution of this essential concept that shapes science and policy.

Global environmental limits and the planetary boundaries framework

Our planet Earth is a complex system sustained by various natural processes, ecosystems, and life forms. Just like our bodies, Earth operates within boundaries that support life as we know it—these are called planetary boundaries.

This concept was developed to help us understand and respect the limits that define a safe operating space where humanity can thrive while maintaining the delicate balance of Earth's ecosystems. Planetary boundaries offer a framework to visualize and quantify thresholds that must not be crossed if we wish to preserve the resilience of Earth's processes.

Understanding planetary boundaries is crucial for making informed decisions, acting responsibly, and collectively building a sustainable and harmonious relationship with our planet. Before presenting key findings from recent research, we'll break down the fundamental aspects of planetary boundaries, including Earth system processes, safe operating limits, tipping points, and their potential transgressions and associated risks.

The original concept of planetary boundaries (PBs 1.0) from 2009: Exploring humanity's safe operating space

1. Processes and Interactions in the Earth System

Earth is a complex, interconnected, and dynamic system where various Earth system processes interact and influence one another. Interactions within the Earth system encompass relationships between the geosphere (Earth's solid structure), hydrosphere (water bodies), atmosphere (air and gases surrounding the planet), biosphere (living organisms), and anthroposphere (human activity). Understanding these interactions is essential to grasp how changes in one component can cascade through the system, leading to far-reaching consequences.

1.1 Geosphere-biosphere interactions:
The geosphere, including Earth's physical and inorganic properties, significantly interacts with the biosphere, the realm of living organisms. These interactions have historically shaped Earth's conditions.

1.2 Climate regulation:
Earth's climate is a dynamic system governed by factors like solar radiation, greenhouse gases, and ocean currents. Climate regulation is essential for maintaining stable, life-supporting conditions within the safe operating space.

1.3 Hydrological cycle:
The continuous movement of water on, above, and below Earth's surface, including processes like evaporation, condensation, precipitation, and runoff, plays a crucial role in shaping landscapes and sustaining life.

1.4 Biogeochemical cycles:
Cycles such as the carbon, nitrogen, and phosphorus cycles involve the movement of elements between the biosphere, geosphere, atmosphere, and hydrosphere, affecting life processes and environmental conditions (e.g., temperature, humidity, nutrient availability).

1.5 Biodiversity dynamics:
This includes the diversity of life on Earth and the ecological processes that sustain it. Biodiversity dynamics contribute to ecosystem resilience and stability.

1.6 Solar energy input:
Solar radiation is Earth's primary external energy source. It regulates climate, weather patterns, and various processes within the Earth system. Understanding solar energy input is critical for assessing environmental changes within the planetary boundaries framework.

* Planetary boundaries. In the publication, both terms—boundaries or limits—are used interchangeably.

2. Planetary Boundaries

Planetary boundaries are thresholds that define a safe operating space for humanity to operate within Earth's system. They signify limits that must not be exceeded; otherwise, human activities could disrupt critical Earth system processes. These boundaries set parameters for climate change, biosphere integrity, land system change, freshwater use, and more. Crossing these boundaries can lead to sudden or permanent changes, posing severe risks to ecosystems and societies (Rockström et al., 2009; Steffen et al., 2015).

3. Tipping Points

Tipping points are critical thresholds within the Earth system where small disruptions can trigger significant and often irreversible changes. Crossing a tipping point can lead to sudden shifts in climate patterns, ecosystems, or other Earth processes. Recognizing and understanding these points is crucial to preventing potential catastrophic outcomes. One example is the potential collapse of the Atlantic Meridional Overturning Circulation (AMOC), a key ocean current system that significantly impacts climate (Lenton et al. 2008).

Figure 2.1: Tipping Points.

* Planetary boundaries. In some sources, the terms boundaries and limits are used interchangeably.
Figure 2.1 – Source: Planetary Health Check 2024. Adapted from: https://www.planetaryhealthcheck.org/

4. Transgressions and Risks

In the context of planetary boundaries, a transgression means exceeding a critical threshold, indicating that human activities have significantly burdened Earth system processes and pushed them beyond their sustainable capacity. Initially set as precautionary limits, these boundaries mark the points where sudden and potentially irreversible changes in ecological processes could occur, crucial for maintaining Earth system stability.

To better understand the concept of transgressing planetary boundaries and the associated risks, two diagrams (Figure 2.2) illustrate various ecosystem and societal responses to boundary breaches. The first diagram depicts global climate change feedback effects, while the second shows local and regional impacts of biodiversity loss. These diagrams visualize the difference between global and local processes, underscoring the importance of timely actions to maintain ecosystem resilience and prevent irreversible changes.

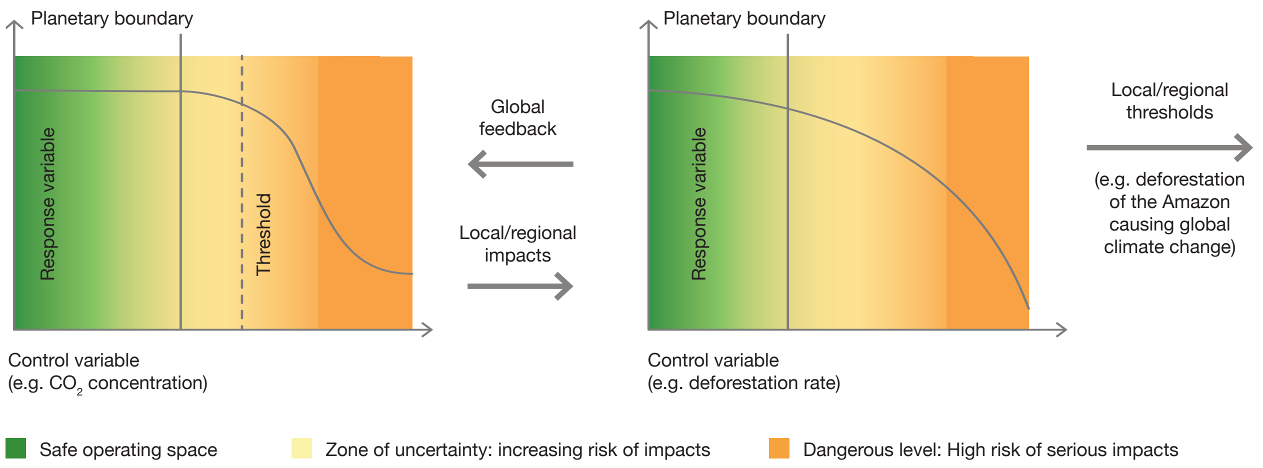
Figure 2.2: Visualizing ecosystem responses to planetary boundary transgressions.

Process X (e.g., Climate change):

This diagram shows how global Earth processes, such as climate change, respond to changes in key factors like atmospheric CO_2 concentration. There is a safe operating space where planetary systems can adapt without major issues. However, when this boundary— known as a threshold— is crossed, the risk of severe consequences greatly increases. Uncontrolled transgressions can result in global feedback effects like extreme weather events, glacial melting, and sea-level rise.

Process Y (e.g., Biodiversity):

This diagram shows how local and regional processes, such as deforestation, impact the global system. While effects are often local (e.g., rainforest disappearance), these changes can lead to larger-scale impacts on climate. The rate of change is crucial— if we reduce forest areas too quickly, we cross a threshold, heightening the risk of global changes like climate shifts and loss of habitats for numerous species.



To understand the evolution of the planetary boundaries concept, we need to review its development over time. The initial framework in 2009 identified key planetary boundaries to protect Earth systems from harmful human impacts. In 2015, researchers updated the concept to better account for dynamic changes and new challenges, such as climate extremes and urban land use. In 2023, focus shifted to emphasizing adaptation to local and regional circumstances and the interconnection between social and ecological dimensions. This update highlights the need for flexible responses to planetary boundaries while incorporating social aspects critical for ensuring equity and a sustainable future.

Figure 2.2 – Source: Barnosky et al., 2012.

2009

The Original planetary boundaries concept from 2009 (PBs 1.0)

The planetary boundaries concept, introduced in 2009 by Johan Rockström and colleagues, marked a fundamental shift in our understanding of earth system processes and humanity's relationship with them. In their seminal paper, Planetary Boundaries: Exploring the Safe Operating Space for Humanity, they outlined a framework describing nine critical Earth system processes that define a safe operating space within which humanity can function to avoid catastrophic environmental consequences. These processes include climate change, chemical pollution, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows, freshwater use, land-system change, and biodiversity loss.

2015

2015 – An advancement of the original concept: Guiding human development on a changing planet (PBs 2.0)

In 2015, Will Steffen and his team enhanced the concept of planetary boundaries. They replaced the boundary for chemical pollution with "introduction of novel entities" and biodiversity loss with "biosphere integrity." Novel entities were defined as new substances, new forms of existing substances, or altered forms of life that could cause undesired geophysical and/or biological effects. Their research provided a more detailed breakdown of the interconnected relationships among boundaries and introduced specific indicators for monitoring them. Alongside updated data, they deepened the understanding of the consequences that arise from transgressing these boundaries. In addition to global boundaries like climate change and biosphere integrity, the researchers emphasized the importance of regional boundaries, such as the South Asian monsoon, which has crucial impacts on agriculture and water supply in the region.

The authors noted that decisions regarding societal development are largely political and that equity should play a central role in these decisions. The consequences of transgressing planetary boundaries are often distributed unevenly—vulnerable regions, such as South Asia, experience the most severe effects of climate change, even though they have contributed the least to its causes. Therefore, it is essential for developed countries to take greater responsibility for addressing these global challenges, both financially and technically, to ensure a fairer transition to a sustainable future.

2023

Safe and just limits for Earth's system

The interconnectedness of Earth's system stability and human well-being is often underestimated. In the article Safe and Just Earth System Boundaries (2023), Rockström and colleagues refined the planetary boundaries concept, introducing principles of equity and justice. They underscore the inseparable connection between environmental sustainability and social justice. The researchers presented a set of Earth system boundaries covering climate, biosphere integrity, freshwater, nutrient flows, and air pollution at both global and sub-global levels. Seven of the eight boundaries analyzed have already been breached, affecting 86% of the world's population. The need for immediate action to protect Earth's systems and people is highlighted.

Slika 2.3: Proposed Safe Earth System Boundaries (ESB) and Just Boundaries (ESG) without Significant Harm (NSH).

Figure 2.3 – Source: Rockström et al., 2023.

The link between safety and justice is crucial for understanding sustainable development, as sustainability cannot be achieved without fair distribution of resources and access to essentials such as clean water, food, and clean air. Justice in this context means that all people should have equitable access to the resources necessary for survival and that transgressing planetary boundaries should not disproportionately burden the poorest or most vulnerable groups.

Safety refers to the stability of environmental and social systems that allow for long-term survival on the planet. Failing to respect Earth system boundaries risks destabilizing key ecosystems, leading to increased risks such as climate disasters, food and water scarcity, and migration pressures. Therefore, global actions must incorporate a just approach, where the benefits and burdens of transitioning to sustainable development are evenly distributed across nations and social strata. Emphasizing justice ensures that no one is left behind or disproportionately impacted by the changes needed to protect the planet.

2023

2023 Reassessment of planetary boundaries (PBs 3.0): Earth exceeds six of nine planetary boundaries

In September 2023, the third update of the planetary boundaries framework (PBs 3.0) was presented in the article Earth beyond six of nine planetary boundaries (Richardson et al., 2023). An international group of scientists further refined the concept of planetary resilience as a safe operating space for humanity. Based on this updated framework, the group found that six out of the nine boundaries have been transgressed, meaning Earth is now operating outside the safe zone. Ocean acidification is close to being transgressed, aerosol load exceeds the boundary regionally, and stratospheric ozone levels have shown slight improvement. The degree of boundary transgression has increased for all exceeded boundaries. The proposed control variable for biosphere integrity, the share of net primary production (NPP) exploited by humans, also surpasses safe limits. These cumulative transgressions represent a critical increase in risks for people and ecosystems, threatening Earth system stability.

Figure 2.4: Current status of control variables for all nine planetary boundaries (from Richardson et al., 2023).

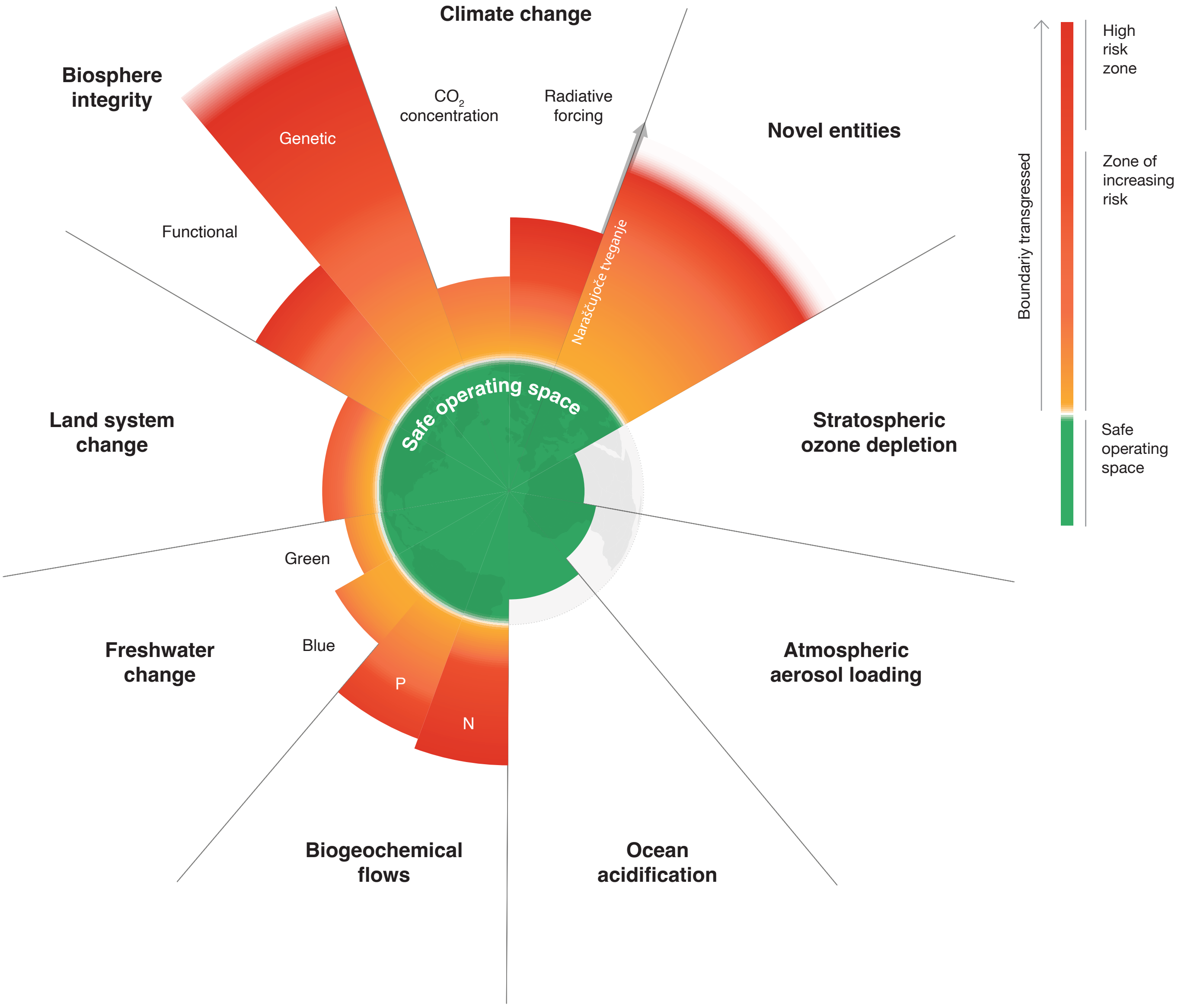


Figure 2.4 displays planetary boundaries with colors. The green area represents the safe operating space zone, orange and light red indicate increasing risk, and dark red represents a high-risk zone. Control variables are normalized based on mid-Holocene conditions. Transgressions reflect significant human disturbance to Earth's system processes, with high scientific uncertainty.

New methodologies have enabled the quantification of boundaries for novel entities, including chemicals, microplastics, and nuclear waste. For freshwater use, both green and blue water are considered, and both boundaries are exceeded. A new approach to assessing biosphere integrity reveals this boundary was already exceeded at the end of the 19th century. Extensive computational models and simulations were crucial to this study.

Figure 2.4 – Source: Richardson et al., 2023.

Core planetary boundaries: Climate change and biosphere integrity

Among planetary boundaries, two core elements are critical: biosphere integrity and climate change. Biosphere integrity emphasizes the holistic preservation of biodiversity and ecosystems, while climate change is essential to prevent catastrophic global warming and maintain a stable climate. Understanding and managing these fundamental boundaries are key to a sustainable future.

1. Climate change as a core planetary boundary

Climate change is considered a core planetary boundary essential for Earth system stability and is intrinsically linked to the balance ecosystems. The primary driver of climate change is anthropogenic greenhouse gas emissions, which result from activities such as:

- industrial production,
- deforestation,
- agriculture,
- fossil fuel combustion.

To ensure climate stability, the objective is to limit the concentration of carbon dioxide concentrations in the atmosphere to below 350 ppm CO_2. Key measures for safeguarding Earth system resilience include:

- minimizing the risk of crossing critical tipping points,
- preserving the biosphere and cryosphere,
- stabilizing global warming below 1.5 °C.

Currently, radiative forcing is at 2.91 W/m^2, with CO_2 concentration at 417 ppm. Maintaining a level of 350 ppm would result in less warming and reduce associated risks to Earth system processes.

2. Biosphere integrity

The integrity of Earth's biosphere is crucial for maintaining Earth system resilience. This integrity is closely linked to the geosphere and plays a key role in regulating Earth's conditions. It depends on:

- Genetic diversity, which forms the foundation of the ecological complexity of the biosphere, shaped by natural selection and evolution. Currently, the extinction rate of species is over 100 times higher than the background (natural) rate (noted as 100 E/MSY). This accelerated rate threatens genetic diversity and destabilizes ecosystems globally.
- Functional Integrity, assessed through indicators like Net Primary Production (NPP), which represents the flow of energy and matter into the biosphere.

Genetic diversity, the rate of species extinction measured in E/MSY units (extinctions per million species per year), and Net Primary Production (NPP) are critical metrics for biosphere stability. The objective is to maintain the extinction rate below 10 E/MSY, as stable ecosystems with sustained biodiversity support efficient biomass production.

3. Biogeochemical flows

The planetary boundary for biogeochemical flows addresses the phosphorus (P) and nitrogen (N) cycles, both essential for ecosystems. Human activities, especially in agriculture and industry, have significantly disrupted the balance of these cycles. Excessive use of fertilizers leads to pollution, algal blooms, and ecosystem imbalances.

For phosphorus (P), the global boundary aims to maintain a flow of 11 Tg (teragrams) of P per year from freshwater to the ocean. However, current estimates (22 Tg P per year) exceed this limit. For nitrogen (N), the planetary boundary is set at 62 Tg N per year, but current usage (112 Tg N per year) surpasses this. The total input of anthropogenically fixed nitrogen is approximately 190 Tg N per year, which globally exceeds the nitrogen boundary.

4. Freshwater Cycle Alterations

The planetary boundary for freshwater use the entire terrestrial water cycle, including:

- Blue Water: Surface and groundwater (liquid water sources).
- Green Water: Soil moisture within the root zone (water available to plants).

Control variables measure deviations from pre-industrial conditions (1661–1860) on a global scale, with limits set at the 95th percentile of pre-industrial variability. Currently, 18% of the world's land area for blue water and 16% for green water experience either wet or dry deviations, indicating a significant transgression of the boundary. These exceedances have been observed for over a century, emphasizing the need for a precautionary approach (Richardson et al., 2023).

5. Land use change

The planetary boundary for land system change focuses on the preservation of major forest biomes:

- Tropical forests: At least 85% of the original forest area should remain intact, as tropical forests are essential for maintaining global biodiversity and absorbing carbon.
- Temperate forests: Recommended conservation of 50% of the remaining area. While temperate forests have lower biodiversity compared to tropical ones, they still provide crucial ecosystem services and habitats for numerous species.

- Boreal forests: At least 85% of the remaining area should be preserved. Boreal forests play a significant role in long-term carbon storage and act as climate stabilizers due to their high biomass and slow organic matter decomposition.

The control variable measures the remaining forest area relative to the potential natural forest cover during the Holocene. Recent land cover data from 2019 reveal that deforestation, particularly in the Amazon rainforest, has transgressed the planetary boundary. While assessment methods and technology continue to evolve, the global trend of decreasing forest cover is evident.

6. Ocean acidification

The control variable for this boundary is the concentration of carbonate ions in the surface layer of seawater, measured as the aragonite saturation state (Ωarag). This reflects the average saturation of surface ocean water with aragonite*, essential for marine life that relies on calcium carbonate. The original planetary boundary remains in effect, requiring that Ωarag be at least 80% of the pre-industrial global average of 3.44. Current estimates place Ωarag at approximately 2.8, or around 81% of the pre-industrial value, placing ocean acidification at the edge of its safe operating space. This trend is worsening due to ongoing increases in anthropogenic CO_2 emissions.

7. Novel entities and other pollutants

The planetary boundary framework for novel entities includes genuinely new, human-made substances and pollutants introduced into Earth's system, such as:

- synthetic chemicals and substances (e.g., microplastics, endocrine disruptors, organic pollutants),
- radioactive substances from human activities (e.g., nuclear waste, nuclear weapons),
- genetically modified organisms.

These novel entities act as geological markers of the Anthropocene epoch. The purpose of this boundary is to assess the impact of novel entities on the stability and resilience of Earth's system, rather than directly on human or ecosystem health. The safe operating space entails either the absence of these entities or confirmation of their harmlessness before release into the environment. The boundary is ideally set at 0% release of untested synthetic compounds into Earth's system. Despite challenges, such as incomplete data, this approach highlights the urgent need to monitor and regulate the release of novel entities.

8. Anthropogenic Aerosol Load

Aerosols affect Earth system processes physically, biogeochemically, and biologically. Anthropogenic aerosol loading has increased significantly, with global dust deposition doubling since 1750. Aerosol Optical Depth (AOD) is the control variable for aerosol loading. Steffen and colleagues (2015) proposed a provisional regional planetary boundary for AOD, which has been exceeded in South Asia.

Key Findings:

- Current global AOD: 0.14
- Regional AOD variations affect monsoon rainfall patterns
- Proposed boundary: 0.1 hemispheric difference, current value is 0.076
- Impacts include changes in precipitation and regional climate, influencing weather patterns in specific regions

A comprehensive understanding of aerosol impacts is essential for accurately define the threshold for safe aerosol loading.

By promoting a global commitment to sustainability, we can work towards harmonious coexistence with our planet and ensure a resilient and thriving Earth for future generations.

* Aragonite is a form of calcium carbonate ($CaCO_3$) that many marine organisms need to build shells and skeletons.

3

Is Europe living within the planetary boundaries?

An analysis examining European production and consumption in the context of planetary boundaries asesses whether Europe operates within safe environmental limits. Findings show that Europe's environmental footprints in certain areas have already exceeded safe thresholds, demanding urgent actions.

Assessment of Europe's environmental footprints in relation to planetary boundaries: Report by the European Environment Agency (EEA) and the Swiss Federal Office for the Environment (FOEN)

Planetary boundaries are calculated on a global scale, but effective application requires assigning portions of these limits to Europe and individual countries. This process, known as "downscaling," involves four key steps to adjust global boundaries for European and national contexts, enabling their integration into European policies and strategic plans. The steps are:

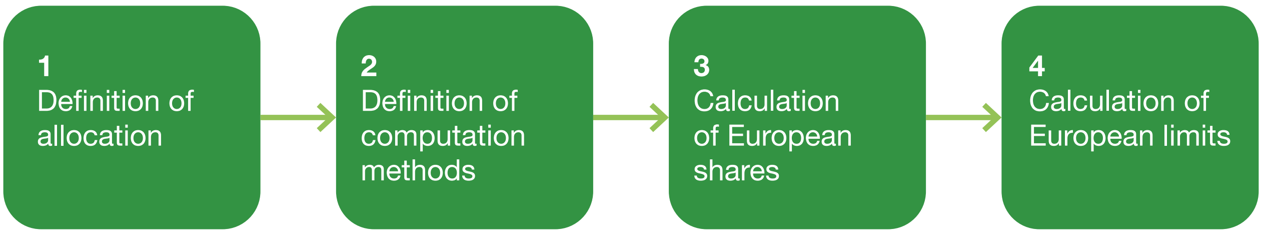
Defining allocation: The first step focuses on how to determine Europe's share of the global boundaries. This share is based on principles such as equity, resource needs, the right to development, and the environmental capacity of each country.

Calculation methods: Various scientific methods are used in this step to calculate these allocations. This involves detailed data on resource consumption, emissions, and environmental impacts contributed by EU member states within the global system.

Calculating Europe's share: With the gathered data, this step calculates the fair share of environmental responsibility that European countries bear in terms of pressure on planetary systems, allowing for comparison with global boundaries.

Calculating Europe's contribution: The final step assesses Europe's contribution toward respecting planetary boundaries, establishing specific goals and thresholds that Europe must adhere to in order to remain within safe environmental limits.

Diagram 3.1: Allocation of planetary caps in four steps: definition of the allocation and then calculation methods (1 and 2), calculation of European shares (3), calculation of European caps (4).



Assessment of Europe's environmental footprints against planetary boundaries

The European Environment Agency (EEA) and the Swiss Federal Office for the Environment (FOEN) report, Is Europe living within the limits of our planet? (EEA/FOEN, 2020), examines how to establish a safe operating space for Europe. It evaluates an approach based on three selected planetary boundaries: biogeochemical flows (phosphorus and nitrogen cycles), land-system change, and freshwater use. The analysis spans 33 EEA member countries, using biophysical control variables adjusted with European data. This adaptation of planetary boundaries to the European context illustrates Europe's contributions to global pressure on critical ecosystems, providing a framework to guide policies aimed at reducing environmental impacts.

Calculating environmental footprints enables precise monitoring of Europe's and its member states' natural resource consumption relative to their shares of planetary boundaries. This process identifies where exceedances occur, enabling timely interventions to mitigate adverse environmental impacts. Additionally, calculated footprints facilitate comparisons across countries, offering insights into how different policies and practices contribute to sustainability goals.
Transitioning to a sustainable society requires more than political will or technical innovation; it necessitates raising global awareness about sustainable practices, encouraging each individual and organization to reduce their environmental footprint. Promoting societal understanding of circular economy principles and reducing resource use can significantly lessen global environmental pressures. Furthermore, corporate responsibility is crucial, as sustainable practices in production and distribution yield long-term benefits for both the environment and society.

Diagram 3.1 – Source: EEA/FOEN.

Five principles for the allocation of global environmental or planetary boundaries

7.3%
NEEDS

8.1%
EQUALITY

4.1%
THE RIGHT TO DEVELOPMENT

12.5%
SOVEREIGNTY

6.2%
CAPABILITY

Using five allocation principles, the average European share is 7.3% of the global limit. The “right to development” principle assumes that lower-income countries need greater access to resources for development, leading to a lower European share (4.1%). Conversely, the “sovereignty” principle, which is based on the right of countries to use resources within their borders, allocates the highest share (12.5%).

In addition to these two principles, the “equality” principle ensures that every individual globally has an equal share in resource use (8.1%), while the “needs” principle allocates resources according to the basic needs of the population (7.3%). The “capabilities” principle assumes that more developed countries, with greater financial and technological capacities, should bear a larger share of responsibility for reducing environmental impacts (6.2%).In calculating Europe’s performance, a consumption-based approach is used, which takes into account the global economy and trade flows, allowing for the assessment of environmental impacts due to European consumption.

Social justice is a fundamental aspect of any environmental policy. In the transition to a sustainable society, it is essential that no one is left behind. Solutions such as access to clean energy, healthy food, and safe living environments must be distributed equitably among all residents. A sustainable transition must incorporate social justice to prevent the exclusion of vulnerable groups and to create conditions where everyone can participate in a sustainable future.

European institutions, such as the European Environment Agency (EEA), play a crucial role in establishing a framework for monitoring and achieving sustainability goals. Their research reports and analyses assist member states in understanding how their policies impact environmental footprints relative to planetary boundaries, providing guidance for reducing negative environmental impacts. Strengthening the institutional framework is essential to ensure that environmental policies align with long-term sustainable development objectives.

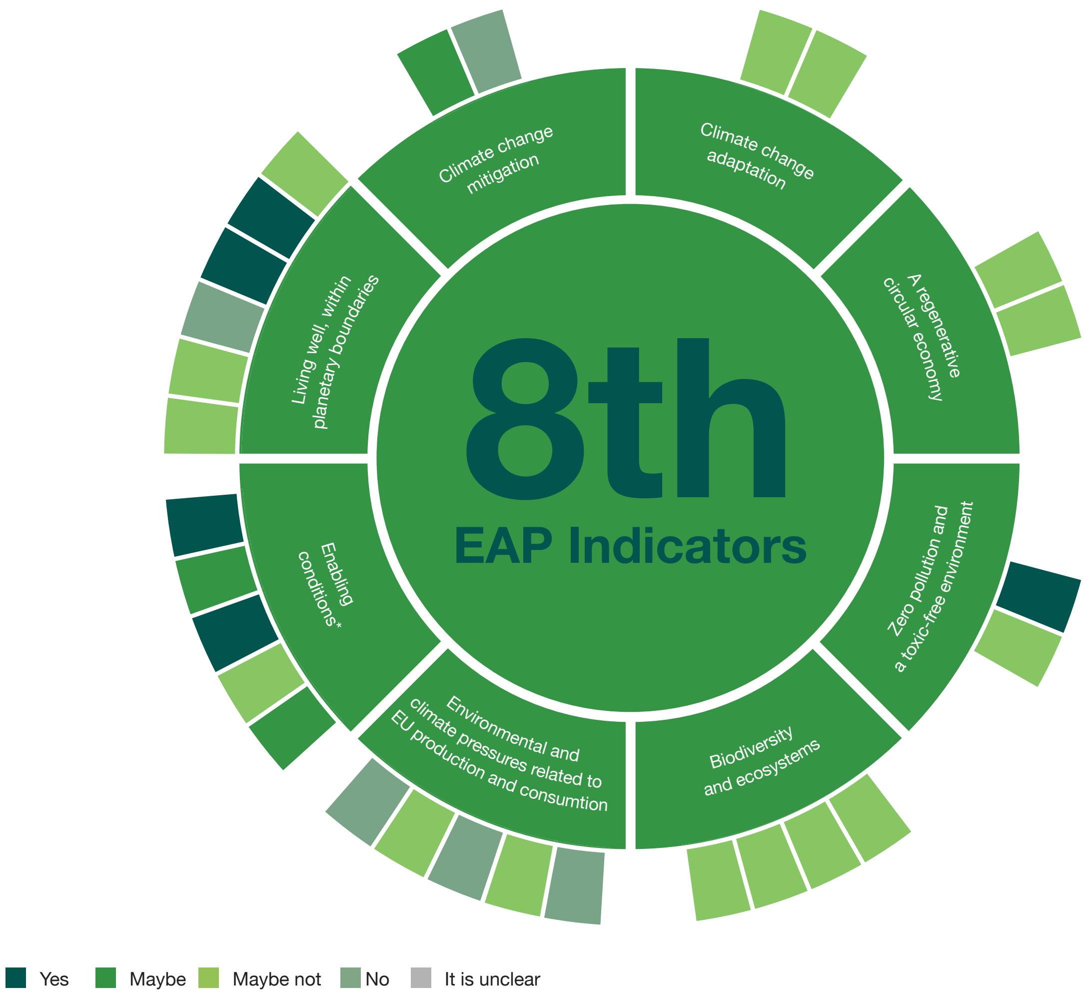
The EEA/FOEN report finds that the European environmental footprint needs to be reduced by a factor of three for nitrogen losses, by a factor of two for phosphorus losses, and nearly by a factor of two for human impacts from land-use changes. Current policies addressing nutrient cycling and land-use change challenges are not sufficiently comprehensive.

The development of the Eighth Environment Action Programme within the framework of the European Green Deal presents an opportunity for a more comprehensive approach to these challenges and for the reduction of Europe's environmental pressures abroad. Food, energy, and mobility systems are the primary drivers of Europe's transgression of planetary boundaries. Transforming the food system is particularly important to achieving sustainability goals.

Climate change and biosphere integrity are central planetary boundaries, as they influence other Earth system processes. Progress in addressing these issues may be hindered by inadequate action addressing other boundaries, such as biogeochemical flows, land-system change, and freshwater use.

Cooperation among European countries is crucial for achieving environmental goals, as no country can address global environmental challenges alone. The European Union, through collective actions such as emission reduction targets and circular economy policies, is laying the groundwork for a sustainable future in which all member states can operate within planetary boundaries. Common European approaches enable faster progress in reaching environmental goals while providing greater support to countries facing more significant challenges in transitioning to sustainability.

Figure 3.1: Indicators for monitoring the achievement of the 2050 targets of the 8th EAP.



* Enabling conditions refer to the establishment of all necessary factors that support the successful implementation of specific activities or the achievement of goals. These include legal and regulatory changes, financial and technical support, and cooperation among stakeholders.
Figure 3.1 – Source: Eighth EAP, 2022.

Assessing European consumption and production in the context of planetary boundaries

The environmental impacts require a shift to responsible consumption and production as soon as possible. Life Cycle Assessment is a comprehensive approach to assessing the environmental impacts of products throughout their life cycle. Although it helps to evaluate impacts, it does not define absolute sustainability. The inclusion of planetary boundaries in the life cycle assessment offers an “absolute sustainability assessment”.

A 2010 study evaluated the impacts of EU production and consumption using indicators that take into account life cycle assessment and compared them with planetary boundaries.

The objectives of the study were:
1. To compare indicators with life cycle assessment to assess the sustainability of the EU-28 system.
2. To present planetary boundaries based on life cycle impact assessment.

The planetary boundaries framework provides a scientifically sound measure of sustainability by measuring ecological thresholds in nine processes. Despite the boundaries, the concept highlights critical environmental limits essential for policy making and achieving sustainability goals. However, a comprehensive assessment of the impact of EU consumption based on them is still limited.

Life Cycle Assessment (LCA) is a key method for assessing the environmental impact of a product throughout its entire life cycle, from production to end use and disposal. Life Cycle Impact Assessment (LCIA) considers all phases, focusing on indicators such as energy consumption, greenhouse gas emissions and resource use. Using these methods ensures that environmental impacts are assessed holistically and accurately, enabling the development of policies aimed at reducing negative impacts through the entire value chain.

Metodology

Socio-economic dimension
To monitor the EU’s progress in decoupling economic growth from resource use and environmental damage, a set of indicators based on life cycle assessment has been developed:

- **Domestic Footprint:** Statistical data of environmental pressures and resource use across the entire EU territory.
- **Consumption Footprint (bottom-up):** Combined production perspective (domestic impacts) with product-based import and export estimates.
- **Consumption Footprint (top-down):** Combined production perspective with environmentally extended multi-regional input-output-based estimates of impact and exports.
- **Final Consumption I/O Footprint:** Allocating emissions and resources to economic sectors using top-down input-output LCA.
- **Consumer Footprint:** Assessing consumption impacts through process-based LCA of representative products.

Biophysical dimension
Planetary boundaries metrics do not correspond to standard Life Cycle Assessment (LCA) models, so planetary boundaries have been developed for 16 impact categories based on Life Cycle Impact Assessment (LCIA) methods. Conversion factors link the planetary boundaries from different methods, helping to assure compliance with EU Environmental Footprint (EnvF) regulations.

Ethical dimension
Two approaches have been used to set planetary limits in the EU:
- Comparison with global planetary boundaries to understand the global context and the role of the EU.
- Allocation on the basis of equity, which assumes equal rights to the environment for all inhabitants.

These approaches reveal the need for more comprehensive sustainability assessments and offer guidance on how to take into account planetary boundaries in life cycle assessments.

Results

The study found that EU consumption significantly exceeded the thresholds for several categories of environmental impacts, with EU citizens having had higher impacts than the average global citizen, with the exception of a few categories. These results are due to consumption behaviour, economic role and differences in environmental policies between countries.

Key aspects of planetary boundaries assessment

Results and policy implications:
- Food, housing and mobility are the main contributors to environmental impacts in the EU.
- Food consumption is responsible for 33% of the climate change footprint and 74% of eutrophication.
- To meet planetary climate change limits, we would need to reduce food waste by 90% per capita.
- Policies on land use, climate change and airborne particulate matter (PM) should be addressed as a priority because they pose the greatest environmental risk.

Uncertainties:
- Uncertainties exist in quantifying sustainability due to incomplete data and modelling limitations.

Planetary boundaries and Life Cycle Assessment (LCA):
- Planetary boundaries do not fit perfectly with LCA impact categories, focusing on, among other things pressure indicators or endpoints.

The use of planetary boundaries in LCA Life Cycle Assessment):
- Efforts to include planetary boundaries in LCA are under development.

In order to comprehensively assess the environmental impacts of production and consumption, it is crucial to have data that allow for the disaggregation of impacts at different levels - from global to local. Resolved EXIOBASE 3 is one of the important tools that allows a detailed analysis of these impacts and supports the design of sustainability strategies.

To meet the planet’s climate change limits, we would need to reduce the amount of food waste per capita by **90%.**

2015

In 2015, EXIOBASE 3 became the key database for analysing the environmental impacts of production and consumption in the EU and globally.

EXIOBASE 3 and REX3

EXIOBASE 3 is a comprehensive database based on extended input-output tables (EE-IO tables) and includes data on environmental, economic and social flows at the global level. It is designed to analyse the interactions between consumption, production and environmental impacts, in particular in the evaluation of the ecological footprints of countries and regions. EXIOBASE 3 provides a detailed spatial breakdown of environmental impacts such as water stress, biodiversity loss, carbon footprint and other categories. This allows more accurate assessments of the environmental impacts of production and consumption and better planning of strategies to reduce these impacts.

The Resolved EXIOBASE version 3 (REX3)* database covers 189 countries, 163 sectors and a state-of-the-art set of environmental and socio-economic indicators for the period 1995 to 2015. The interactive platform with data, which was also used to produce the Global Resource Outlook (GRO2024), is open access.

Resolved EXIOBASE 3 (REX3) and its use

The results for the EU-27 show a significant increase in the EU's environmental footprint on water stress and biodiversity loss, mainly due to the regionalised assessment and spatial disaggregation.

In 2015, one third of the EU's water stress and half of its biodiversity loss footprint was due to imports from countries grouped together as "rest of the world" in EXIOBASE3. This is mainly due to food imports into the EU, which cause high water stress and biodiversity loss in countries such as Egypt and Madagascar.

Cabernard and Pfister used their REX3 database to incorporate environmental footprints such as carbon footprint, water stress and biodiversity loss into a framework for measuring green economy progress (GEP).

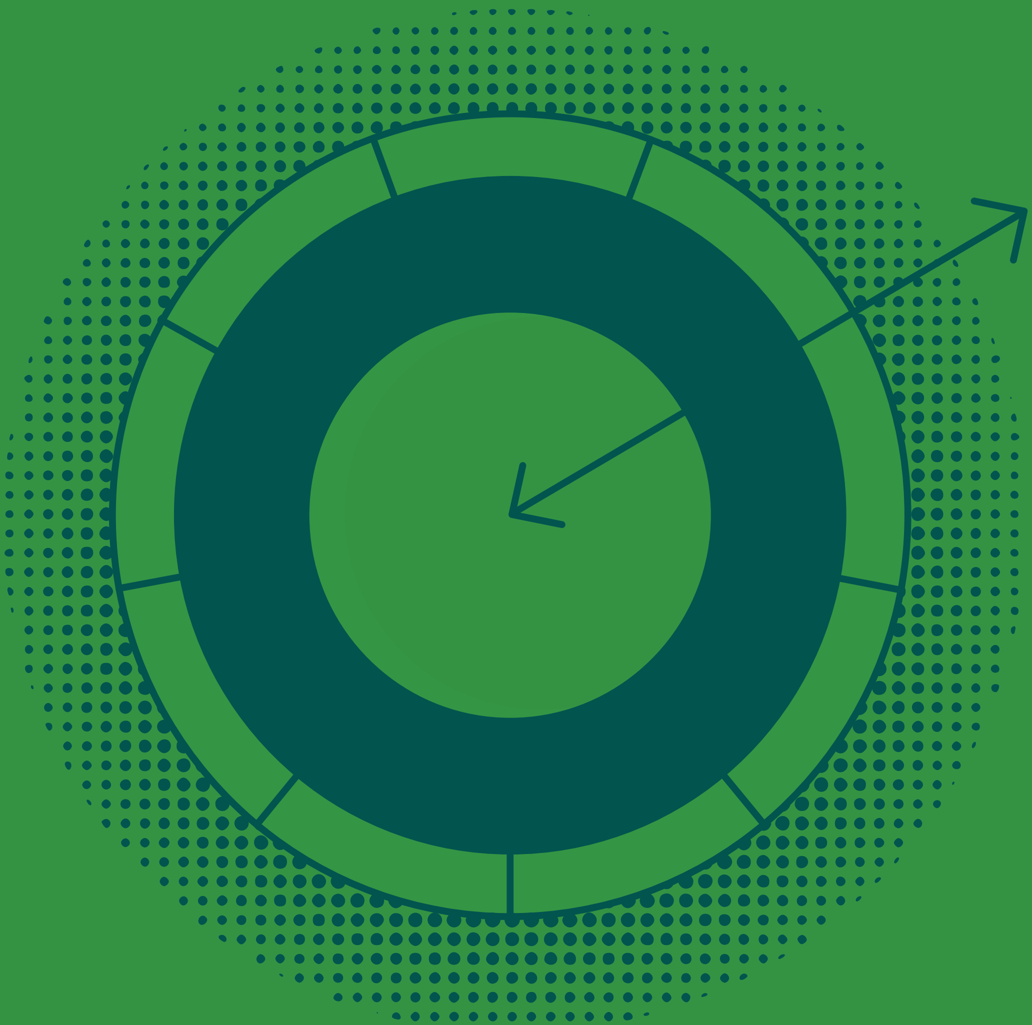
It has shown that most countries have not yet reached their environmental targets, while countries with rapidly growing populations are showing an increasing environmental footprint. Their findings underline that more ambitious action is needed to move towards a greener economy, especially in the management of global supply chains. REX3 provides detailed information on the environmental impacts of global value chains, enabling the design of effective strategies to achieve a green economy.

REX3 provides a detailed spatial breakdown of environmental impacts such as water stress, biodiversity loss, carbon footprint and other categories.

The Environmental Footprint Data Visualizer is a tool developed specifically for visualizing environmental data in support of the preparation of the Global Resource Outlook (GRO) 2024. This tool uses data from several different sources, including EXIOBASE, to display the environmental footprints of countries and facilitates the interpretation of the impacts of different sectors on planetary boundaries.

* REX3 provides raw data and analysis, while the Environmental Footprint Data Visualizer uses this data to show impacts at global and national levels in a more understandable visual format. Source: GRO Data Visualizer, 2024.

4



“Doughnut” Economics: measuring progress with the doughnut model

The concept of “doughnut” economics, developed by Kate Raworth, provides an effective approach to assessing the sustainability of countries and regions. It combines planetary boundaries with social indicators, allowing for a comprehensive evaluation of economic and social progress within environmental limits.

The concept of Doughnut Economics

The Oxford-based Doughnut Economics Action Lab (DEAL) addresses social and ecological challenges using the doughnut model developed by Kate Raworth. This concept, which combines planetary boundaries and sustainability/social indicators, was first introduced in 2012 in an Oxfam report. Raworth took the idea further in her book "Doughnut Economics" (2017), which became an international bestseller. Composed of a social foundation and an ecological ceiling, the doughnut ring acts as a compass for human well-being as it seeks to meet the needs of all people within the capacity of the planet, creating an ecologically safe and socially just space for human development.

The goal of the 21st century is to meet the needs of all people within the limits of our planet – which means entering the "doughnut". This cannot be achieved with the economic approach of the last century. The Doughnut Economics brings a new way of thinking adapted to the challenges of today. It is not just about specific policies or institutions, but a mindset that promotes the sustainable and equitable solutions needed to respond successfully to the challenges of our time.

Drawing on insights from different schools of economics – including ecological, feminist, institutional, behavioural and complexity economics – Doughnut Economics it sets out seven ways to think like a 21st century economist in order to transform economies, local to global.

Doughnut Economics shifts the focus from endless GDP growth to achieving sustainability within safe parameters. It emphasises that the economy is closely linked to society and the natural environment, and that we need to look at these three areas holistically. This approach recognises that human behaviour can foster cooperation and caring as well as competition and individualism. It also emphasises that economies, societies and the natural world are complex and interconnected systems that need to be understood using systems thinking. Doughnut Economics calls for the transformation of today's destructive economies into regenerative ones and for a transition towards more just and inclusive systems. It recognises that growth may be a natural part of development, but nothing grows forever – true success comes when we reach maturity and can move forward without the need for further growth.

Empirical research based on the Doughnut model

Fanning and co-authors (2022) find tdiminishing returns in social performance as resource use increases, and this finding holds across different social indicators or baskets of indicators, such as life satisfaction, life expectancy, CO_2 emissions, energy consumption and ecological footprint. The models examine the impact of achieving the SDGs on planetary boundaries and the socio-economic impacts associated with reducing CO_2 emissions and energy requirements to meet basic needs. However, they point out that many studies often do not disaggregate data at the national level or include multiple planetary boundaries and social indicators. Only one study provides a global analysis of the level of resource consumption to meet minimum societal thresholds using the safe and just space framework, but it is limited to one year.

A two-pronged approach is needed to reach social thresholds without overshooting biophysical limits:

- Limiting excessive affluence and consumption by the rich and
- Preventing extreme deprivation among the least well-off.

A better understanding of countries' trajectories with respect to the doughnut can provide insights into the necessary actions to transform unsustainable systems. Empirical research combining social and biophysical indicators within the doughnut framework is advancing, and this framework is already being used to assess the performance of cities, regions, countries and the world.

The doughnut is a visual framework illustrating the "safe and just space for humanity," where essential human needs of all people are met without overshooting planetary boundaries. The inner ring represents the social foundation—elements like access to food, water, health, and justice, which are essential for a decent life. The outer ring represents the ecological ceiling, encompassing ecological limits such as climate change, biodiversity loss, and pollution. The space between the rings symbolizes an optimal zone where social and ecological goals coexist in balance, enabling sustainable well-being for all.

Figure 4.1: Demonstration of the "doughnut" or doughnut economy - a framework for a safe and fair space for people's well-being, or a compass for people's well-being

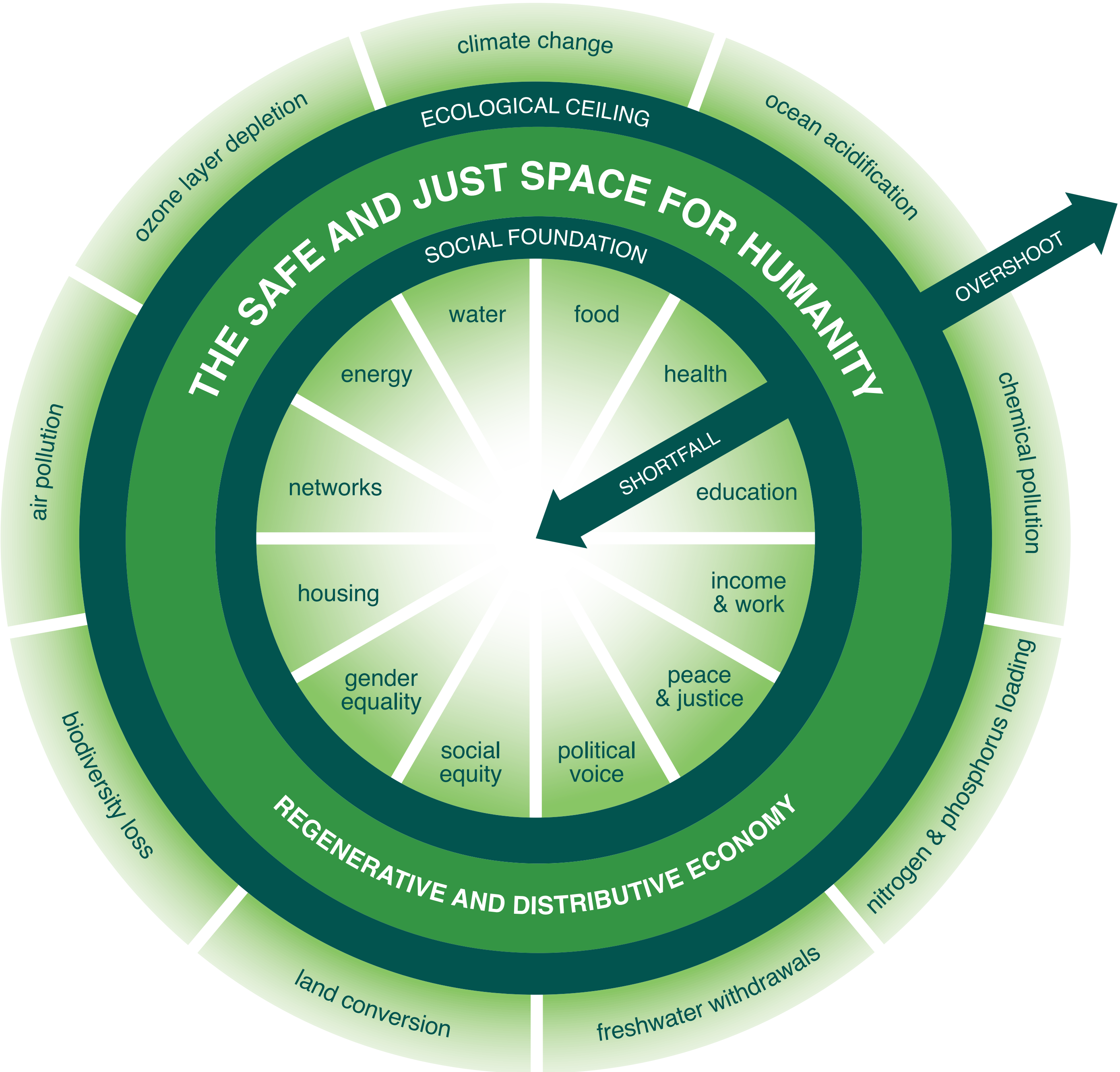
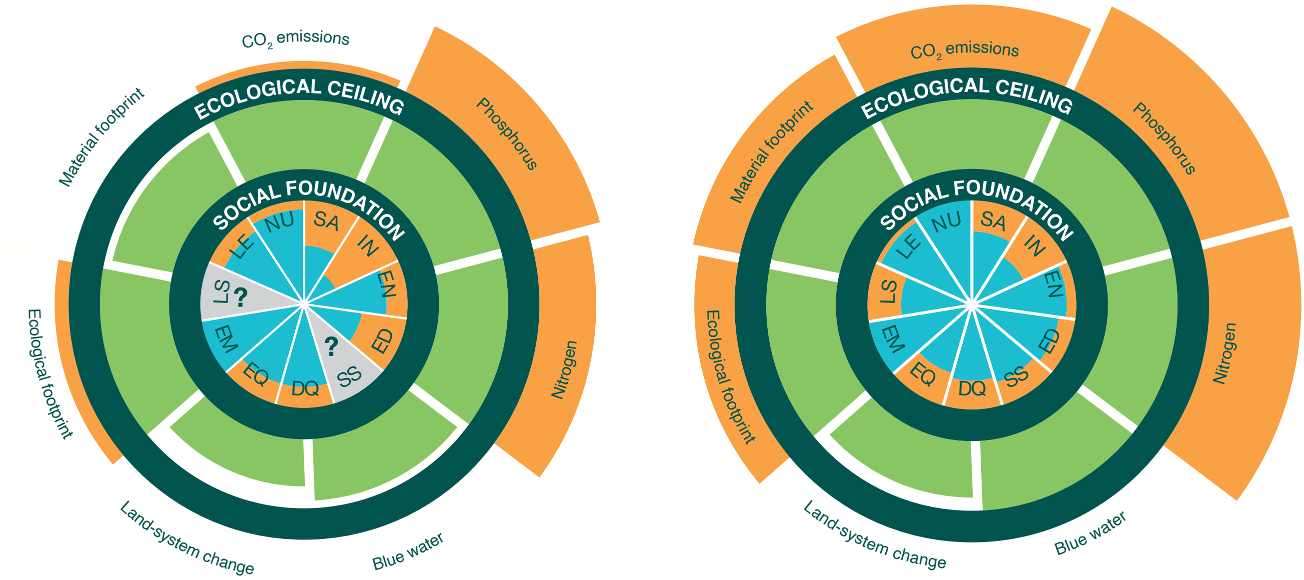


Figure 4.1 – Source: Fanning et al., 2022

Moving from a schematic representation of the doughnut to a doughnut that includes real environmental and socio-economic indicators allows the theoretical doughnut concept to be built upon with data-driven monitoring of the situation. The visualisation concept was developed by the University of Leeds under the leadership of Fanning and colleagues (Fanning, A.L., 2022). This approach allows visualisation of how well countries are doing in meeting the basic needs of their populations without exceeding the natural capacity of the planet. In this way, the Doughnut becomes a data-driven tool for assessing sustainable development and contributing to the design of targeted policies for global prosperity within safe ecological limits.

Figure 4.2: Global performance in meeting biophysical limits and societal thresholds 1992 and 2015.

1992 **2015**



- ecological ceiling and social foundation comprising a doughnut of social and planetary boundaries
- average social performance with regard to each of the social foundations, weighted by population number
- overall consumption of resources with regard to each of the global biophysical boundaries, beginning at the outer edge of social foundations
- shortfall below the social foundation or transgressing the the biophysical boundaries
- indicator with incomplete data

Legend:

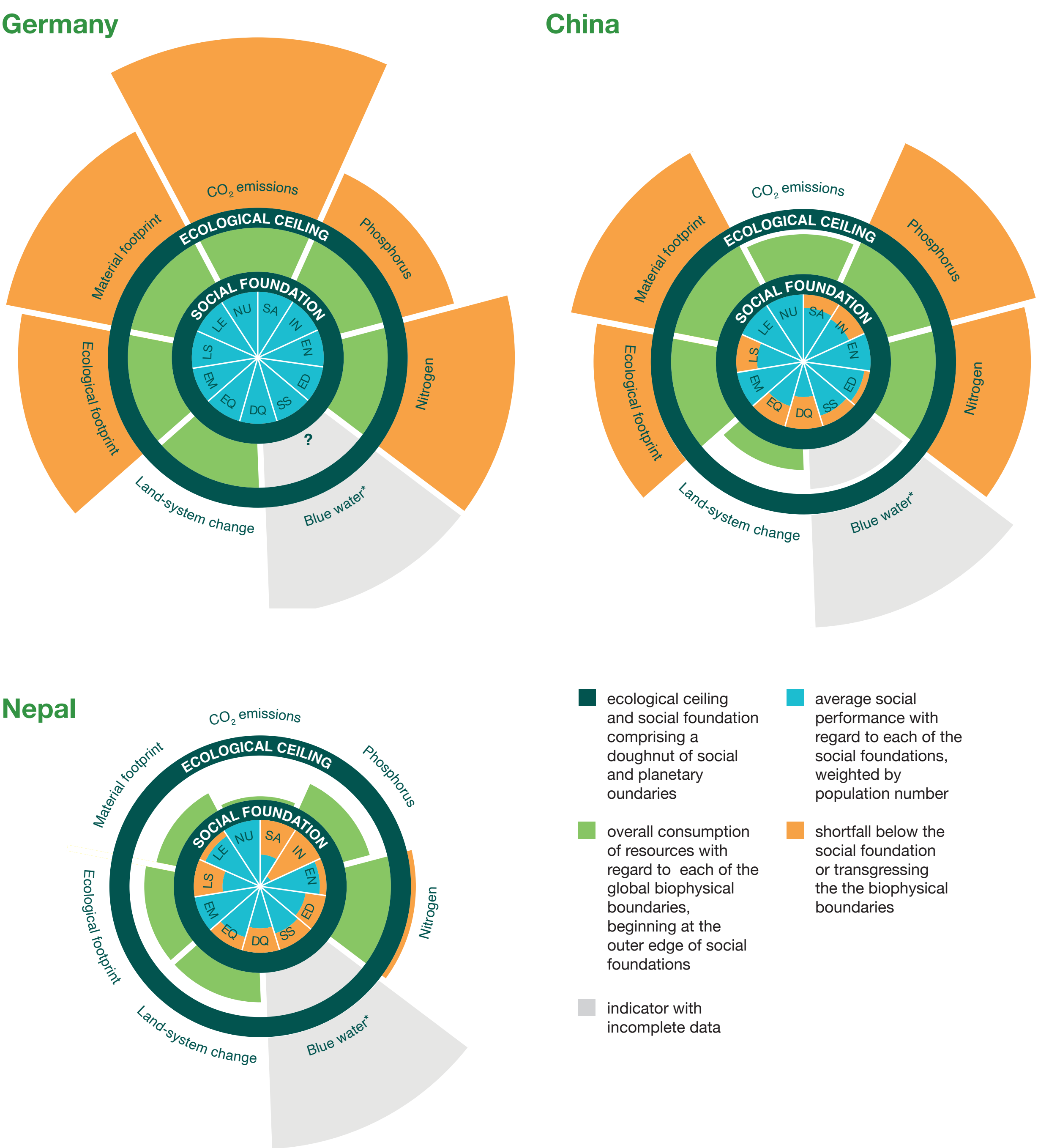
LS Life Satisfaction
LE Life Expectancy
NU Nutrition
SA Sanitation
IN Income Poverty
EN Access to Energy
ED Education
SS Social Support
DQ Democratic Quality
EQ Equality
EM Employment

Historical dynamics of 11 social and 6 biophysical indicators in more than 140 countries were analysed over the period 1992–2015. Three planetary boundaries (climate change, biogeochemical flows and land use) were compared with the environmental footprint of countries, using ecological and material footprints. Social performance was assessed on 11 indicators such as life satisfaction, life expectancy, access to food, sanitation, energy, education, social support, quality of democracy, equality and employment, and compared to minimum values.

The findings show that countries that meet social targets often use resources unsustainably, while countries that use resources sustainably fall short of social standards. Globally, billions of people live in countries that fall below most social thresholds, while humanity as a whole exceeds six of the seven global biophysical limits. Despite some progress since the 1990s, significant deficits remain and global resource use has increased significantly, with respect to material footprint and CO_2 emissions.

* **Blue water** is water found in rivers, lakes and groundwater and used for drinking, irrigation and industrial purposes.
Figure 4.2 – Source: Fanning et al., 2022.

Figure 4.3: National performance in achieving a safe and fair space for Germany, China and Nepal in 2015.



Legend:

LS	Life Satisfaction
LE	Life Expectancy
NU	Nutrition
SA	Sanitation
IN	Income Poverty
EN	Access to Energy
ED	Education
SS	Social Support
DQ	Democratic Quality
EQ	Equality
EM	Employment

* **Blue water** is water found in rivers, lakes and groundwater and used for drinking, irrigation and industrial purposes.
Figure 4.3 – Source: Fanning et al., 2022.

The analysis shows that countries are moving beyond biophysical limits faster than they are reaching social limits. The number of countries exceeding the biophysical limits increased by 32-55%, depending on the indicator, while social performance improved in only five indicators, worsened in two and remained almost unchanged in the rest. The data from this study are available on the DEAL (Doughnut Economics Action Lab) website.

High-performing regions often use resources in an unsustainable way, while low-performing regions do not achieve a sufficient social base.

Projections to 2050 show that current trends are exacerbating the ecological crisis and failing to address societal deficits. The number of countries exceeding CO_2 limits is likely to more than double. High-income countries such as Germany need to reduce resource use, while middle-income countries such as China face the challenge of improving social performance while reducing resource use. Low-income countries such as Nepal can increase resource use, but need to accelerate improvements in social indicators to avoid scarcity.

Doughnut Economy: New economic paradigm

The Doughnut Economics represents a new vision for the economy and sustainable development. The visual framework in the form of a doughnut combines the concept of planetary boundaries with societal needs. The aim is to shift economic priorities from simply increasing GDP to creating a society that provides sufficient goods and services for all, while managing resources sustainably. The advantage of this framework is that it allows an assessment of whether current economic and energy models are working within ecological boundaries. Ideally, different aspects of the economy should operate within regenerative and equitable frameworks for both the environment and society.

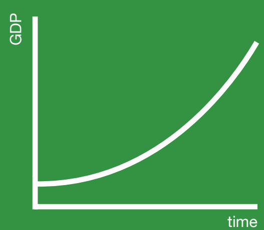
Kate Raworth has expanded on the concept of doughnut economics in her book Doughnut Economicst: Seven Ways to Think Like a 21st Century Economist'. In the book, she describes the frustrations of economics students who cannot find answers in traditional textbooks, and shares her experiences in Zambia and working on human development reports for the UN. The author suggests that economics should be seen through the prism of goals, not just mechanisms, and presents the transition from old to new ways of thinking using a series of diagrams that offer a new, broader perspective for 21st century economists.

Seven ways to think like a 21st century economist

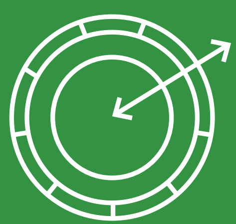
DOUGHNUT ECONOMICS ACTION LAB

Seven Ways to Think	From 20th-Century Economics	To 21st-Century Economics

1.
Change the goal: from GDP growth to the Doughnut

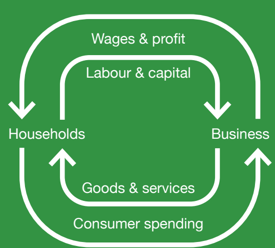


GDP

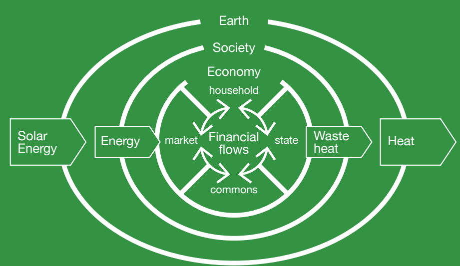


the Doughnut

2.
See the Big Picture: from a self-contained market to an embedded economy



Self-contained market



Embedded economy

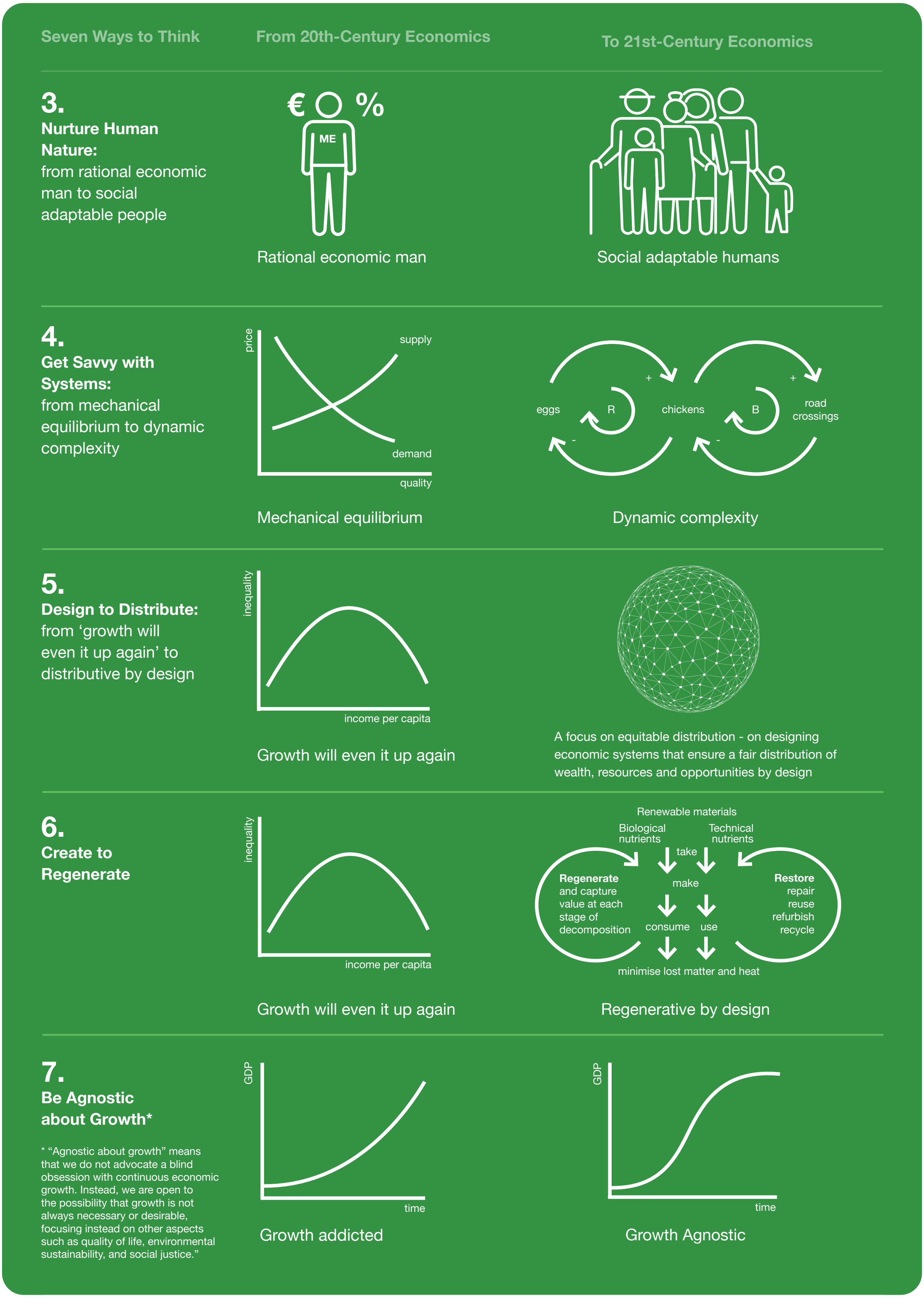


Figure 4.4. – Source: University of Leeds. DEAL website: Chapter summaries for doughnut economics.

5

Ecological footprint as an indicator of biological regenerative capacity, consumption, and well-being in relation to selected planetary boundaries

The ecological footprint is a key metric that measures human impact on ecosystems. It is a metric to monitor the balance between human demands and the regenerative capacity of the planet. Understanding the connections between the ecological footprint and planetary boundaries supports the development of more effective sustainability policies.

Ecological footprint as a measure of regenerative growth

If regenerative growth is understood as economic development within the planet's regenerative capacity, it is crucial to monitor this balance. The ecological footprint serves as a sustainability indicator that measures human pressure on ecosystems. Calculated by the Global Footprint Network for nearly 200 countries, including Slovenia, it aggregates all human demands on biologically productive areas, comparing them with biocapacity. The ecological footprint (EF) is expressed in global hectares (gha) and consists of the partial footprints of cropland, grazing land, forest products, fishing grounds, footprint of built-up areas, and carbon footprint.

Figure 5.1: Composition of Slovenia's ecological footprint by land categories, 1992–2022.

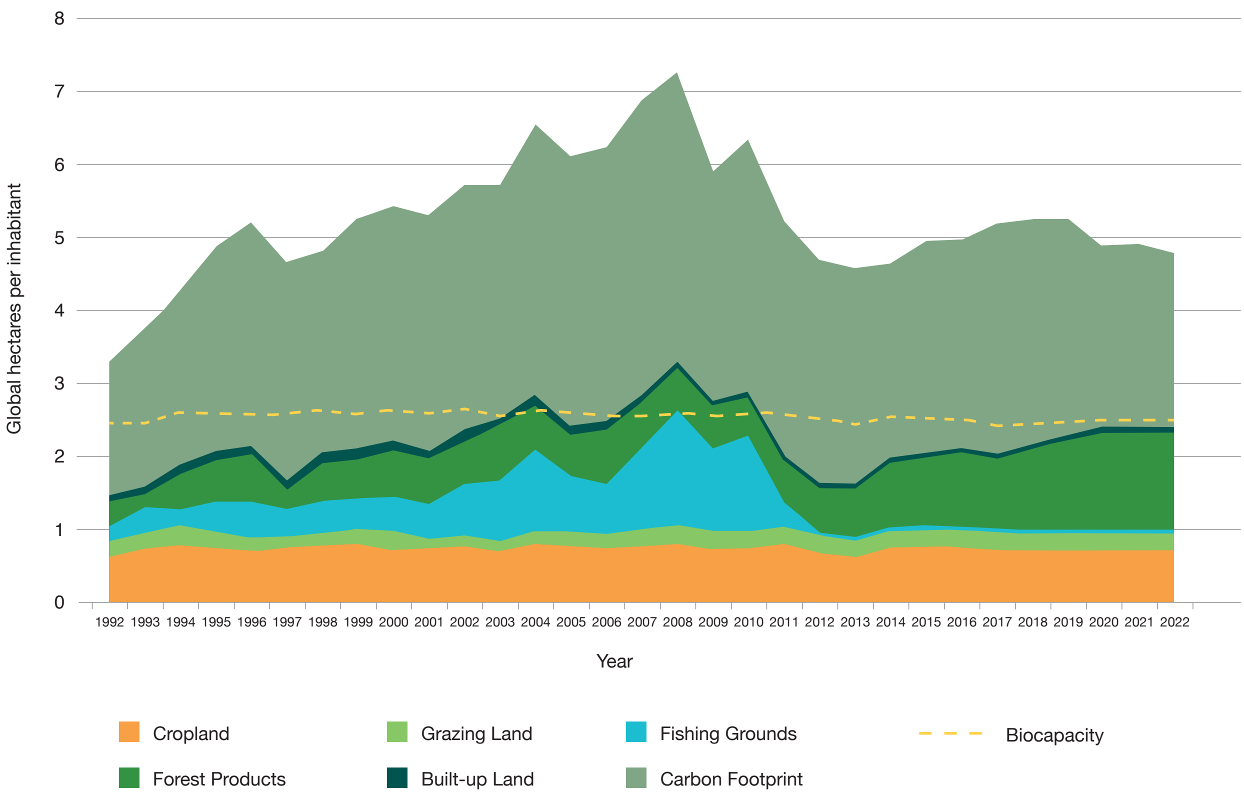


Figure 5.1 – Source: GFN, 2024. Analyze by land types. Data up to and including 2019 are submitted by Slovenia and included in the United Nations data repository; post-2019 data are based on modeled estimates.

The time series of the ecological footprint reveals significant changes, such as a reduction in the carbon footprint after 2008 and an increase in the footprint of forest products due to climate change. If Slovenia achieves a net-zero carbon footprint, its ecological footprint will align more closely with biocapacity. Achieving this will mostly depend on domestic actions to phase out fossil fuels and reduce carbon emissions from imported goods. The ecological footprint is a strategic indicator in Slovenia's Development Strategy 2030 (SRS 2030, 2017) and the National Program for Environmental Protection, with a goal of a 20% reduction by 2030 (ReNPVO20-30, 2020). It is also used in regional development programmes and annual development reports for Slovenia.

Figure 5.2: The connection between two categories of ecological footprint – consumption categories and footprint components for Slovenia, 2017.

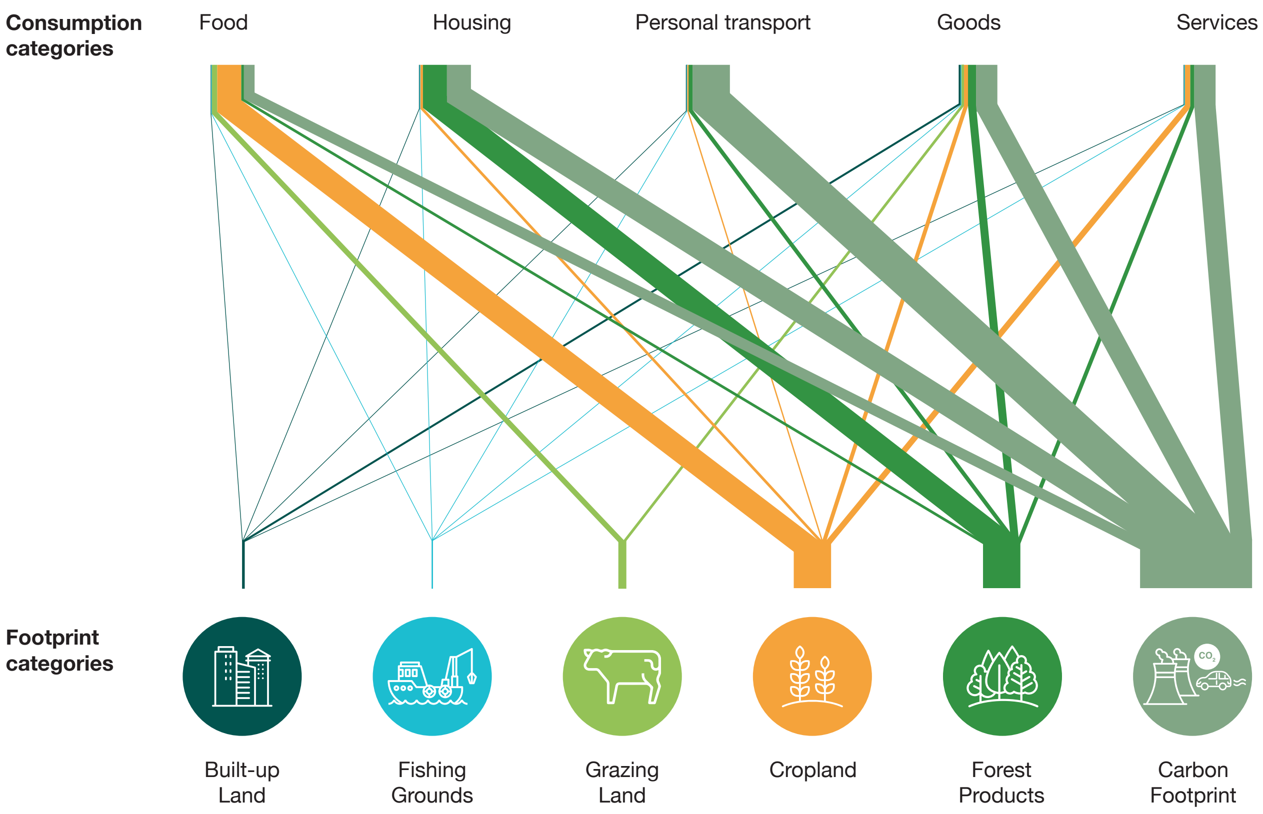


Figure 5.2 – Source: Bolte, T. et al., 2022.

Using the ecological footprint to evaluate impacts on planetary boundaries

Despite the adoption of sustainable development goals, the measurement of ecological footprint and the Human Development Index (HDI) shows that few countries are nearing sustainable development. Higher development is accompanied by a larger ecological footprint, indicating that development occurs without considering environmental capacities. Developing countries follow developed countries in burdening the environment for economic growth, making it essential for all nations to decisively steer their policies toward sustainable development.

The ecological footprint is a tool for assessing the impacts of human activity on planetary boundaries, based on the logic that exceeding the Earth's regenerative capacity leads to the degradation of natural capital. It measures human demand for biologically productive surfaces and natural resources, comparing them with the planet's restorative capacity. It indicates when countries or regions exceed planetary limits, such as carbon absorption capacity, biodiversity, and natural resource consumption.

The burning of fossil fuels is the primary contributor to the ecological footprint in developed countries, as it contributes to climate change and loss of biodiversity. Therefore, the ecological footprint becomes an important strategic indicator in Slovenian Development Strategy 2030 and the Environment Protection Programme 2020-2030. By analyzing it, we can understand how human resource use impacts planetary boundaries, allowing for adjustments in policies at regional and national levels. Thus, the ecological footprint is becoming a key tool for identifying current and future challenges related to the limits of Earth's natural resources and directing actions toward a sustainable future.

Similar conclusions as those derived from using the ecological footprint indicator in conjunction with the Human Development Index can also be drawn based on the Doughnut Economics methodology, as seen in Figure 5.3.The figure shows the number of biophysical boundaries exceeded and the number of societal thresholds reached for different countries over time (1992–2015). The figure shows which countries have exceeded biophysical limits (bottom axis) while achieving social thresholds (left axis), and provides insights into the progress and challenges countries have faced in balancing social development with environmental limits.

Slovenia is shown in the top right part, which means that it exceeds six biophysical boundaries and at the same time achieves a relatively high level of social thresholds. This shows that Slovenia, like many developed countries, enjoys a higher level of living standards, such as access to energy, education and health services, but at the cost of over-exploiting natural resources and exceeding ecological or planetary limits.

How to simultaneously monitor planetary boundaries and a green economy focused on well-being?

The Doughnut Economics concept by Kate Raworth provides a way to monitor both planetary boundaries and the development of a green economy focused on equitable and sustainable well-being. The DEAL (Doughnut Economics Action Lab) methodology, which builds on this idea, combines environmental limits with social foundations and sustainability indicators, offering a comprehensive approach that allows for balanced monitoring of economic progress without exceeding the planet's ecological capacities.

In Figure 5.4, Slovenia's position is clearly depicted in comparison to the EU-28 concerning ecological ceilings and social foundations. Slovenia, like the EU-28, exceeds several planetary boundaries, especially in CO_2 emissions and land use, while also achieving high values in social foundation indicators, such as access to education and energy. The visual representation highlights how countries like Slovenia manage to meet basic social needs of their populations despite exceeding biophysical limits.

In this context, the study by Fanning and co-authors (Fanning, A.L. et al, 2022) addresses three key planetary boundaries – climate change, biogeochemical flows and land-system change – and includes indicators such as CO_2 emissions, human appropriation of net primary production, and nitrogen and phosphorus levels. These indicators can be used to measure how countries are progressing in the transition towards a green economy that supports prosperity without exceeding natural resource boundaries. Data on ecological and material footprints are also included to complement this analysis.

The research draws on historical data (1992–2015) and includes projections up to 2050, focusing specifically on the applicability of this approach for Slovenia. Relevant data and graphical representations illustrate how Slovenia aligns sustainable resource use with green economy objectives. The methodology is based on the principle of equity, assessing whether countries sustainably meet their populations' basic needs while respecting the planet's regenerative capacity.

This approach allows for tracking both environmental limits and progress toward building an economy that prioritizes equitable and sustainable well-being over traditional growth metrics.

Figure 5.3: Dynamics of exceeding biophysical limits and achieving social thresholds in various countries, 1992–2015.

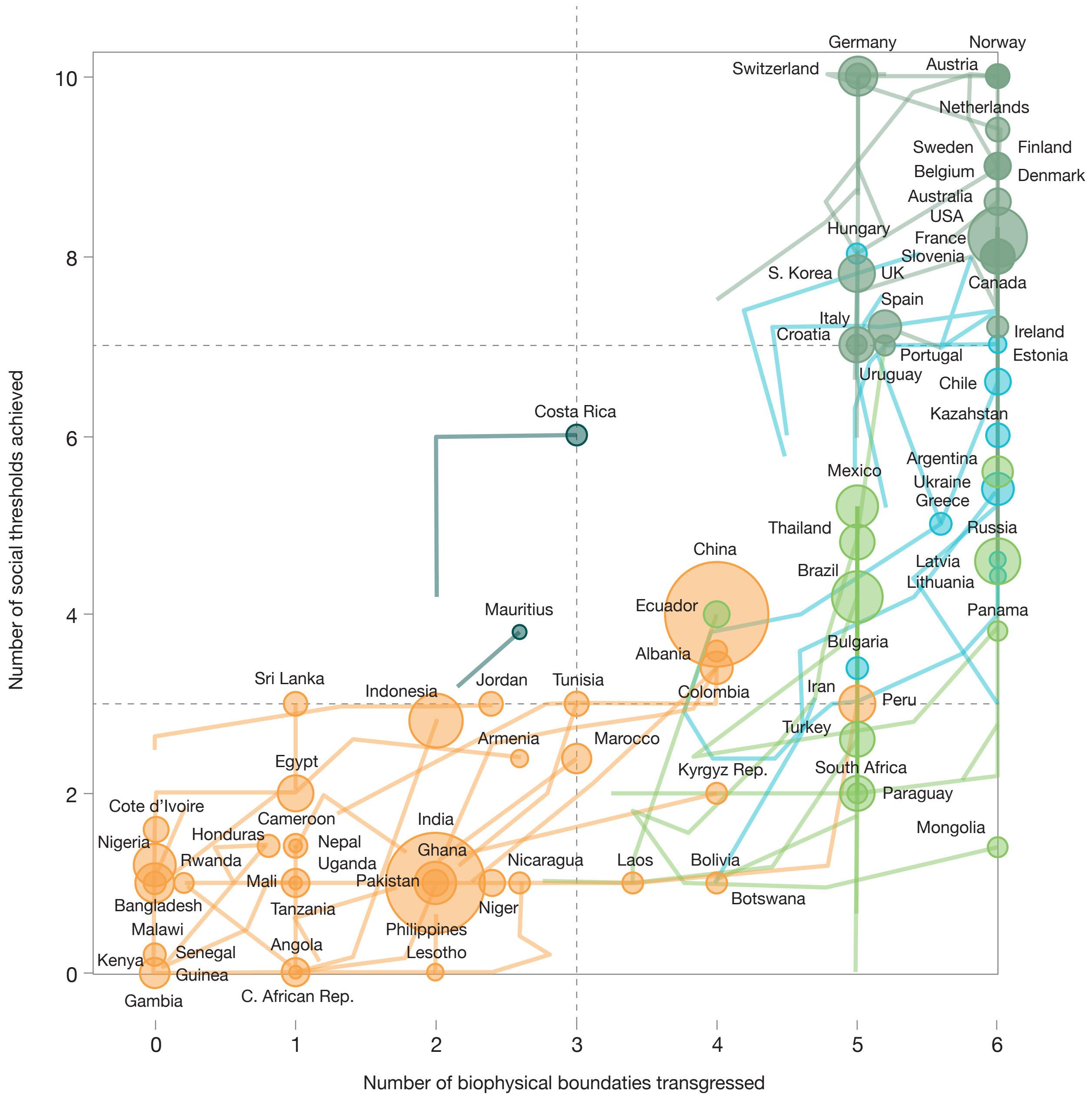
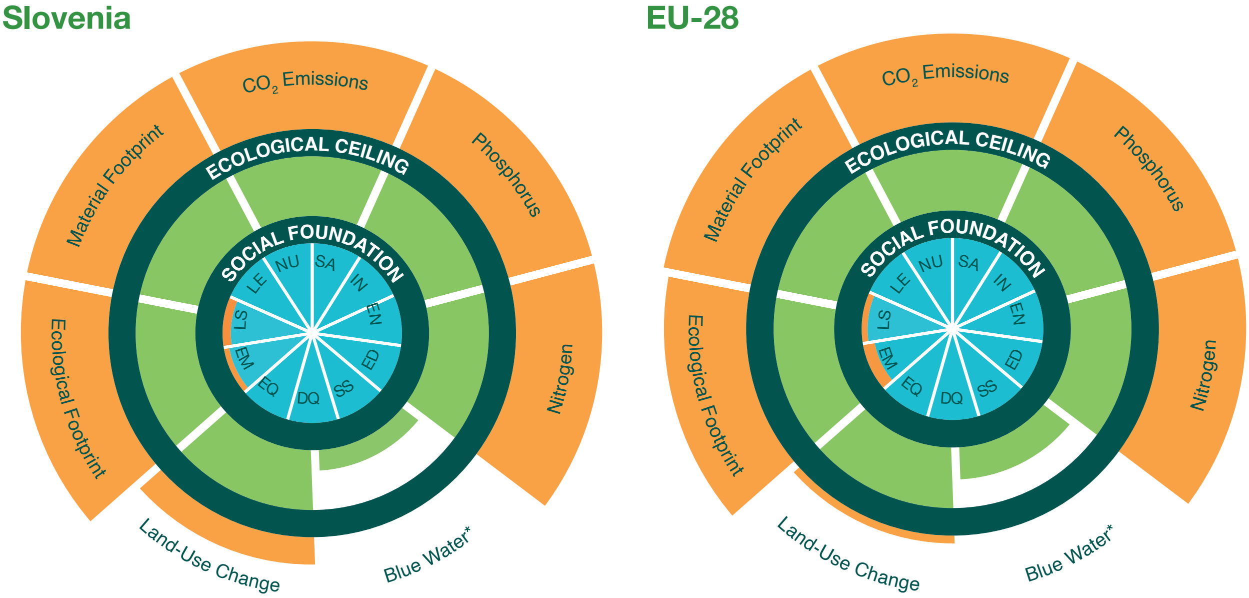


Figure 5.3 – Source: University of Leeds, 2024. DEAL website. A Good Life For All Within Planetary Boundaries. Pathways. (https://goodlife.leeds.ac.uk/national-trends/pathways/)

Figure 5.4: A good life for all within planetary boundaries – comparison between Slovenia and EU-28.



- ecological ceiling and social foundation comprising a doughnut of social and planetary boundaries
- average social performance with regard to each of the social foundations, weighted by population number
- overall consumption of resources with regard to each of the global biophysical boundaries, beginning at the outer edge of social foundations
- shortfall below the social foundation or transgressing the the biophysical boundaries
- indicator with incomplete data

Legend:

LS	Life Satisfaction
LE	Life Expectancy
NU	Nutrition
SA	Sanitation
IN	Income Poverty
EN	Access to Energy
ED	Education
SS	Social Support
DQ	Democratic Quality
EQ	Equality
EM	Employment

The study by Fanning and co-authors (2022) does not include time series data, as most indicators relate to the year 2011. These indicators provide a detailed view of developments in Slovenia, particularly in comparison with other EU countries, which may indicate gaps in policies or specific geographical characteristics of Slovenia. For example, despite exceeding thresholds for nitrogen and phosphorus, Slovenia has less intensive agriculture compared to the EU average due to its terrain, which favours livestock farming over crop farming.

Another essential aspect is understanding how these threshold values are determined. Some thresholds are based on well-defined logic, such as comparing ecological footprint with biocapacity, or are backed by extensive research, such as those related to climate neutrality. Other thresholds, however, are more challenging to define, as they can be influenced by local or regional geographic characteristics (e.g., the impact of nitrogen and phosphorus on specific watersheds).

Using footprints to evaluate planetary boundaries

Experts report that since 1996, when Wackernagel and Rees introduced the first measurement of the ecological footprint, many other footprints have emerged. Most articles focus on carbon, water, and ecological footprints, while others include footprints related to soil, nitrogen, phosphorus and material footprint, as well as footprints for biodiversity, chemicals, $PM_{2.5}$ particles, PM_{10}, ozone, and energy. This terminology is also used in the environmental footprint of products and organizations based on the Life Cycle Assessment (LCA) of the European Commission.

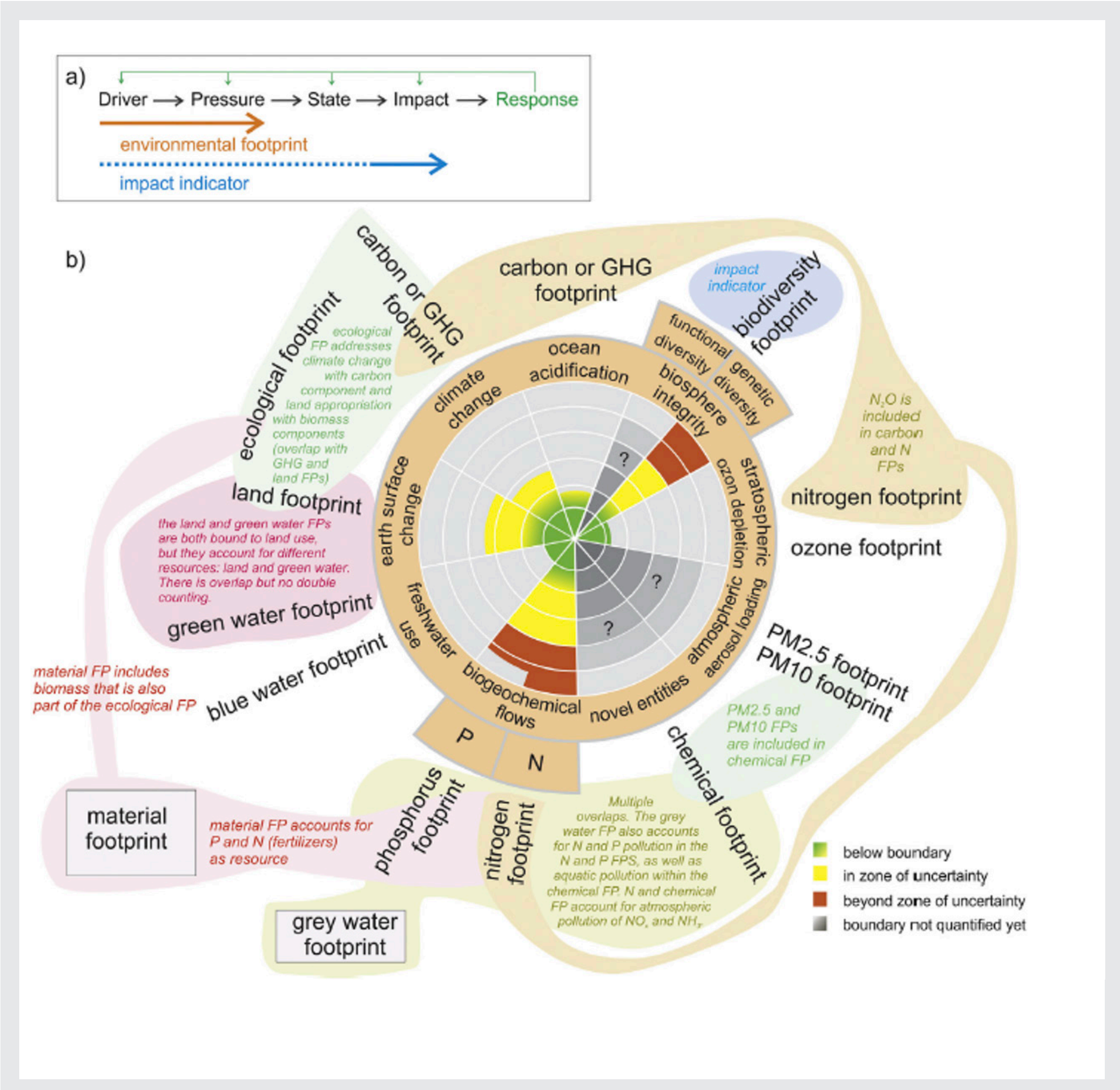
In the 2019 paper, Vanham and co-authors illustrate the diversity of footprints and the linkages between them within the broader framework of the DPSIR assessment (drivers, pressures, status, impacts, responses). In doing so, they present the main environmental footprints (e.g. ecological, carbon, material footprints) and the linkages with other planetary boundaries such as phosphorus, nitrogen and chemical emissions. This gives a clearer picture of how the different footprints are interlinked and how they affect the state of environmental resources.

* **Blue water** is water found in rivers, lakes and groundwater and used for drinking, irrigation and industrial purposes.
Figure 5.4 – Source: University of Leeds, DEAL website. A Good Life For All Within Planetary Boundaries. Country comparisons https://goodlife.leeds.ac.uk/national-snapshots/countries/

Figure 5.5: The DPSIR framework and its connection to environmental footprints and the compliance of footprint indicators with planetary boundaries.

a) Linear representation of the DPSIR assessment framework (Driving forces, Pressures, State, Impacts, Responses) (OECD, 2003) and its theoretical relationship with environmental footprints and impact indicators. Since recently, some authors also use terminology "impact footprints" as relating to impact indicators, in addition to the pressure-related footprints we describe here.

b) Correspondence of existing footprint indicators with the nine planetary boundaries, with visualization of overlap between different footprints. Chemical pollution is already included as a planetary boundary (new entity) with the associated chemical footprint. Material footprints and grey water footprints do not directly correspond to the planetary boundary. FP = footprint.

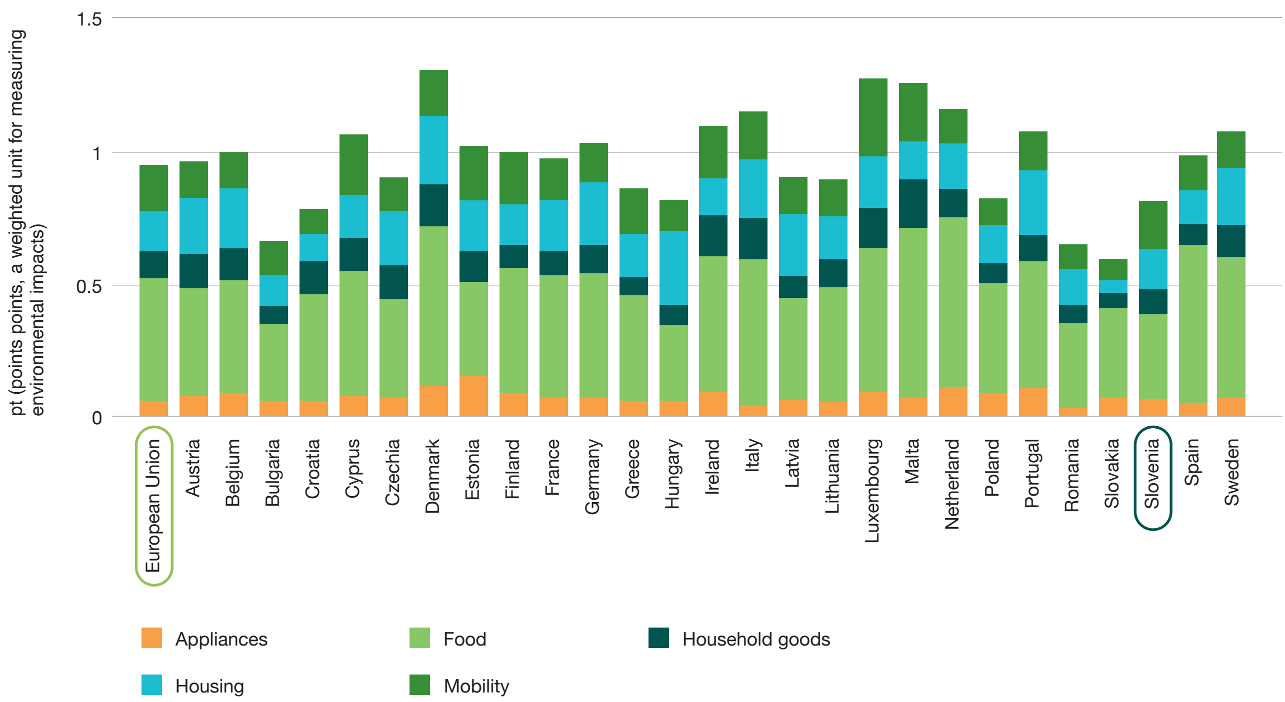


* **Grey water** is wastewater from domestic activities, usually containing no faecal matter.
Figure 5.5 – Source: Vanham et al., 2019, Figure 2.b.

Footprints can also be calculated for individual products and services, allowing precise tracking of their environmental impacts. The JRC Consumption Footprint Platform provides EU-27 data on the environmental impacts of consumption from 2010–2021, published in 2023. This assessment includes detailed analyses of the environmental footprint across products, services, and sectors, enabling more accurate tracking of consumption's environmental impacts. A comparison of weighted results – impact per capita – shows that Slovenia's total consumption footprint is lower than the EU-27 average (0.81 for Slovenia and 0.95 for EU-27). Within the structure of the environmental footprint, the largest shares come from food, housing, and mobility, providing valuable insights for policy planning to reduce consumption's environmental impacts. The platform's results indicate that in Slovenia, the contribution of mobility to the consumption footprint is higher than the EU average, a finding corroborated by other studies.

Although the JRC platform offers a comprehensive insight into the impacts of consumption on the environment, even more in-depth and detailed data can be obtained by using the EXIOBASE database, upgraded to REX3.

Figure 5.6: Contribution of consumption to overall footprint per capita, EU-27, 2021



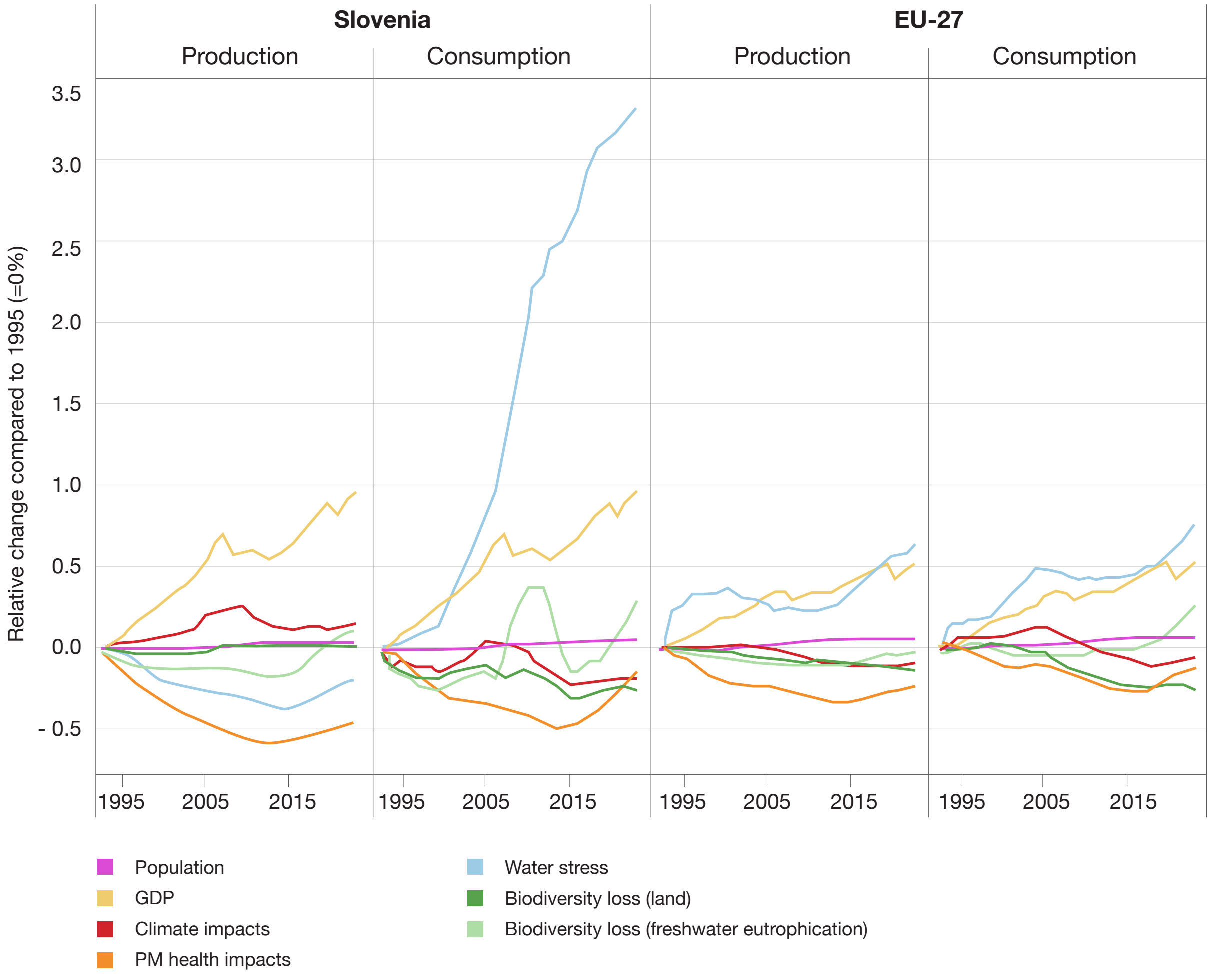
REX3 (Resolved EXIOBASE3 version 3) contains a comprehensive set of environmental indicators related to climate impacts, health impacts of particulate emissions, water stress, and loss of biodiversity due to land use changes and freshwater eutrophication. The system allows for the evaluation of impacts from two perspectives – production and consumption – enabling detailed analysis of the environmental impacts of domestic production as well as the impacts of demand for goods and services, including imported products that have effects beyond national borders.

The assessment of climate impacts in the REX3 system includes not only greenhouse gas emissions related to combustion and biogenic greenhouse gas emissions but also emissions resulting from land use changes. To evaluate the impact on biodiversity, spatially resolved data are used, combined with ecoregion-specific global species loss factors, thus providing detailed insights into the loss of biodiversity due to changes in natural habitats and subsequent gains from restoration measures. The evaluation is conducted at a high spatial resolution, which also includes the latest temporal trends.

In addition to environmental impacts, REX3 also includes the socio-economic indicators of “labor force” and “value added,” which allow for an assessment of the broader social and economic consequences of both production and consumption.

Figure 5.6 – Source: JRC Consumption Footprint Platform.

Figure 5.7: Temporal evolution of the environmental impacts of Slovenia and the EU-27 in total compared to population and GDP growth from 1995 to 2022. The impacts of the three planetary boundaries (climate, water stress and biodiversity) and particulate emissions are shown in terms of production and consumption. Calculated with REX3.



GDP: Both Slovenia and the EU-27 have experienced continuous GDP growth during the observed periods, exceeding the growth rates of all impact categories (relative decoupling of impacts from GDP). The exception is water stress, where decoupling has not been achieved.

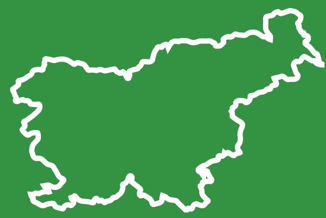
Climate: Consumption-based climate impacts have decreased in both Slovenia and the EU-27 (absolute decoupling from GDP). However, production-based climate impacts have decreased in the EU-27, while they have increased in Slovenia, particularly in the 1995–2010 period. This difference can be attributed to more robust technological advancements and greater efforts to phase out coal and transition to renewable energy sources in the EU-27 compared to Slovenia.

Health: The health impacts of particulate emission have decreased in both Slovenia and the EU-27 from both perspectives. This reduction can be attributed to domestic technological advancements, such as improved flue gas cleaning, and efforts to phase out coal in favour of renewable energy sources.

Water: In the EU-27, water stress has increased similarly from both perspectives, while in Slovenia, water stress has decreased in terms of production but significantly increased in terms of consumption. This increase is linked to a noticeable rise in imports of agri-food products from regions such as China, India, other Asia, and the Middle East, including products like rice, vegetables, fruits, nuts, and textiles.

Biodiversity: Land-related impacts on biodiversity have decreased in the EU-27 from both perspectives, while in Slovenia, land-related impacts on biodiversity have decreased in terms of consumption but remained constant in terms of production.

Figure 5.7 – Source: ARSO, 2024.



The EXIOBASE REX3 database provides tools to connect planetary boundaries with green growth, supporting climate actions alongside biodiversity and natural environment objectives. The findings for Slovenia underscore the need to address water stress through consumption and trade policy, emphasizing the importance of sustainable resource use within the context of global supply chains.

6

Well-being Economy

The well-being economy is a new paradigm of economic development beyond traditional metrics like GDP. It advocates for systems that ensure well-being for all while remaining within environmental limits. Earth4All and economist Mark Anielski are important in rethinking economic development towards holistic well-being that prioritizes both human and environmental well-being.

The well-being economy in the Earth4All initiative

The authors of the Earth4All report identify the three most powerful socio-economic levers for each transformation. At the base of the pyramid, in their view, are fundamental policy changes within the current economic paradigm. From there, they move upwards to more ambitious policies that actually define a new economic paradigm suitable for the Anthropocene. At the top of the pyramid are the levers that truly ensure the transformation into a new economic paradigm, which some refer to as the "well-being economy."

The Earth for All program presents a few key ideas: **only through the early and decisive activation of bold levers can the Earth4All model achieve an accelerated transformation towards a fairer, more equitable, and safer world by the middle of this century.** Returning humanity to a safe operating space within this century may be challenging and complex, but, as with many other complex projects, this process can be triggered by a handful of well-chosen levers executed by dedicated groups of people.

Figure 6.1: Key turnarounds of the Earth4All initiative.

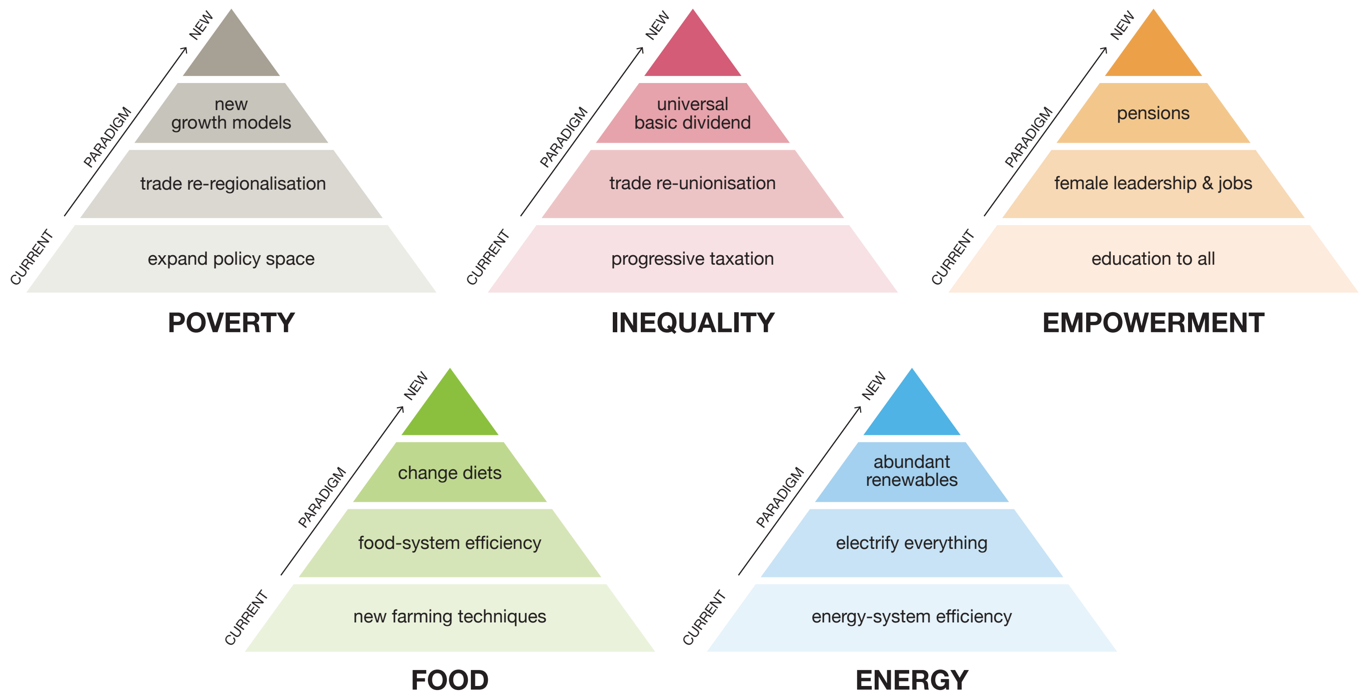


Figure 5.1 – Source: Dixson-Declève et al., 2022.

Experts stress that socio-economic levers are clearly identifiable and ready to use. They all stem from one key area – the economy. Key among them are:

The establishment of citizens' funds

for the fair distribution of the wealth of global common goods among all citizens.

Government intervention

(subsidies, incentives and regulations) to accelerate turnarounds.

Transformation of the international financial system

to enable the rapid reduction of poverty in much of the world.

De-risking investments

in low-income countries and debt cancellation.

Investments

in efficient, regenerative food systems and renewable energy systems.

The well-being economy of Mark Anielski: the concept and its implementation in Slovenia

The concept of the well-being economy by Mark Anielski

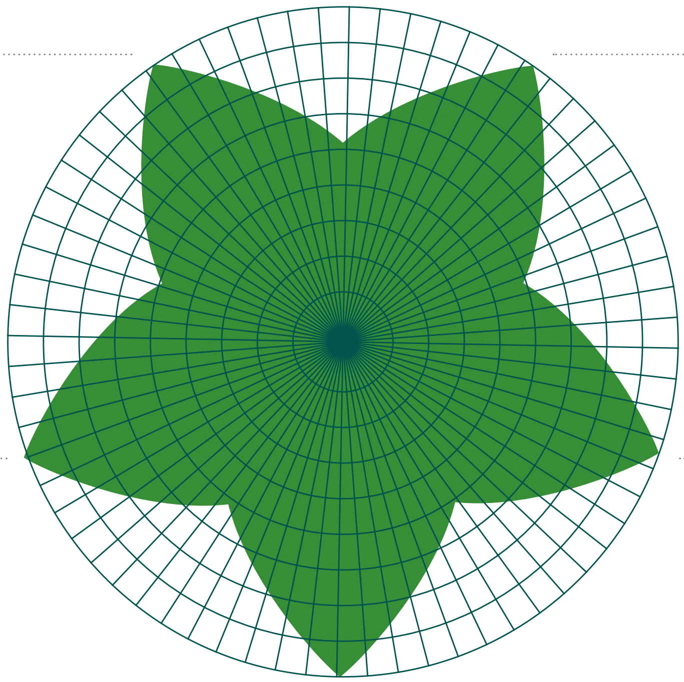
Mark Anielski introduced the concept of the economy of well-being in his books The Economics of Happiness (Anielski, 2007) and An Economy of Well-being (Anielski, 2018). He proposed a model for creating economies of well-being using an accounting system that measures the conditions of well-being in communities that are grounded in the values and virtues that matter most to citizens, offering a framework of genuine wealth that provides tools for assessing and managing these values within economic systems. Anielski has advised numerous regional and governmental institutions.

According to Anielski, the Genuine Wealth assessment model is designed to support economies based on well-being. This model measures and manages well-being by focusing on community-defined values and virtues, with progress and success tailored to the goals of each community or organization. Using a modified financial accounting framework, it assesses returns on investments in five key assets or genuine wealth assets of a community or organization. Additionally, it provides practical tools for guiding economic development, shaping policies and budgets, and supporting strategic economic, social, and environmental decision-making.

Figure 6.2: Genuine Wealth: Model of the Five Capital Assets

FINANCIAL CAPITAL
Financial assets (money, cash, stocks, bonds, derivates), liabilities (debt) and equity.

BUILT CAPITAL
Infrastructure, buildings, roads, houses, factories, machinery, equipment and manufactured goods, and intellectual property (patents, copyright) that mkae up the material structure of society.



HUMAN CAPITAL
Individual skills, education, knowledge, capabilities, and health (mental, physical, emotional and spiritual) of individuals that make up households, organizations and communities.

NATURAL CAPITAL
The land and natural resources, including soils, forests, water, air, and other species and life forms, and the services which the earth and its atmosphere provide, including ecological systems and life-support services.

SOCIAL CAPITAL
The web of interpersonal connections, relationships and networks, including trust, institutional arrangements, rules, and norms that facilitate human interactions. Also, the set of values, history, traditions and behaviours which link a specific group of people together.

Asset:
Any tangible or intangible economic resource that is capable of being owned or controlled to produce value and that is help to have positive economic value.

The model combines a genuine way of living that is aligned with values and conditions for well-being, leading to the creation of resilient and sustainable communities.

Figure 6.2 – Source: Anielski, 2023.

Indicators of genuine progress in the case of well-being for Alberta, Canada

Over the past 25 years, alternative indicators of progress have emerged in response to criticism of GDP as a measure of well-being. One of the most important is the Genuine Progress Indicator (GPI), introduced in 1995 in the US. The GPI includes environmental and social costs such as pollution, crime, inequality, and chronic diseases. The Alberta GPI project, led by Mark Anielski, developed a more comprehensive well-being balance sheet for the province of Alberta, Canada, which considers 51 key indicators of genuine wealth—human, social, natural, built, and financial capital.

These 51 indicators of genuine wealth were monitored from 1961 to 2001, showing similar results to the US GPI index. While Alberta's GDP increased, the overall state of well-being has decreased and stagnated since the 1960s. Work on the GPI involved converting raw data into a scale from 1 to 100, where 100 represents optimal well-being. The system enables exploration of connections between GDP growth and other indicators such as life expectancy, chronic diseases, air quality, and ecological footprint.

Figure 6.3: Genuine Progress Indicators in the Case of Alberta, Canada

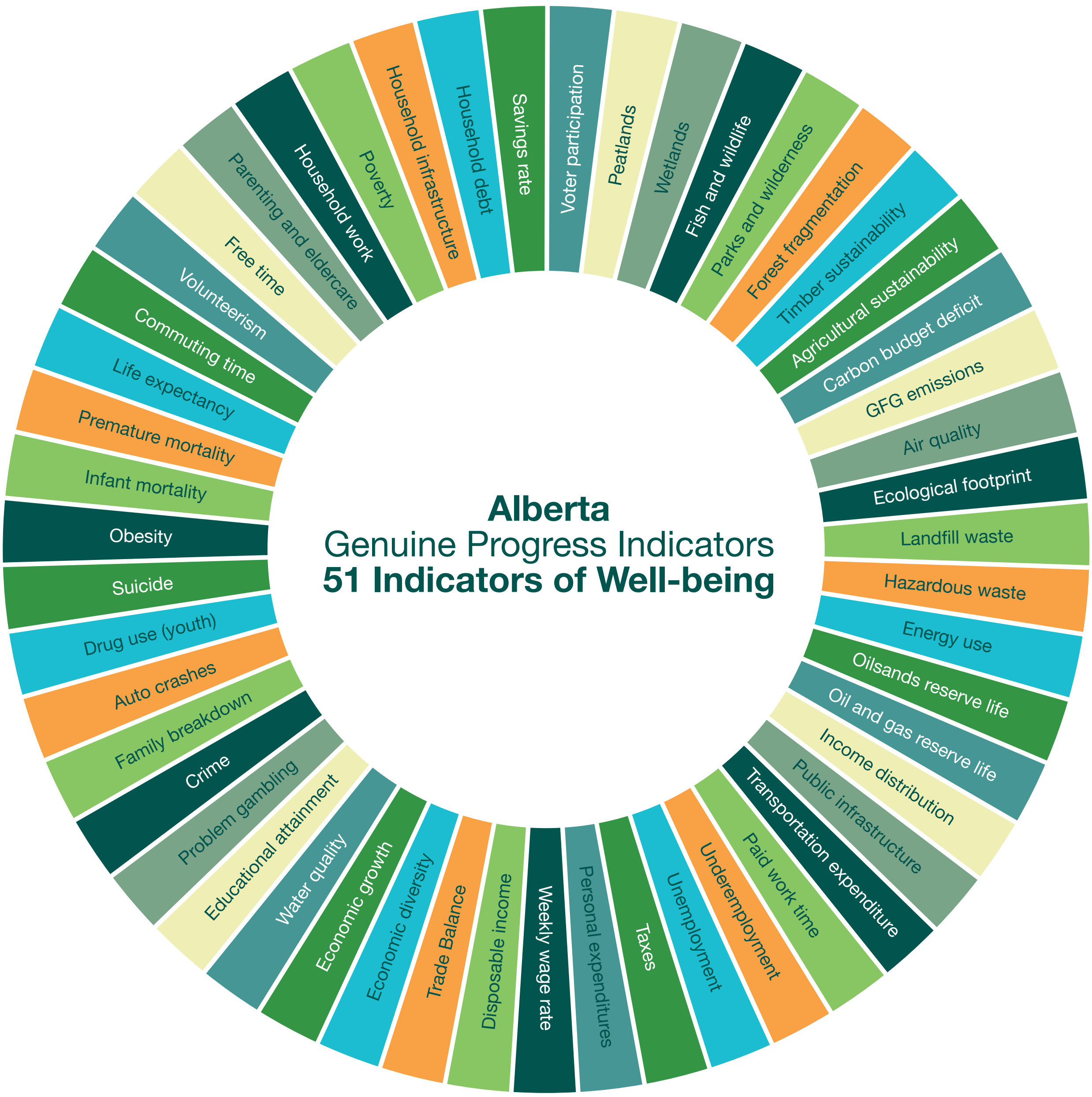


Figure 6.3 – Source: Anielski, 2023.

Creating a Well-Being Economy for Slovenia

Anielski (2023) states that Slovenia is ideally positioned to become a model well-being economy. Opportunities for adopting a well-being economy management approach include:

1. **Utilizing an integrated accounting and decision-making system** for genuine wealth (five capitals: human, socio-cultural, natural, built, and financial).
2. **Incorporating the UN Sustainable Development Goals** into Slovenia's economic-ecological-well-being framework.
3. **Offering comparative advantages** in quality of life among EU countries.
4. **Highlighting the need for improvements** in certain areas, that reflects in ongoing efforts to align with the principles of sustainable development and well-being as outlined in the Slovenian Development Strategy 2030.

Slovenia's Development Strategy 2030 – Key Aspects and Efforts for Achieving Sustainable Well-Being:

It includes

12

goals, strategies, and

6

key 'quality of life' indicators, aligned with the well-being economy model.

A commitment to measuring and reporting on genuine progress

A commitment to measuring and reporting on genuine progress in achieving goals (among them: life expectancy, healthy lifestyle, low inequality, vibrant culture, sustainable resource management, high employment, trust, security, low-carbon circular economy, and efficient high-quality public services and governance).

Table 6.1: The Legatum Prosperity Index for Slovenia - environmental quality indicators (2nd column), by sector (1st column), Slovenia's ranking in the world (last column)

Area	Environmental quality indicators	Slovenia's global ranking
Emissions	CO_2 emissions	108
	SO_2 emissions	42
	NO_x emissions	29
	Black carbon emissions	82
	Methane emissions	32
Exposure to Air Pollution	Exposure to fine particulate matter	114
	Health impact of air pollution	30
	Satisfaction with air quality	48
Forest, Land and Soil	Forest area	15
	Flood occurence	138
	Sustainable nitrogen management	61
Freshwater	Renewable water resources	46
	Wastewater treatment	15
	Freshwater withdrawal	70
	Satisfaction with water quality	7
Preservation Efforts	Terrestrial protected areas	2
	Long term management of forest areas	14
	Protection for biodiverse areas	24
	Pesticide regulation	18
	Satisfaction with preservation efforts	33

Data from Table (6.1) shows that Slovenia achieves solid results in natural capital conservation, particularly in protected land areas (2nd place) and forest management (14th place). This reflects efforts to safeguard natural resources, which are crucial for long-term sustainable well-being within the well-being economy framework as proposed by Anielski.

However, Slovenia faces challenges in CO_2 emissions (108th place) and air pollution (e.g., health impacts from pollution, 30th place).

Despite progress in conserving natural capital and water resources, environmental pressures from emissions and pollution remain issues. This suggests the need for further efforts to reduce Slovenia's ecological footprint and improve air quality.

In the context of the well-being economy, it is essential for Slovenia not only to conserve natural resources but also to reduce environmental pressures, particularly in emissions, to achieve more sustainable and equitable economic growth.

Table 6.1 – Source: Anielski, 2023.

Anielski believes that Slovenia is on a promising path to becoming a model for the well-being economy in Europe. The country has a long-lived population, resilient forests, low income inequality, a highly educated population, strong social capital, good employment conditions, and high life satisfaction.

However, Slovenia also faces challenges in social and natural capital as well as aligning its ecological footprint with biocapacity. Anielski recommends measuring subjective well-being, conducting resident surveys, and adopting budgetary and political approach based on well-being, similar to practices in New Zealand (in the previous decade), Iceland, Finland, and Scotland.

7

Key measures for the food and energy turnarounds and reducing ecological debt: Solutions and opportunities

Food and energy systems are crucial for sustainable development. Various solutions and opportunities emerging in relation to the transformation of key sectors can contribute to reducing ecological debt. Urgent systemic changes are needed to enable sustainable resource use and reduce negative environmental impacts.

A food and energy turnaround in the Earth4All initiative

The Earth4All study suggests that five major turnarounds can be achieved through specific policy objectives. This chapter delves into two turnarounds linked to environmental challenges and the green transition – food and energy.

Food Turnaround:
- The food system must become regenerative and nature positive by 2050.
- Local food production should be incentivized, with a reduction in fertilizer and other chemical use.
- Key goals include healthy diets for all, soil and ecosystem protection, and reducing food waste.

Energy Turnaround:
- Energy systems should be transformed to increase efficiency and the rollout of wind and solar electricity should be accelerated; provide clean energy to those without.
- Greenhouse gas emissions should be halved every decade.
- The key goal is climate neutrality (net-zero emissions) by 2050.

Food Turnaround – A healthy food system for people and the planet

The food turnaround involves a comprehensive change in the entire food system, reducing diseases associated with unhealthy diets.

The plan emphasizes three key levers (Dixson-Declève et al., 2022):
1. Dietary change: Transitioning to a more plant-based and local diet, reducing the need for intensive livestock farming, a major greenhouse gas emitter.
2. Food system efficiency: Optimizing food production, transport, and consumption to reduce waste and better utilize natural resources.
3. New farming methods: Moving toward sustainable practices like regenerative agriculture and agroecology, which protect biodiversity, reduce emissions, and use water more efficiently.

Transitioning to a sustainable food system is crucial for respecting planetary boundaries and improving human health by promoting balanced diets and reducing diseases associated with unhealthy food.

Figure 7.1: Key levers of the Food Turnaround are leading to a new paradigm.

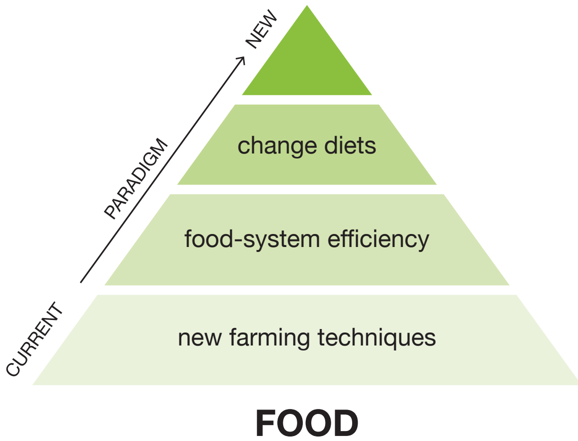


Figure 7.1 – Source: Dixson-Declève et al., 2022, figure 6.1.

The three key areas of the food turnaround are food production, eating habits and reducing food waste.

Food production:
Rapid reform is needed, including sustainable intensification and regenerative agriculture. The expansion of agricultural land must be halted and degraded land must be restored. Farms must contribute to carbon storage in soils and vegetation, which helps to reduce greenhouse gas emissions.

Dietary habits:
The well-fed must adopt healthy, lower-impact diets, while the malnourished and undernourished must be lifted out of their predicament with regeneratively grown, healthier foods.

Food waste:
Waste must be reduced throughout the food chain. If we eliminated 25% of waste, we could feed everyone on Earth.

Our challenge is to turn the food system around to provide healthy food for nine billion people without increasing land consumption or exploiting marine areas. This requires reducing freshwater use, optimizing fertilizer application, and transitioning to net positive CO_2 emissions. Farmers must be treated as stewards of the biosphere and appropriately rewarded for their role in protecting the environment.

Energy Turnaround – "Electrifying almost everything"

People often express shocked disbelief that societies are failing to remove fossil fuels from the global economy at the speed and scale required. However, as this requires a comprehensive restructuring of industrial foundations. Fossil fuels have long supported economic growth. Although calls for action are correct, transforming energy policy is challenging due to the continued influence of the powerful fossil fuel industry.

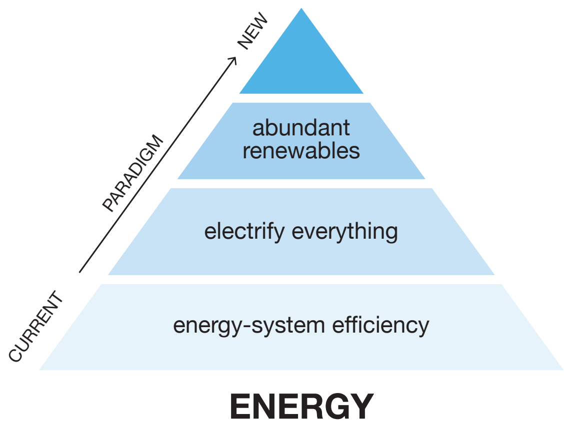
The energy turnaround involves a fundamental restructuring of the energy sector. Under the Paris Agreement, we must halve greenhouse gas emissions in this decade and achieve climate neutrality by 2050. Key to this will be increasing energy efficiency and using renewable energy sources. This transition also requires extensive electrification, expanding solar and wind power, promoting electric vehicle use, implementing suitable energy storage solutions, and an overall shift to circular manufacturing practices.

The world is already on the verge of the fastest energy system transformation in history. Clean energy technologies are developing exponentially. In 2021, wind and solar energy produced 10% of global electricity (compared to 5% in 2016), and this share could rise to 50% by 2030.

The critical questions remain: will the transition be fast and fair enough? Moving away from fossil fuel-intensive industries in energy, transport, and food will free up land, allow oceans to recover, eliminate air pollution, and provide sufficient energy for poorer populations.

The energy turnaround begins with system efficiency across all existing energy systems. At the same time, heat generation, industrial processes, and transport require a shift to renewable electricity and energy carriers such as green hydrogen. Major investments in abundant renewable energy sources with storage solutions continue are required to reduce energy costs due to zero marginal costs, thanks to "free sun."

Figure 7.2: Key actions of the energy transition leading to a new paradigm



Global Footprint Network: promising actions for #MoveTheDate in the food and energy sectors

Founded by Mathis Wackernagel and Susan Burns in 2003, the Global Footprint Network provides access to data on the ecological footprint as the only metrics that comprehensively compares humanity's demand on nature against the planet's regenerative capacity.

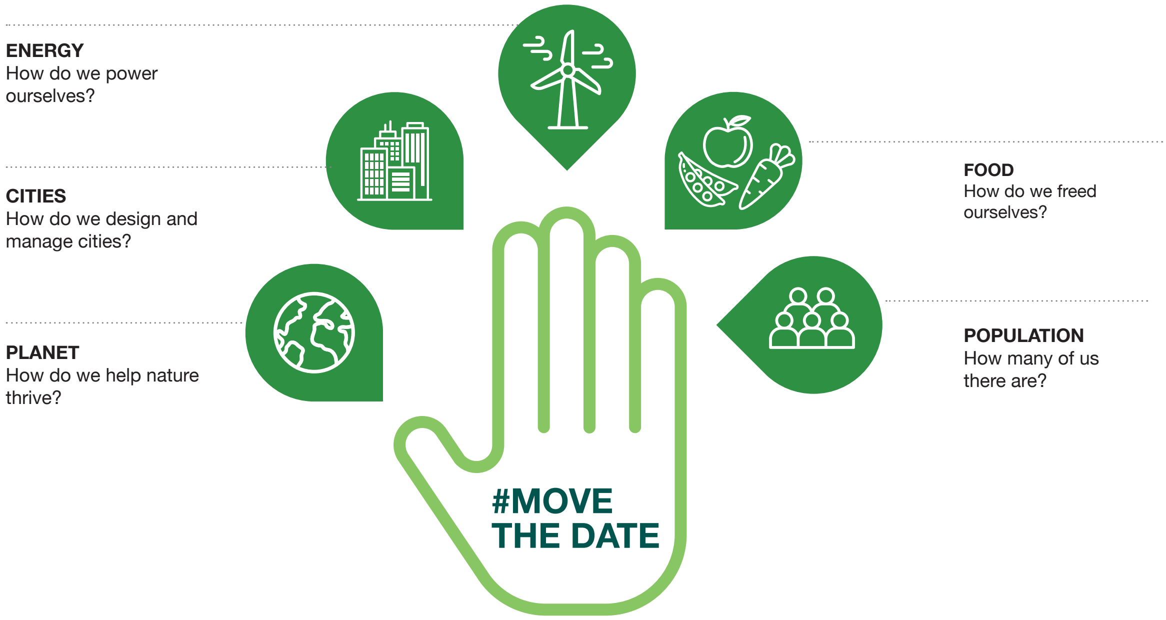
In 2006, they launched the annual Earth Overshoot Day campaign, which marks the date when humanity had used more resources than the planet can regenerate in the entire year (in 2024, the global Overshoot Day was August 1).

They also presented how to shift this date closer to the end of the year (#MoveTheDate campaign). In 2021, they showcased ways to use existing technology to replace conventional practices for 100 days, from the global overshoot day to the UN Climate Change Conference in Glasgow (COP26). Achieving these changes in line with IPCC goals by 2030 would require moving the global overshoot date by 10 days each year to meet climate goals.

The Global Footprint Network classifies its actions into five key areas: cities, energy, food, the planet, "and population (Figure 7.3).

Figure 7.2 – Source: Dixson-Declève et al., 2022,

Slika 7.3: Vizualni prikaz rešitev #MoveTheDate



Energy and Cities

ENERGY:
The carbon footprint represents 60% of humanity's ecological footprint. Decarbonizing the economy is key to addressing climate change and improving ecological balance. Over 150 years ago, the carbon footprint was nearly zero. To limit global temperature rise to below 2°C and achieve carbon neutrality, the carbon footprint must return to zero by 2050.

Solutions for energy:
Reducing the carbon footprint by 50% would **move the Earth Overshoot Day by 93 days toward the end of the year.** Using existing technologies for energy efficiency and electricity production would **move the Earth Overshoot Day at least by 21 days.**

CITIES:
By 2050, 70-80% of people will live in cities. Smart city planning and urban development strategies are key to biological restoration. Energy-efficient buildings, integrated planning, and 15-minute cities, as well as effective sustainable mobility options, are examples of essential solutions.

Transport:
City planning significantly influences the need for cars, which is important as personal mobility accounts for 17% of the carbon footprint. Reducing the driving footprint by 50% and replacing it with public transport, cycling, and walking would move the Earth Overshoot Day **by 13 days.**

Solutions in energy and their effects - moving the Earth Overshoot Day towards the end of the year:

- New Green Deal for half the world: **moves by 42 days.**
- Smart cities: **moves by 29 days.**
- Low-carbon energy sources: **moves by 26 days.**
- Financing the decarbonization of the electricity system by 50%: **moves by 22 days.**
- Battery technology*, energy storage systems: **moves by 15 days.**
- Green hydrogen for one-third of aviation fuel and half of industrial needs: **moves by 18 days.**
- Effective water management and wastewater treatment: **moves by 21 days.**
- Carbon emission price ($100/ton): **moves by 63 days.**

Figure 7.3. – Source: Earth Overshoot Day, https://www.overshootday.org/solutions/
* Battery technology refers to the storage of energy from renewable sources, such as solar and wind energy, and its use when these sources are not available.

Food and Planet

FOOD:
Half of the Earth's biocapacity is used for food production.

Two main issues are highlighted:
1. Resource inefficiency in food production: Livestock farming requires significantly more natural resources than plant-based food production for the same amount of calories.
   Current agriculture is also fossil fuel intensive, increasing the ecological footprint.
2. Approximately one-third of all the food produced in the world for human consumption gets lost or wasted, which occurs in both high- and low-income countries.

PLANET:
Fertile soil, clean water, and air are essential for food and health. Natural ecosystems, such as oceans and forests, play crucial roles in regulating the climate and absorbing carbon. Overexploitation of biological resources limits economies.

Interventions:
1. Traditional nature conservation.
2. Restoration.
3. Regenerative agriculture and sustainable fishing.

Highlighted Solution: Reforesting 350 million hectares of forests would move the Earth Overshoot Day by eight days towards the end of the year.

Opportunities for improvement:

- Transitioning to a plant-based diet by reducing meat consumption by 50% would move the Earth Overshoot Day by **17 days towards the end of the year.**
- Halving food waste would move the Earth Overshoot Day by **13 days.**

Other solutions to move the Earth Overshoot Day towards the end of the year:

- Low-impact beef production: **moves by 5 days.**
- Intercropping of trees: **moves by 2.1 days.**
- Grazing management: **moves by 2.2 days.**
- Silvopasture*, 40% increase: **moves by 4 days.**

* **Silvopasture** is a sustainable practice that combines forestry and grazing. It is a form of agriculture where animals graze on land where trees are grown, allowing for the simultaneous production of food (livestock) and timber resources (trees). Trees provide shade, improve soil quality, and increase biodiversity. This system has numerous environmental benefits, as it reduces greenhouse gas emissions, enhances carbon storage in soils and trees, and contributes to more sustainable land **use.**

8

Ecological footprint of Slovenia and measures for its reduction

Slovenia is on a path toward sustainable development; however, despite better results in certain areas compared to the EU, it still exceeds planetary boundaries. Analyzing Slovenia's ecological footprint and proposing concrete measures to reduce it allows for the adaptation of national policies and strategies that lead to sustainable development and living within the planet's limits.

Ecological Footprint and Biocapacity of Slovenia

In 2017, Slovenia adopted the national Development Strategy, committing to a 20% reduction in its ecological footprint by 2030 (from 4.7 global hectares per capita in 2013 to 3.6 gha per capita by 2030). Projections from the Global Footprint Network for 2022 indicate that Slovenia's ecological footprint in 2022 was 4.78 gha per capita, while its biocapacity was 2.49 gha, nearly half the footprint. Maintaining such a lifestyle would require 3.17 Earths. Slovenia's ecological footprint exceeds the European average (4.65 gha per capita).

In Slovenia, the largest portion of the ecological footprint comes from the carbon footprint (50% in 2022), comparable to European and global averages. Slovenia's ecological footprint shows a marked difference in the area of forest products, which is 45% higher than the European average in 2022. In contrast, the footprints for built-up land, cropland, and fishing grounds are significantly lower (Bolte, T., et al., 2022; Stritih, 2018–2023).

Figure 8.1: Composition of Slovenia's ecological footprint, 1992–2022

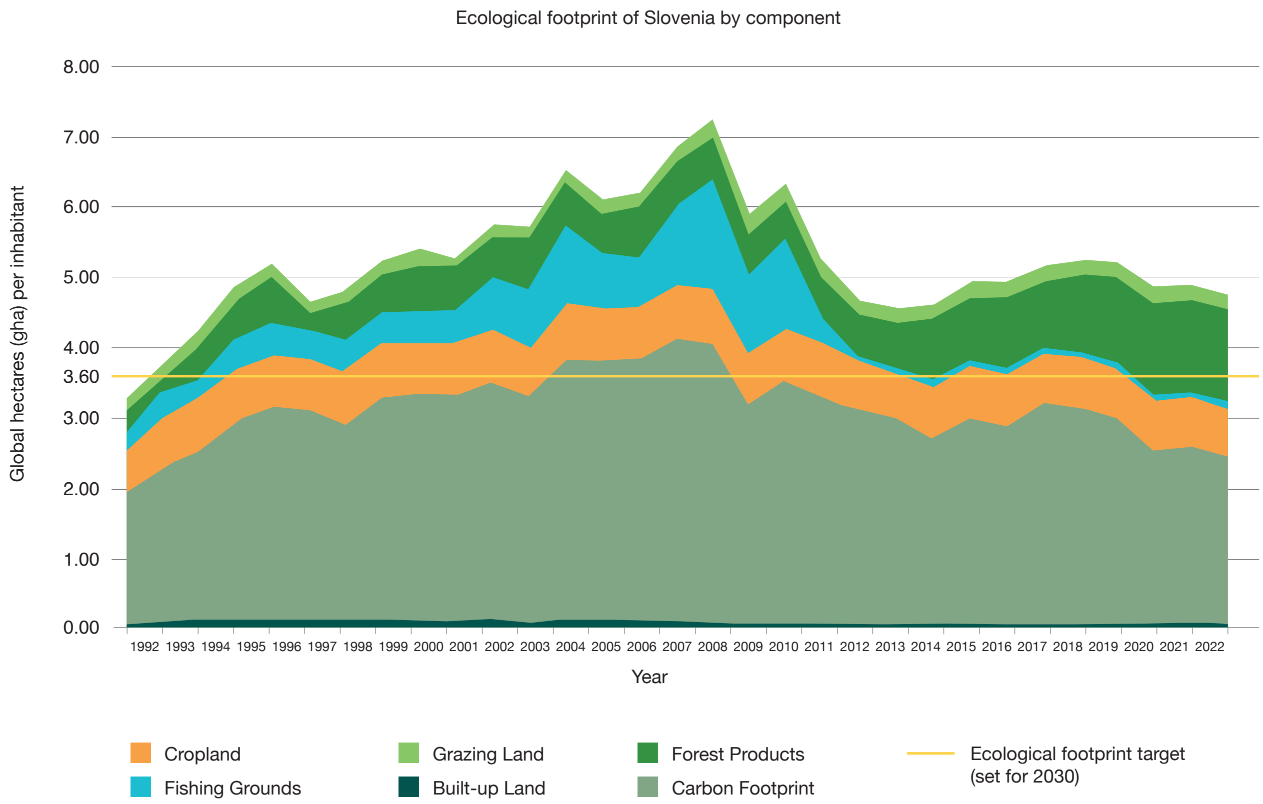
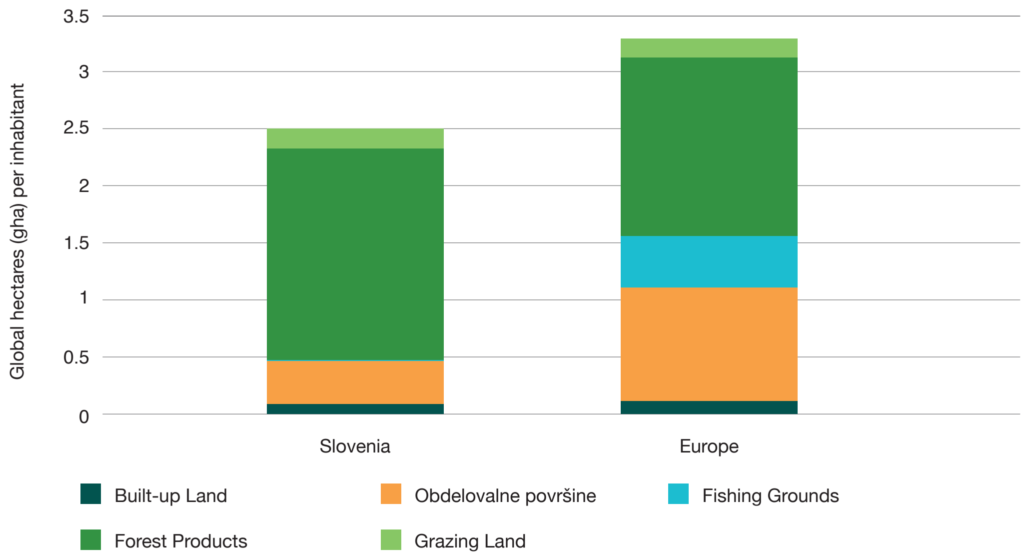


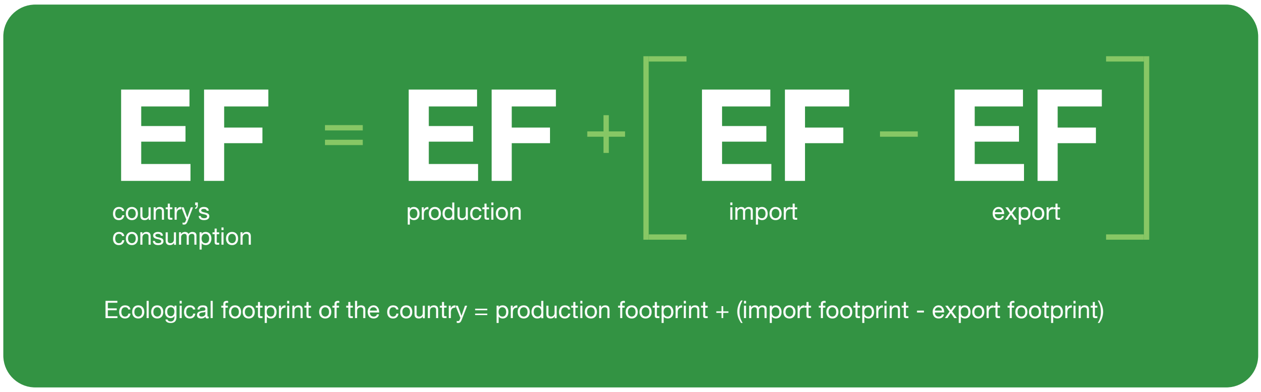
Figure 8.1 – Source: GFN, 2024. Analyze by Land Types, Slovenia.

In 2022, Slovenia's biocapacity was 2.49 global hectares (gha) per capita, below the European average of 3.31 gha per capita. Forests provide the largest share of biocapacity (74%), while the contribution from cropland is notably lower than the European average (16% compared to 40% in Europe).

Figure 8.2: Slovenia's biocapacity compared to Europe by land category



The total consumption-based ecological footprint is calculated as the sum of the ecological footprint from domestic production plus the footprint of imports minus the footprint of exports:



For built-up land, unlike other components of the ecological footprint that account for the consumption and import of resources, only the actual physical built-up areas within a country's borders are included. This means that, although the consumption-based ecological footprint accounts for resources from other countries (e.g., imported food or energy), the built-up land footprint only reflects land that is physically developed within the country. Built-up areas include infrastructure, buildings, roads, and other spaces permanently altered by human activity.

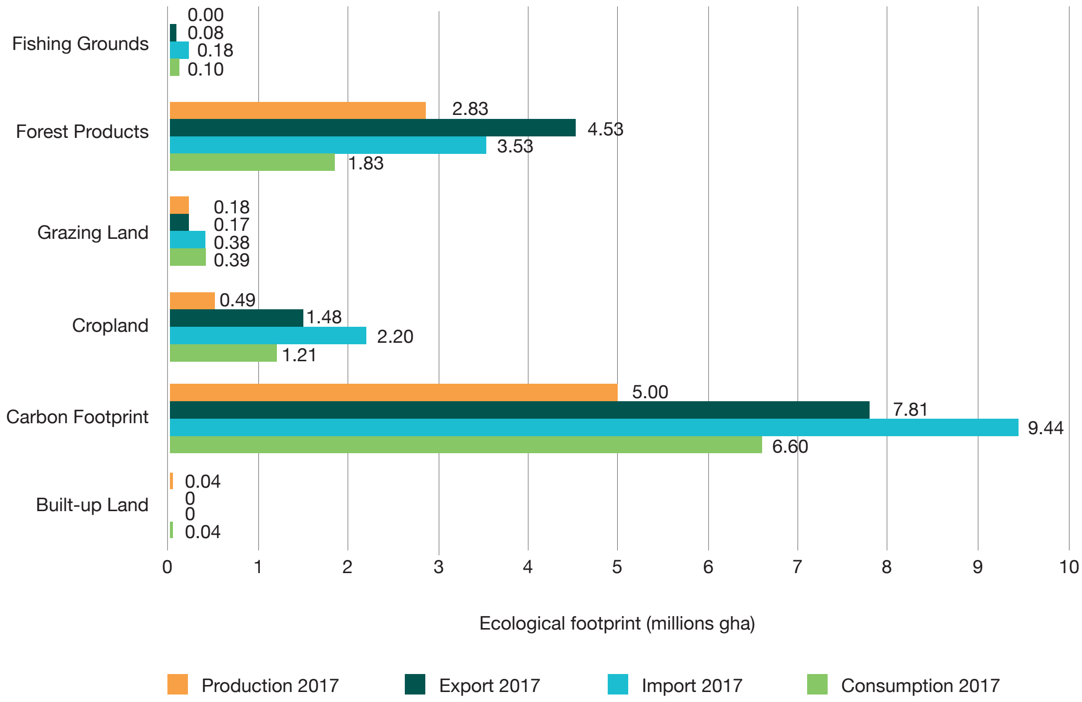
The ecological footprint presented by the Global Footprint Network refers specifically to the consumption-based ecological footprint of a country. This means that the footprint includes all resources and ecosystem services needed to meet the needs of the country's population, including resources sourced from abroad.

For example, if a country imports and consumes products requiring substantial resources for production (e.g., food, energy), this is considered part of its ecological footprint, even if the resources were not directly extracted within the country's borders.

Figure 8.2 – Source: GFN, 2023. Compare Countries, Slovenia.

Data analysis from 2017 indicates that Slovenia demands more ecological resources than it produces domestically, making it a net importer of ecological footprint. In 2017, the net footprint from imports exceeded domestic production footprint across all categories except one: Slovenia is a net exporter only in forestry.

Figure 8.3: Biologically productive land required by Slovenia for domestic production, imports, exports, and total consumption, 2017



In terms of consumption type, in 2019, housing contributed the largest share to Slovenia's ecological footprint (26% of the total), followed by personal transport (20%), services (18%), food (19%), and goods (17%).

Figure 8.4: Composition of the ecological footprint by consumption category in 2019

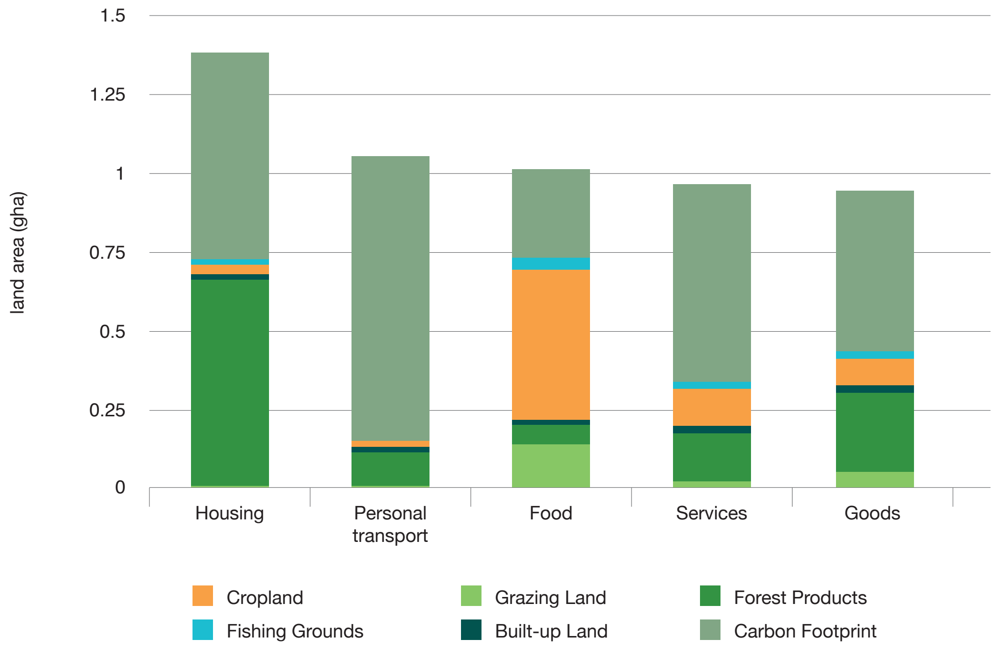
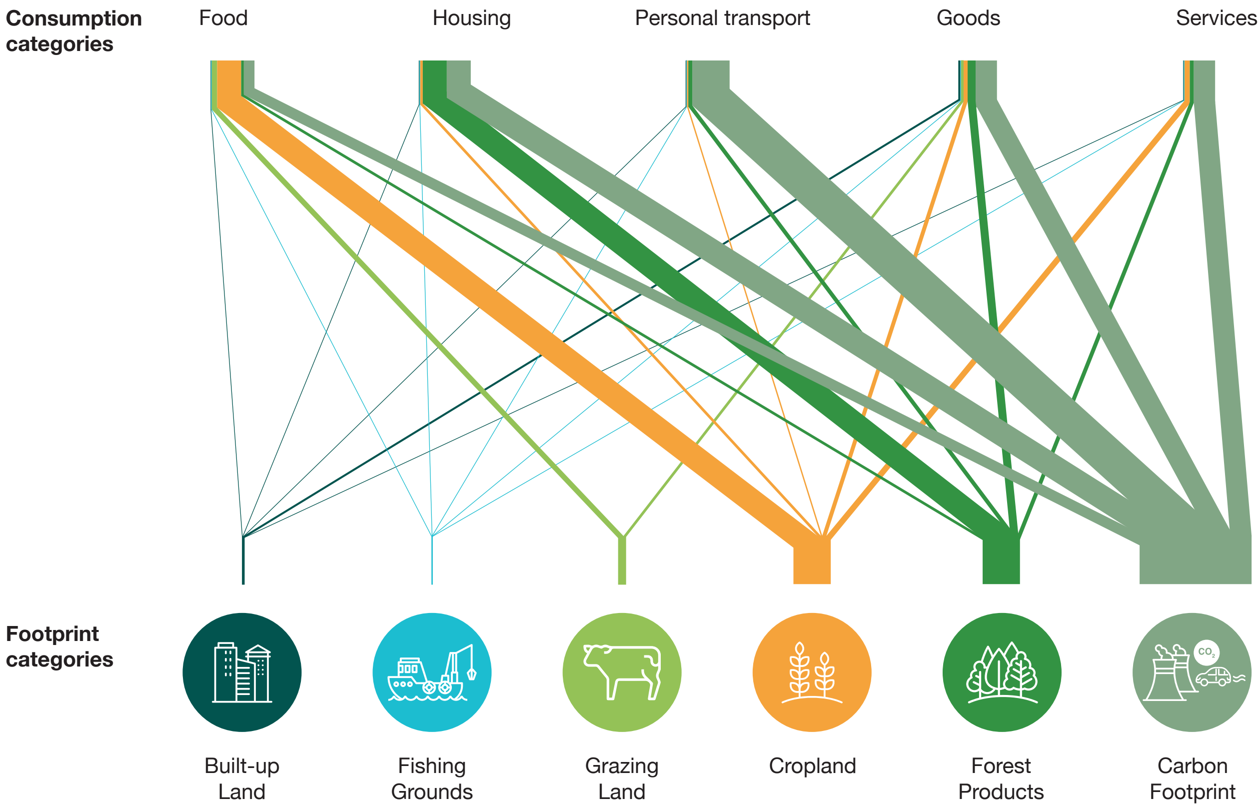


Figure 8.3 – Source: Bolte, T. et al, 2022; cit. po: GFN, 2021. *Selected text and figures for the 2022 State of the Environment Report for Slovenia.*
Figure 8.4 – Source: ARSO, 2022; cit. po: GFN Slovenia Consumption Land Use Matrix (CLUM) 2017.

Figure 8.5: Relationship between two categories of the ecological footprint – consumption categories and footprint components for Slovenia, 2017



Importance of consumption in the ecological footprint and the need for a new economic approach

Focusing on consumption, the ecological footprint is crucial for understanding the environmental pressures created by our daily activities. Categories such as food, transport, and goods illustrate how lifestyle and consumer habits impact natural resources and often exceed Earth's regenerative capacity. This means that the current consumption patterns are unsustainable, leading to resource depletion and ecosystem degradation.

However, consumption is an integral part of gross domestic product (GDP), creating a paradox: higher consumption drives economic growth but exacerbates environmental harm. Measuring countries' success solely by GDP growth is no longer sufficient to address the environmental challenges of the 21st century.

A new economic model is urgently needed for a more sustainable future. The Earth4All initiative, as well as frameworks by Kate Raworth (Doughnut Economics) and Mark Anielski (the well-being economy), emphasize an economy centered on well-being that goes beyond traditional growth metrics to focus on building a fair and sustainable economy. This approach advocates for responsible resource use, economic equity, and long-term stability of natural systems, aligning closely with the goals of sustainable development.

Figure 8.5 – Source: Bolte idr., 2022 in GFN 2022.

Ecological footprint of Slovenia

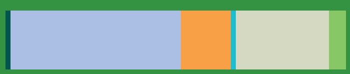
In 2022, Slovenia's average ecological footprint was estimated at

4.78 gha

In 2022, Slovenia's average ecological footprint was estimated at 4.78 gha
(the target value to be achieved by 2030 is 3.6 gha per capita)

Total ecological footprint of consumption (2022)

10,137,073 gha



Grazing Land
Forest Products
Built-up Land
Cropland
Fishing Grounds
Carbon footprint

The total ecological footprint measures how many natural resources we consume to sustain our lifestyle.

Total biocapacity (2022)

5,269,580 gha

Grazing Land
Forest Products
Built-up Land
Cropland
Fishing Grounds

Total biocapacity represents the ability of natural ecosystems to regenerate and provide the resources necessary for our survival.

According to Slovenia's biocapacity, in order to meet its needs, its land area would have to be multiplied by

3.17 Slovenias

Every day we consume the resources provided by the Earth. **This is our ecological footprint.**

We must reduce our ecological footprint, for we have only one precious Earth to protect.

Source: data.footprintnetwork.org

Global Hectare (gha) - a unit for measuring ecological productivity

The global hectare (gha) is a standardized unit that measures the biological productivity of land and sea areas worldwide.

While a regular hectare (ha) simply represents an area of land, a global hectare accounts for the quantity of natural resources that a specific area can provide, including soil fertility and the regenerative capacity of ecosystems. This allows for comparing different types of land with varying productivity levels—from forests to agricultural areas.

Why is gha important?

Because the global hectare standardizes land productivity differences, it serves as an “ecological currency” with which we can measure and compare ecological footprints and biocapacity across different countries.

Global hectares enable an assessment of whether regions consume more resources than their ecosystems can sustainably provide, thus offering insights into sustainable resource management.

Using global hectares assists in global sustainability calculations by providing a uniform measurement of human demands on nature relative to Earth’s capacity, a metric that is increasingly important in environmental policy planning.

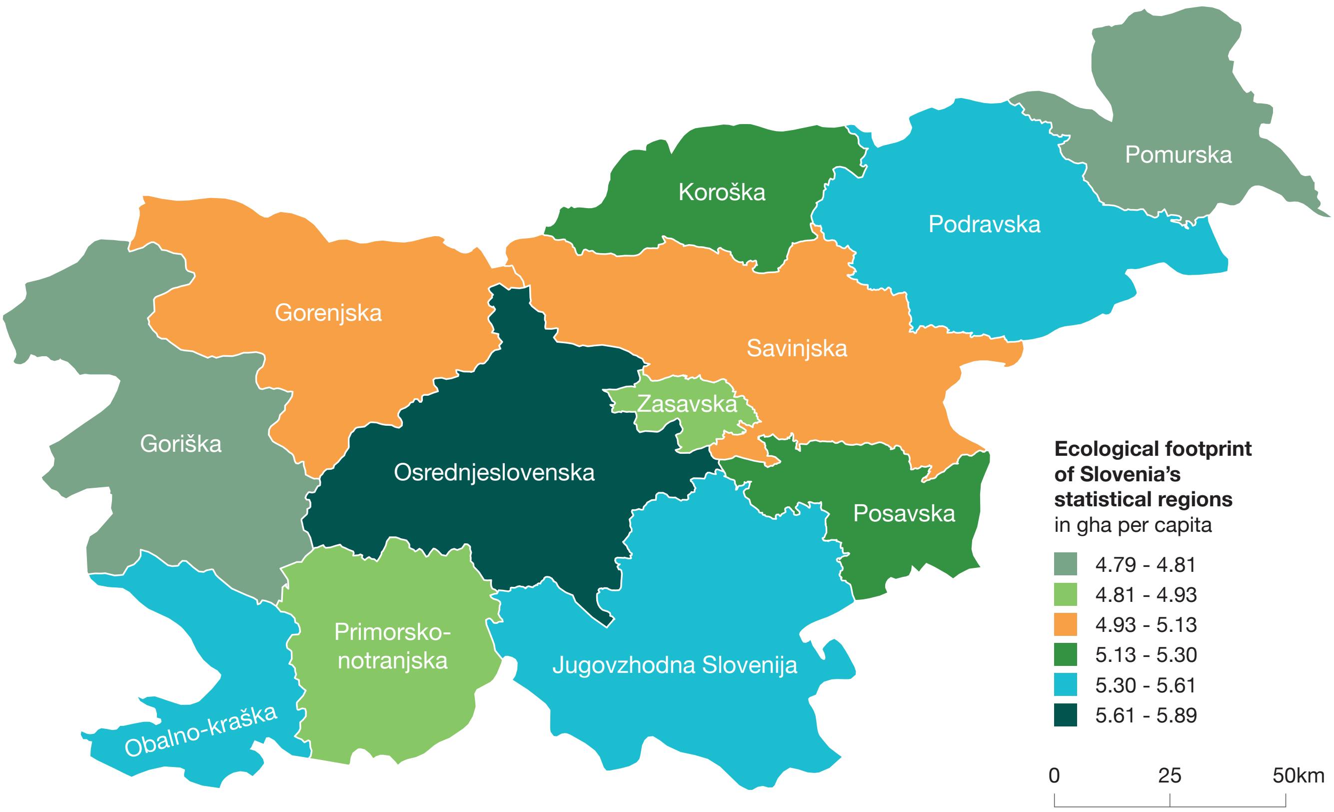
gha

Ecological Footprint by Statistical Regions

Operational Plan on the Cooperation of Ministries in the Preparation of Regional Development Programmes 2017–2027 (adopted in 2019) stipulates that the the state of the environment as regards the quality of life is monitored based on the ecological footprint of statistical regions.

Data from 2018 shows that the Osrednjeslovenska Statistical Region has the highest expected ecological footprint, at 5.8 gha per capita, which is 8% higher than the national average (5.37 gha per capita in 2018). The most populated and wealthiest region in Slovenia contributes a quarter of the total ecological footprint of Slovenia. The lowest ecological footprints per capita are in the Pomurska (4.81 gha per capita) and Goriška (4.79 gha per capita) regions, which are 10% lower than the national average.

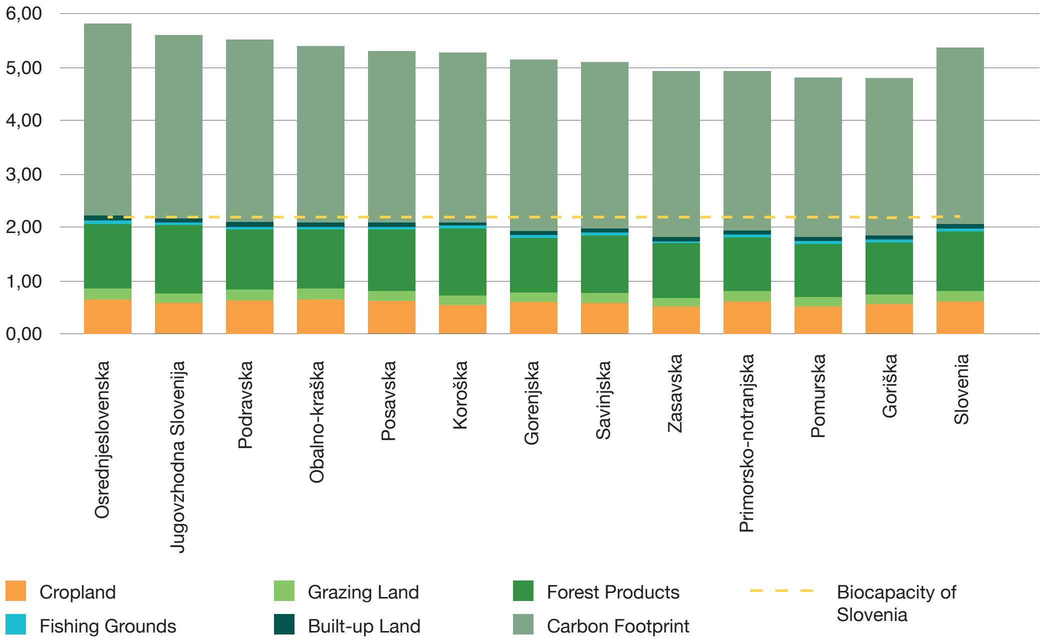
Figure 8.6: Ecological footprint per capita by statistical region of Slovenia in 2018



In all statistical regions of Slovenia, the largest ecological footprint per capita is caused by the carbon footprint and the footprint of forest products. The carbon footprint per capita is highest in the Osrednjeslovenska Statistical Region. In 2018, its share in Slovenia's total footprint accounted for as much as 62%, making it the main source of ecological deficit. This share can be directly reduced through decarbonization. The footprint of forest products is largest in forested and cooler regions, such as Southeast Slovenia and Koroška, where annual temperatures are generally lower, and wood biomass is an easibily accessible heating source.

Figure 8.6 – Source: Stritih, 2023a. Development of ecological footprint indicators for 12 statistical regions.

Figure 8.7: Ecological footprint of regions and Slovenia per capita by component



When breaking down the ecological footprint of statistical regions into individual consumption categories, we see that the largest footprint arises from "housing, water, electricity, gas, and other fuels," followed by "transport" and "food and non-alcoholic beverages." Together, these three consumption categories account for two-thirds of resource demand.

Figure 8.8: Ecological footprint of regions and Slovenia per capita by COICOP category

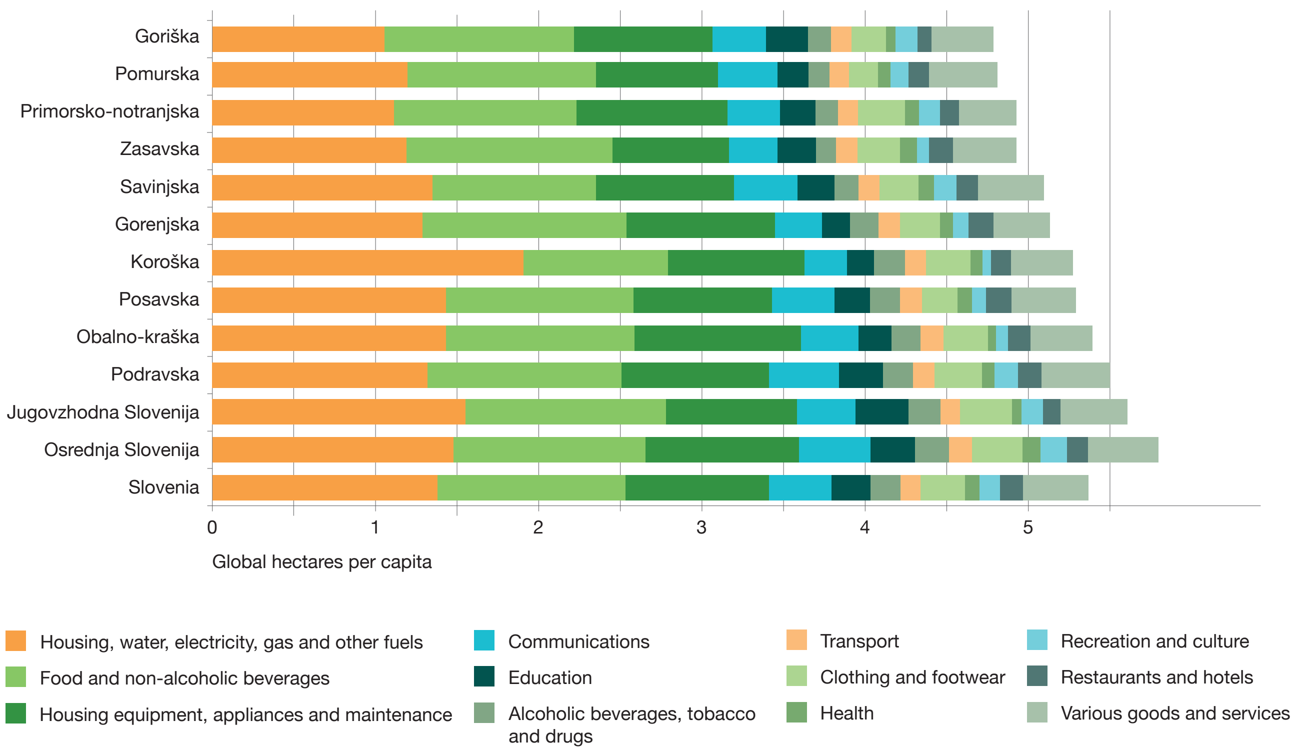


Figure 8.7 – Source: Stritih, 2023a. Development of ecological footprint indicators for 12 statistical regions.
Figure 8.8 – Source: Stritih, 2023a. Development of ecological footprint indicators for 12 statistical regions.

Measures and scenarios

The Ministry responsible for the environment, has committed to reducing Slovenia's footprint by 20% by 2030 and has allocated resources for monitoring the ecological footprint and analyzing potential measures.

The latest study (Stritih, 2023b) indicates that ambitious measures in sustainable forest management, sustainable mobility, and energy efficiency could significantly contribute to reducing Slovenia's ecological footprint. Since the ecological footprint measures how much natural resources we consume, reducing it would lessen environmental pressures.

In the baseline scenario, sustainable forest management may initially increase the ecological footprint by 3.27%. However, additional measures could result in a significant reduction of –5.82%.

Electromobility (use of electric vehicles) could reduce the ecological footprint by –3.51% in the baseline scenario, with potential for further reduction up to –6.14% with additional measures.

Expanding public transport and cycling networks can reduce the ecological footprint by –2.49% in the baseline scenario, while additional measures may increase this reduction to –5.97%.

Improving energy efficiency and adopting renewable energy sources in buildings could lead to a –4.35% reduction in the baseline scenario and up to –7.06% with additional measures.

Overall, these combined measures could achieve a 7.08% reduction in the baseline scenario and as much as 24.99% with enhanced measures.

Table 8.1: Projections of scenarios for reducing the ecological footprint

Area	Net change of ecological footprint in the baseline scenario [gha]	Net impact in the baseline scenario [%]	Net change of ecological footprint in the scenario with additional measures [gha]	Net impact in the scenario with additional measures [%]
Sustainable forest management	361,166	+3.27 %	-642,809	-5.82 %
Electromobility	-387,674	-3.51 %	-678,153	-6.14 %
Development of public passenger transport, multimodal hubs and the cycling network	-275,016	-2.49 %	-659,376	-5.97 %
Energy efficiency and renewable energy sources in buildings	-480,450	-4.35 %	-779,765	-7.06 %
Total	**-781,974**	**-7.08 %**	**-3.471,800**	**- 24.99%**

Source: Slovenian Environment Agency, 2023 (calculation by Stritih d.o.o.)

The cost-benefit analysis indicates that a significant portion of the measures can be achieved by eliminating administrative barriers and implementing financial reforms. For instance, removing legislative restrictions and adapting regulations for financial support would facilitate the installation of solar power plants. Sustainable forest management measures, however, require longer-term financing cycles. Additionally, a green tax reform is essential to achieving these targets.

Key measures include energy renovations of buildings, adoption of renewable energy sources, and enhancement of sustainable mobility. Forests contribute the most to Slovenia's biocapacity, making their sustainable management critical.

The greatest challenges are found in public transport and railway infrastructure within the Ljubljana region.

The ecological footprint analysis (Stritih, 2023b) suggests that additional measures across various sectors could reduce Slovenia's footprint by up to 24.99%. Despite some missed opportunities and an increase in the ecological footprint over the last decade, substantial reduction potential remains, particularly through decarbonization and technological advancements.

To achieve these goals, rapid reforms in the transport sector are vital, such as expanding electromobility, enhancing public transport and cycling networks, and strengthening renewable energy networks and energy efficiency in buildings. These measures are complementary, and their simultaneous implementation would accelerate progress toward the goals.

Table 8.1 – Source: Stritih, 2023b.

9

Turning point for the future: Synergistic paths within planetary boundaries

Planetary boundaries have been scientifically studied as a key framework for understanding environmental challenges since the early 2000s. Exceeding these boundaries already has serious consequences for ecosystem stability, underscoring the urgency for swift action. The commitment to respecting planetary boundaries is also embedded in the EU's 8th Environment Action Programme (8th EAP).

A landmark report by Rockström et al. in 2009 introduced the concept of planetary boundaries, and further detailed definitions and indicators were established in 2023 (Richardson et al., 2023). Today, it is understood that humanity exceeds six of the nine planetary boundaries, jeopardizing the long-term resilience of ecosystems (namely, biogeochemical flows, freshwater use, land-use change, biosphere integrity, climate stability, and novel entities). Various approaches, including regional analyses for Europe and specific countries, continue to build on this framework. Regardless of the methodology used to assess planetary boundaries, findings consistently indicate an environmental crisis of significant scale, necessitating immediate action. For example, analyses reveal that food consumption patterns in both the EU and Slovenia are unsustainable, impacting multiple planetary boundaries.

Slovenia is among the countries that use the ecological footprint as a tool for measuring and monitoring sustainable development. This indicator, unlike usual planetary boundary indicators, is already integrated into national frameworks, such as the Slovenian Development Strategy 2030 and the National Environmental Protection Program until 2030. The ecological footprint is monitored annually, both globally by GFN and nationally in Slovenia (by UMAR, Development Report). Since incorporating the ecological footprint into national development planning, analyses of measures to reduce it have been carried out (Stritih, 2018–2023). Data and analyses of the ecological footprint are valuable for broader environmental and sustainability assessments. However, it is essential that future monitoring framework more directly incorporate planetary boundaries, addressing issues like water stress in relation to consumption and trade.

With growing environmental and social crises, where delaying action by another 10 to 15 years it will be too late to address them, rapid implementation of effective measures is critical. Effectiveness in this case means addressing systemic challenges and the interconnected economic and social dimensions of sustainable development. An integrated perspective is necessary for addressing planetary boundaries holistically, as emphasized by the influential Earth for All – A Survival Guide for Humanity report from the Club of Rome (Dixson-Declève et al., 2022), published 50 years after The Limits to Growth. The authors highlight the need for the most rapid economic transformation in history over the next decade, driven by profound turnarounds in five key areas: food, energy, poverty, inequality, and empowerment – what they call the Giant Leap scenario. We summarized the global solutions and measures proposed to reshape the food and energy systems, which are integral to achieving environmental goals and facilitating the green transition.

Recognizing the urgency for economic transformation, and aligned with the long-term priority goals of the 8th EAP, we draw on recommendations from Earth4All and insights from Mark Anielski, who has provided specific guidance for Slovenia. An important contribution to integrating diverse sustainable development goals also comes from Doughnut Economics by Kate Raworth, which merges planetary boundaries with social and sustainability indicators into a cohesive framework.

Slovenia has a long tradition of sustainable initiatives and systemic thinking (see Chapter 1; Piciga et al., 2016; Piciga & Schieffer, 2022), along with numerous opportunities and leverage points to achieve an ambitious vision of well-being for all within planetary boundaries, consistent with the recommendations of Earth4All. However, findings specific to Slovenia indicate that ambitious additional measures are required to integrate various sectors and achieve synergistic effects.

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Appendices

Appendix 1

Table 1: Updated control variables, their current values, proposed boundaries, and zones of uncertainty for all nine planetary boundaries. The first column lists the Earth system process names used in the original planetary boundary publication for comparison.

Earth-system process	Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
Climate change (R2009: same)	Atmospheric CO_2 concentration, ppm	350 ppm CO_2 (350–450 ppm)	398.5 ppm CO_2
	Energy imbalance at top-of-atmosphere, W m^{-2}	+1.0 W m^{-2} (+1.0–1.5 W m^{-2})	2.3 W m^{-2} (1.1 - 3.3 W m^{-2})
Change in biosphere integrity (R2009: Rate of biodiversity loss)	Genetic diversity: Extinction rate	< 10 E/MSY (10–100 E/MSY) but with an aspirational goal of ca. 1 E/MSY (the background rate of extinction loss). E/MSY = extinctions per million species-years	100–1000 E/MSY
	Functional diversity: Biodiversity Intactness Index (BII) *Note: These are interim control variables until more appropriate ones are developed*	Maintain BII at 90% (90–30%) or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups	84%, applied to southern Africa only
Stratospheric ozone depletion (R2009: same)	Stratospheric O_3 concentration, DU	<5% reduction from preindustrial level of 290 DU (5%–10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)
Ocean acidification **(R2009: same)**	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%– ≥70%)	~84% of the pre-industrial aragonite saturation state
Biogeochemical flows: **(P and N cycles)** (R2009: Biogeochemical flows: (interference with P and N cycles)	**P Global:** P flow from freshwater systems into the ocean	11 Tg P yr^{-1} (11–100 Tg P yr^{-1})	~22 Tg P yr^{-1}
	P Regional: P flow from fertilizers to erodible soils	6.2 Tg yr^{-1} mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts.	~14 Tg P yr^{-1}
	N Global: Industrial and intentional biological fixation of N	N Global: Industrial and intentional biological fixation of N 62 Tg N yr^{-1} (62–82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr^{-1}
Land-system change (R2009: same)	**Global:** Area of forested land as % of original forest cover	**Global:** 75% (75–54%) Values are a weighted average of the three individual biome boundaries and their uncertainty zones	62%
	Biome: Area of forested land as % of potential forest	**Biome:** Tropical: 85% (85–60%) Temperate: 50% (50–30%) Boreal: 85% (85–60%)	
Freshwater use (R2009: Global freshwater use)	**Global:** Maximum amount of consumptive blue water use (km^3 yr^{-1})	**Global:** 4000 km^3 yr^{-1} (4000–6000 km^3 yr^{-1})	~2600 km^3 yr^{-1}

Table 1 – Source: Steffen et al., 2015. For column 1 Rockström et al., 2009–R2009.
Note: Tg N represents teragrams of nitrogen; Tg P represents teragrams of phosphorus.

Earth-system process	Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
	Basin: Blue water withdrawal as % of mean monthly river flow	**Basin:** Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25–55%); for intermediateflow months: 30% (30–60%); for high-flow months: 55% (55–85%)	
Atmospheric aerosol loading (R2009: same)	**Global:** Aerosol Optical Depth (AOD), but much regional variation		
	Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study	Regional: (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25–0.50); absorbing (warming) AOD less than 10% of total AOD	0.30 AOD, over South Asian region
Introduction of novel entities (R2009: Chemical pollution)	No control variable currently defined	No boundary currently identified, but see boundary for stratospheric ozone for an example of a boundary related to a novel entity (CFCs)	

Table 1 – Source: Steffen et al., 2015. For column 1 Rockström et al., 2009–R2009.
Note: Tg N represents teragrams of nitrogen; Tg P represents teragrams of phosphorus.

Appendix 2

Table 1: Summary of control variables and global limits from the EEA/FOEN 2020 report, compared with those from the planetary boundary framework. (Appendix 1, Table 1)

Planetary boundary	Control variable(s) in Steffen et al. (2015)	Control variable in this reposrt (compatible with European foorprint data)
Biogeochemical flows: nitrogen cycle	Industrial and intentional biological fixation of nitrogen per year **Global limit:** 62 Tg N/year (62-82 Tg N/year).	Loss of nitrogen from agriculture per year **Global limit:** 28.5 Tg N/year
Biogeochemical flows: phosphorus cycle	**Global:** phosphorus flow from freshwater systems into the ocean per year **Global limit:** 11 Tg P/year (11-100 Tg P/year) **Regional:** phosphorus flow from fertilisers to erodible soils	Loss of phosphorus from agriculture and wastewater per year **Global limit:** 0.92 Tg P/year
Land system change	**Global:** area of forested land as a percentage of original forest cover **Global limit:** 75 % (75-54 %) **Biome:** area of forested land as a percentage of potential forest cover	Area of anthropised land **Global limit:** 19 400 000 km^2
Freshwater use	**Global:** maximum amount of consumptive blue water use per year **Global limit:** 4 000 km^3/year (4 000-6 000 km3/year) **Basin:** blue water withdrawal as a percentage of mean monthly river flow	Maximum amount of consumptive blue water use per year **Global limit:** 4 000 km^3/year

Note: Tg N represents teragrams of nitrogen; Tg P represents teragrams of phosphorus.

Table 2: Comparison between European boundaries and Europe's environmental footprint.

		Results question A			Results question B	Results question C
Planetary boundary		**European limit**				
Name	Control variable	Minimum	Median	Maximum	European footprint	Faktor over-/ undershoot
Nitrogen cycle	Loss of nitrogen from agriculture per year (tg N/ year)	0.80	2.10	6.00	6.80	3.3
Phosphorus cycle	Loss of phosphorus from fertilisers and waste per year (Tg P/year)	0.03	0.07	0.19	0.13	2.0
Land system change	Antropised land (10^6 km^2)	0.50	1.40	4.10	2.50	1.8
Freshwater use	Blue water consumption (km^3)	110	291	840	99.1	0.3

QUESTIONS:
A) What is the safe operating zone for Europe?
B) What is the global environmental footprint of Europe?
C) Does Europe live within the safe operating zone?

Table 1 – Source: Steffen et al., 2015.
Table 2 – Source: EEA/FOEN, 2020.

Table 3: Connection between Life Cycle Impact Assessment (LCIA) categories of the Environmental Footprint (EF) method, Sustainable Development Goals (SDGs), and planetary boundaries.

		Planetary boundaries								
SDGs	**LCA impact categories (EF 2017)**	Biodiversity integrity - Functional / Biodiversity integrity - Genetic	Climate change	Novel entities	Stratospheric ozone depletion	Atmospheric aerosol loading	Ocean acidification	Biogeothermal flows - Nitrogen / Biogeothermal flows - Phosphorus	Freshwater use	Land-system change
3 GOOD HEALTH AND WELL-BEING	Human toxicity, cancer			◆						
	Human toxicity, non cancer			◆						
	Particulate matter					◆				
	Photochemical ozone formation	◆		◆						
	Ionising radiation			◆						
6 CLEAN WATER AND SANITATION	Water use	◆							◆	
	Ecotoxicity, freshwater	◆		◆						
13 CLIMATE ACTION	Climate change	◆	◆				◆			
	Resource use, fossil		◆							
	Ozone depletion				◆					
14 LIFE BELOW WATER	Eutrophication, marine	◆						◆		
	Eutrophication, freshwater	◆						◆		
15 LIFE ON LAND	Land use	◆								◆
	Eutrophication, terrestrial	◆						◆		
	Acidification	◆						◆		
	Resource use minerals and metals		◆							

Table 3 – Source: Sala et al., 2021.

Appendix 3

Table 1: National performance regarding social thresholds and biophysical boundaries (1992–2015).

INDICATOR	N	THRESHOLD/ BOUNDARY		UNIT	1992	2015
Social					**Countries above threshold (%)**	
Life satisfaction	45 (119)	6.5		[0-10] Cantril ladder scale	(22)	21
Life expectancy	147	74		Years	18	47
nutrition	137	2,700		Kilocalories per person per day	40	64
Sanitation	137	95		Population with access to improved sanitation, %	25	35
Income poverty	114	95		Population earning above 5.50 $ per day (2011 PPP), %	29	33
Access to energy	131	95		Population with access to electricity, %	47	60
Secondary education	129	95		Gross enrolment in secondary school, %	16	42
Social support	(118)	90		Population with friends or family they can depend on, %	(39)	28
Democratic quality	144	7		[0-10] scale	29	28
Equality	125	70		[0-10] scale (eqivalent to Gini index of 0.3)	21	15
Employment	148	94		Labour force, employed %	50	49
Biophysical		**1992**	**2015**		**Countries withinthreshold (%)**	
CO_2 emissions	147	Population share of cumulative emissions		$MtCO_2 yr^{-1}$	68	50
Phosphorus	136	1.1	0.8	$kg\ yr^{-1}$ P	47	44
Nitrogen	136	11.3	8.4	$kg\ yr^{-1}$ N	45	38
Land-system change	142	3.3	2.4	$tC\ yr^{-1}$	61	47
Ecological footprint	145	2.1	1.7	gha	51	34
Material footprint	147	9.1	6.9	$t yr^{-1}$	61	47

Note: N indicates the number of countries considered. Data on social indicators like life satisfaction and social support are only available for a larger number of countries starting from 2005 (values for 2005 are in parentheses), so a shorter period (2005–2015) is used for aggregated comparisons between countries. Biophysical boundaries are presented as global per capita values for 1992 and 2015, decreasing over time due to population growth, except for emissions limits calculated based on each country's share, weighted by population, in the cumulative 770 Gt global CO_2 emissions from 1850–1988 (the year the 350 ppm CO_2 threshold was surpassed). For more details, refer to the original article and data sources for each social and biophysical indicator.

Table 1 – Source: Fanning et al., 2022.

Appendix 4

Table 1: Specific details for individual countries regarding social and planetary boundaries, for Slovenia and EU-28.

Biophysical Indicator	Slovenia	EU-28	Per Capita Boundary	Unit
CO_2 Emissions	10.6	10.1	1.6	tonnes CO_2 per year
Phosphorus	3.8	4.6	0.9	kilograms P per year
Nitrogen	45.3	62.9	8.9	kilograms N per year
Blue Water	259	336	574	cubic metres H2O per year
Embodied human appropriation of net primary production eHANPP	4.2	3	2.6	tonnes C per year
Ecological Footprint	4.5	4.1	1.7	global hectares (gha) per year
Material Footprint	25.7	24.2	7.2	tonnes per year
Social Indicator	**Slovenia**	**EU-28**	**Threshold**	**Unit**
Life Satisfaction	6	6.2	6.5	[0-10] Cantril scale
Healthy Life Expect.	70	69.4	65	years of healthy life
Nutrition	3173	3306	2700	kilocalories per capita per day
Sanitation	100	99.9	95	% with access to improved sanitation
Income	100	99.9	95	% who earn above $1.90 per day
Access to Energy	100	100	95	% with access to electricity
Education	97.8	105.4	95	% enrolment in secondary school
Social Support	93.1	91.8	90	% with friends or family they can depend on
Democratic Quality	1	0.9	0.8	Democratic Quality Index
Equality	77.1	70.6	70	[0-100] Scale -> (1 - Gini Index) * 100
Employment	91.8	89.6	94	% of labour force employed

Table 1 – Source: University of Leeds, DEAL website.

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