Transforming human systems to safeguard the Global Commons

An integrated assessment of deep transformations in human energy, land use, and production and consumption systems towards keeping the Global Commons within the safe space of the Planetary Boundaries

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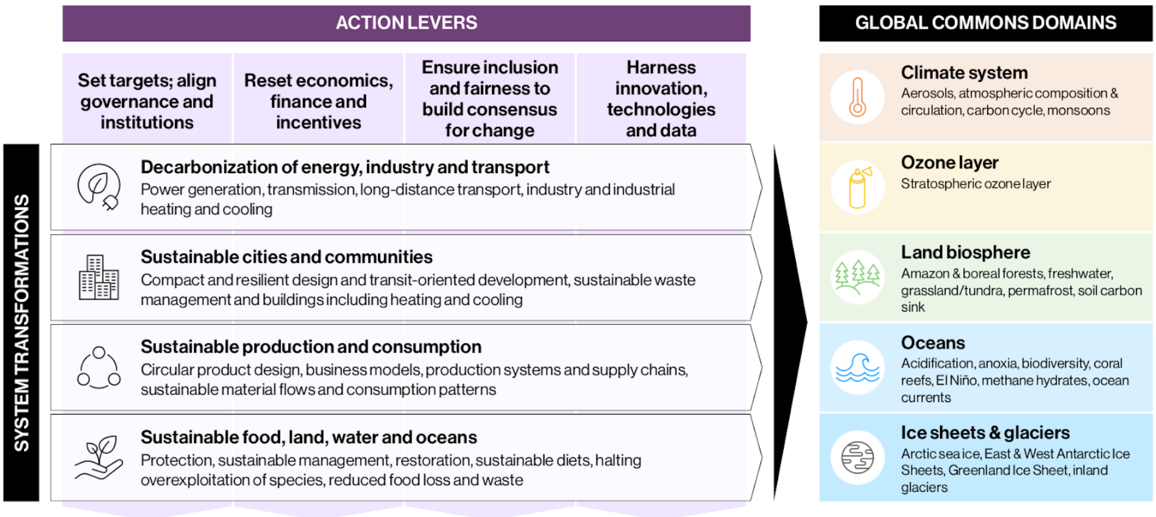
The Global Commons Stewardship Project

The Global Commons Stewardship (GCS) project, initiated and led by the **Center for Global Commons (CGC)** at the **University of Tokyo**, in partnership with **PIK, SDSN, WRI** and **SYSTEMIQ**, aims at the **development of a conceptual framework and strategies for Global Commons Stewardship.**

Within the GCS project, the **Potsdam Institute for Climate Impact Research (PIK)** is responsible for conducting **interdisciplinary modelling, performing a comprehensive assessment of how the system transformations identified in the GCS project can contribute to the stewardship of the Global Commons.**



The Global Commons Stewardship Framework

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Executive Summary

Current policies and the Global Commons

Safeguarding the Global Commons requires a global perspective. The Global Commons, the biophysical systems that as a whole keep the Earth System stable and resilient, consisting of several global commons domains, are the foundation of human development and prosperity. Currently, human activities have already pushed several of these systems outside the safe operating space of the Planetary Boundaries.

Our integrated assessment results show that, with current policies, humanity is on track to worsen the state of most Global Commons domains and cross several Planetary Boundaries by mid-century (Fig A). The boundaries for Nitrogen Flow, Land System Change and Biosphere Integrity have already been transgressed today, and continuing current policies would not reverse the underlying trends by returning the associated indicators to a position substantially closer to their Planetary boundaries by 2050. With just the controls currently in place on emissions of CO_2 and other greenhouse gases, the Planetary Boundaries for Climate Change and Ocean Acidification would also be crossed by 2050.[1] **The only indicator that is set to improve is the one for the Ozone Layer, with the successful implementation of the Montreal Protocol** bringing ozone depletion back inside the Planetary Boundary.

A complete worldwide implementation of the Nationally Determined Contributions (NDC) on emissions reduction, land protection and afforestation by 2030 and the continuation of this level of ambition until 2050 would not substantially change the worsening trends under current policies. Only small progress back towards the Planetary Boundaries for Climate Change, Ocean Acidification and Land System Change would be made, **which is not enough to remain inside the Planetary Boundaries or even stop degradation at current values**. Furthermore, the pressures of increased land scarcity and a possible reliance on bioenergy for reducing emissions would lead agriculture to further **worsen the state of the Nitrogen Flow indicators.**

A holistic transformation pathway

A scenario in which transformations of energy use, land use, and production and consumption patterns are implemented jointly would allow humanity to reverse the degradation of the Global Commons domains to levels very close to or within the Planetary Boundaries by 2050. Although even these deep systems transformations would not be able to keep warming below 1.5°C without a small overshoot in 2050, a combination of CO_2 removal and continued reduction of non-CO_2 emissions would revert warming, so that global mean temperatures would stay below the Paris Agreement target by 2100 and beyond. However, CO_2 concentrations and radiative forcing would still

[1] As described in Section 2.3, we define the Planetary Boundary as 1.5°C warming over the preindustrial value, the target set by the Paris Agreement. As current warming is around 1.1°C, the target has not been crossed yet, but would be in 2050 if current policies continue. In this point we deviate from the Planetary Boundaries framework (Steffen et al. 2015) which defines Climate Change as an atmospheric CO_2 concentration of 350 ppm. Based on this indicator and value, the Planetary boundary for Climate has already been crossed, and even all the transformations investigated here cannot bring CO_2 concentrations back below that value.

only be stabilized at around current levels, at which changes in climate harmful to human and natural systems are already observed.

In the scenarios considered, the proposed interventions lead to dramatic changes in the energy, land and production and consumption systems. In our modeling framework, these changes are a combination of direct model assumptions and endogenous responses to them. Some of the most relevant are:

- The average global price on GHG emissions in both the energy and land sectors reaches around **90 U.S. dollars per ton of CO2eq in 2050**. These levels are relatively low, being enough to limit warming to 1.5°C by 2100 (with limited overshoot) only in combination with all other transformations. Prices are phased in more slowly in developing countries. In the absence of these other transformations, the prices required for the same temperature limit are over three times higher.
- Diets worldwide move towards more healthy and sustainable patterns, along the lines of the **EAT-Lancet diet recommendations**, by 2050. **Global consumption of livestock products, which is currently increasing, decreases by around half**, especially moving away from ruminant meat. Most of this reduction comes from developed countries with meat-rich diets.
- **Food waste is halved by 2050.**
- Global average **crop nitrogen use efficiency (NUE),** the fraction of nitrogen in fertilizer that is taken up by the crops, **improves from the current 50% to 70%.**
- All areas currently listed as protected in the World Database of Protected Areas (WDPA) are effectively protected, plus all intact forest landscapes and biodiversity hotspots, in total **protecting around 30% of the global land environment by 2030**. This value is in line with the **commitments in the Kunming-Montreal Global Biodiversity Framework**. GHG pricing is applied to land use change to disincentive loss of carbon, natural vegetation and biodiversity in non-protected areas.
- The **share of electricity in the global final energy supply** increases from currently below 20% to ~25% in 2030, **to 45% in 2050**. A combination of reduction in the cost of renewables and carbon pricing leads to an almost complete **phase out of coal and oil use in electricity generation**, and reliance on gas falls below 2% of the electricity supply in 2050.
- The **per-capita demand for cement is reduced** by 20%, as a result of price changes in the energy system and through the promotion of higher material efficiency in the buildings sector.

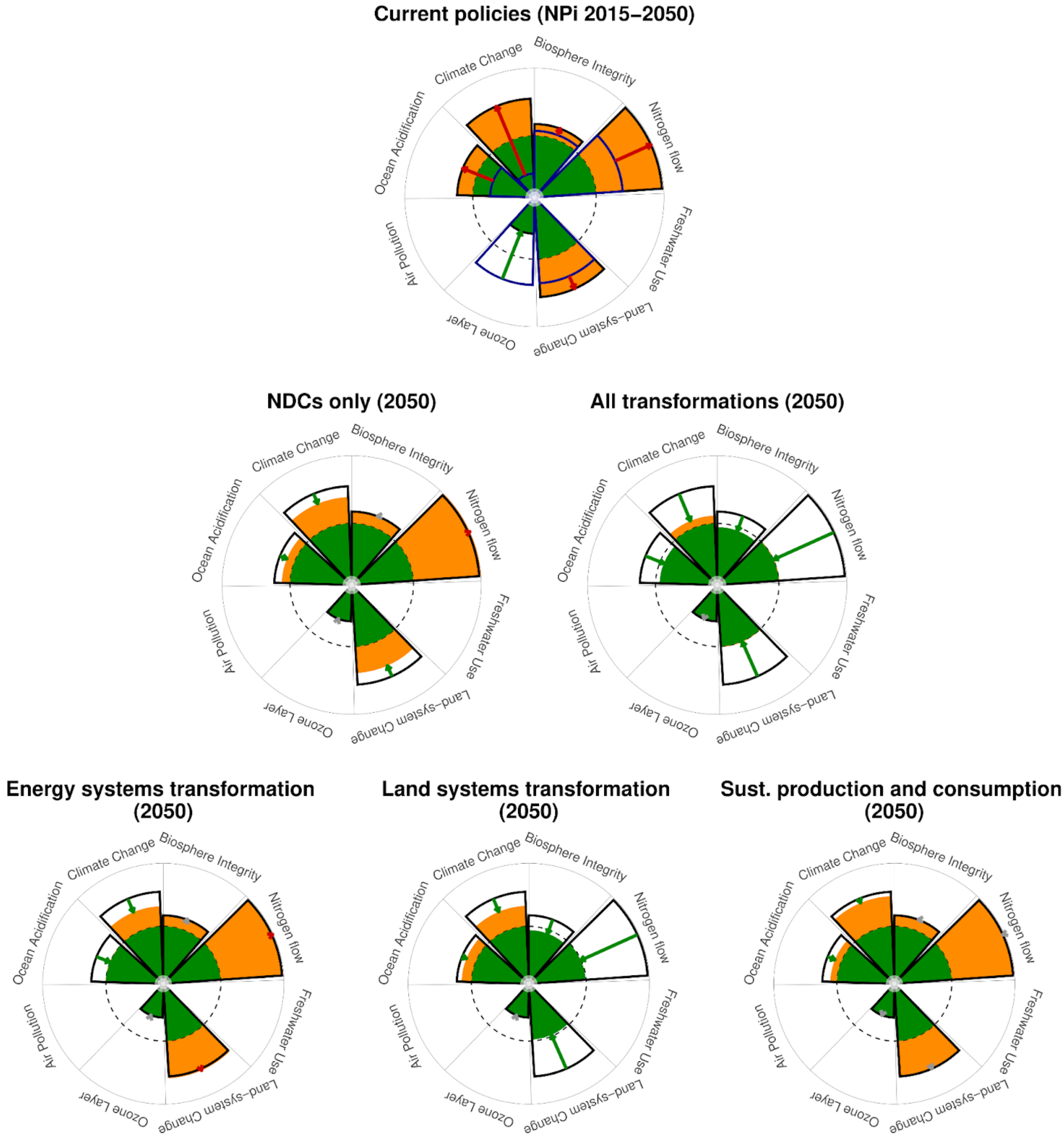

Fig. A: Effects of the continuation of current policies (from 2015 to 2050, top row) and of various transformations (in 2050) on keeping the Global Commons domains within selected the Planetary Boundaries. Inner dotted lines mark the Planetary Boundary value (or the 1.5C global mean temperature change limit in the case of the Climate Change boundary). Green (red) arrows indicate an improvement (worsening) of an indicator due to a certain transformation in 2050 in relation to either 2015 (blue lines in NPi) or to the current policies continued scenario in 2050 (black lines). Wedges show the relative value of each indicator, with green (orange) portions showing the part inside (outside) the defined safe space. The starting points of the wedges at the center were chosen so as to visually emphasize the effects and their relation to the Planetary Boundary value, and are not comparable across indicators. Effects on the Air Pollution and Freshwater Use boundaries were not explicitly quantified in this study.

Modelling transformations

In this study, we used the REMIND-MAgPIE integrated assessment framework to simulate scenarios that implement different combinations of these transformations in addition to existing policies. Results show how they affect the future development of five Global Commons Domains, (Climate, Cryosphere, Oceans, Ozone Layer and Land Biosphere) relative to the Planetary Boundaries over the course of the next century.

Due to the high relevance of the land and industry sectors for the pressure on several planetary boundaries, special sets of scenarios also offer insights into the effects and trade-offs of dedicated land- and industry-specific transformations. In the land sector, options for changing current food systems, improving resource efficiency in agriculture, and land-based solutions for climate change were investigated. In the industry sector, reductions in the demand for materials, the introduction of carbon capture and storage (CCS) technologies, and widespread use of hydrogen were analyzed in combination with GHG pricing in the sector. Additionally, the potential of circular economy strategies in the plastics sector was examined in relation to the planetary boundaries of climate change and the introduction of novel entities.

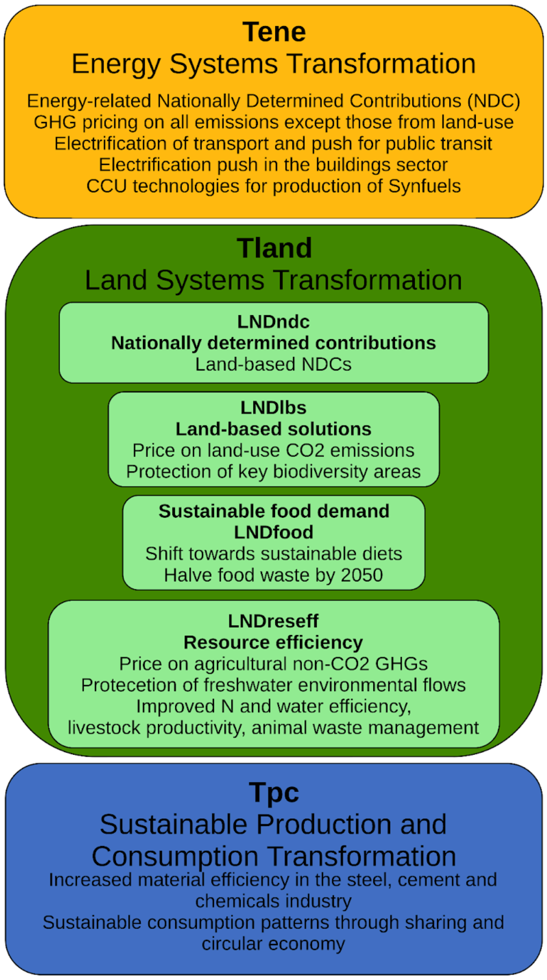

Fig. B: System Transformations implemented in the REMIND-MAgPIE modelling framework

Effects of individual transformations

Implemented individually, the transformations of energy use, land use, and production and consumption patterns have different effects on safeguarding the Global Commons. Most but not all of them are positive.

- **The Energy Systems Transformation has strong effects on safeguarding the Climate, Cryosphere and Oceans, but can have detrimental effects on the Land Biosphere Global Commons domains.** Transforming the energy systems towards sustainable energy sources and shifting towards more sustainable transport modes would reduce GHG emissions by 39 Gt CO_2eq/year in 2050, a 60% reduction relative to a scenario with only the currently implemented policies. This would prevent around 0.19°C of warming. Most of the avoided emissions would be of CO_2, keeping **Ocean Acidification at relatively safe levels inside the Planetary Boundary** throughout the century. However, an **increased reliance on bioenergy ultimately has detrimental effects on the Land Biosphere**, leading to higher deforestation rates, use of nitrogen fertilizers, agricultural consumption and degradation of biodiversity.
- **The Land Systems Transformation is fundamental for preserving the Land Biosphere, but also has substantial positive impacts on the other Global Commons domains.** By 2050, it would halt the loss of natural forest, reduce agricultural water consumption and improve human-induced nitrogen fixation and biodiversity intactness to conditions superior to those of today. This would bring Land System Change, Nitrogen Flow and Biosphere Integrity back within their Planetary Boundaries. **These effects are more than enough to counteract negative effects from the Energy Systems transformation in these Global Commons domains.** The combination of land interventions would also reduce GHG emissions by 19 Gt CO_2eq/year. Methane emissions would be particularly reduced, preventing 0.18°C of warming in the medium term (2050) and **minimizing overshoot of the 1.5°C Paris Agreement target.** The avoided CO_2 emissions would have positive impacts on Ocean Acidification, but not enough to prevent it from degrading to levels outside the Planetary Boundary.
- **Individual components of the Land Systems Transformation focusing on resource-efficient production, reduction of GHG emissions, and dietary changes, differ in terms of their individual impact on safeguarding the Global Commons domains, and exhibit synergies and tradeoffs between them and with other transformations.**
    - **Transitioning to resource-efficient production systems** is a key supply-side intervention to reduce human-induced nitrogen fixation and agricultural water use. However, reducing water consumption by limiting irrigation can increase pressures on Land System Change and Biosphere Integrity, as replacing irrigated systems with relatively lower-yielding rainfed ones requires more land area.
    - **Pricing GHG emissions from land use change** can prevent leakage effects from other interventions, including those that can occur if regulation-based land protection or afforestation schemes like current NDCs miss sufficient coverage in terms of regional distribution and types of included ecosystem.
    - **Each of these land protection measures are of paramount importance if interventions in other sectors further increase biomass demand**, e.g. for energy use. On the other hand,

land-based solutions alone can push unsustainable intensification practices and can create tradeoffs with water use.

- ○ **In contrast, transforming food demand towards more sustainable diets and reducing food waste leads to strong beneficial impacts across most Global Commons domains. It can combine synergistically with other land interventions, leading to more than additive outcomes in Land Systems Change and Biosphere Integrity**, as reduced demand for food frees more land to be used for mitigation and conservation. Its beneficial effect on reducing emissions and the use of nitrogen and water are slightly diminished when evaluated in conjunction with the other land interventions, which ultimately make the food system more environmentally efficient and therefore reduces the burden of additional food demand. However, it still **positively affects economic variables such as food and bioenergy prices**, which are mostly negatively influenced by the other land interventions. It is also key to facilitating a multi-dimensional transformation to sustainability that also **addresses human well-being and development**.

- **The Sustainable Production and Consumption Transformation has some effects on safeguarding the Climate, Cryosphere and Oceans, but is not enough to protect them on its own.** The improvements in material efficiency and more sustainable consumption habits ultimately lead to lower industrial production and energy demand, which reduces GHG emissions by 16 Gt CO_2eq/yr relative to current policies in 2050. These reductions can prevent 0.09°C of warming overshoot in 2050 and have benefits for Ocean Acidification. When combined with other transformations, Sustainable Production and Consumption can further limit peak warming, facilitate the Energy Systems Transformation and ease the pressure on the Land Biosphere.
- **The transformations have little to no effect on the Ozone Layer beyond the Montreal Protocol.** With continued compliance to the Montreal Protocol on the emissions of ozone-depleting substances, the ozone layer should return to pre-1980 levels between 2030 and 2050.

The role of demand reductions

Interventions that reduce demand for goods and services, be it for industrial materials (such as the Sustainable Production and Consumption Transformation), or for unsustainable food products (Sustainable Food demand) **can have very substantial effects on safeguarding the Global Commons. But even within our deep transformations, demand-side interventions alone will not be sufficient to reach any of the assessed targets.** Furthermore, when coupled with structural changes in the systems themselves, such as the decarbonisation of energy supply and more resource-efficient agricultural production, these demand-side interventions tend to have a smaller effect than when considered alone. This arises from the fact that these transformed production systems can fulfill the same demand with less impact on the Global Commons.

However, reductions in demand can be fundamental in reducing the socioeconomic burden of these production systems transformations, making the same targets achievable with lower prices for food, energy and GHG emissions for example. Since most of the demand reductions assessed require deep behavioural changes, implementing them is posing a major policy challenge.

Industry transformation

Industry-specific modelling shows that carbon pricing is essential for reducing the sector's environmental impacts, but implementing industry-specific policies enables faster and deeper de-carbonization of the sector.

Reducing the material demand of the economy through sustainable production and consumption practices **offers significant reductions of the pressure that industry puts on the Global Commons domains**. However, the feasibility of deep dematerialization remains uncertain.

Carbon capture and storage (CCS) is important for deep decarbonization of the global industry to tackle process emissions, as these cannot be mitigated by means of low-carbon energy carriers. However, **CCS technology is not a viable replacement for phasing out fossil fuels for energy use**. Robust policy making for deep decarbonization cannot be avoided.

The adoption of hydrogen-driven technologies in the industry sector should concentrate on the specific applications where electrification is not feasible, as it is generally not the most cost-effective solution .

Circular approaches for plastic waste mitigation can help mitigate the introduction of novel entities in the earth system while avoiding putting further pressure on the climate and the energy transition but further research is required that defines the technical, economic, and environmental limits of this alternative.

Policy recommendations

An integrated, comprehensive design of policies is needed for a Global Commons stewardship: Global Commons stewardship needs combined and comprehensive policy settings, targeting transformations on multiple sectors at the same time. To protect and preserve the Global Commons and planetary integrity, such an integrated approach is of utmost importance. The interventions considered in our scenario analysis are mutually supportive in preserving the Global Commons in many cases, and can avoid or compensate for policy trade-offs if applied together. This is of particular importance between and within the Energy and Land Systems Transformations, to avoid trade-offs between land-based mitigation, growing bioenergy crops and nature conservation.

Current policies and commitments need to be substantially strengthened and increase their coverage of the broad set of changes and transformations required for safeguarding the Global Commons: Current commitments should not only be implemented, but strengthened with more ambitious targets in terms of emissions reductions by 2030 and 2050, but also of land and biodiversity protection. The recently adopted Global Biodiversity Framework represents a major step in this direction. Policy measures should also have a more comprehensive focus on multiple sectors and producer and consumer-facing interventions. This could help fill gaps in policy coverage, for example, with regard to better taking into account the effects of agricultural systems on the water and nutrient cycles, inducing a change towards more sustainable consumption patterns, and increasing the material efficiency of production.

An emissions pricing scheme to safeguard the Global Commons should play a critical role to penalize actions that lead to more GHG emissions and reward those that reduce emissions. It should be designed to cover all emitting sectors, have prices that rise over time, and explicitly address its own equity and distributional impacts: Measures that effectively put a price on emitting GHGs can have large positive effects on many Global Commons domains. Actual measures can include direct carbon pricing or taxation, but also carbon markets (such as the EU Emissions Trading Scheme) or regulations. Emission pricing directly targets the protection of the climate, and thus also the preservation of ice sheets and glaciers and the prevention of further Ocean Acidification. It also discourages the use of coal and other fossil fuels, thus improving air quality especially in cities and communities. Including the **land use sector** in such a pricing scheme creates incentives to protect and expand forests. It also **disincentivizes** an **excessive reliance on bioenergy** for decarbonizing the energy sector. Including **GHGs other than CO_2** in the pricing scheme also favours **less meat consumption** and fosters a more **sustainable use of nitrogen fertilizers**. However, GHG pricing should be **accompanied by specific land protection measures** to alleviate the pressure that some climate mitigation options such as bioenergy use and afforestation can cause on natural and semi-natural land, which is critical for halting and reversing biodiversity loss. GHG pricing instruments should **address their equity and distributional impacts by design** to ensure their acceptance, directing their revenues to lower income regions and households and phasing in prices more slowly in developing countries.

The GHG price levels required for safeguarding the Global Commons domains, especially the Climate, depend crucially on all other measures implemented: In the absence of any other measures, energy system GHG prices in our scenarios would have to reach around 350 U.S. dollars per ton of CO_2 equivalent by 2050 to reach the 1.5°C climate goal. Combining it with other policies, especially **encouraging the reduction of total demand for high emissions products and services, such as industrial materials, energy and animal-source foods, and pricing emissions in the land sector lowers the GHG prices necessary to achieve the same climate target.** Demand reductions, although difficult to implement, ease the cost of transition and have several co-benefits for the land biosphere. Combined with strong levels of demand reduction, a comprehensive GHG pricing scheme in the energy and land use could achieve the 1.5°C climate goal with prices as low as 90 U.S. dollars per ton of CO_2 equivalent by 2050.

The role of bioenergy in decarbonising the energy system should be limited and coupled with land conservation policies: Bioenergy production can lead to severe trade-offs, threatening the integrity of the land biosphere and increasing food prices. Many of these effects could be counteracted by very ambitious conservation policies and a shift towards more sustainable food consumption behaviour, which are challenging to implement at a global scale. Therefore, a mix of regulations on energy markets to limit their reliance on bioenergy and comprehensive conservation policies on bioenergy producing regions is recommended.

Foster sustainable production and consumption of industrial goods: A reduction in per-capita production of material goods in high-income countries facilitates the decarbonization of the energy supply, thus contributing directly to the protection of climate, cryosphere and oceans, as well as to a reduction of air pollution and associated health effects and the amount of waste to be disposed of. Part of these reductions can be achieved through material efficiency measures and technological improvements in the producing industries. But promoting a shift to more sustainable consumption patterns, with a focus on sharing and circular economies, could also lead to massive benefits.

A sound strategy for the sustainable transformation of the global industry requires a set of sector-specific policies to overcome potential bottlenecks and carbon lock-ins. Incentives that speed up the development and rapid scale-up of Carbon capture and storage technologies are needed to mitigate process emissions in industry. However, **deploying CCS is not a license to continue to use fossil fuels, as it cannot provide full decarbonization**. Robust policy making for the industry transformation should hedge against the deep uncertainties underlying both new technologies and reductions in demand. **More research must be done to define the techno-economic boundaries of dematerialization and material efficiency**, as well as advancing the understanding of cross-sectoral interactions. Incentives that foster the scale-up of **hydrogen** are needed, but should be **targeted to applications where electrification of processes is technically constrained**. Subsidizing the deployment of hydrogen beyond the necessary scope risks triggering additional transformational challenges which can hinder the transformation of industry.

Promotion of healthy and sustainable diets and a reduction of food waste: The food system is one of the key drivers for environmental degradation. A transition to lower meat and dairy consumption, as recommended by the 'Planetary Health' diet of the EAT-Lancet expert commission, improves human health and has far-reaching positive consequences for the Global Commons. Together with a reduction of food waste, an adoption of the Planetary Health diet reduces food sector emissions of CH_4 and N_2O drastically. By reducing land requirements for food production, in addition to inputs for agriculture such as irrigation and nitrogen fertilizer, sustainable diets are key to facilitating ambitious climate targets and preserving biodiversity.

Pull all levers to make land and food systems more sustainable: Although supply-side measures to make agricultural production systems more resource-efficient, demand-side transitions to healthy diets and low food waste, and systemic solutions to disincentive land system change and associated GHG emissions are each yielding substantial progress on some Global Commons domains, none can on their own achieve - despite their ambitious design - the vision of returning within those Planetary Boundaries that are closely tied to land use and agriculture. Thus, policy coherence is key to harnessing the many synergies between individual strategies and is likely to have many co-benefits in other areas, such as nitrogen-related air and water pollution and public health.

Beyond the physical dimensions of the Global Commons domains assessed, we also recommend to further take into account measures that primarily target societal development goals and that can also have substantial impacts on the Global Commons. Many of these interventions can directly or indirectly affect the justice, acceptability and feasibility of policies targeting the Global Commons domains, such as improving global justice in sharing the burden for implementing transformations, gender equality and access to education.

The feasibility of the implementation of such ambitious measures will depend on well-working governmental institutions and strong international cooperation. Although each government should control its own transformation strategy, coordination and compensation mechanisms at the global level are critical given the significant challenges arising from the profound transformations in the energy, agricultural and industrial systems, particularly in the global south. International cooperation and strong regional institutions will be needed to prevent leakages in the impact of policies, especially in the land sector and between the Global South and Global North. Moreover, due to the non-predictability of all impacts of certain measures, monitoring and readjustment strategies will be necessary and should be included in the conception of governance strategies aiming to keep the impacts of human activities on the Global Commons domains within Planetary Boundaries.

1. Introduction

There are increasing signs that the Global Commons, the biophysical systems that as a whole keep the Earth System stable and resilient and are the foundation of human development and prosperity, are under threat. Our Earth System is to a considerable extent outside of the safe operating space for humanity. Six of the nine Planetary Boundaries are already transgressed (Richardson et al. 2023). Rapid, far-reaching and decisive action is needed to improve the state of the Global Commons to such an extent that the stability and resilience of the Earth System can be restored and maintained in the long term.

The Global Commons Stewardship (GCS) project, initiated and led by the Center for Global Commons (CGC) at the University of Tokyo, in partnership with PIK, SDSN, WRI and SYSTEMIQ, aims at the development of a conceptual framework and strategies for Global Commons Stewardship.

The lead questions guiding this assessment report are:

- To which extent can deep transformations in the energy and the land use sector, and the production and consumption sectors contribute to effectively safeguarding the Global Commons domains by keeping in or returning the Earth System into the safe operating space of the Planetary Boundaries?
- Which synergies and trade-offs between these transformations have to be taken into account when designing policy strategies?

To address these questions, we used the PIK integrated assessment modelling framework (PIAM), at the core of which is the REMIND-MAgPIE model (see Annex 1) to perform a comprehensive assessment of how the system transformations identified in the GCS project can contribute to the stewardship of the Global Commons. We evaluated a number of scenarios describing the evolution of indicators of the five Global Commons domains (Fig 1.1.) under different sets of assumptions, including the implementation of three Systems Transformations (Fig1.2). The transformations assessed here were based on the System Transformations described in the Global Commons Stewardship Framework (GCSF 2022) developed within the CGS project. For a more detailed description of the transformations and how they were implemented in the modelling framework, see Annex 3.

Fig. 1.1: The five Global Commons domains (GCSF 2021)

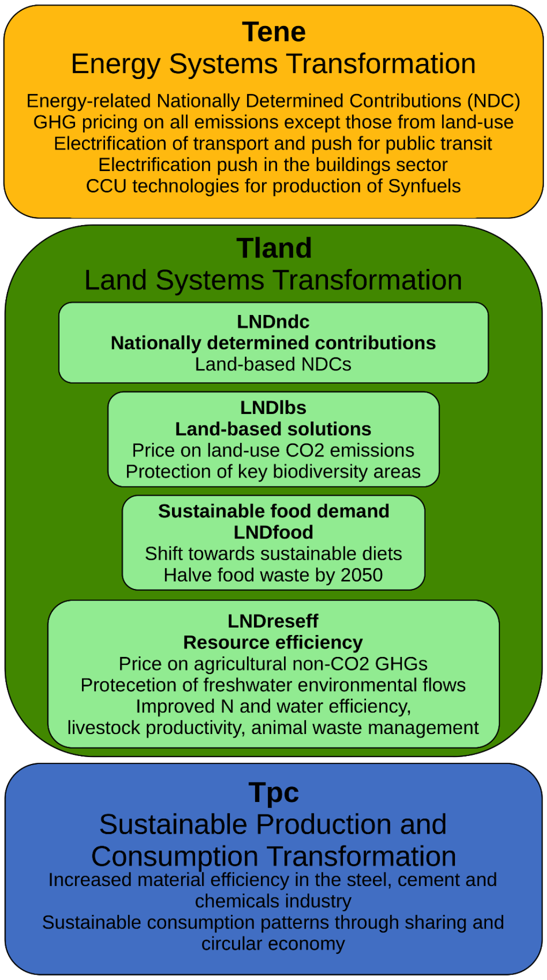

Fig. 1.2: System Transformations implemented in the REMIND-MAgPIE modelling framework

Main scenarios assessed

The scenarios assessed combined projections of underlying societal development with sets of interventions related to the Energy Systems, the Land Use, and the Production and Consumption transformations (Fig 1.2). Societal development was represented by the Shared socioeconomic pathways (SSPs), mostly SSP2, the "middle of the road" projection (see Riahi et al. 2017), and, in one case, by SSP1 - the "sustainability" pathway. The sets of interventions selected tied with the System Transformations described in the framework paper developed in the GCS project (GCSF 2022), although not all aspects could be implemented in REMIND-MAgPIE. To enable a more detailed, systematic analysis of the contributions of certain aspects of a Land Systems transformation to successfully preserving the Global Commons domains, we distinguished a number of subtransformations in this field. The scenarios were designed in a way that they can be compared in different sequences to analyse the individual effects of the Interventions in different combinations. Figure 1.3 provides an overview of the scenarios and the scenario sequences implemented, which include:

- An "National Policies Implemented (NPi)" scenario, including only policies that are currently in effect
- A "Nationally Determined Contributions (NDC)" scenario, assuming the implementation of the NDCs pledged until the time of COP26
- A "All transformations" or "Global Commons Stewardship" scenario, designed to sustainably manage all the Global Commons domains assessed by combining all transformations assessed
- A "Sustainable Development" scenario, that combines all transformations with assumptions on more sustainable GDP and population growth as described by the Shared Socieconomic Pathway 1 (Riahi et al. 2017)
- Scenarios including only one of each of the System Transformations ("Energy Systems Transformation", "Land Systems Transformation", "Production and Consumption Transformation")
- Scenarios with only subtransformations of the Land Systems transformation ("land-based solutions", "resource efficiency on land", and "sustainable food consumption")
- Several scenarios combining two or more subtransformations and/or transformations.

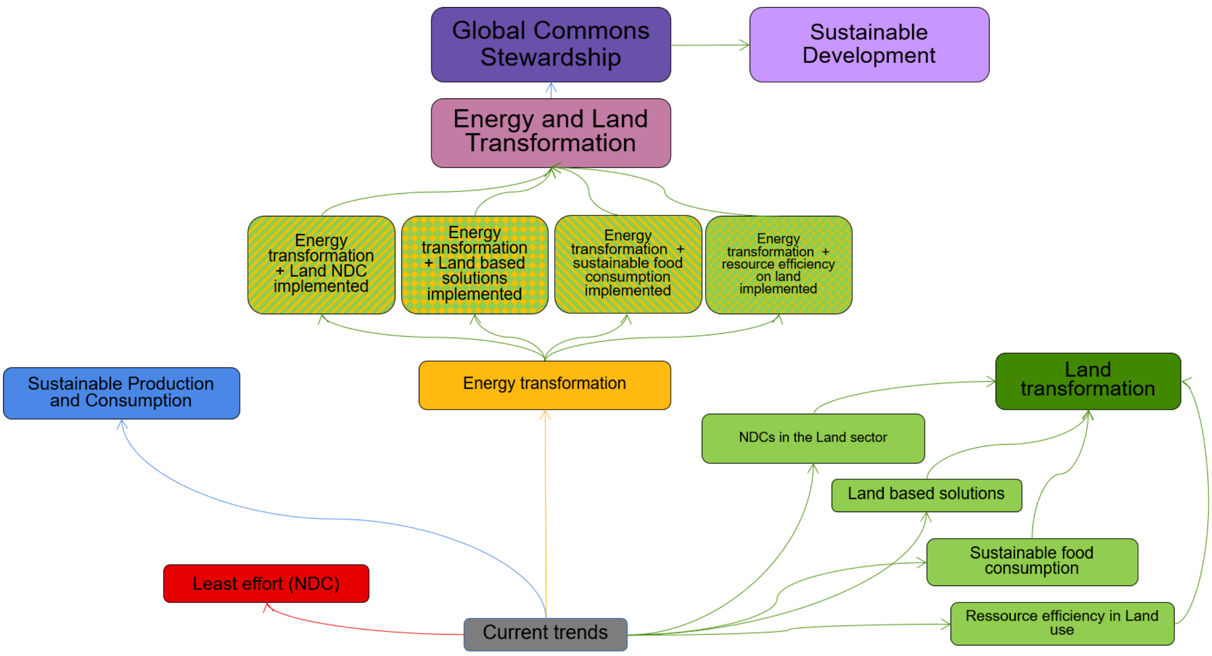

Fig. 1.3: Overview of the main scenarios simulated and some possible comparisons. Comparing two scenarios linked with an arrow allows identifying the contribution of a specific intervention in a certain combination.

Indicators used for the Global Commons domains

Key indicators of the Global Commons domains, along with targets based on the Planetary Boundaries framework were used to assess the contribution of the transformations to successfully safeguard these domains. The outcomes of the scenario runs were compared with the effects of the trends continued (NPi) scenario, and a set of targets for Global Commons domains key indicators, most of them compatible with the Planetary Boundaries framework by Steffen et al. (2015). For a list of target values, see Annex 2.

An exception was made only for the indicators for the Climate System and the Cryosphere. To avoid ongoing impact on the Climate system in the long term, GHG emissions have to remain stable, and the net emissions of long-lived gases such as CO_2 must reach zero. Thus, targets for GHG emissions for 2030 and 20250 were chosen as intermediate values for a trajectory that has a high probability of keeping global temperature change below 1.5°C with limited overshoot

Table 1.1: Description of key indicators for assessing the contribution of the Transformations to preserving the Global Commons domains and their relationship with the Planetary Boundaries. The indicator used for direct comparisons with each Planetary Boundary is marked in bold.[2]

Global Commons domain	Key indicator used for assessment	Description of the indicator's relationship with the Global Commons domain	Related Planetary Boundaries
Climate system Aerosols, Atmospheric composition & circulation, Carbon cycle, Monsoons	GHG emissions	Acts as a proxy for climate change mitigation ambition. Measured in GWP100 CO_2 equivalent emissions. Targets for each year are chosen to be consistent with trajectories that would lead to 1.5°C by the end of the century with minimal overshoot.	**Climate Change, Ocean Acidification**
Ice sheets and glaciers Arctic Sea Ice, East & West Antarctic Ice Sheets, Greenland Ice Sheet, Inland Glaciers	Global Mean Temperature (GMT) change	Indicates the human impact in both the climate system and the cryosphere. The response of GMT to human activities follows complex dynamics, being dependent on the timing and nature of emissions of both GHG gases and aerosols.	**Climate Change**
Oceans Acidification, AMOC, Anoxia, biodiversity, Coral reefs, ENSO, Methane hydrates	Aragonite saturation rate	Direct proxy to ocean acidification. Under low saturation rates, corals and other calcifying organisms have more difficulty creating and maintaining their shells, which affects the stability and diversity of marine ecosystems. Human activity affects aragonite saturation rate mainly via CO_2 emissions to the atmosphere. The CO_2 gas dissolved in seawater increases its acidity and reduces aragonite saturation rate.	**Ocean Acidification**
Ozone layer Stratospheric ozone layer	Effective Equivalent Stratospheric Chlorine (EESC)	Indicates the effective amount of ozone-depleting substances in the atmosphere.	**Ozone Layer**
Land biosphere Amazon & Boreal Forests, Freshwater, Grassland/Tundra, Permafrost, Soil carbon sink	Forest cover	Total forest area, including both natural and managed forests.	**Land System Change**
	Consumptive agricultural water use	Consumptive freshwater use in agriculture, excluding infiltration and runoff but including irrigation losses through evaporation.	**Freshwater Use**
	Human-induced N fixation	Total Nitrogen (N) added to the landscape due to human activities, including inorganic N fertilisation	**Nitrogen Flows**

[2] The indicators are also represented in the GCS Index (SDSN et al. 2021). However, trade in goods is not fully considered in a way that allows statements about spillover effects. For more information on spillover effects between regions and policy options to tackle them, see GCS 2023. Effects of trade in primary energy sources, although represented in REMIND-MAgPIE as well, are not listed separately. The associated emissions are allocated to the region where they are used, regardless of where the product produced thereby (e.g. steel) is ultimately consumed.

		and biological fixation by crops.	
	Biodiversity Intactness Index	Ratio of the averaged plant and vertebrate populations to their presumed pre-modern levels.	**Biosphere Integrity**

2. Implemented policies and current commitments

Motivation and Methods

The state of the Global Commons is currently threatened by human activity, with several Planetary Boundaries already transgressed. Although many forms of anthropogenic pressure to the Global Commons continue to increase, the past decades have seen some level of progress in environmental policy that do alleviate some of this pressure. Besides, most countries have voluntarily committed to achieve climate protection goals throughout the 21st century as part of the Nationally Determined Contributions (NDCs) of the Paris Agreement, which would have effects on other Global Commons domains besides the climate.

Here we evaluate scenarios that project the continuation of implemented policies or the realisation of current commitments into the future. In the Nationally Implemented Policies (NPi) scenario, it was assumed that only currently implemented policies, including protected areas, are continued throughout the century. Greenhouse gas (GHG) prices are assumed to grow and converge more slowly, leading to emission trajectories in line with bottom-up studies on the effect of current policies. In the Nationally Determined Contributions (NDC) scenario, on top of current policies all NDC targets submitted by the UNFCCC parties by 2021 are assumed to be achieved. This includes regional technology adoption, deforestation reduction, afforestation and general GHG reduction targets, the latter being achieved by implementing regional prices on GHG emissions.

Key findings

If only the currently nationally implemented policies remain in place until 2050 (NPi scenario), humanity is on track to worsen the state of most Global Commons domains and cross several Planetary boundaries in the next century. The boundaries for Nitrogen Flow, Land-System Change and Biosphere Integrity have already been crossed today, and no further action envisaged under the NPi's would move these indicators substantially away from their boundaries by 2050. With just the controls currently in place on emissions of CO_2 and other greenhouse gases, the Planetary Boundaries for Climate Change and Ocean Acidification would also be crossed by 2050.[3] Although the sustainable limits for global total agricultural water use would not be crossed by then, current trends would also increase water consumption towards unsustainable levels in many regions of the world. The only indicator that is set to improve is the one for the Ozone Layer, with the successful implementation of the Montreal Protocol bringing ozone depletion back inside the Planetary Boundary.

A complete worldwide implementation of the Nationally Determined Contributions (NDC scenario) on emissions reduction, land protection and afforestation would lead to substantial progress back towards the Planetary boundaries for Climate Change, Ocean Acidification and Land systems Change, but not enough to remain inside the boundaries or even stop degradation at current (2015) values. Furthermore, the pressures of increased land scarcity and a possible reliance on bioenergy for

[3] As described in Section 2.3, we define the Planetary Boundary as 1.5°C warming over the preindustrial value, the target set by the Paris Agreement. As current warming is around 1.1°C, the target has not been crossed yet, but would be in 2050 if current policies continue. In this point we deviate from the Planetary Boundaries framework (Steffen et al. 2015) which defines Climate Change as an atmospheric CO_2 concentration of 350 ppm. Based on this indicator and value, the Planetary boundary for Climate has already been crossed, and even all the transformations investigated here cannot bring CO_2 concentrations back below that value.

reducing emissions would lead agriculture to somewhat worsen the state of the Nitrogen Flow and Freshwater Use indicators.

Effects of implemented policies (NPi) and current commitments (NDC) scenarios on the Global Commons domains

Effects on the Climate: If just the current nationally implemented policies (NPi) are kept in place, climate change will advance significantly, with 1.95°C warming above preindustrial levels in 2050, already surpassing the 1.5°C target in 2035. This is caused by GHG emissions increasing to 64Gt CO_2eq/yr by 2050. Compared to the NPi scenario, the NDC contributions as agreed at the COP26 in Glasgow could reduce GHG emissions by 22 Gt CO_2eq/yr, just around 40% of the reduction required to stay on track for the 1.5°C target. We assume the target trajectory of GHG emissions to be that of our all-transformations scenario (11 Gt CO_2eq/yr in 2050), in which warming is kept under 1.5°C with limited overshoot.

Consequently, the NDCs would prevent just 0.13°C of warming by 2050, with global mean temperatures still rising by 1.8°C in 2050. Crucially, since net zero CO_2 emissions are not reached before 2100 in the NDC scenario, temperatures continue to steadily rise into the next century.

Effects on Ocean Acidification: The continued CO_2 emissions under the NPi scenario lead to a substantial worsening of ocean acidification by 2050, with aragonite saturation rate dipping to well below 2.8, a level considered minimum to safeguard marine ecosystems. Reductions in emissions due to the NDCs improve these conditions, but increase aragonite saturation just halfway towards the target level.

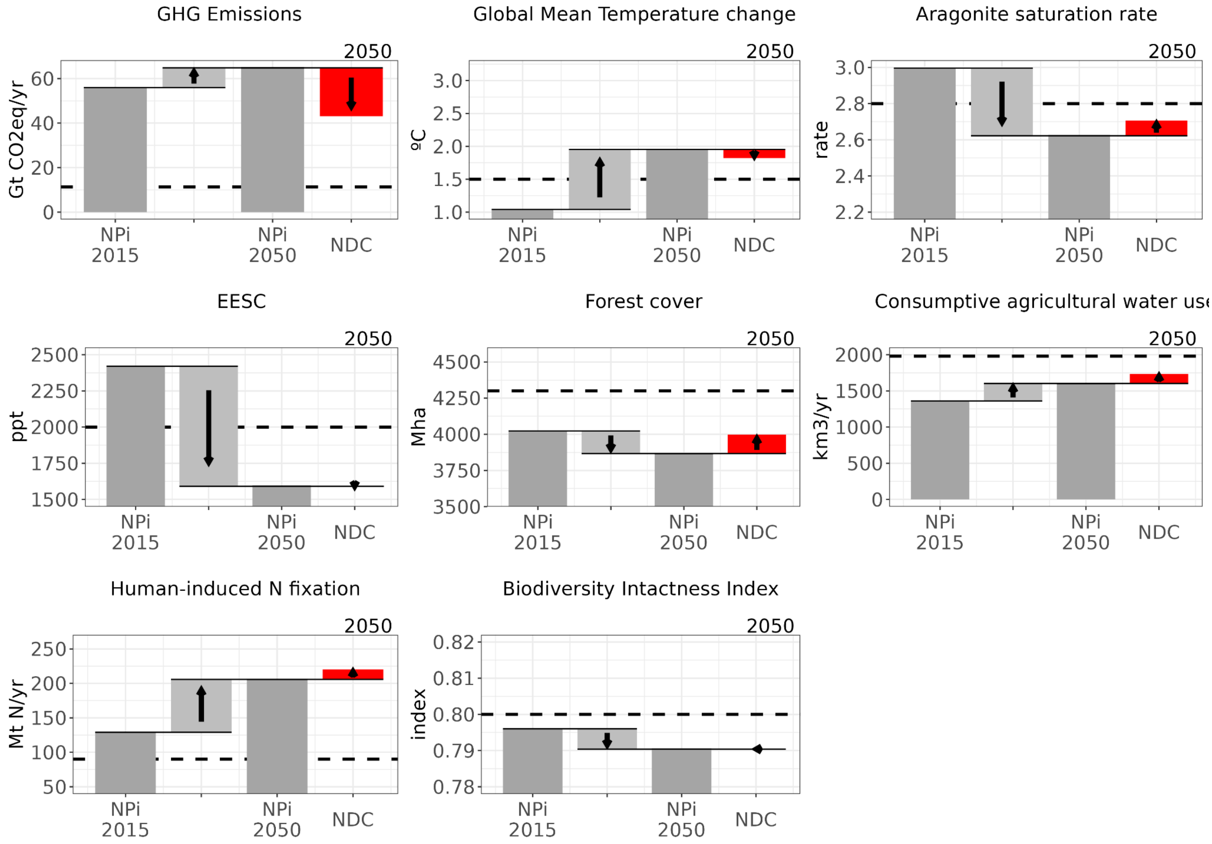

Fig. 2.1: Effects of existing commitments (NDCs) on the Global Commons domains indicators. The grey rectangles show the evolution of the indicators between 2015 and 2050 in the scenario with only the Nationally Implemented Policies (NPi) for comparison, while the red rectangles show the effect of the NDCs relative to the NPis in 2050. Dashed lines represent the defined 2050 targets for each indicator.

Effects on the Ozone Layer: The nationally implemented policies scenario includes full compliance with the Montreal Protocol, which effectively regulates emissions of ozone depleting substances. Those policies are also included in all other scenarios. Therefore, ozone depletion potential (as measured by EESC) returns to safe pre-1980 levels before 2050 in all scenarios.

Effects on the Land Biosphere: The effects of the NDCs on the land biosphere are the result of complex interactions between the pledges on emissions reductions and those on land conservation, and afforestation. Mostly due to large afforestation pledges, especially from China, the NDCs substantially increase forest cover by 131 Mha in 2050. Still, the NDCs fall short of reaching the 4300 Mha target by almost 300 Mha.

However, in order to reach the emissions reduction NDC pledges, the energy system demands high amounts of bioenergy, especially from biofuels, to decarbonize the transport sector. This creates pressures in the agricultural system and leads to an expansion of irrigated agriculture, increasing agricultural consumptive water use by 132 km^3/year, and to higher nitrogen use. The effects from the different kinds of pledges on land use, involving an increase in both cropland and managed forests, counteract each other regarding the aggregate impacts on biodiversity, leading to little to no effect on the Biodiversity Intactness Index (BII).

3. Transforming Energy Systems

Motivation and Methods

Human energy systems exert immense pressure on the Global Commons. Besides generating the majority of carbon dioxide emissions, which threaten both the climate system and the oceans through acidification, they also cause widespread air pollution. The use of bioenergy as a replacement for fossil fuel sources is a promising cheap option for reducing GHG emissions, and technologies such as Bioenergy with Carbon Capture and Storage (BECCS) can even lead to the net removal of carbon dioxide from the atmosphere. However, producing cheap biomass at the scale demanded by ambitious climate targets leads to massive pressure on land systems.

Here we evaluate the outcomes of an Energy Systems Transformation (Tene) on indicators of the five Global Commons domains. The Energy Systems transformation includes policies and assumptions throughout human energy systems, including carbon pricing, electrification and pushes for certain technologies (Fig 3.1).

Energy Systems Transformation (Tene)

- Energy-related Nationally Determined Contributions (NDCs)
- Pricing on GHG emissions for all sectors except Land Use
- Rapid decarbonization of electricity sector by renewable energy deployment
- Electrification of transport and push for public transit
- CCU for production of Synfuels
- CDR
- Electrification push in the buildings sector

Fig. 3.1: Main interventions included in the Energy Systems Transformation (Tene).

In the Energy Systems Transformation, a price is set on all GHG emissions, except for those from the land use sector. Non-CO_2 emissions are priced according to their GWP100 CO_2 equivalent. Prices increase over time, and are set at a level that, if applied together with all other interventions, keeps global mean temperature change under 1.5° C with 66% probability with limited overshoot. GHG prices start at lower levels in developing countries, converge to a single global price of 92 USD per tonne of CO_2eq in 2050 and continue rising steadily after that (see Chapter 6).

For the transport sector, the Energy Systems Transformation includes a strong push for electrification, and a general push for public transit: Almost all light driving vehicles are assumed to be battery electric by 2050, as well as most trucks. Personal mobility demands in wealthy regions converge to sustainable levels and are more reliant on public transit and non-motorized modes. Intercity travel routes are served by high-speed electric rail wherever it is feasible. We also assume a reduction in overall freight transportation demand due to the phase-out of fossil fuels, which make up for a large part of long-distance shipping demands today. Light vehicles and most trucks are assumed to be battery electric by 2050. Moreover, options are included for Carbon Capture and Use (CCU) technologies, which, coupled with hydrogen production, can help provide lower emission fuels for harder to decarbonize sectors such as aviation and long-haul transport.

For the buildings sector, the Energy Systems Transformation assumes a strong push for electrification, induced by lowered costs for heat pumps (i.e. substantial subsidy to foster heat pump adoption for climate control).

Finally, Direct Air Capture (DAC) technologies are made available to abate leftover emissions, along with other Carbon Dioxide Removal (CDR) technologies. Adoption of these and many of the technologies in the transport and buildings sector depends on their relative prices and the inclusion of a price on GHG emissions.

Key findings

The Energy Systems Transformation has strong effects on safeguarding the Climate, Cryosphere and Oceans, but can have detrimental effects on the Land Biosphere Global Commons domains. Transforming the energy systems towards sustainable energy sources and shifting towards more sustainable transport modes would reduce GHG emissions by 39 Gt CO_2eq/year in 2050, a 60% reduction relative to a scenario with only the currently implemented policies. This would prevent around 0.19°C of warming. Most of the avoided emissions would be of CO_2, keeping Ocean Acidification at relatively safe levels inside the Planetary Boundary throughout the century. However, an increased reliance on bioenergy ultimately has detrimental effects on the Land Biosphere, leading to higher deforestation rates, use of nitrogen fertilizers, agricultural water consumption and degradation of biodiversity.

The GHG price levels implemented in the energy sector are relatively modest, reaching around 90 U.S. dollars per ton of CO2eq in 2050, being enough to limit warming to 1.5°C by 2100 (with limited overshoot) only in combination with all other transformations. However, it is already enough to cause substantial transformations in the energy system. Electrification of final energy uses and decarbonization of the electricity supply arises as the most cost-effective strategy in most cases where it’s technically feasible. The share of electricity in the global final energy supply increases from currently below 20% to ~25% in 2030, to 45% in 2050. A combination of reduction in the cost of renewables and carbon pricing leads to an almost complete phase out of coal and oil use in electricity generation, and reliance on gas falls below 2% of the electricity supply in 2050.

Effects of the Energy Systems Transformation on the Global Commons domains

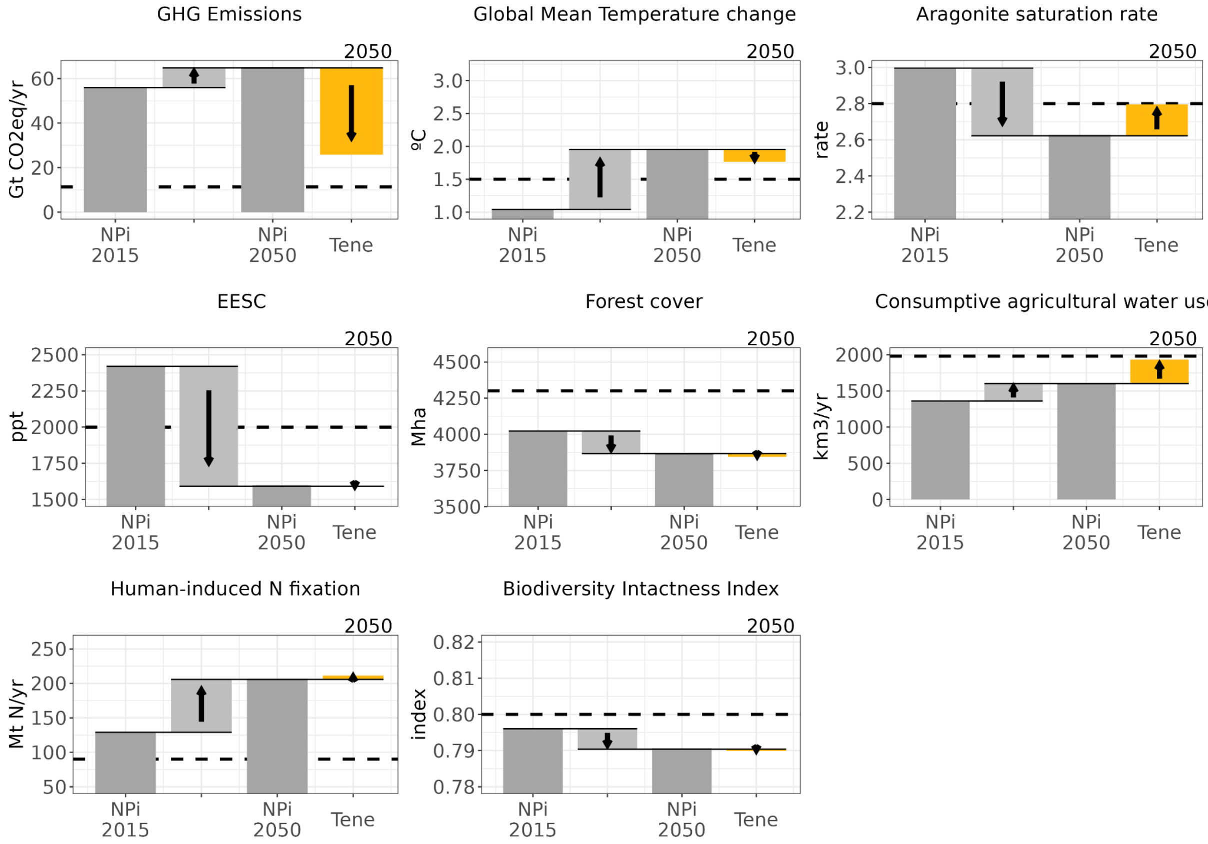

Fig. 3.2: Effects of the Energy Systems Transformation (Tene) on the Global Commons domains indicators. The grey rectangles show the evolution of the indicators between 2015 and 2050 in the scenario with only the Nationally Implemented Policies (NPi) for comparison, while the yellow rectangles show the effect of the transformation relative to the NPis in 2050. Dashed lines represent the defined 2050 targets for each indicator.

The interventions included in the Energy Systems Transformation (Tene) have a strong positive impact in safeguarding the Climate, the Cryosphere and the Oceans. By 2050 GHG emissions are reduced by 39 Gt CO_2eq/yr from 65 to 26 Gt CO_2eq/yr. This is ~70% of the reduction required to reach the 1.5°C-compatible levels of the all-transformations scenario (11 Gt CO_2eq/yr). The reductions in GHG emissions lead to the avoidance of 0.19°C warming in 2050, and almost 0.5°C by 2100 (fig. 3.2). Furthermore, the Energy Systems Transformation is the only transformation that allows achieving CO_2 neutrality in this century (although only by 2100), leading to a stabilisation of warming at around 2°C after then.

The GHG reductions are achieved mainly due to the introduction of a moderate price on GHG emissions in the energy, industry and transport sectors, but is also linked to the reduction in overall energy demand with the pushes for sustainable options in transport and buildings heating.

Introducing Carbon Capture and Utilization (CCU) technologies plays a relatively minor role in the transformation, reusing less than 0.5 Gt CO_2eq/yr in 2050 and roughly doubling by 2100. Carbon Dioxide Removal (CDR) technologies do play a somewhat larger role in offsetting residual emissions (respectively 2.5 and 7.5 Gt CO_2eq/yr in 2050 and 2100). However, Direct Air Capture (DAC) technologies are not competitive at the moderate GHG prices of the Energy Systems Transformation, with Bioenergy with Carbon Capture and Storage (BECCS) being the dominant CDR technology in this scenario.

The reductions in GHG emissions lead to the avoidance of 0.19°C warming in 2050, and almost 0.5°C by 2100 (Figure 3.3). The Energy Systems Transformation can achieve CO_2 neutrality in 2100, being the only intervention analysed to achieve it in this century and leading to the stabilisation of warming around 2°C after then. The strong reductions in CO_2 emissions induced by the Energy Systems Transformation also make it necessary to successfully steward the Oceans, as only scenarios that include it prevent Ocean Acidification from crossing the Planetary Boundary, even in the scenario with only the Energy Systems Transformation, with global aragonite saturation rate remaining above 2.8 throughout the century.

On the other hand, the implementation of GHG pricing exclusively in the energy sector leads to a heavy reliance on bioenergy for its decarbonization, creating pressure on the land biosphere in the absence of specific policies to safeguard it or prevent the reliance on bioenergy. Deforestation increases slightly on top of the already high levels of the NPi scenario, leading to the loss of an additional 2.6 Mha of forest by 2050. This pressure not only on forests but also on other natural environments leads to some additional biodiversity loss, although the effect is much weaker than that of current trends (NPi) between 2015 and 2050.

Even though our scenarios assume that 2nd generation bioenergy crops themselves should not be irrigated, the additional pressure on land pushes an increase in irrigation of other crops. Water withdrawals for irrigation also increase due to a higher availability of water during the growing period of cultivated crops in this scenario. This happens as a consequence of mitigation efforts in the energy system, which involves changes in intensity and patterns of climate change impacts that affect agriculture, such as crop yields and accessible freshwater resources for irrigation. Resulting expansion of irrigated agriculture causes consumptive agricultural water use to increase dramatically, which pushes global agricultural water use close to crossing the Planetary Boundary, being the only boundary not crossed in the NPi scenario by 2050. Even though the Planetary Boundary is not crossed, at regional scales this effect can be very significant, making an additional 35 Mha of irrigated area suffer by having water needs above their local environmental flow requirements. The overall pressure on agricultural systems also increases nitrogen fixation.

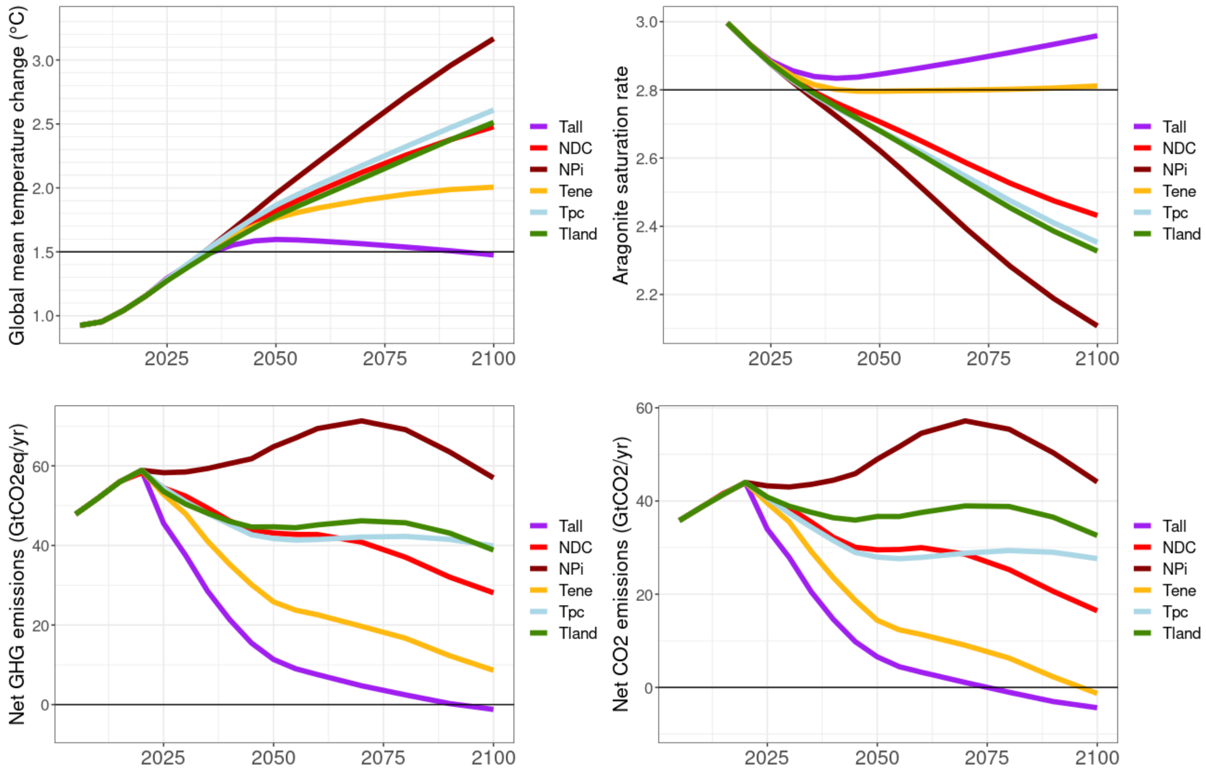

Fig. 3.3: XXI century trajectories of median estimates of Global Mean Temperature change relative to the preindustrial period (top left), Aragonite saturation rate (top right) and net GHG (bottom left) and CO_2 (bottom right) emissions for the scenarios with only the currently implemented policies (NPi), only the NDCs (NDC), only the individual transformations (Tene, Tland, Tpc) and with all transformations combined (Tall). The horizontal black line shows target values for reference.

4. Transforming the industry sector

Motivation and Methods

The global industry has been the fastest-growing sector in terms of greenhouse gas emissions in the last 20 years, accounting for 14 or 20 $GtCO_2$ (without and with indirect emissions, respectively) in 2019 (Bashmakov et al. 2022). In addition to being a major emitter of greenhouse gases, the global industry puts pressure on other planetary boundaries. Of particular interest is the boundary for the introduction of novel entities. Recent research suggests that this boundary is also already exceeded (Persson et al. 2022).

The decarbonization of the industry sector is expected to be particularly challenging as relevant technologies are still to be developed or deployed to a significant scale. Moreover, significant uncertainty remains about the main technologies that will drive the transformation of the industry sector. Significant efforts are necessary to avoid that the industry becomes a bottleneck in the global transition towards a sustainable economy which supports/allows for keeping the Global Commons domains in the safe operating space of the Planetary Boundaries.

Here we compare a scenario with only the current Nationally Implemented Policies (NPi) with a scenario that additionally includes a Sustainable Production and Consumption Transformation (Tpc). This transformation assumes radical changes in the use and production of material goods which lead to substantial increase in material efficiency. For the consumption side, more sustainable consumption patterns lead to longer and more communal use of consumer goods (which is enabled by products with longer durability and repairability (sharing and circular economy). Examples are an increased use of car-sharing services, preferred buying of second-hand items or extended use of single items. The total amount of materials required to provide a specific service (or use) is lower. On the production side, we assume a more efficient use of materials in the production of goods. Examples are products manufactured with less materials or more durable products, whose longer lifetime would allow for the same service or use to be provided using less materials.

These assumptions are implemented in REMIND-MAgPIE as reductions in the demand for materials in the industry sector. Based on bottom-up estimates of the effects of these assumptions (Grübler et al. 2018), we implement substantial reductions in demand for the steel (76%), cement (20%) and chemicals (32%) sectors in the absence of other interventions for the Sustainable Production and Consumption Transformation. These reductions are phased-in from 2020 to 2050. With less material production, the demand for energy in these sectors is also reduced. It’s important to note that industrial production can also be further reduced in response to other interventions, especially those that change energy prices for the sector.

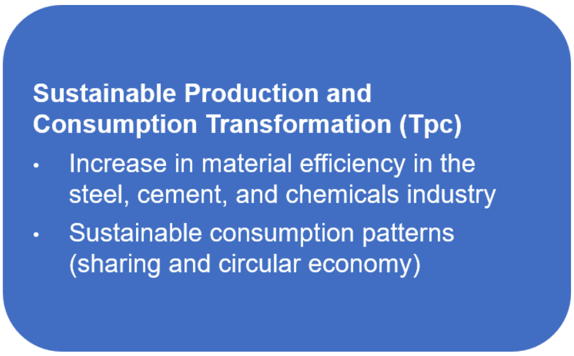

Fig. 4.1: Interventions included in the Sustainable Production and Consumption Transformation.

We further evaluated scenarios examining the potential independent and combined contributions of specific interventions on the industry subsector for reducing CO_2 emissions and plastic waste disposal. Those include carbon pricing at 1.5°C compatible levels (see Chapter 3: Transforming Energy Systems), the same reduction in demand for materials as in the Sustainable Production and Consumption, here called Low Material Demand (LMD), the use of carbon capture and storage (CCS) technologies, and an additional push for deeper adoption of hydrogen (H2 push).

We also evaluate scenarios that compare how plastic flows to the environment change in response to a circular economy strategy for the plastics sector. The plastics sector is fossil-based and often produces short-lived products that have detrimental effects on the environment at their end of life. These scenarios further implement a push for circularity where high recycling rates are achieved rapidly at a global scale, besides an acceleration of the transition from primary to secondary steel production.

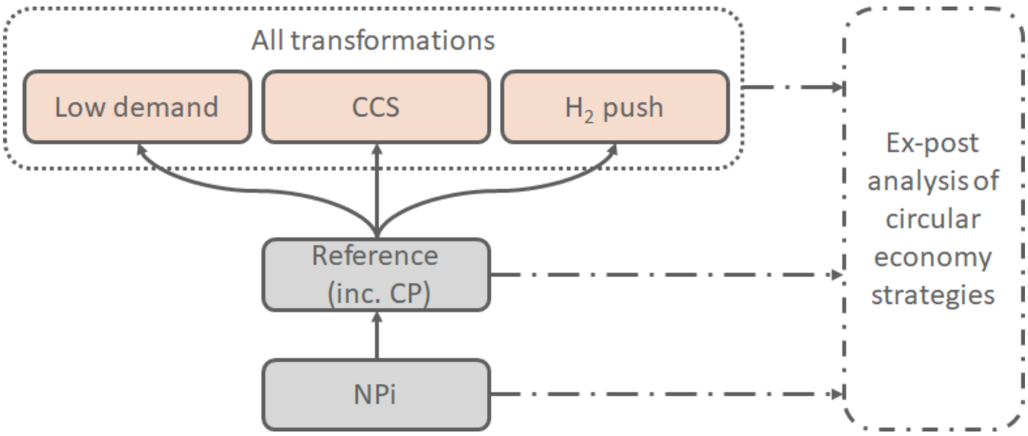

Fig. 4.2: General setup of the industry-specific scenarios. A set of individual industry-specific transformations are assessed on top of the reference scenario, as well as a scenario including all interventions. The effect of circular approaches for waste management is tested in an ex-post analysis.

Key findings

The Sustainable Production and Consumption Transformation has relatively small effects on safeguarding the Climate, Cryosphere and Oceans. The improvements in material efficiency and more sustainable consumption habits ultimately lead to lower industrial production and energy demand, which reduces GHG emissions by 16 Gt CO_2eq/yr relative to current policies in 2050. These reductions can prevent 0.09°C of warming overshoot in 2050 and also have benefits for Ocean Acidification.

Results of the industry-specific pathway modelling show that carbon pricing is essential but implementing industry-specific policies will enable a faster and deeper de-carbonization of the sector. Results suggest that circular economy approaches have the potential to mitigate plastic pollution without compromising climate goals.

De-materialization of the economy offers significant reductions of the pressure that the global industry puts on global commons. However, its feasibility remains uncertain, which is why robust policy for the transformation of the global industry should not rely strongly on a deep de-materialization of the economy. Carbon capture and storage is critical for deep decarbonization of the global industry as process emissions cannot be mitigated by means of low-carbon energy carriers.

At the same time, deploying carbon capture is not a licence to continue to use fossil fuels. The adoption of hydrogen-driven technologies in the industry should concentrate on the specific applications where this technology is critical for deep decarbonization.

Finally, circular approaches for plastic waste mitigation could help mitigate the introduction of novel entities in the earth system while avoiding putting further pressure on the climate and the energy transition. However, further research is required that defines the technical, economic, and environmental limits of this alternative, including the potential release of microplastics and other species in recycling processes.

Effects of the Sustainable Production and Consumption Transformation on the Global Commons domains

The Sustainable Production and Consumption Transformation helps safeguard the Climate and Oceans relative to the current policies (NPi) scenario. In the absence of other policies, the reduced industrial production leads to a strong reduction of industry's GHG emissions. These reductions come not only from the emissions associated with industrial processes and fuel burning in the industry itself, but also from the reduction in energy demand, especially electricity, which in turn reduces emissions from the energy supply.

In total, the Sustainable Production and Consumption Transformation alone reduces GHG emissions by 16 Gt Gt CO_2eq/yr in 2050, which is close to the amount achieved by the NDC commitments currently in place. This leads to an avoided 0.09°C of warming. Since a large share of the avoided emissions are of CO_2, Ocean Acidification also improves significantly, but not enough to move aragonite saturation back into the safe space of the Planetary Boundary if only this transformation is affected.

The reduction of industrial material has very small effects on the indicators related to the Land Biosphere. Effects relative to the NPi scenario, are mostly due to small relocations of agricultural production. Although it would be expected that the lower industrial activity would require less energy, and therefore less bioenergy, if current policies are followed bioenergy plays a very small role on energy systems worldwide. Therefore, the reduction in energy demand from more sustainable production and consumption patterns has but a weak link to the land systems. However, that can change if the energy systems are also transformed toward having a higher reliance on bioenergy, as can be seen in the next sections.

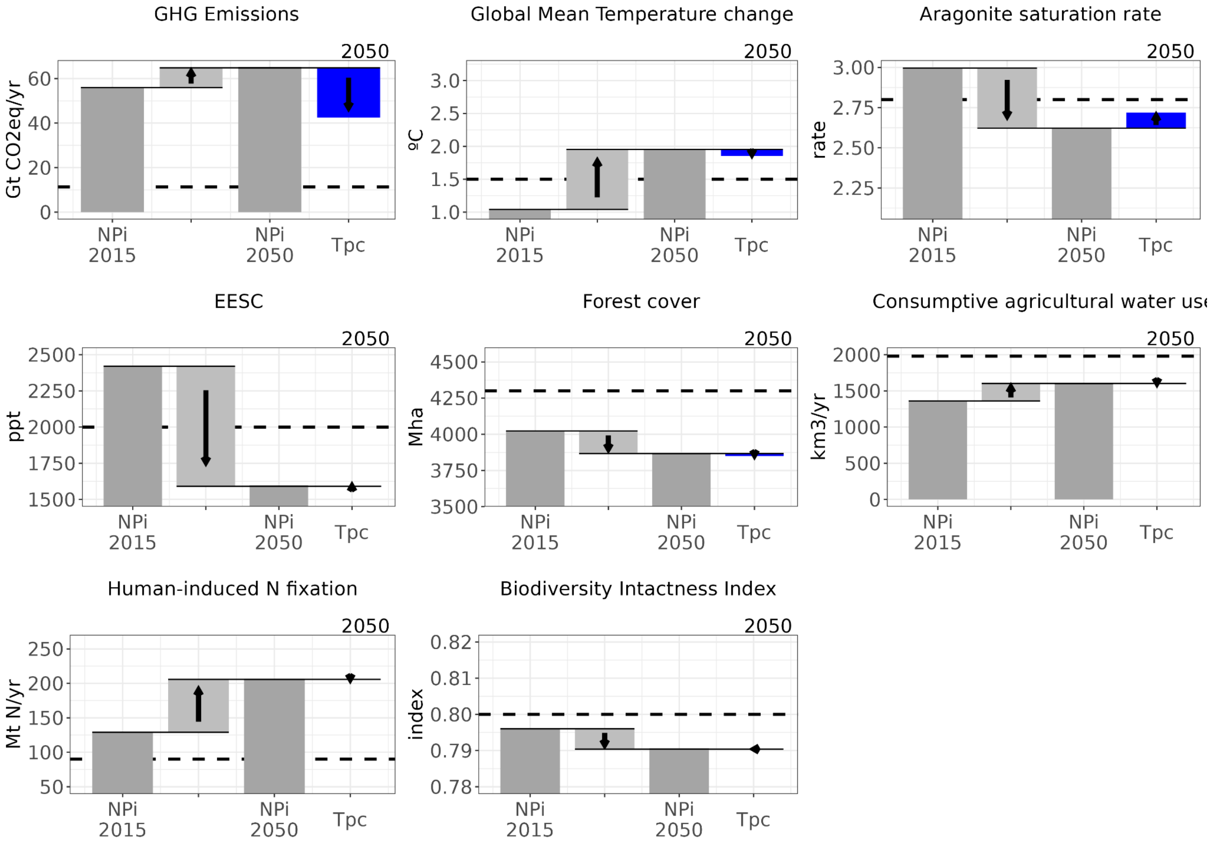

Fig. 4.2: Effects of the Sustainable Production and Consumption Transformation (Tpc, blue) on the Global Commons domains indicators. The grey rectangles show the evolution of the indicators between 2015 and 2050 in the scenario with only the Nationally Implemented Policies (NPi) for comparison, while the blue rectangles show the effect of the transformation relative to the NPis in 2050. Dashed lines represent the defined 2050 targets for each indicator.

GHG emissions from the global industry

Under currently implemented policies, greenhouse gas emissions from the global industry are expected to increase by 2.4 $GtCO_2eq/yr$ by 2050, reaching 14.1 $GtCO_2eq/yr$. While carbon pricing roughly halves GHG emissions to 6.7 $GtCO_2eq/yr$ by 2050, the proposed industry-specific transformations enable significant further reductions, reaching 3.6 $GtCO_2eq/yr$ by 2050. This is a significant reduction of 10.5 $GtCO_2eq/yr$ compared to NPi.

Dedicated industry-specific policies can complement carbon pricing, allowing for a deeper and faster decarbonization of the global industry. The push for lower material demands further reduces emissions by 1.6 $GtCO_2eq/yr$ by 2050 on top of the reductions achieved by carbon pricing. Introducing carbon capture and storage as an option has a similar effect, with a reduction of 1.7 $GtCO_2eq/yr$. A stronger deployment of hydrogen-driven technologies in the industry allows for saving 0.3 $GtCO_2eq/yr$. Deploying the full set of industry-specific interventions takes us beyond reductions from carbon pricing with a total additional reduction of 3.1 $GtCO_2eq/yr$ by 2050.

The importance of each intervention for reducing industry emissions can be quite different across its subsectors. Lowering the demand for materials has a substantial effect on steel, cement and chemicals emissions, following the reductions in demand of those specific materials. Carbon pricing has a very important contribution on decarbonizing the steel sector, as electrification of secondary steel production is much simpler than that of cement, from which a large share of emissions come from the processes themselves, and of chemicals, where besides process emissions, fossils are also used as feedstocks. Setting a price on carbon emissions also creates an incentive for steel recycling, with the share of secondary steel increasing from under half to two thirds of total production with the implementation of carbon pricing.

For similar reasons, the use of Carbon Capture and Storage technologies can be more important than lowering material demand for reducing emissions in the cement and chemicals sectors, as it allows capturing emissions that are not related to energy use. It is important to stress that deploying CCS technologies does not mean that the industry can continue to use fossil fuels, as the scale-up of this young technology is challenging and massive efforts are already required to be on-track to the required capacities to capture process emissions in climate-compatible futures. This way, phasing out fossil fuels and deploying CCS for the remaining process-emissions are complementary measures and incentives for the development and rapid scale-up of carbon capture and storage technologies are needed to mitigate process emissions. Other alternatives to mitigate carbon emissions from the cement subsector include the development of novel chemistry for the process and the replacement of cement by other materials.

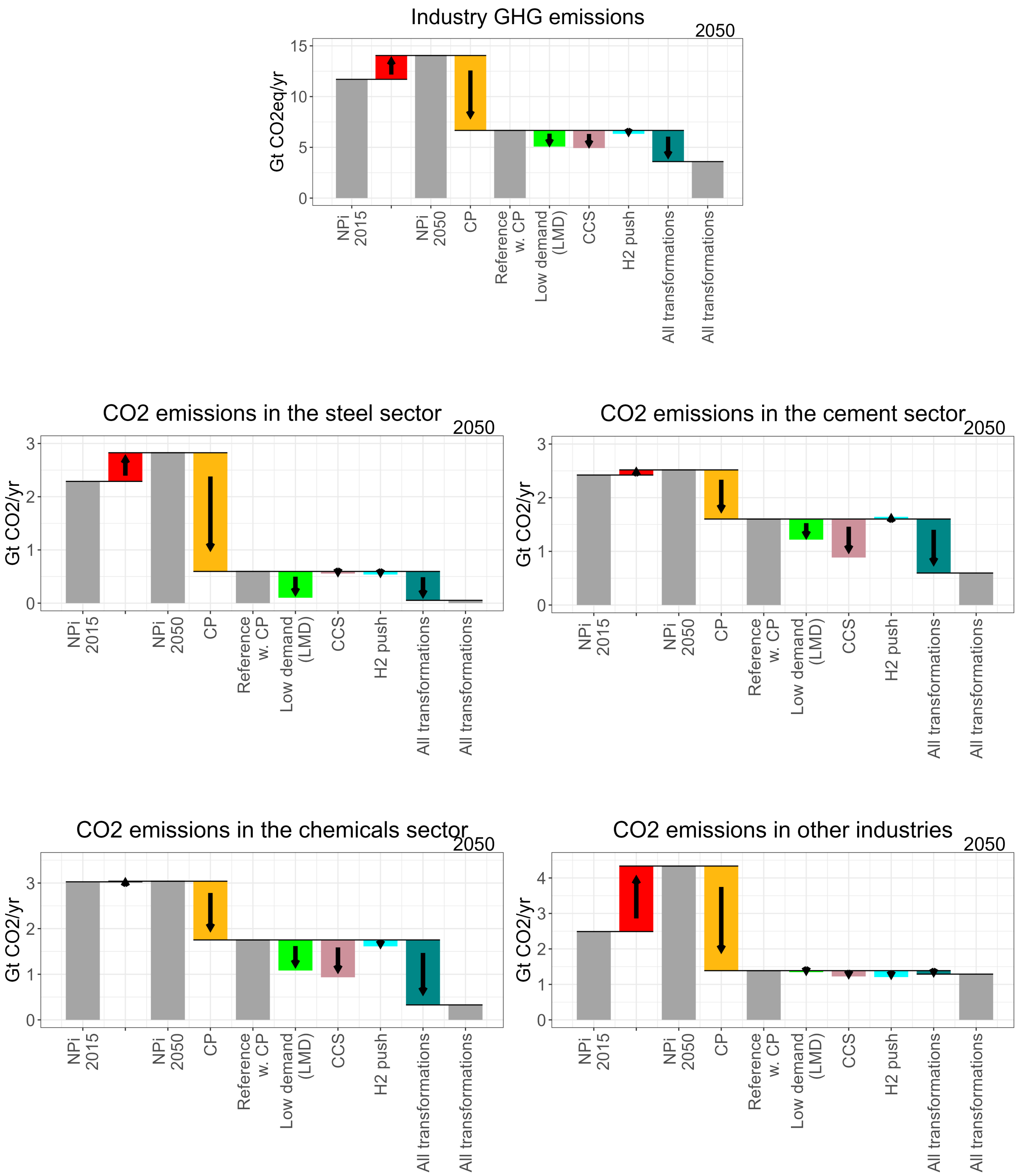

Figure 4.3: Effects of the industry-specific interventions on total GHG emissions of the global industry (top) and CO_2 emissions of its subsectors in 2050.

Pushing for hydrogen adoption beyond the economic optimum under carbon pricing has just a small effect on reducing industry emissions across sectors, as it is generally crowded out by electrification where possible. The effect on emissions is small despite the hydrogen push intervention leading to a substantial increase in hydrogen use in industry of 12 EJ/yr worldwide, which is around 8% of current

(2020) total industry energy use, beyond the 15 EJ/yr resulting from the reference carbon price-driven scenario.

Transformational challenges

Electricity and hydrogen use

Electrification is in most cases the most efficient and proven path for decarbonizing industry, but will put more pressure on the transformation of power systems. The path to decarbonizing the power sector relies on proven technologies whose scale-up has gathered considerable pace in the last decade, such as photovoltaic solar and wind power.

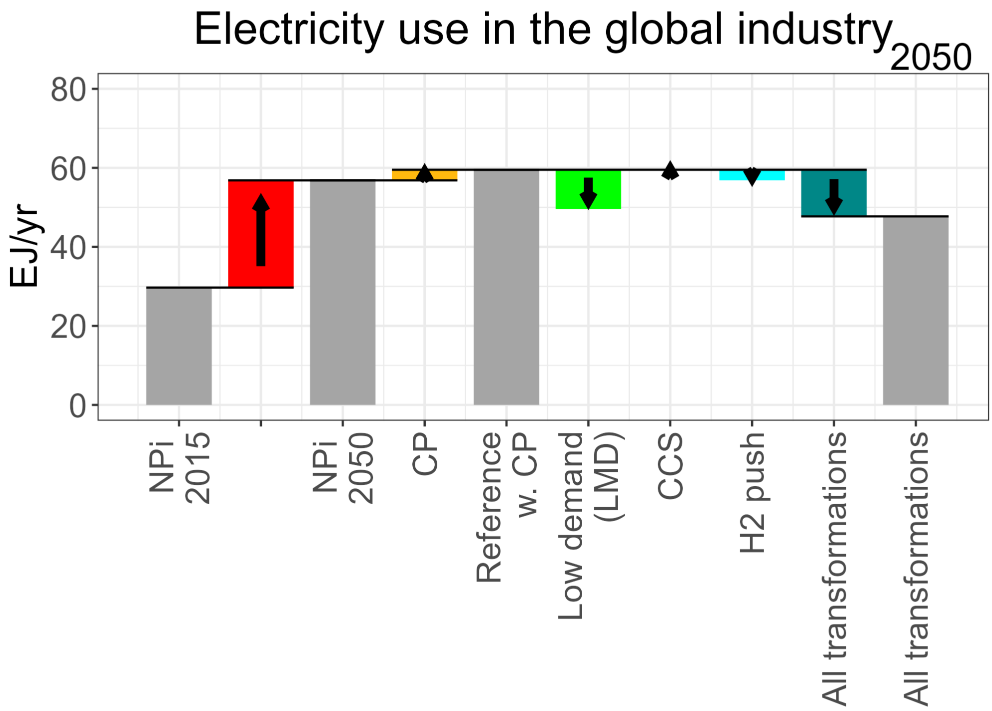

Figure 4.4: Electricity use in the global industry for the proposed scenarios and interventions.

Electricity use in the industry at the global level is expected to roughly double by 2050, reaching 56.8 EJ/yr, in a future where current policies continue. Introducing carbon pricing increases electricity demand slightly by 2.7 EJ/yr. The LMD push is the intervention that most significantly reduces the pressure that the global industry puts on the power sector, reducing electricity demand by 9.9 EJ/yr in 2050 as compared to the reference scenario. The effect of CCS is neglectable and the H_2 push decreases the direct use of electricity in the industry by only 2.7 EJ/yr. However, producing green hydrogen requires large amounts of electricity, which would in turn put more pressure on the power sector.

The electrification of some processes in the industry sector, such as the reduction of iron ore, is technically constrained. Thus, incentives are required that foster the fast adoption of hydrogen for these applications. However, subsidising the deployment of hydrogen beyond the necessary scope risks triggering additional transformational challenges which can hinder the pace of transformation and the economic performance of the system. Although pushing for hydrogen reduces electricity use in the industry sector itself, it disproportionately increases the demand for electricity in the energy sector for hydrogen and synfuels production. Therefore, an excessive reliance on indirect electrification, through hydrogen production, instead of directly electrifying processes where possible, leads to further pressure on the transformation of the electricity sector.

Demand for bioenergy in the industry sector

Analysis of the effects of the interventions on the total demand for bioenergy in the industry sector points to an important potential tradeoff. It underlines the results of Chapters 5 and 6, highlighting how an intensive use of biogenic energy sources for industrial energy demand can contribute to increasing pressure on agricultural systems and may threaten the land biosphere.

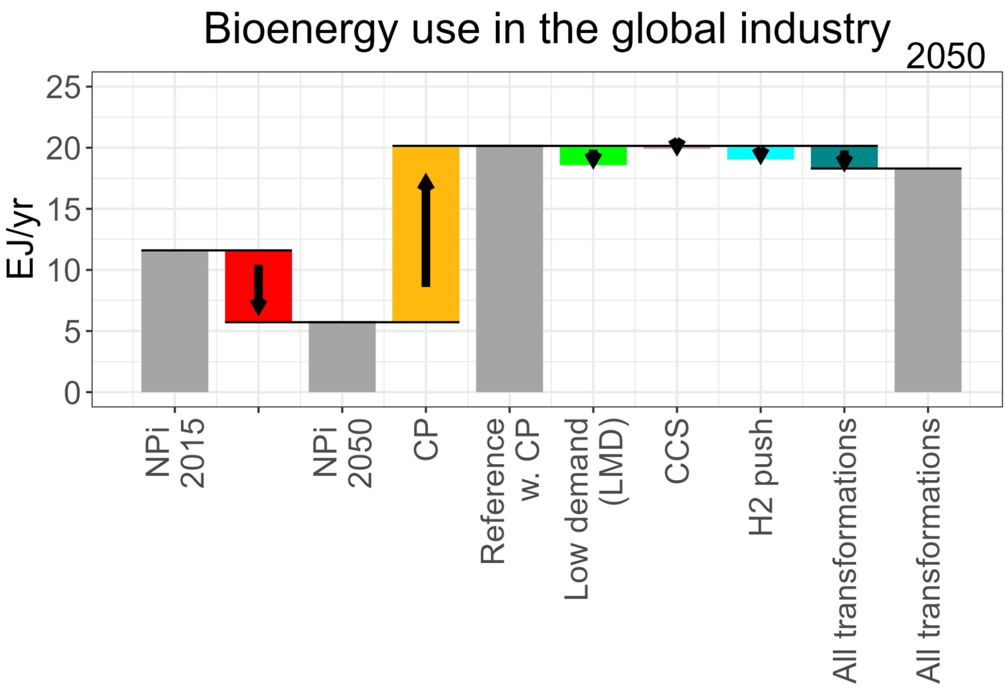

Figure 4.5: Use of bioenergy in the global industry for the proposed scenarios and interventions.

The use of bioenergy is expected to decrease by 5.9 EJ/yr to reach 5.7 EJ/yr in 2050, for the scenario where only currently implemented national policies remain. Implementing carbon pricing as prescribed in our reference scenario is projected to increase the demand for bioenergy in the industry sector by 14.4 EJ/yr (if no countermeasures are implemented), as there is an incentive in place to use low-carbon energy carriers.

Residual fossil fuels use (carbon lock-ins)

Figure 4.6 shows the residual use of fossil fuels in the global industry sector for selected years. We observe that in the short term, until 2030, carbon pricing in the reference scenario allows for a limited reduction in the use of fossil sources. The LMD intervention achieves further reductions already by 2030. By 2050, carbon pricing is able to phase out a major share of fossil sources. The reference scenario with carbon pricing is the most effective in phasing out the use of solid fossil energy sources. Again, the only sector-specific intervention delivering a significantly deeper de-fossilization is the transition to lower material demands in the economy. When all sector-specific interventions are deployed, the use of liquid fossil fuels in the industry is reduced. In the long term, all mitigation scenarios manage to phase out most fossil sources.

The scenario where CCS has deployed exhibits a slightly higher amount of fossil sources in the long term, whose corresponding emissions could be captured and stored. However, the amount is very low and it is clear that phasing out fossils is part of all mitigation strategies. With this, CCS is relevant for the transformation of the global industry to mitigate process emissions, not emissions from fossil sources.

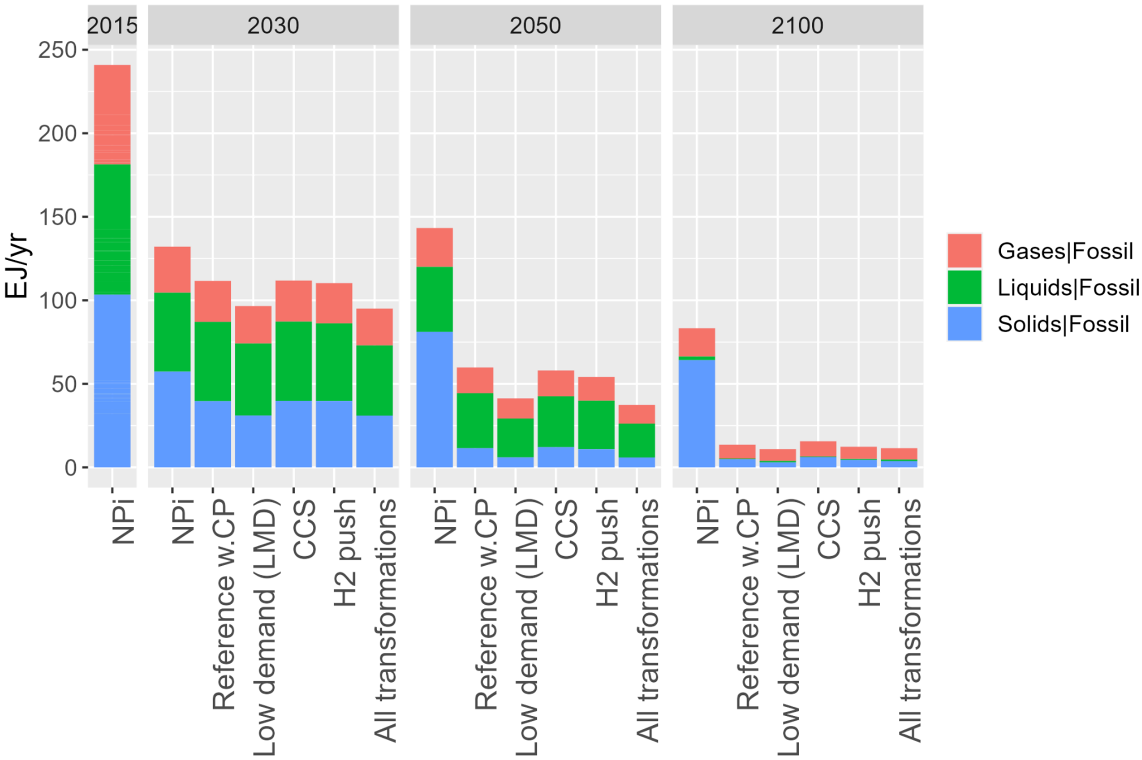

Figure 4.6: Residual use of fossil fuels in the global industry by type of fuel.

Circularity push

In the following, we present the results of the ex-post analysis of the effects of a stronger deployment of circular strategies for plastic waste mitigation. We compare the effects of a circular future against those of a reference scenario based on SSP2-type socio-economic developments. First, we present our projections for plastics production in the next decades, for three selected scenarios. Second, we analyze the fate of plastics for these two scenarios in terms of carbon flows. Later, we present our estimation of variables relevant to the protection of global commons domains. In particular, we analyze plastic waste introduction into the environment and the emission of greenhouse gases.

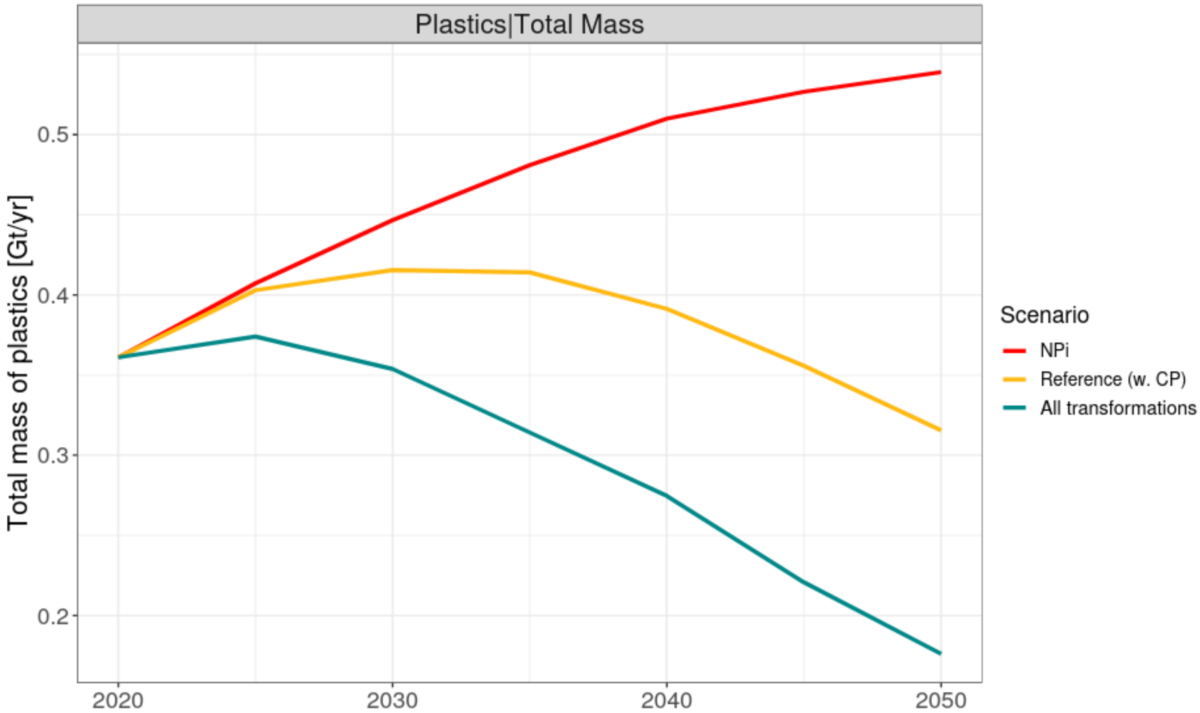

Figure 4.7: Evolution of plastic waste production under different scenarios.

Before analysing the effect of circularity strategies, it is necessary to understand the effect that different policies have on the production of plastics and plastic waste in our models. Figure 4.7 shows the total projected production of plastic waste until 2050 for the scenarios selected for the circularity analysis: NPi, reference (with carbon pricing), and the full set of transformations (*all transformations*). We observe a strong reaction of the production system to carbon pricing, with a complete deviation from the NPi trend. While under currently implemented national climate policies (NPi) our models project a nearly production of plastic waste of 539 Mt/yr by 2050, this figure goes down to 316 million tons when the assumed carbon price trajectory is implemented. These projections are comparatively low, with other sources estimating future production at 1 Gt of plastics per year by 2050, for a middle-of-the-road-like development scenario (SSP2)[4]. This could lead to

[4] Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D. P. & Junginger, M. Plastic futures and their CO2 emissions. *Nature* **612**, 272–276 (2022).

underestimating impacts and should therefore be carefully analysed in future assessments. Under the *full-transformation* scenario, plastic waste generation is further reduced to a significant extent, all the way down to 176 Mt/yr by 2050. This is due mostly to the deployment of de-materialization in the chemicals sector, under our LMD transformation.

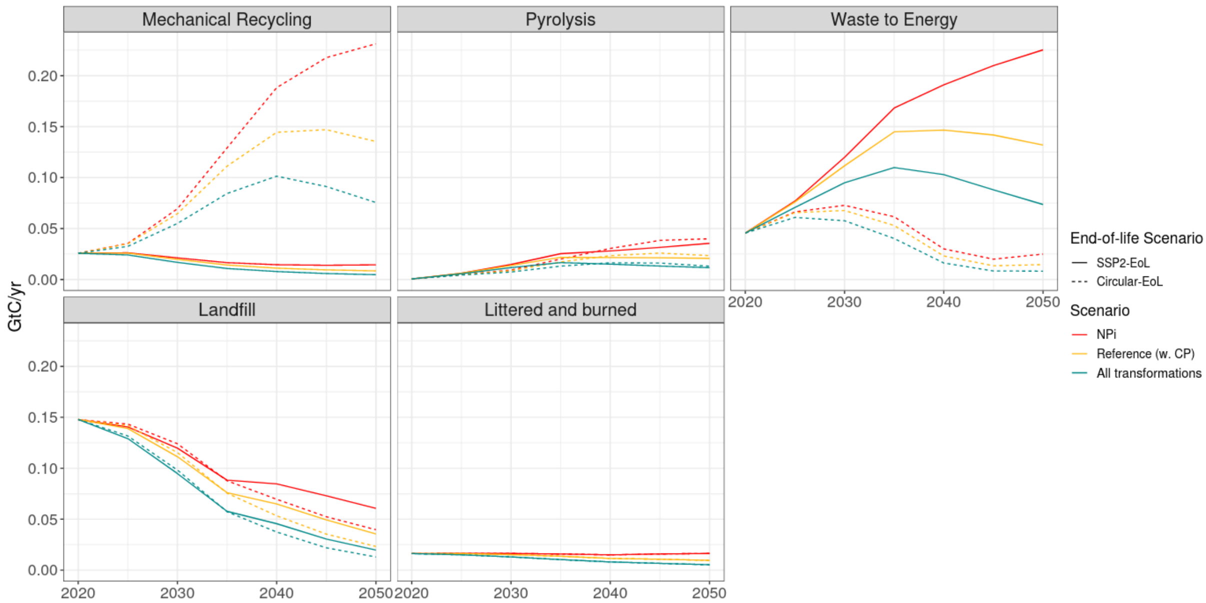

Figure 4.8: End-of-life fate of plastic waste under different scenarios including circular economy strategies.

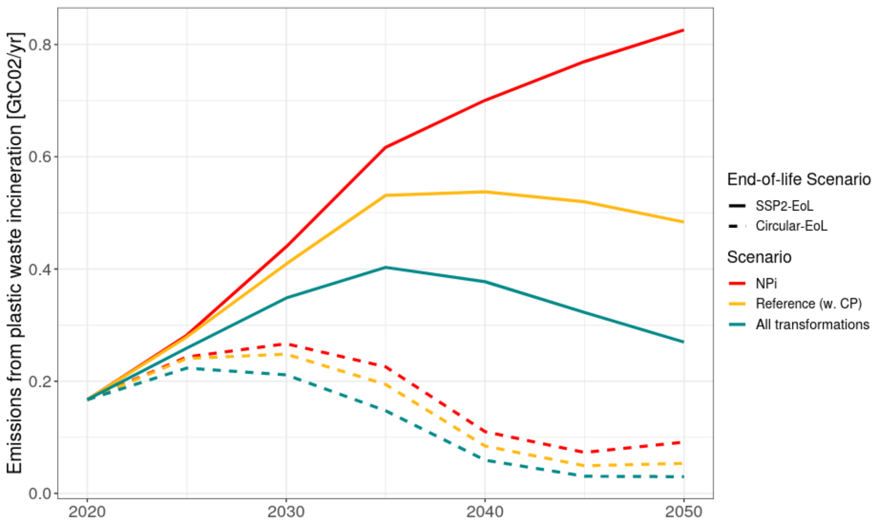

Figure 4.9: Emissions from plastic waste incineration for different policy scenarios and plastic waste mitigation strategies.

Figure 4.8 compares different futures for managing the end-of-life of plastics products, for an SSP2-like future, it compares a linear and a circular approach (solid and dotted curves) with the previously described transformation on top (marked with different colors). Figure 4.9 offers a closer look at the resulting direct emissions from plastics incineration. While in the reference case, following an SSP2-like future, plastic pollution mitigation is achieved via incineration, in the circular economy scenario, the shares of plastic recycling increase in the next 25 years.

5. Transforming Land Systems

Motivation and Methods

Humanity has appropriated most of the world’s land area for its use. The impacts of human alterations on natural land and the use of land for agriculture or infrastructure are among the oldest and most significant human drivers of degradation of the Global Commons. Conversion and degradation of natural land is a constant threat to biodiversity and are an important source of carbon dioxide emissions. Intensive and extensive agricultural practices, besides displacing natural land, affect water and nutrient cycles and release air pollutants and multiple greenhouse gases into the atmosphere. The scale and complexity of human land use systems, and the multiple Global Commons Domains they can impact, makes interventions on them particularly prone to tradeoffs.

Here we examine the effects of a Land Systems Transformation (Tland) on the Global Commons Domains, as well as interactions between different subsets of its interventions. Tland is a model interpretation of the “Sustainable Food, Land, Water and Oceans'' transformation in the GCS framework. We assume radical but gradual changes in food consumption patterns, including a reduction in per-capita food waste and a global shift towards healthier and more environmentally friendly diets by 2050. The dietary transition involves partial shifts from animal source foods to plant-based based products, a decreasing share of processed foods and an increasing share of healthy foods such as vegetables, fruits and nuts, as proposed by the EAT-Lancet Commission. In addition, daily per-capita calorie intake of different population sub-groups (differentiated by age and sex) converges to levels consistent with a healthy body weight, thus implying substantial improvements regarding the prevalence of underweight and breaking with current trends of increasing prevalence of overweight and obesity (Bodirsky et al. 2020).

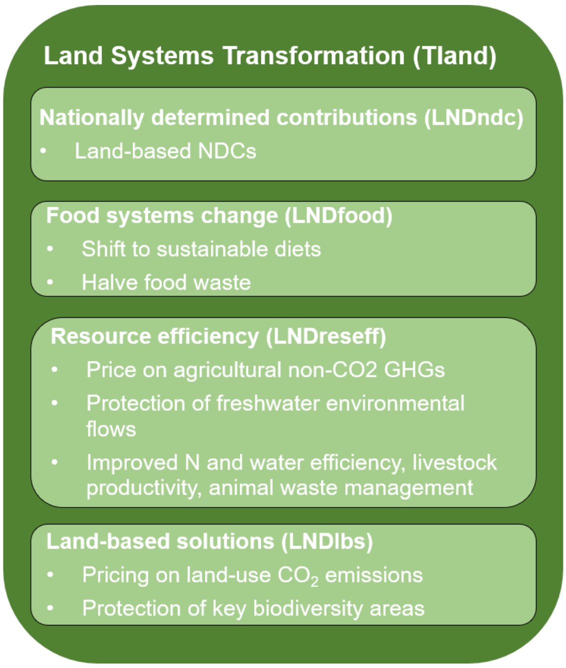

Fig 5.1: Interventions included in the Land Systems Transformation

On the supply side, it is assumed that the sustainability of food production improves on several fronts. Policies decreasing the amount of land available for agricultural production safeguard nature and the climate, while simultaneously spurring investment into agricultural research and development. This endogenous technological innovation facilitates higher crop yields without sacrificing the Global Commons. Crop yields endogenously increase as a result of nature and climate protection policies that decrease the availability of land for agriculture - described below - and incentivize investments into agricultural research and development. Livestock productivity and feed efficiencies of several animal food systems also strongly improve, which reduces biomass and land requirements. Efficient nitrogen fertilisation of crops and improved manure management reduce pollution from excess nutrients in terrestrial and aquatic ecosystems as well as non-CO_2 GHG emissions. Irrigation efficiency is improved and the basic environmental flow requirements of aquatic ecosystems are protected. Second generation bioenergy crops are only produced in rainfed production systems to avoid trade-offs between climate protection and sustainable water use.

Several policies for the protection and restoration of natural ecosystems are included. Damage caused by shifting cultivation to natural forests will be prevented from 2030 onwards. Natural landscapes within areas classified by Conservation International (CI) as biodiversity hotspots (Mittermeier et al. 2004) are protected from conversion, besides all intact forest landscapes and currently protected areas. In total, around 30% of the global land environment is protected by 2030, in line with the commitments in the Kunming-Montreal Global Biodiversity Framework. A GHG pricing scheme on land use sources is also implemented. This has the effect of disincentivizing conversion of natural land and the degradation of peatlands, as well as fostering afforestation as a land-based mitigation measure. The inclusion of agricultural non-CO_2 emissions into the GHG pricing scheme economically incentivises technical abatement of N_2O and CH_4 emissions.

To enable a more detailed, systematic analysis of the contributions of certain interventions to preserving the different Global Commons domains, we distinguish the following subtransformations which comprise the Land Systems Transformation (Tland):

Land-related Nationally Determined Contributions (LNDndc)

This subtransformation only includes compliance with the Nationally Determined Contributions related to the land use sector, achieving targets for land protection and afforestation.

Sustainable food demand (LNDfood)

The LNDfood subtransformation includes interventions assigned to the assumptions that level and composition of food demand changes due to food waste reductions and a shift to healthy and more sustainable diets. These diets are characterised by a low share of processed and animal-source foods, and by a total food energy intake that is consistent with a healthy body weight. This is implemented by assuming developments towards full convergence to the EAT-Lancet diet and to a BMI considered as healthy in all sex and age groups in 2050. Reductions in food waste are implemented by halving the currently observed levels of food waste in High Income Countries (HIC) by 2050.

Resource-efficient production systems (LNDreseff)

For the interventions covered by LNDreseff it is assumed that agricultural production shifts to more resource efficient and less polluting systems and management practices, thereby reducing pressures on land and water resources, decreasing nitrogen-related environmental degradation and mitigating agricultural non-CO_2 emissions. Implementation in our models include more intensive livestock production systems, more efficient animal waste management systems, improved nitrogen use efficiency, pricing of agricultural non-CO_2 emissions, a phase-out of first-generation bioenergy crops, protection of environmental flow requirements, and higher irrigation efficiencies.

Land-based solutions (LNDlbs)

The land-based solutions subtransformation is targeted at the dual challenge of mitigating climate change as well as biodiversity loss. It includes the protection of forested and non-forested ecosystems (including peatlands) by both price-based measures and regulatory land protection schemes. Moreover, rewetting of drained peatlands as well as afforestation with native species are included as land-based mitigation options.

This is implemented by pricing of CO_2 emissions from conversion of natural land and of GHG emissions from degraded peatlands, protection of biodiversity hotspots, a carbon-price incentivized afforestation using native species (restricted to the tropics due to albedo effects and confined to a global maximum), and prevention of damage from shifting agriculture to natural forests.

All these measures decrease land availability, which is compensated by investments into research and development to increase food production while preventing land expansion.

Key findings

The Land Systems Transformation is fundamental for preserving the Land Biosphere, but also has substantial positive impacts on the other Global Commons domains. By 2050, it would halt the loss of natural forest, reduce agricultural water consumption and improve human-induced nitrogen fixation and biodiversity intactness to conditions superior to those of today. This would bring Land System Change, Nitrogen Flow and Biosphere Integrity back within their Planetary Boundaries. These effects are more than enough to counteract negative effects from the Energy Systems transformation in these Global Commons domains. The combination of land interventions would also reduce GHG emissions by 19 Gt CO2eq/year. Methane emissions would be particularly reduced, preventing 0.18°C of warming in the medium term (2050) and minimising overshoot of the 1.5°C Paris Agreement target. The avoided CO2 emissions would have positive impacts on Ocean Acidification, but not enough to prevent it from degrading to levels outside the Planetary Boundary.

Individual components of the Land Systems Transformation focusing on resource-efficient production, reduction of GHG emissions, and dietary changes, differ in terms of their individual impact on safeguarding the Global Commons domains, and exhibit synergies and tradeoffs between them and with other transformations.

Transitioning to resource-efficient production systems is a key supply-side intervention to reduce human-induced nitrogen fixation and agricultural water use. However, reducing water consumption by limiting irrigation can increase pressures on Land System Change and Biosphere Integrity, as replacing irrigated systems with relatively lower-yielding rainfed ones requires more land area.

Pricing GHG emissions from land use change can prevent leakage effects from other interventions, including those that can occur if regulation-based land protection or afforestation schemes like current NDCs miss sufficient coverage in terms of regional distribution and types of included ecosystem.

Each of these land protection measures are of paramount importance if interventions in other sectors further increase biomass demand, e.g. for energy use. On the other hand, land-based solutions alone can push unsustainable intensification practices and can create tradeoffs with water use.

In contrast, transforming food demand towards more sustainable diets and reducing food waste leads to strong beneficial impacts across most Global Commons domains. It can combine synergistically with other land interventions, leading to more than additive outcomes in Land Systems

Change and Biosphere Integrity, as reduced demand for food frees more land to be used for mitigation and conservation. Its beneficial effect on reducing emissions and the use of nitrogen and water are slightly diminished when evaluated in conjunction with the other land interventions, which ultimately make the food system more environmentally efficient and therefore reduces the burden of additional food demand. However, it still positively affects economic variables such as food and bioenergy prices, which are mostly negatively influenced by the other land interventions. It is also key to facilitating a multi-dimensional transformation to sustainability that also addresses human well-being and development.

Effects of the Land Systems Transformation and its components on the Global Commons domains

The Land Systems Transformation (Tland) implementation combines all four land-based subtransformations, which encompass the inclusion of a price on GHG emissions, efficiency improvements, dietary shift, food waste reduction and meeting the NDCs for land emissions, in addition to other land-based mitigation solutions. As such, it emerges to be by far the most effective transformation for safeguarding the Land Biosphere, but also has important effects on the Climate and the Oceans.

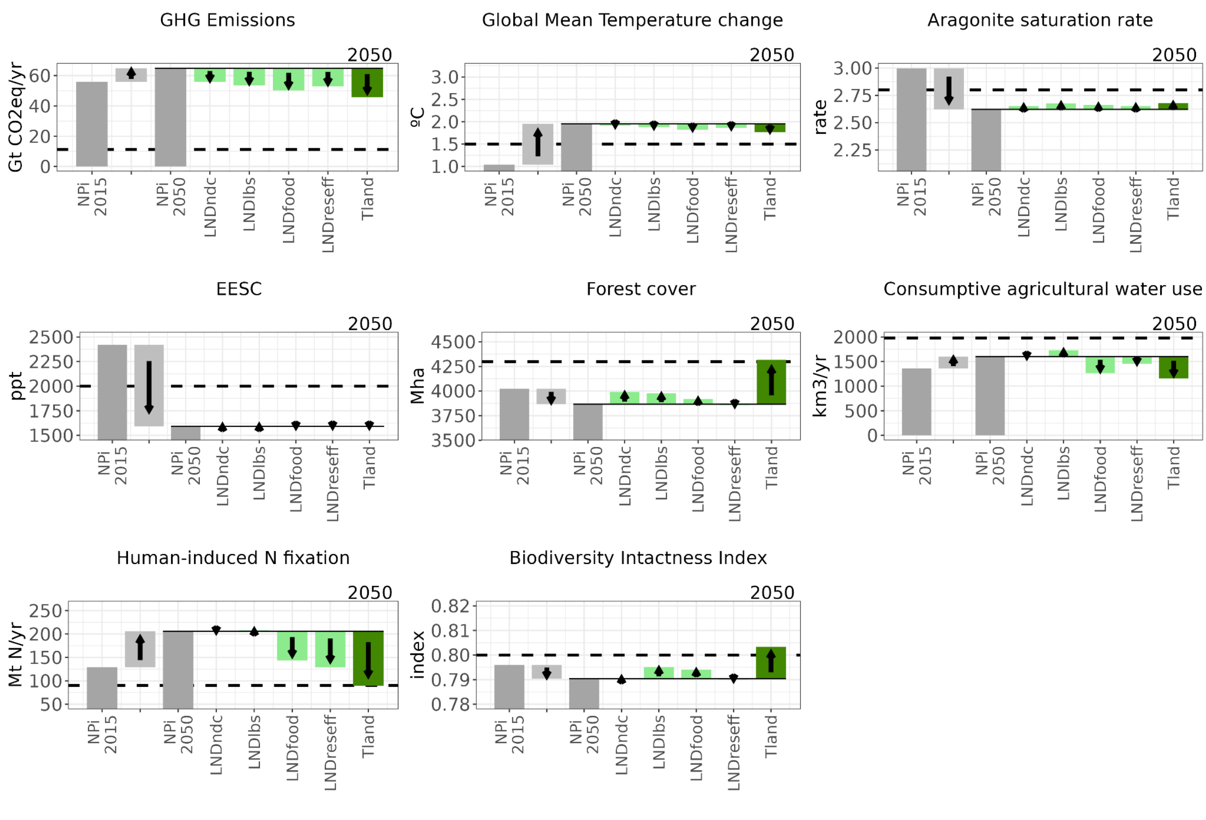

Fig 5.2: Effects of the Land Systems Transformation (Tland, dark green) and its subtransformations (light green) on the Global Commons domains indicators. The grey rectangles show the evolution of the indicators between 2015 and 2050 in the scenario with only the Nationally Implemented Policies (NPi) for comparison, while the blue rectangles show the effect of the transformation relative to the NPis in 2050. Dashed lines represent the defined 2050 targets for each indicator. Subtransformations are labelled as follows LNDndc: Current

deforestation and afforestation commitments; LNDlbs: Land-based solutions intervention; LNDfood: Sustainable food demand; LNDresff: Resource-efficient production systems

Relative to the NPi scenario in 2050, the Land Systems Transformation reduces greenhouse gas emissions by 19 Gt CO_2eq/yr, which is 37% of the gap to the 2050 emissions target, and around half of the emissions reduction achieved by the energy transformation. This leads to a reduction in global mean temperature (GMT) by 0.18°C, which is a similar amount to the 0.19°C reduction achievable with the Energy Systems Transformation. The Land Systems Transformation had a particularly pronounced effect on 2050 temperature due to the strong reductions in emissions of non-CO_2 gases with high radiative forcing (e.g. CH4, N2O), thus making it especially important for reducing peak warming.

The implementation of the Land Systems Transformation also leads to an increase in aragonite saturation rate by 0.06, although this contribution was relatively small due to the more moderate reductions in CO_2 emissions compared to those of the other transformations.

As expected, the Land Systems Transformation has an important effect on safeguarding the land biosphere indicators. Globally, it increases forest cover by 450 Mha and reduces consumptive agricultural water use by 442 km^3/yr in 2050. Moreover, it decreases nitrogen fixation by 116 Mt N/yr, being the only transformation that can bring this indicator into the safe space below the 90 Mt N/yr Planetary boundary. Finally, it increases the Biodiversity Intactness Index (BII) by 0.013, suggesting that this transformation is critical to reaching the 80% intactness target.

The decomposition of the Land Systems Transformation into individual subtransformations shows that for many indicators the overall transformation demonstrates a less-than-additive effect (e.g. GHG emissions and global mean temperature). These diminishing returns suggest that the subtransformations have overlapping effects. However, several indicators appear to be synergistic, such as the increase in forest area and ensuing increases in biodiversity intactness. This likely emerges as reductions in the consumption of red meat from the Sustainable Food Demand (LNDfood) subtransformation facilitates the conversion of cropland to forests, which however is only incentivized with the CO_2 pricing introduced by the Land Based Solutions intervention (LNDlbs).

Land-related Nationally Determined Contributions (LNDndc)

The implementation of only the land-based NDC commitments leads to significant positive impacts on the Global Commons domains Climate, Oceans, and the Land Biosphere. In particular, it leads to a 9 Gt CO_2eq/yr reduction in greenhouse gas emissions in 2050, which is approximately half that achieved by the full Land Systems Transformation. This reduction in emissions causes a reduction in GMT by 0.04°C, which is around 20% of that achieved by the full Land Systems Transformation and its CO_2 component leads to an increase in aragonite saturation All the land protection and afforestation commitments increase forest cover by 125 Mha, with an ensuing slight increase in BII of 0.001. Importantly, implementation of the land-based NDC commitments had negligible impacts on both agricultural water use and human-induced nitrogen fixation. These indicators were likely unaffected because the transformation lacks any changes in demand patterns or technologies reducing environmental impacts of agriculture. Without these drivers, while significantly more forest is spared from land conversion, conversion will still occur in some regions and existing croplands and pastures are intensified in order to meet food demand.

Land-based solutions (LNDlbs)

The land-based solutions subtransformation had significant impacts on the assessed Climate, Oceans, Land Biosphere Global Commons domains indicators in 2050. It includes land protection schemes and the extension of GHG to land carbon. The intervention reduces greenhouse gas emissions by 11 Gt CO_2eq/yr, a little over a half of the full Land Systems Transformation and more than the land-based NDCs subtransformation. Additionally, the subtransformation reduces Global Mean Temperature by 0.07°C, i.e., almost double the effect of the land-based NDCs alone. The intervention had the largest contribution to increasing aragonite saturation, with an increase of 0.05 due to the proportionally large reduction in CO_2 emissions versus non- CO_2 emissions. Forest cover increases by 110 Mha, making this the most important intervention after the land-based NDCs in increasing forest cover. Furthermore, LNDlbs increased BII by 0.004, representing the strongest single positive effect.

However, this subtransformation can also have negative side effects. As the intervention lacks mechanisms to reduce demand or increase production efficiency, we observed increases in consumptive agricultural water use by 126 km3/yr as well as a slight increase in nitrogen fixation of 1.9 Mt N/yr. As land protection measures decrease the availability of productive land, intensification is required to meet food demand where agriculture is still possible. While land-based solutions demonstrate large potential to reduce greenhouse gas emissions and improve environmental indicators, they will also necessitate complementary measures to reduce potentially strong, negative side-effects.

Resource-efficient production systems (LNDreseff)

The resource efficiency subtransformation (LNDreseff) includes improvements in N and water efficiency, livestock intensification, improvements to animal waste management, a price on non-GHG emissions in the land sector, and the protection of environmental flow requirements, notably without any exogenous agricultural yield improvements. The scenario led to significant reductions in GHG emissions (11Gt CO_2eq/yr), which is a little over half the reduction achieved by the full land transformation, and increased aragonite saturation rate. It also reduces GMT by 0.09°C, which is proportionally higher than other interventions due to the strong reduction in short-lived, high-forcing non-CO_2 emissions. The subtransformation also reduces consumptive agricultural water use by 148 km^3/yr. As agricultural water availability is highly spatially variable, this decrease in consumption will likely reduce regional violations of this important boundary. However, it slightly reduces forest cover (by 7.6 Mha), as agricultural expansion is required to meet food demand while preventing violations of regional water availability. The scenario very slightly decreases BII, in line with the forest losses. Lastly, efficiency gains strongly reduce N fixation by 77 Mt N/yr.

Sustainable food demand (LNDfood)

The sustainable food demand subtransformation is defined as a global convergence to the EAT-Lancet Diet and strong reduction of food waste. Among the different interventions in the Land Systems Transformation, it represents the most substantial contribution in reducing GHG emissions, amounting to 14 Gt CO_2eq/yr. This alone accounts for 27% of the total reductions required to achieve the 1.5 compatible emissions target. It thus also leads to a 0.12°C reduction in Global Mean Temperature, the largest reduction among the land-based scenarios. The intervention also increases forest cover by 53 Mha, which occurs as dietary change reduces the pressure on the land system to produce livestock and the food necessary to feed them. However, the increase in aragonite saturation rate by 0.04 is proportionally less than expected, as the emissions reductions tend to come from a high share of non-CO_2 mitigation. Consumptive agricultural water use decreases by 336 km3/yr and human-induced N-fixation by 63 Mt N/yr, and improves BII by 0.003. Importantly, LNDfood is unique in that its ability to synergistically increase forest and BII within the Land Systems Transformation (see respective section above).

6. Combining the Transformations: Synergies, trade-offs, and alternative socioeconomic assumptions

Motivation and Methods

The world's energy, land use and production systems are fundamentally interconnected, and so are the different Global Commons domains. Therefore, the deep Systems Transformations considered here can interact with each other inside and across domains in complex ways. As shown in previous chapters, some transformations that are beneficial to certain Global Commons domains, such as the Energy Systems transformation, can generate additional pressure on other domains, such as the Land Biosphere, and slow the effects of other Transformations. Other transformations may have synergistic effects, enhancing or facilitating each other, while others still explore similar solution spaces and don't have additive effects.

We here present a more detailed description of the effects when the Transformations are applied jointly in an all-transformations (Tall) scenario. To decompose individual effects and examine synergies and tradeoffs, we also explore intermediate scenarios where the transformations are progressively applied in combination with each other. We focus on a sequence beginning with the Energy Systems Transformation, followed by the Land Systems Transformation and its component interventions, and ending with the Sustainable Production and Consumption Transformation. As the effects of human activities on the Global Commons are fundamentally affected by GDP development and population growth rates, we go beyond the all-transformations scenario and estimate the effects of different assumptions on GDP and population growth as in the Shared Socioeconomic Pathway 1.

Key findings

The scenario in which all proposed transformations are implemented jointly (Tall) would allow humanity to reverse the degradation of the assessed Global Commons domains to levels very close to or within the safe space of the Planetary Boundaries by 2050. Although even these deep systems transformations wouldn't be able to keep warming below 1.5°C without some overshoot in 2050, a combination of CO_2 removal and continued reduction of non-CO_2 emissions would revert warming, so that Global Mean Temperatures would stay below the Paris Agreement target by 2100 and beyond. However, CO_2 concentrations and radiative forcing would still only be stabilised at around current levels, at which changes in climate harmful to human and natural systems are already observed.

The GHG price levels required for safeguarding the Global Commons domains, especially the Climate, depend crucially on all other measures implemented: In the absence of any other measures, energy system GHG prices in our scenarios would have to reach around 350 U.S. dollars per ton of CO2 equivalent by 2050 to reach the 1.5°C climate goal. Combining it with other policies, especially encouraging the reduction of total demand for high emissions products and services, such as industrial materials, energy and animal-source foods, and pricing emissions in the land sector lowers the GHG prices necessary to achieve the same climate target. Demand reductions, although difficult to implement, ease the cost of transition and have several co-benefits for the land biosphere. Combined with strong levels of demand reduction, a comprehensive GHG pricing scheme in the energy and land use could achieve the 1.5°C climate goal with prices as low as 90 U.S. dollars per ton of CO2 equivalent by 2050.

As noted in the previous sections, transforming the Energy System has the strongest positive effects in preventing Climate Change. Among the transformations assessed, it is the only one that can alone keep Ocean Acidification from crossing its Planetary Boundary. It is also necessary to achieve net-zero CO_2 emissions and stabilise warming into the next century, even though it cannot keep Climate Change within the safe space by itself.

However, a transformation of energy systems with no limitations on bioenergy reliance for decarbonising the energy sector will have detrimental effects on Land System Change and Nitrogen Flows, and push Freshwater Use close to its Planetary Boundary. Such impacts could be counteracted by jointly transforming the land systems as shown in Section 3.5, but also via specific demand-side policies on the energy sector to limit its reliance on bioenergy.

Most of these impacts can be counteracted by jointly transforming Land Systems. The Land Systems transformation can bring Land System Change, Nitrogen Flow and Biosphere Integrity back within their Planetary Boundaries, substantially reduce Freshwater Use and counteract negative effects from the Energy Systems Transformation in these Commons domains. The interventions in the Land Systems Transformation have a smaller impact on reducing GHG emissions and therefore safeguarding the climate when applied together with the Energy Systems Transformation than when considered alone. This is mostly because, if applied without specific policies to prevent, the GHG pricing on the energy sector leads to a relatively high reliance on bioenergy, particularly purpose-grown biomass. This leads to higher direct agricultural emissions and increased pressure on natural land, which makes mitigation from the Land Systems Transformation policies somewhat harder to achieve.

Reducing the demand for materials in the Sustainable Production and Consumption Transformation has a much weaker effect on reducing GHG emissions when combined with the already combined Energy Systems and Land Systems Transformations. This arises from the fact that currently most emissions in the industry sector are caused by the energy supply, so reducing industrial production has a weaker effect in reducing emissions in a transformed energy system. However, as the remaining process emissions are particularly hard to abate, the demand reductions help reduce the costs of transformation and lead to the relatively low reliance on Carbon Dioxide Removal (CDR) in the all transformations scenario.

Similarly, assuming smaller population and GDP growth as in SSP1 leads to relatively modest additional progress in safeguarding the Global Commons domains. Although population and GDP are important drivers of global environmental impacts (Riahi et al. 2017, Rockström et al. 2020), the per-capita and per-dollar intensity of impacts is already greatly reduced by the three transformations implemented before as follows: The Sustainable Production and Consumption Transformation assumes less demand for materials per person, which reduces the energy demand for the production of goods. The pricing schemes and land regulations in the Energy and Land systems Transformations shift these systems to provide energy and agricultural products in more environmentally-efficient ways. The shifts in diets and food waste reduction in the Sustainable Food Demand intervention additionally substantially reduces the amount of agricultural production, and therefore environmental impacts and land pressure, required to feed a growing population. Similarly, the pushes for more sustainable transport modes and efficient heating systems reduce the per-capita demand for energy services.

Although there can be significant tradeoffs to the Land Biosphere between the components of the Land Systems transformation (as shown in the previous section), the joint implementation of all components of the Land Systems Transformation exhibits a more than additive effect on preserving biodiversity. This is due to the complementarity of especially the demand-focused diet and food waste measures with the systemic approach of disincentivizing loss of natural terrestrial ecosystems of the Land-based solutions intervention, and to a certain extent also bioenergy production.

The massive transformations assessed here can also have large impacts on agricultural prices, with potentially important consequences for food security and the justice of these transformations. Interventions that create additional pressure on the land system tend to increase costs and therefore prices. Consequently, the Energy Systems transformation can have such an effect when the production of bioenergy competes with food production. The same is true for the NDCs, which additionally include large amounts of afforestation that competes for land with agriculture. Lower material demands from the Sustainable Production and Consumption Transformation reduces agricultural prices. Since there's a somewhat heavy reliance on bioenergy on the transformed energy systems

A key insight from the assessment of the land subtransformation scenarios is that safeguarding the Land Biosphere through supply-side interventions alone can substantially increase the price of food. The land competition effect is particularly intense for our Land-based solutions subtransformation, that includes a price on CO_2 emissions from the conversion of natural land, as well as more stringent protection of biodiverse regions. The Resource-efficient production systems subtransformation shows the largest increase of food prices, around 15% in 2050 compared to the NPi scenario, as it increases production costs in multiple ways. Only a shift in demand patterns, as assumed in the Sustainable food demand subtransformation, can keep food prices relatively stable at low values over the 21st century. The Sustainable food demand subtransformation, which models an adoption of the EAT-Lancet planetary health diet and halving of food waste, dramatically reduces the environmental impact of peoples' diets by transitioning away from livestock products.

In general, interventions that only reduce demand, be it for industrial materials (such as the Sustainable Production and Consumption Transformation), for unsustainable food products (Sustainable Food demand) or even reduces the size of the economy in general (lower population and GDP growth in SSP1) can have very substantial effects on safeguarding the assessed Global Commons domains. But even within our deep transformations, reduced demand alone will not be sufficient to reach any of the assessed targets. Furthermore, when coupled with structural changes in the systems themselves, such as the decarbonisation of energy supply and more resource-efficient agricultural production, these demand-side interventions tend to have a smaller effect than when considered alone. This arises from the fact that these transformed production systems can fulfil the same demand with less impact on the Global Commons. However, reductions in demand can be fundamental in reducing the societal costs of these production systems transformations, making the same targets achievable with lower prices for food, energy and GHG emissions for example. Though as most of the demand reductions assessed require deep behavioural changes, implementing them would pose a major policy challenge.

Although this study focuses on physical dimensions of the Global Commons domains assessed, measures that primarily target societal development goals and can also have substantial impacts on the Global Commons. Many of these interventions can directly or indirectly affect the justice, acceptability and feasibility of policies targeting the Global Commons domains, such as improving global justice in sharing the burden for implementing transformations, gender equality and access to education.

The system transformations described here are very ambitious. The feasibility of the implementation of such measures will likely depend on well-working governmental institutions and strong international cooperation. Although each government should control its own transformation strategy, coordination and compensation mechanisms at the global level are critical given the significant challenges arising from the profound transformations in the energy, agricultural and industrial systems, particularly in the global south. International cooperation and strong regional institutions will be needed to prevent leakages in the impact of policies, especially in the land sector and between the Global South and Global North. Moreover, due to the non-predictability of all impacts of certain measures, monitoring and readjustment strategies will be necessary and should be included in the conception of governance strategies aiming to keep the impacts of human activities on the Global Commons domains within Planetary Boundaries.

GHG prices required for 1.5°C target

In our scenarios, setting a price on greenhouse gas emissions (GHG price) is a crucial intervention. It is included in both the Energy Systems and Land Systems Transformations. We define the GHG price path in most of our scenarios as the optimal, cost-minimising path that can keep warming in the All Transformations Implemented scenario (SSP2-Tall) below 1.5°C (with limited overshoot). The same price (fig. 6.2) is applied for GHG emissions both from the Land Use sector as part of the Land Systems Transformation and from all other sectors as part of the Energy Systems Transformation.

However, since this scenario includes all interventions used in the other scenarios, many of which ease the transition or directly reduce emissions, it can achieve the same climate goal with much lower GHG prices than any other scenario (Fig 6.1). If GHG pricing is implemented only on energy systems, the price level required by 2050 is around 350 USD/tCO2eq. However, with all other transformations applied, this price falls drastically to around 90 USD/tCO2eq. Therefore, the GHG price path used can be described as one that is high enough to keep warming below 1.5°C if all transformations are applied, but not necessarily so if only parts of them are.

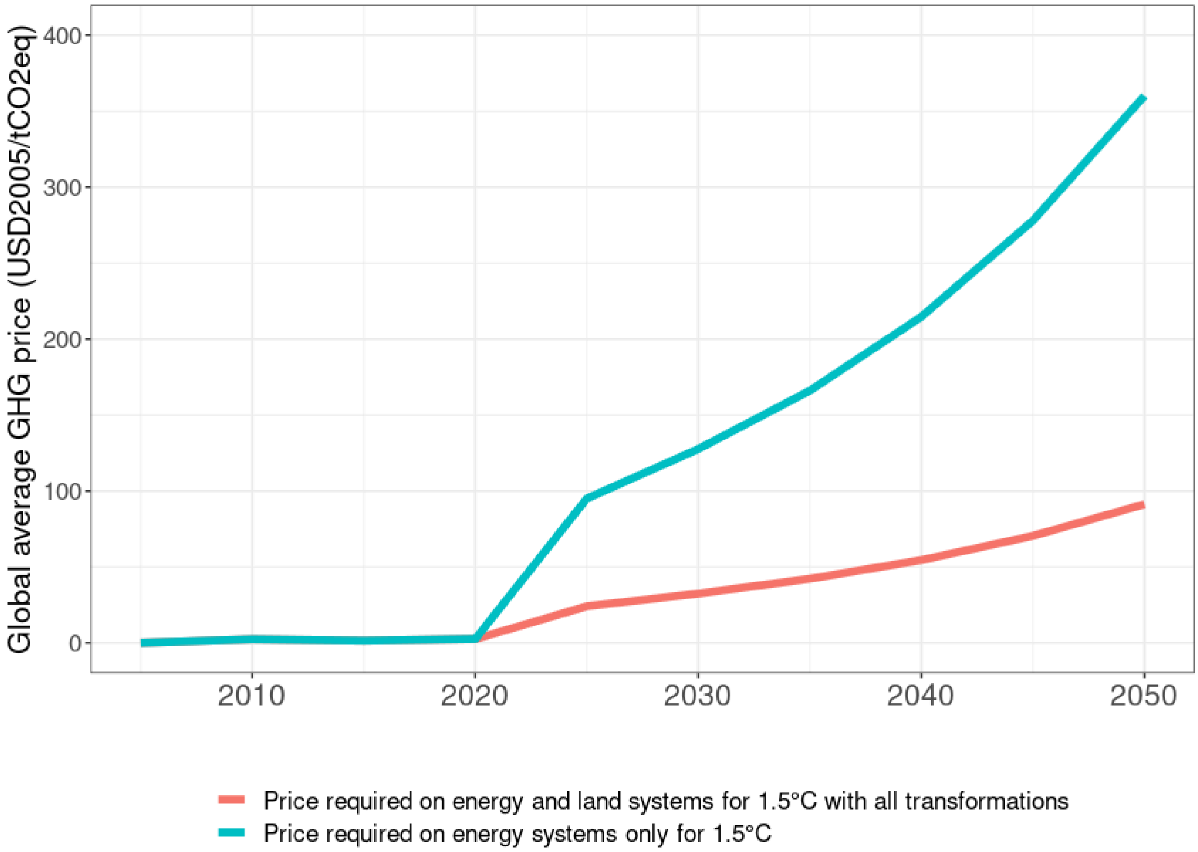

Fig. 6.1: Trajectories of GHG emissions pricing required for global mean temperature change to remain under 1.5°C with limited overshoot in: the all-transformations scenario (red) and; in a scenario where prices are applied only in the energy sector and in the absence of any other interventions (blue).

The GHG price however differs by regions. This differentiation is made based on the GDP per capita of each region in earlier years, so that developing regions face lower prices initially. The prices eventually converge to a uniform global price of 91 USD/t CO_2eq in 2050, and reach 219 USD/t CO_2eq.

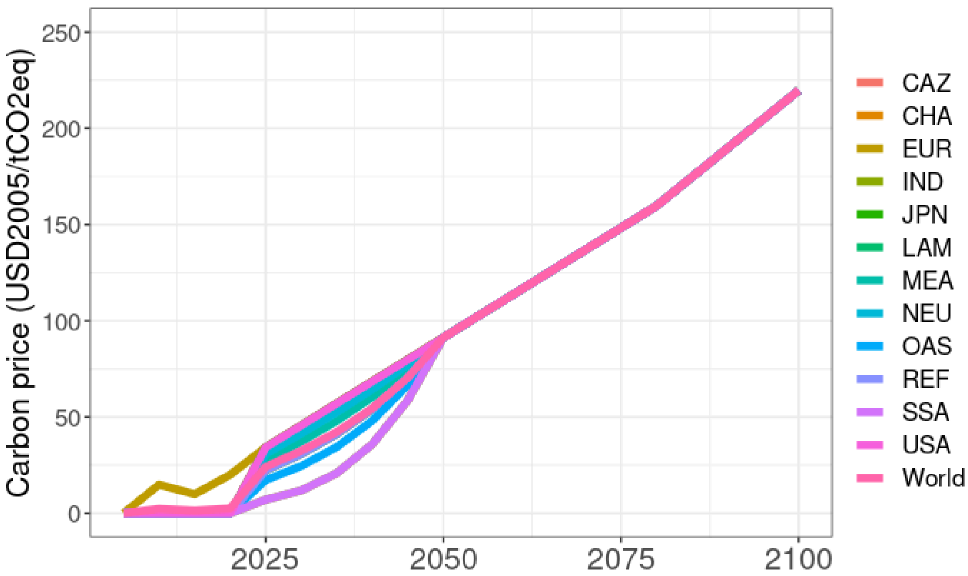

Fig. 6.2: Prices on GHG emissions (per ton of CO_2 equivalent), applied as part of the Energy Systems and Lands System Transformations. Region codes: CAZ: Canada, NZ, Australia; CHA: China; EUR: EU28 Europe; IND: India; JPN: Japan; LAM: Latin America and the Caribbean; MEA: Middle East, North Africa, Central Asia; NEU: Non-EU28 Europe; OAS: Other Asia; REF: Countries from the reforming economies of the former Soviet Union; SSA: Sub-Saharan Africa; USA; United States of America.

Effects on the Climate system and the Cryosphere

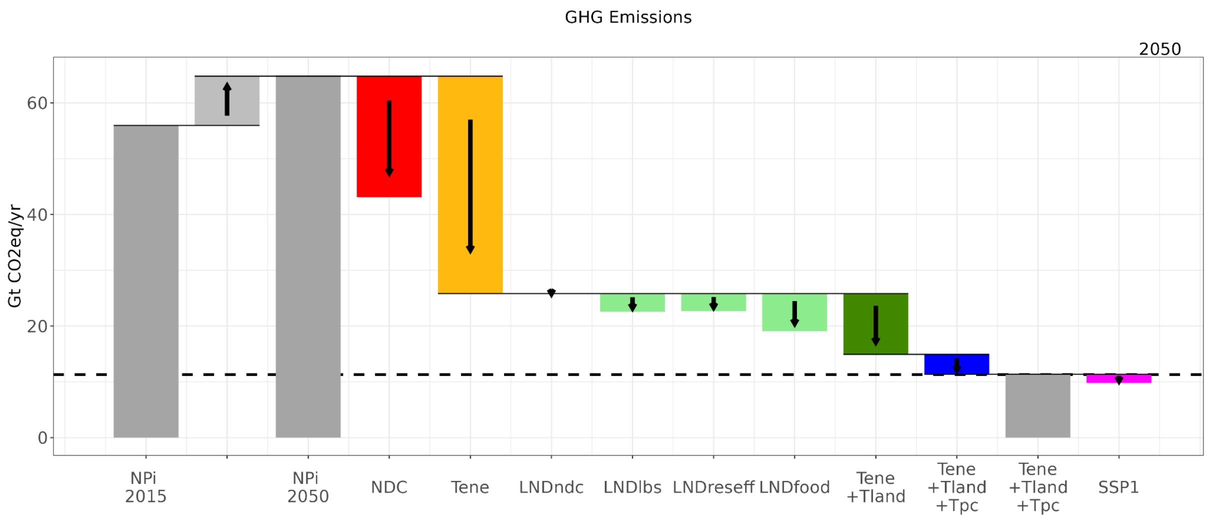

Fig. 6.3: Effects of the combined transformations on yearly GHG emissions. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

The All transformations scenario (Tall) can, by design, keep warming below 1.5ºC by 2100 with around 0.1ºC overshoot in 2050. Therefore, we use the emissions trajectory of the all-transformations scenario as intermediate targets to compare progress in scenarios with fewer interventions. GHG emissions in that scenario are at 11 Gt CO_2eq/yr in 2050, and net-zero CO_2 emissions are reached in 2070.

As described in Section 2, under current policies (NPi), GHG emissions (Fig. 6.3) would reach 64 Gt CO_2eq/yr by 2050, and the current NDC commitments would reduce them by 22 GtC CO_2eq/yr, less than half the reduction needed to achieve the target value of 11 Gt CO_2eq/yr. We set this intermediate target for emissions based on our all-transformations scenario, in which global mean temperature change remains below 1.5C by 2100 with limited overshoot. Transforming the energy system can close more than 70% of that gap, mainly through reductions in CO_2 emissions in the energy and industry sectors due to the introduction of emissions pricing.

The interventions in the Land Systems Transformation have a smaller impact on reducing GHG emissions when applied together with the Energy Systems Transformation, 11 Gt CO_2eq/yr, but nevertheless adds another 20% to closing the gap. This is mostly because, if applied without specific policies to prevent, the GHG pricing on the energy sector leads to a relatively high reliance on bioenergy, particularly purpose-grown biomass (20 EJ/yr in 2050 and 288 EJ/yr in 2100 from energy crops). This leads to higher direct agricultural emissions and increased pressure on natural land, which makes mitigation from the Land Systems Transformation policies somewhat harder to achieve. For this reason, the effect of the overall transformation, as well as of its component interventions, in reducing GHG emissions by 2050 is around 10 Gt CO_2eq/yr weaker than when they are applied on top of the scenario with only the currently implemented policies. The land scarcity induced by the conservation policies in the Land Systems Transformation also increases production prices for bioenergy, which leads to a somewhat lower reliance on energy crops by the end of the century (188 EJ/yr), but little effect in 2050.

Reducing the demand for materials in the Sustainable Production and Consumption Transformation has a much weaker effect on reducing GHG emissions when combined with the already combined Energy Systems and Land Systems Transformations. This arises from the fact that currently most emissions in the industry sector are caused by the energy supply, and a smaller but still substantial share by the industrial processes themselves. Reducing the demand for industrial products leads to less production and proportionally reduces GHG emissions from both sources. But if the energy system is transformed, this already reduces the emissions needed for the production of one unit of industrial goods. Therefore, reducing the total demand for these goods has a weaker effect in reducing emissions in a transformed energy system. However, as the remaining process emissions are particularly hard to abate, the demand reductions help reduce the costs of transformation and lead to the relatively low reliance on Carbon Dioxide Removal (CDR) in this scenario.

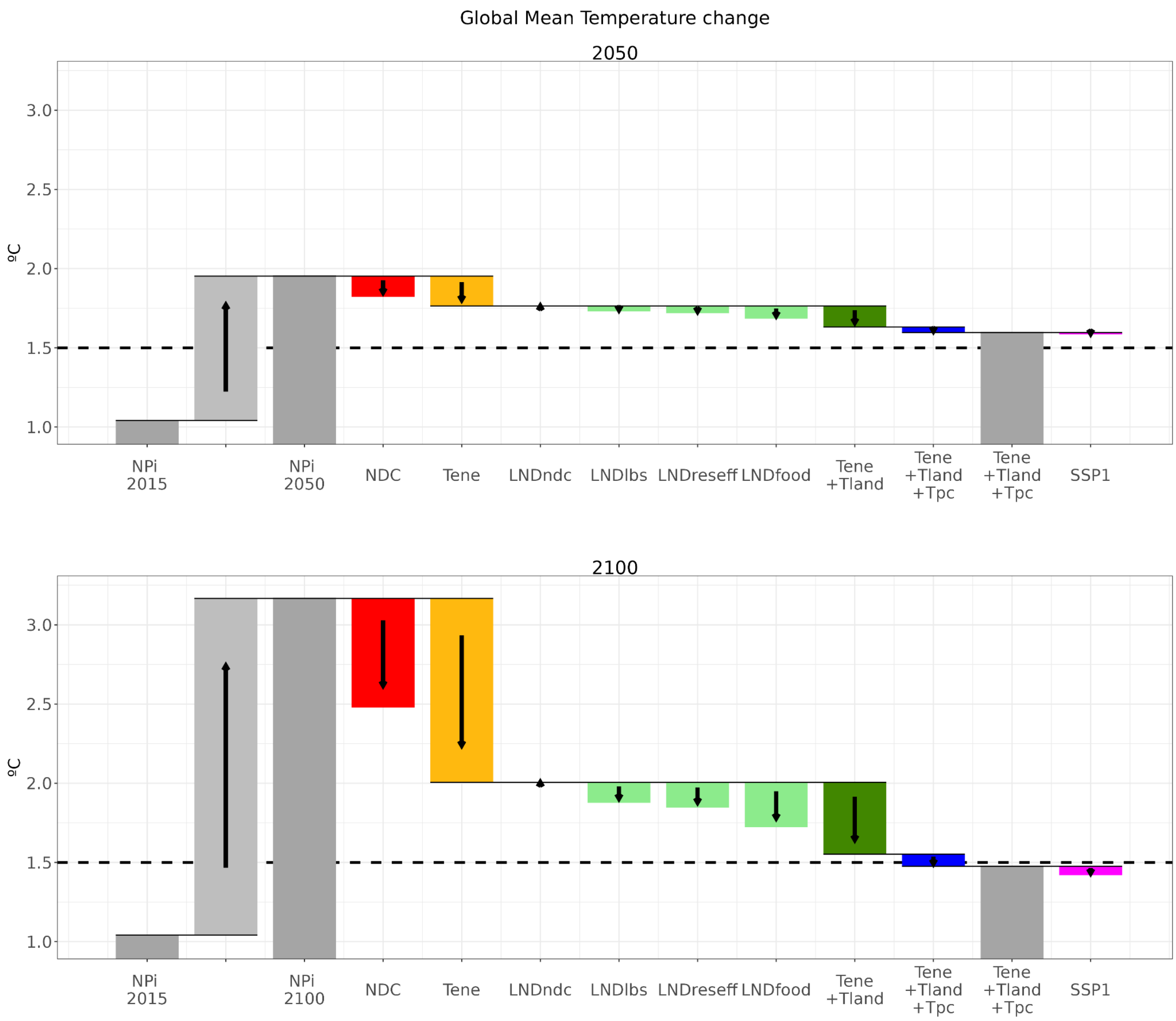

Fig. 6.4: Effects of the combined transformations on global mean temperature (GMT) change. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 (top) or 2100 (bottom) in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050 (top) or 2100 (bottom). The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Similarly, assuming smaller population and GDP growth as in SSP1 leads to a relatively modest additional reduction in GHG emissions (1.5 Gt CO_2eq/yr). Although population and GDP are important drivers of global environmental impacts (Riahi et al. 2017, Rockström et al. 2020), the per-capita and per-dollar intensity of emissions is already greatly reduced by the three transformations implemented before as follows: The Sustainable Production and Consumption Transformation assumes less demand for materials per person, which reduces the energy demand for the production of goods. The GHG pricing schemes in the Energy and Land systems Transformations shift these systems to provide energy and agricultural products in more emissions-efficient ways. The shifts in diets and food waste reduction in the Sustainable Food Demand intervention additionally substantially reduces the amount of agricultural production, and therefore agricultural emissions and land pressure, required to feed a growing population. Similarly, the pushes for more sustainable transport modes and efficient heating systems reduce the per-capita demand for energy services.

The effects of the transformations on preventing *Global Mean Temperature change* broadly follow those on reducing equivalent GHG emissions, but with different short- and long-term dynamics. By 2100, the scenario with all transformations is able to limit warming to below 1.5°C, with the Energy Systems Transformation being responsible for preventing around 70% of the warming that would happen under current policies. However, the Land Systems Transformation is particularly important to minimise the overshoot of the 1.5°C in the short term due to its ability to quickly reduce methane emissions. Methane is a strong greenhouse gas, but has a relatively short lifetime in the atmosphere. Therefore, the earlier methane reductions of the Land Systems Transformation result in stronger reductions in short-term warming, having the strongest effect around 2030 when the target is first overshot in most scenarios (Fig.6.5). However, the Energy Systems Transformation is the only one that is able to, alone, reach net-zero CO_2 emissions by 2100 and prevent warming to continue well into the next century.

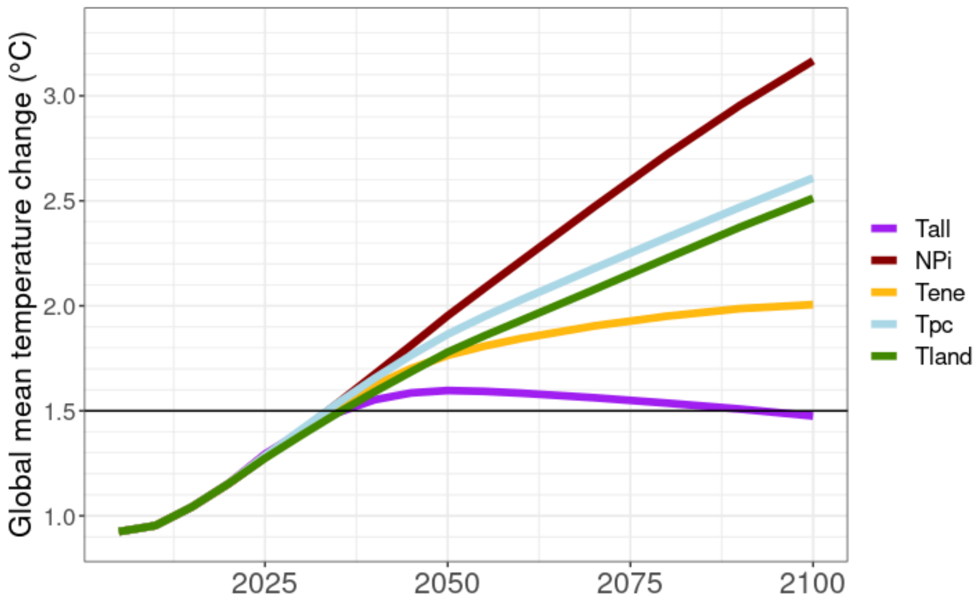

Fig. 6.5: XXI century trajectories of median estimates of Global Mean Temperature change relative to the preindustrial period for the scenarios with only the currently implemented policies (NPi), only the individual transformations (Tene, Tland, Tpc) and with all transformations combined (Tall). The horizontal black line shows the 1.5°C target.

Effects on the Oceans

The aragonite saturation rate is a direct proxy for the Planetary Boundary of Ocean Acidification, with lower values being detrimental to the stability of marine ecosystems. The main human-driven cause of ocean acidification is the increase in the concentration of CO_2 in the atmosphere caused by CO_2 emissions. A large fraction of the CO_2 emitted by human activities is eventually dissolved in the ocean waters, which increases their acidity and lowers the aragonite saturation rate.

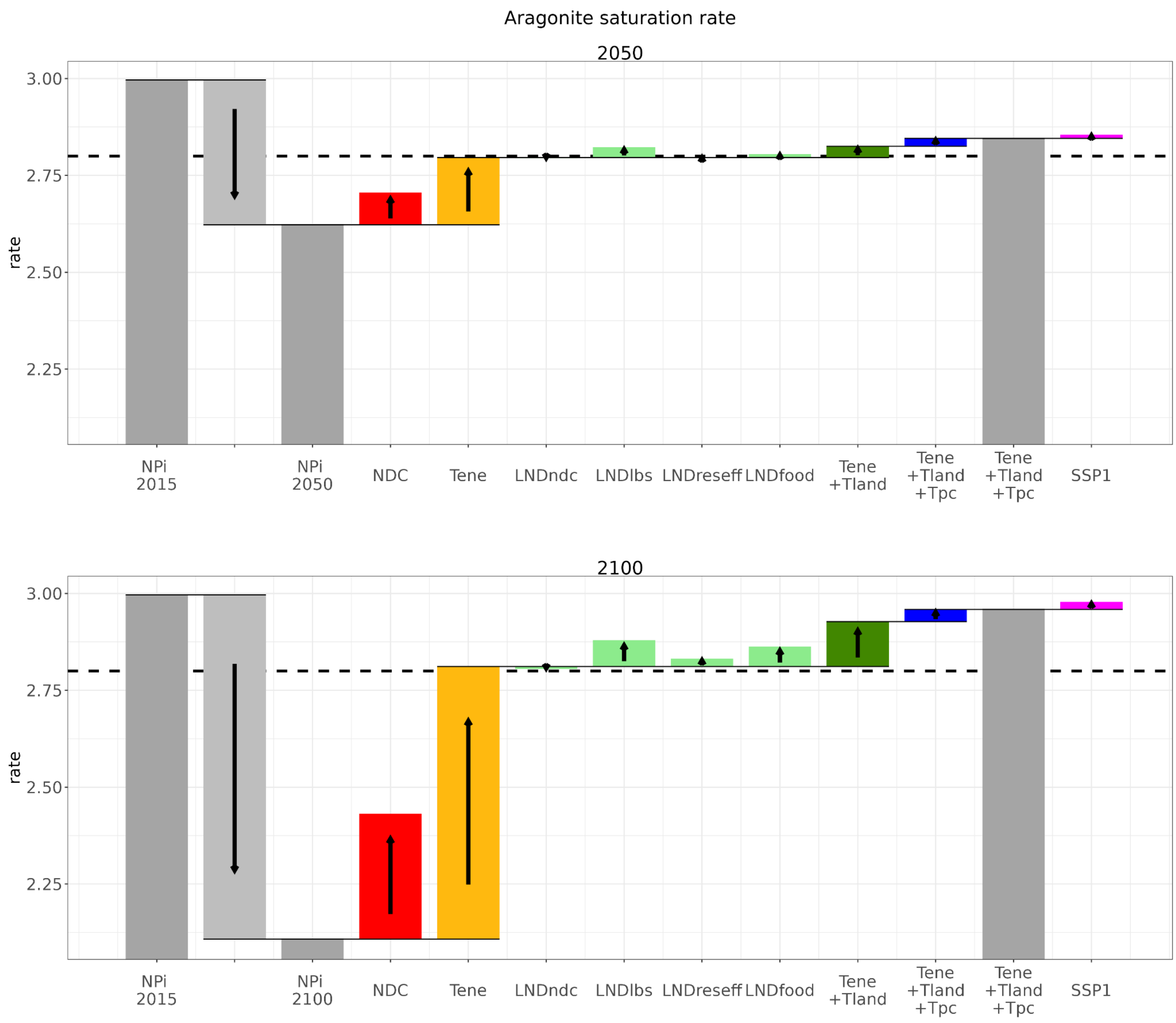

Fig. 6.6: Effects of the combined transformations on Aragonite Saturation Rate. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 (top) or 2100 (bottom) in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050 (top) or 2100 (bottom). The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Since it has the strongest effects in reducing CO_2 emissions, the Energy Systems Transformation is responsible for the largest positive impact on the aragonite saturation rate. With only the current NDCs, aragonite saturation would fall below the target value already in 2050. In fact, only scenarios that include the Energy Systems Transformation remain consistently above the target value throughout the century (fig 6.7). Therefore, transforming the energy systems is essential to keep Ocean Acidification within relatively safe levels.

The interactions between the Energy Systems Transformation and the other two mentioned for GHG emissions similarly apply for Ocean Acidification. The Land Systems Transformation has a substantial positive effect on aragonite saturation, although it's just about half as strong when applied alongside the Energy Systems Transformation. This is due to the increased bioenergy demand induced by the latter. All its component interventions reduce CO_2 emissions and have individually positive impacts, with the Land-based solutions having the strongest. Similarly, the reduced energy and material demand induced by the Sustainable Production and Consumption Transformation has a diminished effect in reducing CO_2 emissions when the energy systems are already decarbonized, and therefore a smaller but still positive impact on aragonite saturation.

Also, for similar reasons, assuming lower GDP and population growth as in the SSP1 scenario has a positive but modest effect on increasing aragonite saturation rate when assessed on top of all transformations. Each transformation directly or indirectly reduces the CO_2 emissions needed to produce one unit of GDP or to fulfil one person's needs, either by reducing demand for food, materials and energy or by producing them in more efficient ways.

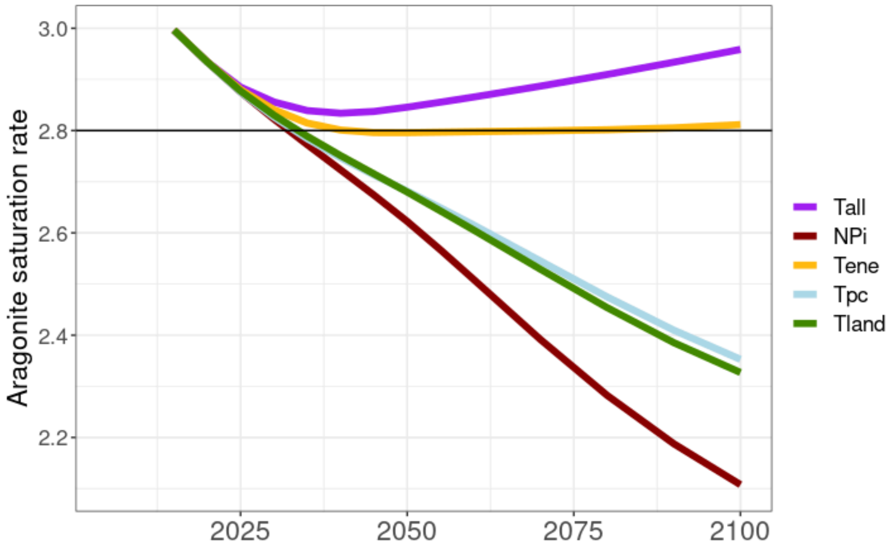

Fig. 6.7: XXI century trajectories of global mean aragonite saturation rate for the scenarios with only the currently implemented policies (NPi), only the individual transformations (Tene, Tland, Tpc) and with all transformations combined (Tall). Lower values of aragonite saturation rate lead to higher impacts on marine ecosystems.

Effects on the Ozone Layer

All our scenarios, including the national policies implemented (NPi) scenario, include full compliance with the Montreal Protocol. Under this assumption, emissions of ozone-depleting substances are phased out quickly, leading to the gradual recovery of the Ozone Layer and co-benefits to the climate system by avoiding warming. Effective Equivalent Stratospheric Chlorine (EESC), an indicator of the potential damage of anthropogenic activity on the health of stratospheric ozone, returns to pre-1980 levels (around 2000 ppt) between 2030 and 2050 (Fig. 6.8). This finding is broadly in agreement with those of the latest UN Scientific Assessment of Ozone Depletion (WMO 2022), which finds that under continued compliance the near-global average levels of tropospheric column ozone should return to pre-1980 levels by around 2040.

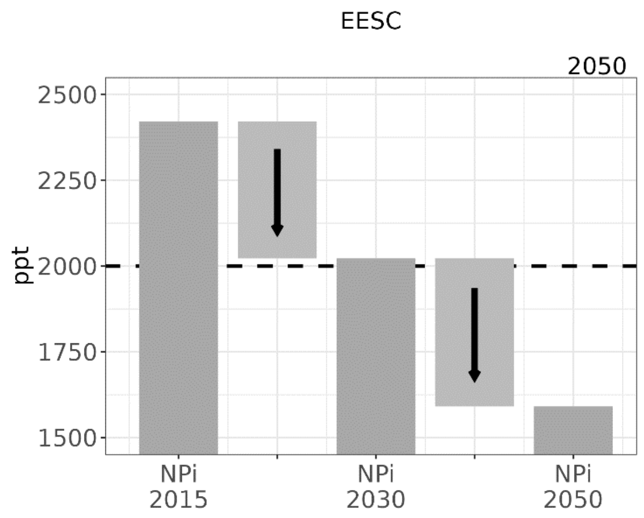

Fig. 6.8: Effects of the base national policies implemented (NPi) assumptions on Effective Equivalent Stratospheric Chlorine (EESC), a measure of ozone-depleting substances in the stratosphere. All our scenarios, including NDC, assume full compliance with the Montreal Protocol's reductions in the emissions of ozone-depleting substances.

Effects on the Land Biosphere

Forest cover

The different transformations show synergies as well as trade-offs regarding the future development of forest cover. If all transformations are applied jointly in the Global Commons stewardship scenario, forest cover increases compared to 2015 and reaches the target level of 4300 Mha in 2050, defined as 75% of original forest cover (see Annex). This is made possible especially by combining different interventions in the land and food systems. These together increase forest cover by 428 Mha and more than compensate the projected decreases caused by the continuation of current policies and the increased bioenergy demand from the Energy Systems Transformation.

The current NDCs include afforestation commitments that unfold a strong positive impact on forest cover in the short-term. However, forest cover in the NDC scenario is again slightly below the value of 2015 in the middle of the century, and commitments are not successful in stopping deforestation in the long-term, due to leakage effects and resulting loss of unprotected natural forests. While the land-based NDCs are largely beneficial for the forest cover indicator, they are not enough to counteract the current trends in deforestation, and trade-offs from NDC implementation in other sectors occur due to the resulting substantial increase in demand for purpose-grown bioenergy crops.

The Energy Systems Transformation additionally drives demand for second generation bioenergy - with resulting pressures on the land systems, and having detrimental consequences for forest cover.

The land-based solutions subtransformation is critical to prevent trade-offs from mitigation measures in the energy system such as bioenergy production, especially in the long-term. If applied on top of the Energy Systems Transformation, it leads to effects on aggregate forest cover in 2050 similar to those of the land sector commitments of the NDCs, yet involving different underlying dynamics. The temporal dynamics in the NDC scenario are driven mainly by an early increase in managed forest but simultaneous unabated decline in natural forest cover. In contrast, land-based mitigation measures such as GHG emissions pricing from natural land conversion and additional land protection schemes stabilise forest cover throughout the century, halt further loss of primary forests, and prevent the majority of decline in secondary natural forests. Thus, stabilising forest cover on top of the Energy Systems Transformation is realised with only a small contribution of additional afforestation, and goes hand in hand with a relative reduction in bioenergy deployment compared to accomplishing the energy transformation without such price- and regulation-based land protection measures.

If applied on top of the Energy System Transformation, the resource efficiency subtransformation in the land sector slightly increases forest cover in the first half of the century. This is due to synergies of lower demand for pastures in the wake of livestock system intensification with biomass use in the energy system.

The sustainable food demand subtransformation increases forest cover by a substantial amount, but it is less effective when bundled with mitigation efforts in the energy system. This is mostly caused by bioenergy crops competing for the land freed by the reduced food production.

Combining the individual subtransformations within the Land Systems Transformation yields a more than additive effect. This is due to synergies, created by both temporal complementarity (different emphases in the long- and short-term impacts) and complementarity of the underlying processes, such as in the combination of the food system transformation and land-based climate change mitigation actions. This synergistic interplay between the subtransformations in the land sector, however, is similar to their behaviour without implementation of energy system interventions.

The effect of the Sustainable Production and Consumption Transformation on forest cover is positive and much more substantial when applied on top of the Energy and Land Systems Transformations. With the decarbonisation of the energy system, industrial production relies much more on biofuels and bioenergy-based electricity than under current policies. Therefore, the reduction of industrial activity has a smaller effect on GHG emissions as mentioned before, but a much larger effect on reducing bioenergy demand and therefore reducing pressure on the land systems.

Finally, assuming lower population and GDP growth according to the more sustainable socio-economic pathway (SSP1) leads to a relatively modest increase in forest cover on top of all transformations. as these already reduce the demand for agricultural products as well as the detrimental impacts of biomass production on forests.

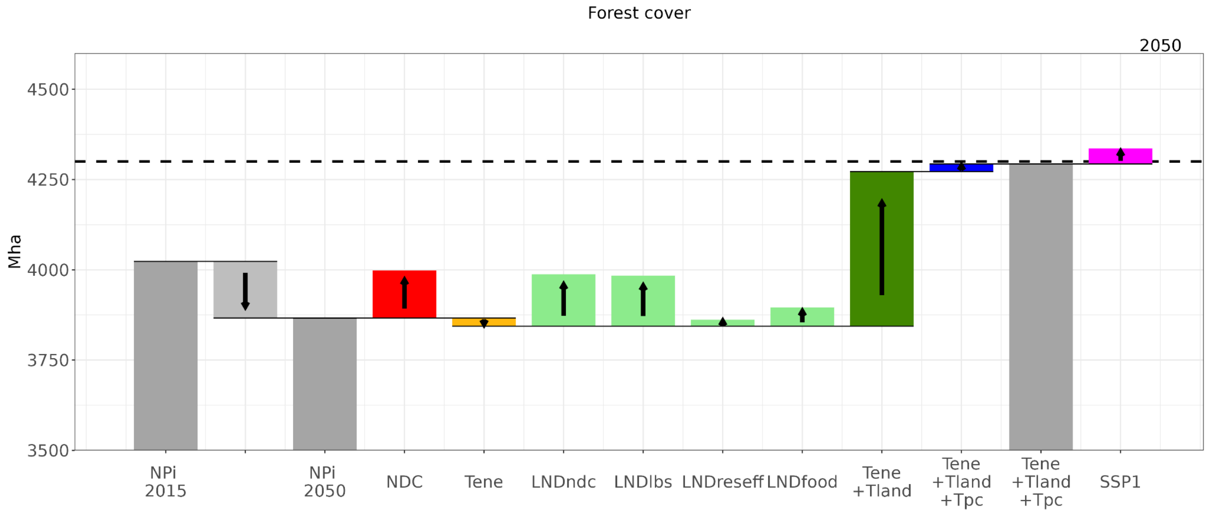

Fig. 6.9: Effects of the combined transformations on total global Forest Cover. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Human-induced nitrogen fixation

Our transformation scenarios demonstrate the profound importance of measures increasing resource-use efficiency (LNDreseff) within the agricultural sector – particularly in tandem with a shift towards a flexitarian EAT-Lancet diet (LNDfood) – if the Planetary Boundary for human-induced nitrogen fixation is to be met. Indeed, these transformations alone are able to mitigate N-fixation to levels approaching the Planetary Boundary. However, coupling these measures with the Energy Systems Transformation (Tene) and especially the Sustainable Production and Consumption Transformation (Tpc), the Planetary Boundary is achieved. Without these critical land interventions, transformations targeted solely at the energy sector will only exacerbate the problem of human-induced nitrogen fixation.

Meeting the NDCs increases the level of human-induced N fixation through two pathways. Directly, without disincentivizing emissions from the land use sector, meeting the NDCs will result in the significant deployment of N-intensive bioenergy crops. Indirectly, mirroring the increase in consumptive agriculture use, a reliance on bioenergy will drive competition for land, inducing cropland expansion necessary to meet food and bioenergy demand. The combined effect increases our projections of human-induced N fixation by 7% (14 MtN/yr) over the NPi alone in 2050. In contrast, a full Energy Systems Transformation (Tene), despite also relying heavily on bioenergy, leads to a lower total demand for biomass than that of the NDC scenario (but still higher than NPi). This is due to the more sustainable assumptions in the transport sector including electrification, which reduces the demand for biofuels. This mitigates – though does not entirely eliminate - the increase in N fixation compared to the NPi scenario.

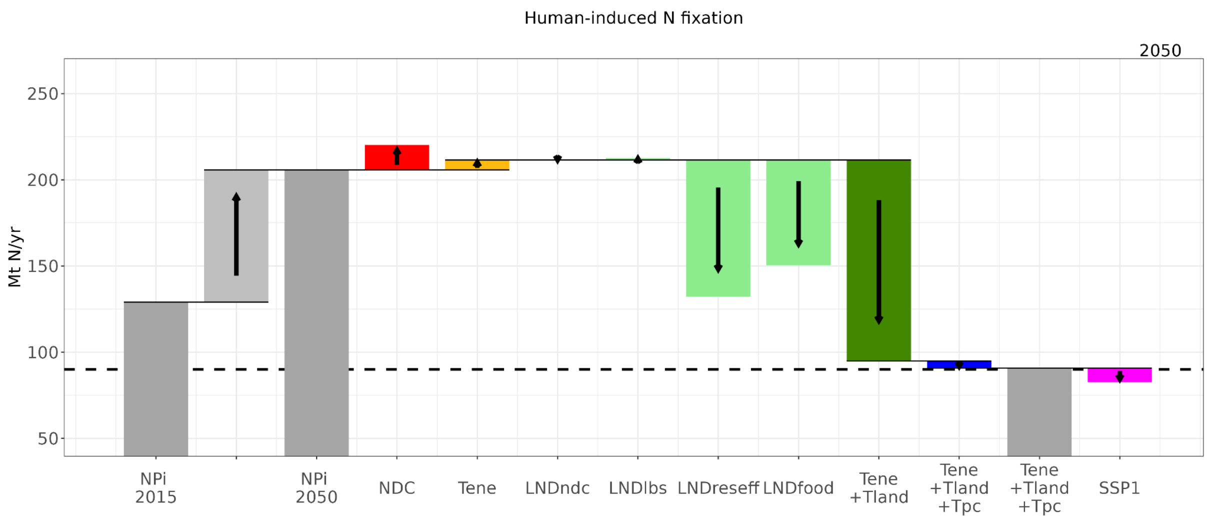

Fig. 6.10: Effects of the combined transformations on Human-induced N fixation. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Transformations in the land sector targeting either the land-based NDCs (LNDndc) or land-based solutions (LNDlbs) do little to mitigate human-induced nitrogen fixation, as they relocate food production rather than either reducing the resource-intensity of food demand (LNDfood) or increasing the resource efficiency of food production (LNDreseff). Applied on top of the Energy Systems Transformation, a transition towards more plant-based diets or increasing the efficiency of N usage decreases N pollution by 29% and 37% respectively. When integrated together into the full Land Systems Transformation (Tland), the Planetary Boundary for human-induced nitrogen fixation is within reach; in total fixation reaches 95 Mt N/yr, near the Planetary Boundary of 90 Mt N/yr. Further transforming the industrial sector through the Sustainable Production and Consumption Transformation (Tpc) reduces total N-fixation by 5 Mt N/yr, successfully lowering total human-induced N fixation to just slightly above the Planetary Boundary. Integrating SSP1 assumptions of population and GDP further decreases total fixation to 83 MtN/yr, as demand for agricultural and industrial products is reduced. However, compared to the enormous potential for efficiency gains and dietary shift, integrating more optimistic SSP assumptions makes relatively little difference in the final accounting for N-fixation.

Like consumptive agricultural water use, the boundary for N-fixation is highly relevant in a spatially-explicit context. Thus, quantifying regional boundaries will be critical for future work. Recent literature accounting for the spatial variability of both ecosystems' sensitivity to nitrogen pollution and agricultural nitrogen losses has found that incorporating these regional boundaries likely decreases the safe operating space for nitrogen usage. This suggests a further increase in the necessity of enhancing nitrogen use efficiency, as well as the coordinated reduction of non-agricultural nitrogen sources (Schulte-Uebbing et al. 2022).

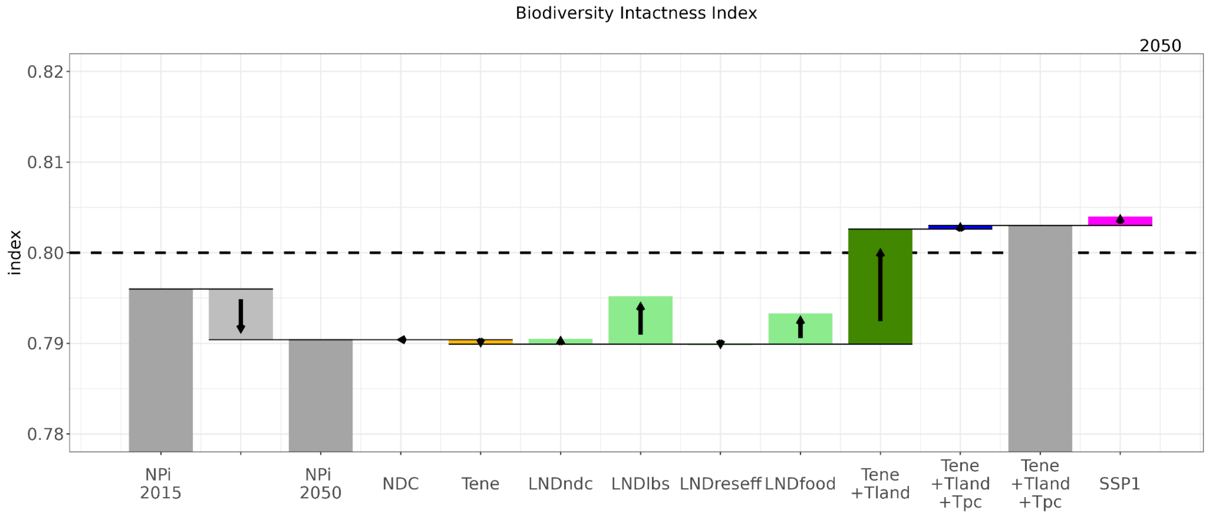

Fig. 6.11: Effects of the combined transformations on Biodiversity Intactness Index. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Biodiversity Intactness

Biodiversity intactness as measured by the BII indicator will further decrease as a result of conversion of natural land into managed land and an increasing relative importance of cropland compared to pasture within agricultural landscapes, if no interventions are to be taken against land system change. When climate mitigation measures include biomass as energy carrier and are implemented in the energy sector without adequate precautions against detrimental impacts of large-scale bioenergy production on the biosphere, BII will even decrease beyond the level of the NPi scenario, especially in the long-term. These trade-offs from energy system measures on the land system are observable both for the Energy Systems Transformation as well as for the NDC scenario mainly in the second half of the century.

When all system transformations are implemented jointly in the Global Commons Stewardship scenario, the BII increases relative to 2015, exceeds the target of 0.8 in 2050 (see Annex 2), and continues to improve throughout the end of the century, largely due the Land Systems Transformation and the complementary benefits of ambitious dietary changes towards healthy nutrition and land-based solutions to mitigate climate change in the land sector. Although current land-based NDCs also slightly counterbalance trade-offs from large-scale bioenergy production that are part of the mitigation measures in the NDC scenario and the Energy Systems Transformation, positive effects on BII are small, and less perceivable than their positive effects on forest cover. The regionally diverse pledges for afforestation and avoided land conversion cannot systematically prevent leakage effects, both in terms of teleconnections and in terms of affected land cover types, resulting in a relative shift from natural to managed forests and loss of non-forested land and pastures, with all described leakage channels negatively affecting biodiversity intactness. Despite small positive effects on forest cover, the resource efficiency subtransformation in the land sector does not improve BII in the first half of the century, due to a stronger expansion of cropland in the wake of livestock system intensification with a higher reliance on cropland-based feed and less irrigation. In the second half of the century, there are, however, small synergies between bioenergy demand and a higher availability of pastures for bioenergy plantations, which averts pressures from natural land cover types and improves BII outcomes, if resource efficiency interventions are applied on top of the Energy Systems Transformation.

The land-based solutions subtransformation is the single most important bundle of measures to foster progress towards the BII target, which more than counterbalances the negative developments under the NPi scenario, stabilising the BII in the first half of the century and slightly bending the curve until the end of the century, regardless of whether the interventions of the Energy Systems Transformation are in place. Since the latter exhibits, as individual strategy, detrimental effects on BII beyond the NPi scenario, the interventions included in the LNDlbs scenario are especially relevant in the context of multi-sector pathways, showing a higher relative improvement of BII in combination with the Energy Systems Transformation compared to effects based on the NPi scenario. Pricing GHG emissions from natural land conversion exert positive impacts on BII especially due to the resulting preservation of remaining primary forests and incentives to curb cropland expansion, which also makes bioenergy production more expensive and somewhat dampens the high demand for biomass from the energy sector. In contrast to land-based solutions, the positive impacts of the food transformation in combination with the Energy Systems Transformation on BII are comparable to its effects as individual intervention and do not moderate bioenergy deployment. The transition to healthy diets and low food waste represents the second most important subtransformation for improving BII, while also substantially slowing down the speed of agricultural intensification and decreasing the size of the livestock sector, with many potential co-benefits on biodiversity beyond those from land use change, such as the use of pesticides and landscape homogenisation, which are not quantified in the here presented work.

The joint implementation of all components of the Land Systems Transformation exhibits a more than additive effect, due to the complementarity of especially the demand-focused diet and food waste measures with the systemic approach of disincentivizing loss of natural terrestrial ecosystems in the LNDlbs scenario and to a certain extent also bioenergy production. The land-based NDCs additionally contribute early action to increase afforestation efforts. The Sustainable Production and Consumption Transformation, applied as the last system transformation, has a positive impact on Land System Change and BII by reducing mitigation pressures in the energy system and thus dependence on bioenergy, as opposed to applying it on top of current policies with little deployment of bioenergy. Finally, following population and GDP growth of the more sustainable socio-economic pathway of SSP1 turns out to have strongest benefits for BII after LNDlbs and LNDfood, mainly due to the lower biomass requirements for food, feed and biomass for energy use.

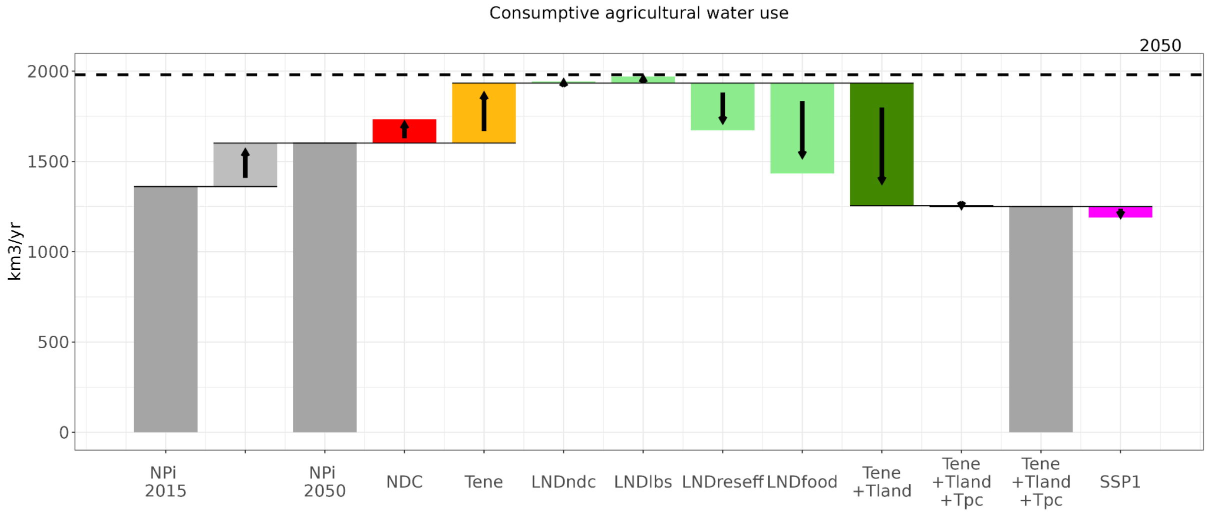

Fig. 6.12: Effects of the combined transformations on Consumptive agricultural water use. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Consumptive agricultural water use

Our analysis shows that changes in consumptive agricultural water use follows a pattern similar to other global indicators that reflect agricultural inputs. For instance, similar to human-induced nitrogen fixation, the Energy Systems Transformation (Tene) without coordinated protections against an over-reliance on bioenergy production will put extreme pressure on the agricultural system to meet climate targets. In this case, consumptive agricultural water use increases by 17% (332 km^3/yr), reaching levels slightly below the prescribed boundary of 1980 km^3/yr. This effect emerges because, despite being limited to rainfed production, bioenergy production displaces food production towards marginal croplands, thus indirectly increasing irrigation to meet food demand. The three land-based subtransformations have strong synergies that, when applied together on top of the Energy Systems Transformation, reduce pressure on the land system such that bioenergy deployment can coexist with food production, and reaching the targets for other global indicators such as biodiversity and forest cover remain possible.

Avoiding negative leakage effects related to bioenergy requires concerted, ambitious, and global efforts to shift patterns of food demand towards sustainable consumption and away from resource and land-intensive production. Livestock production necessitates significant water, both as a primary input to the animals themselves, but also for growing feed crops. Thus, large-scale reduction in livestock consumption reduces two factors responsible for substantial shares of water use. Thus, this transformation is a trade-off free solution to the overconsumption of agricultural water.

Resources efficiency gains, as modelled in the Resource-efficient production systems subtransformation, is another critical component of a Land Systems Transformation respecting boundaries for water use, but suffers a severe negative externality when applied in isolation. This subtransformation introduces critical efficiency improvements, as well as necessary restrictions on environmental flow violations. Thus, it leads to strong reductions in agricultural water consumption. However, when coupled with the Energy Systems Transformation alone, it leads to significant cropland expansion. This is because, if there is no possibility of intensifying food crops, the growing demand for food can only be met by expanding the croplands and relying more on rain-fed rather than irrigated yields.

In 2050, the Land-based solutions (LNDlbs) subtransformation appears relatively unimportant in terms of agricultural water use. If applied in isolation, it would however drastically increase the usage of agricultural water over the second half of the century. The reason is that it introduces a CO_2 price in the agricultural sector that includes emissions from land conversion. Thus, even as demand increases, it is unprofitable to convert forests to cropland, and water use is intensified on existing croplands instead. On the other hand, integrated into the Land Systems Transformation, land-based solutions are critical to balance the Resource-efficient production systems subtransformation.

The integration of all three land-based subtransformations dampens their respective negative side-effects, and successfully offsets the consequences of the Energy Systems Transformation scenario. Water usage reaches levels lower than those seen in 2015, despite the pressure of large-scale bioenergy production on the agricultural system. Even cropland area is held nearly constant from today. Lastly, adopting SSP1 population and GDP trajectories has negligible impact on shifting aggregate water usage.

Although all scenarios fall within the Planetary Boundary in 2050, water availability, and its consumptive use, is heterogeneously distributed. Therefore, in many regions, an unconstrained energy transition will almost inevitably push the availability of water for agriculture below regional thresholds, even if the global boundary is apparently safe from transgression. These regional impacts endanger not only critical ecosystem services but also human health and wellbeing. Thus, incorporating these "regional boundaries" is a necessary step for future research and fundamental for policymakers focusing on regional planning.

Effects on agricultural prices

Although this study focuses on the physical outcomes of the transformations in safeguarding the Global Commons domains, the massive transformations assessed here can have large impacts on agricultural prices, with potentially important consequences for food security and the justice of these transformations. For this reason, we also analyse the effects of the different transformations on an agricultural commodity price index. This is the production-weighted average price index of agricultural commodities (all consumer products, including food and bioenergy) with respect to 2020.

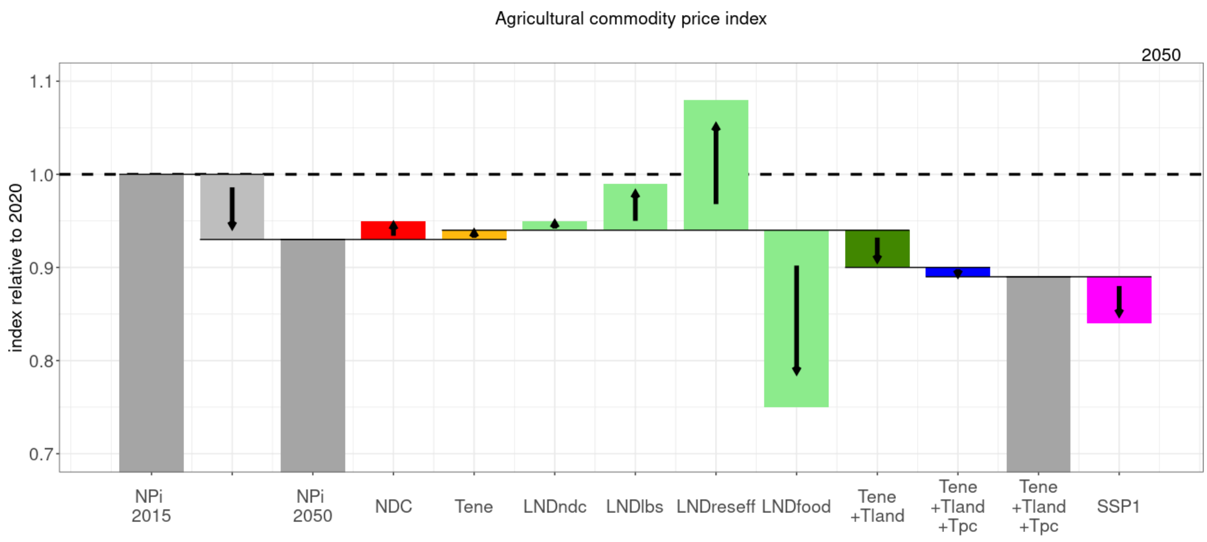

Fig. 6.13: Effects of the combined transformations on agricultural commodity prices. Values are shown for an aggregated price index relative to the year 2020. For comparison, the gray rectangles on the left side show the evolution of the indicator between 2015 and 2050 in the current policies implemented (SSP2-NPi) scenario. The other rectangles represent the decomposition of the effects, relative to the NPi scenario, of the Energy Systems Transformation (yellow), followed by the Land Systems Transformation (Tland, dark green) with its subtransformations (light green) and the Sustainable Production and Consumption Transformation (blue). The grey rectangle on the right side shows the state of the all transformations (SSP2-Tall) scenario in 2050. The magenta rectangle on the right side shows the additional effects of SSP1 assumptions on GDP and population growth.

Due to continued improvements in agricultural technologies, agricultural food prices tend to decline by 2050 in the national policies implemented (NPi) scenario.

Interventions that create additional pressure on the land system tend to increase costs and therefore prices. Consequently, the Energy Systems transformation can have such an effect when the production of bioenergy competes with food production. For the same reason, the nationally determined contributions (NDCs) for decarbonizing energy systems lead to pressure on food prices.

Interventions aimed at protecting land also create pressures on agricultural prices, as they limit the expansion of agriculture. That is the case of the land-based NDCs (LNDndc), which further increase food prices as forested land that could otherwise be converted into cropland is restricted from expansion. Land-based solutions (LNDlbs) is yet more extreme, because it includes a price on CO_2 emissions from the conversion of natural land, as well as more stringent protection of biodiverse regions. These would further reduce the total land available for cropland and pasture expansion.

The Resource-efficient production systems subtransformation shows the largest increase of food prices. This striking result emerges as a price on non-CO_2 GHG emissions is introduced into the agricultural sector, in addition to protections on freshwater environmental flows. Both measures increase the price of food production, especially for livestock products which produce significant non-CO_2 emissions. Protection of freshwater environmental flows, and the subsequent displacement of irrigated areas leads to significant conversion of land to cropland, further increasing food prices.

A key insight from the assessment of the land subtransformation scenarios is that safeguarding the Land Biosphere through supply-side interventions alone will increase the price of food. Only a shift in demand patterns, as assumed in the Sustainable food demand subtransformation (LNDfood), can keep food prices relatively stable at low values over the 21st century. The Sustainable food demand subtransformation, which models an adoption of the EAT-Lancet planetary health diet and halving of food waste, dramatically reduces the environmental impact of peoples' diets by transitioning away from livestock products. But since these products also tend to be the most expensive – in addition to being the most polluting – reducing the share of livestock products leads to large decreases in the price of food by 2050.

Adopting this transition on top of the Energy Systems Transformation and the other Land Systems subtransformations enables significant progress towards the Planetary Boundaries while even slightly decreasing the food prices by around 5% relative to the prices in the national policies implemented (NPi) scenario. This result affirms that the transition towards healthy, affordable diets is one of the most pressing issues for policymakers to address into the 21st century. Only measures targeting shifts to more sustainable diets and reducing food waste will reduce pressure on the land system and create leeway for implementing policies which preserve the long-term health of the Global Commons domains without negatively impacting livelihoods and human wellbeing.

Lower material demands from the Sustainable Production and Consumption Transformation also reduces agricultural prices. Since there's a somewhat heavy reliance on bioenergy on the transformed energy systems, the reduction in industrial demand leads to less pressure on land and ultimately affects prices.

Lastly, adopting SSP1 assumptions for population and GDP expectedly makes a large difference in the agricultural prices, reducing them by more than 5% relative to the All-transformations scenario (that considers SSP2 assumptions). This is largely a consequence of the reduced demand from a population smaller by around 0.5 billion people in 2050. However, it's interesting to note that even this substantial reduction in population has a much smaller effect on food prices than that of shifting to more sustainable food consumption patterns.

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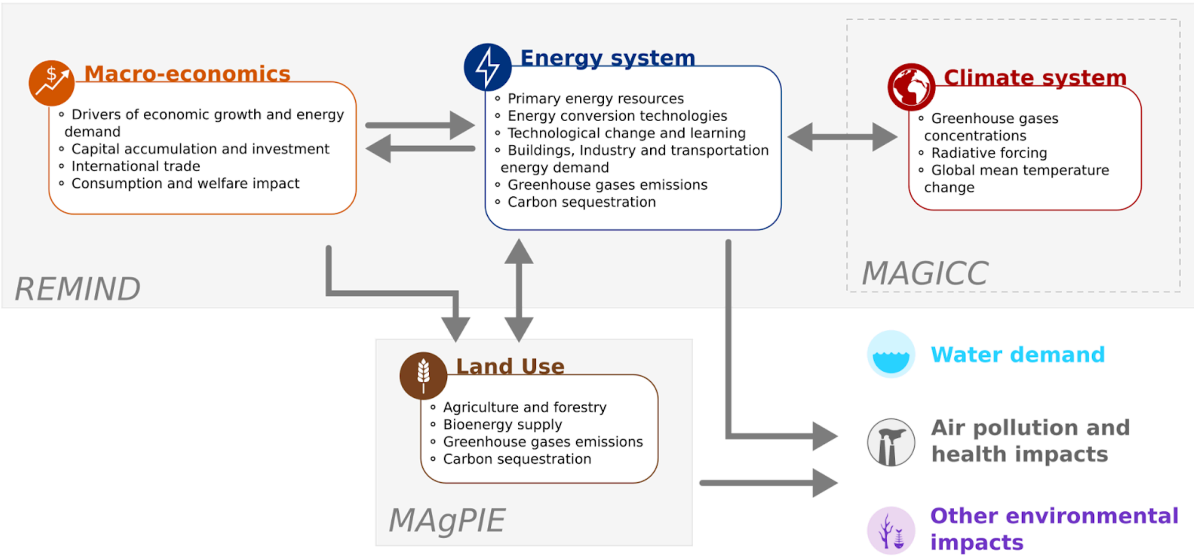
Annex

Annex 1: Model descriptions

We use and extend the PIK integrated assessment modelling (PIAM) framework to simulate the System Transformations, interactions between them, and their impacts on the Global Commons. The core of the framework consists of the energy-economy-climate model REMIND coupled to the spatially explicit land-system model MagPIE. The core REMIND-MagPIE models are complemented by MAGICC, a simple global climate model, and LPJmL, a vegetation and hydrology model.

Here we present brief descriptions of the core REMIND-MagPIE, MAGICC and LPJml models, along with lists of references that provide more detailed descriptions as well as examples of successful applications.



Annex Fig. 1.1: Overview of the modelling framework, showing some of the simulated processes and linkages between models.

REMIND - REgional Model of INvestments and Development

REMIND (REgional Model of Investment and Development) is a numerical model that represents the future evolution of the world economies with a special focus on the development of the energy sector and the implications for our world climate. The goal of REMIND is to find the optimal mix of investments in the economy and the energy sectors of each model region given a set of population, technology, policy and climate constraints. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances. All greenhouse gas emissions due to human activities are represented in the model.

More information can be found in the sources below:

- https://rse.pik-potsdam.de/doc/remind/2.1.3
- https://github.com/remindmodel/remind
- https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND-MAgPIE

- Luderer, G., Bauer, N., Baumstark, L., Bertram, C., et al.: REMIND - REgional Model of INvestments and Development, https://github.com/remindmodel/remind, 10.5281/zenodo.4091409. https://doi.org/10.5281/zenodo.4091409, https://www.pik-potsdam.de/research/transformation-pathways/models/remind
- Baumstark, L., Bauer, N., Benke, et al. (2021). REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. Geoscientific Model Development Discussions, 1–50. https://doi.org/10.5194/gmd-2021-85

MAgPIE - Model of Agricultural Production and its Impact on the Environment

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global partial-equilibrium model used to analyse potential developments in the land system, given different scenarios of socio-economic development and climate change. A spatially-explicit model, it minimises the total costs of the land-use sector (production, investment and transportation) under spatially-explicit biogeophysical constraints, while meeting demand for regional and globally-traded agricultural goods. Demand incorporates country-level food intake, food waste and dietary composition based on projected future scenarios of GDP, demographic structure and population growth. Biogeophysical constraints, e.g. crop yield potentials and water availability, are derived from the dynamic vegetation model LPJmL(Lund-Potsdam-Jena managed Land) on a 0.5°x0.5° grid scale.

More information can be found in the sources below:

- https://rse.pik-potsdam.de/doc/magpie/4.4.0/
- https://github.com/magpiemodel/magpie
- Dietrich J, Bodirsky B, Weindl I, Humpenöder F, Stevanovic M, Kreidenweis U, Wang X, Karstens K, Mishra A, Beier F, Molina Bacca E, Klein D, Ambrósio G, Araujo E, Biewald A, Lotze-Campen H, Popp A (2020). “MAgPIE - An Open Source land-use modeling framework - Version 4.3.0.” doi: 10.5281/zenodo.1418752, https://doi.org/10.5281/zenodo.1418752), https://github.com/magpiemodel/magpie.
- Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., et al. (2019): MAgPIE 4 – a modular open-source framework for modeling global land systems, Geosci. Model Dev., 12, 1299–1317, https://doi.org/10.5194/gmd-12-1299-2019.

MAGICC - Model for the Assessment of Greenhouse Gas Induced Climate Change

MAGICC is a simple/reduced complexity climate model. It consists of a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model. MAGICC has been widely used in various IPCC Assessment Reports.

- Meinshausen, M., Raper, S. C. B., & Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. Atmospheric Chemistry and Physics, 11(4), 1417–1456. https://doi.org/10.5194/acp-11-1417-2011
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LPJmL - Lund-Potsdam-Jena managed Land dynamic global vegetation, hydrology and crop model

The model LPJmL ("Lund-Potsdam-Jena managed Land") is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. Using a combination of plant physiological relations, generalized empirically established functions and plant trait parameters, it simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation and vegetation structure.

- https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml/key-publications#section-0
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Annex 2: Indicators used for the Global Commons domains

Global Commons	Key Indicator	Target 2030	Target 2050	Units	Target source
Climate system	GHG Emissions	37	11	Gt CO_2eq/yr	Defined by our own 1.5°C-compatible pathway (SSP2-Tall)
Cryosphere/Climate	Global Mean Temperature change	1.5	1.5	°C	Paris Agreement
Ocean	Aragonite saturation rate	2.8	2.8	-	Steffen et al. 2015: 80% of pre-industrial value of approximately 3.5
Ozone	Equivalent Effective Stratospheric Chlorine (EESC)	2000	2000	ppt	1980 value, before substantial ozone depletion (Newman et al. 2007)
Land Biosphere	Forest cover	4300	4300	Mha	van Vuuren et al. (2021) target for 2050: 75% of forested land as % of original forest cover. Potential forest cover (without woodlands) taken from the Global Map of Potential Forest Cover. World Resources Institute (Potapov et al. 2021).
Land Biosphere	Yearly natural forest loss (net)	0	0	Mha/yr	van Vuuren et al. (2021) target for 2030: No further primary forest loss
Land Biosphere	Consumptive agricultural water use	1980	1980	km3/yr	Central estimate from Springmann et al. (2018): 1980 (780-3190) km^3
Land Biosphere	Human-induced N fixation	90	90	Mt N/yr	From Soergel et al. (2021). Proxy for nitrogen losses to the environment, representing a driver of ecosystem degradation Fixation as an indicator follows van Vuuren et al. (2021). Quantitative target: adopted from the EAT-Lancet Commission (Willett et al. 2019).
Land Biosphere	Biodiversity Intactness Index	0.8	0.8	-	From Soergel et al. (2021). Adapted from van Vuuren et al. (2021) ("no further degradation"), which we translate into a numerical value of 0.8 based on MAgPIE results

Annex 3: Assumptions and interventions used to implement the system transformations in REMIND-MAgPIE

1. The Energy Systems Transformation (Tene)

Intervention	Description of setting in models
Power	
Decarbonisation of power generation	In the power sector, even low CO_2-prices, consistent with the Paris Agreement only if all other transformations are also achieved, is sufficient to decarbonise the sector by around 2060. Also includes direct air capture (DAC) as an option to abate leftover emissions from all sectors.
Decrease of battery storage costs	Learning for battery storage is considered by default in the model as a response to the CO_2 price.
Improvement of energy efficiency	Energy efficiency (and thus demand) is closely correlated to the CO_2-price: An increasing CO_2-price triggers energy efficiency improvement in all sectors.
Transport	
Improve transport infrastructure	Preference changes and infrastructure availability drive higher adoption of public, shared and non-motorized transport. In conjunction with all other interventions (including GHG pricing) the share of the total distance travelled in trains and non-motorized modes roughly doubles by 2050.
Provide alternatives to car and plane transportation, shifts in preferences	
Foster higher adoption of public, shared and non-motorized transport	
Increased preference for battery electric vehicles	Increased preference for battery electric vehicles (BEVs). The expansion of charging infrastructure is represented indirectly by reducing inconvenience costs as demand for BEvs increase. As a result, almost all Light-Duty Vehicles (LDV) and most trucks are Battery electric vehicles (BEV) in 2050 in a current policy scenario. BEV adoption also responds to changes in fuel/energy prices driven by other interventions.
Use of synthetic gases and liquids as alternative, low-emission fuels.	Increase of use of synthetic gases and liquids as alternative, low-emission fuels. Include CCU as an option for the production of synthetic fuels.

2. The Land Systems Transformation (Tland)

Land-based solutions (LNDlbs)

Intervention	Description of setting in models
Forests	
CO_2 pricing policy on land-use change	Inclusion of CO_2 emissions from conversion of natural land (i.e. forests and non-forest natural vegetation) into the GHG pricing scheme economically dis-incentivises expansion of cropland and other managed land

Peatland protection	Inclusion of GHG emissions from degraded peatlands into the GHG pricing scheme dis-incentivises further degradation of intact peatlands. *(for more information on peatland protection in MAgPIE see Humpenoeder et al. 2020)*
Protection of biodiversity hotspots	The land protection scheme covers all natural landscapes within areas that were classified by Conservation International (CI) as biodiversity hotspots (high prevalence of endemic species, whose native habitat has already been lost by 70%). *(for more information on the protection of biodiversity hotspots in MAgPIE see Kreidenweis et al. 2018)*
Afforestation	The GHG pricing scheme incentivises afforestation as a land-based mitigation measure, which is restricted to the tropics due to albedo effects. Moreover, afforestation is confined to a global maximum of 500 Mha and the application of native species, motivated by broader sustainability considerations.
Restoration of peatlands	Rewetting of drained peatland is considered as a land-based mitigation measure and incentivised by GHG pricing, where the GHG emission reduction between the degraded and rewetted state is rewarded. *(for more information on peatland restoration in MAgPIE see Humpenoeder et al. 2020)*
Protection of forests from shifting agriculture	Damage from shifting agriculture to natural forests is assumed to be prevented from 2030 onwards.
Food	
Investments in research and development in the agricultural sector	Resource scarcity and demand pressure increase the incentives to invest into agricultural research and development (R&D) that foster crop yield gains. Land protection and GHG pricing policies can increase land scarcity, thereby also strengthening efforts to improve crop yields and increase crop production without land expansion. (*for more information on R&D investments in MAgPIE see Dietrich et al. 2014)*

Sustainable food demand (LNDfood)

Food	
Reduction of food waste	Regional per-capita food waste is reduced to a maximum of 50% the currently observed levels in high income regions until 2050.
Dietary transition towards the EAT-Lancet diet and daily per-capita kcal consumption consistent with a healthy body weight	Diets change gradually towards healthy dietary patterns, which are characterized by a shift from resource-intensive animal-source foods to plant-based products associated with lower environmental impacts and by an increasing share of healthy foods like fruits, vegetables, and nuts, as proposed by the EAT–Lancet Commission. *(see Willett et al. 2019)* Total daily per-capita kcal consumption of different population sub-groups converges to levels consistent with a healthy body weight.

Ressource-efficient production systems (LNDreseff)

Food	
Intensification of livestock production systems	Strong increase of livestock productivity results in improved feed efficiencies in five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens). *(for more information on the livestock sector in MAgPIE see Weindl et al. 2017a, b)*
More efficient animal waste management systems	Improved management of manure leads to a lower share of nutrients that are lost due to volatilization and denitrification, a higher share of recycled nutrients, and lower non-CO_2 emissions. *(see Bodirsky et al. 2012)*
Improved nitrogen use efficiency	Efficient fertilization and associated increased soil nitrogen uptake efficiency, converging to 75% by 2050, reduces excessive nitrogen from agricultural systems and related negative impacts on terrestrial and aquatic ecosystems as well as N2O emissions. *(for more information on efficient fertilization as a measure to mitigate nitrogen pollution in MAgPIE see Birdirsky et al. 2014)*
GHG policy pricing agricultural non-CO_2 emissions	A GHG pricing scheme targeting agricultural non-CO_2 emissions economically incentivises investments into technical measures to reduce N20 and CH4 emissions from agriculture, e.g. feed additives. *(for more information on the abatement of agricultural non-CO_2 emissions in MAgPIE see Stevanović et al. 2016)*
Phase out 1st generation bioenergy	First generation bioenergy production is gradually phased out between 2020 and 2050 *(for more information on the default scenario trajectory for first generation bioenergy (based on currently established and planned bioenergy policies), on which the phase-out is applied see Lotze-Campen et al. 2014).*
Freshwater Management	
Protection of environmental flow requirements	The water protection scheme reserves a certain fraction of locally available freshwater, which is needed to preserve freshwater-dependent ecosystems. The high- and low-flow requirements on which the parametrization of the protection scheme is based are selected to maintain freshwater-dependent ecosystems in an at least "fair" condition (Smakhtin, Revenga, and Döll 2004). *(for more information on the protection of environmental flow requirements in MAgPIE see Bonsch et al. 2015).*
Improved nitrogen use efficiency	See description above. Measures to mitigate excessive nitrogen from agricultural systems reduce the influx of nitrogen into rivers and lakes, a driver of water pollution, and improve water quality.
Protection of environmental flow requirements	See description above.
Increase in irrigation efficiency	Water management in agriculture can be improved by increasing the ratio of withdrawn water that reaches the plants, by reducing losses in conveyance systems and from application to the field. *(for more information on irrigation efficiency in MAgPIE see Schmitz et al. 2013).*

3. The Sustainable Production and Consumption Transformation (Tpc)

Intervention	Description of setting in models
Increasing material efficiency in production	More efficient use of materials in industry, less waste in production and extended lifetimes of products lead to reductions in total material demand for steel and cement by 77% and 20% respectively. These reductions are gradually achieved between 2020 and 2050.
Change in consumption patterns	Changes in consumption patterns, including the move towards a more sharing and circular economy, lead to reductions in total material demand for steel and chemicals (which includes plastics) by 10% and 32% respectively. These reductions are gradually achieved between 2020 and 2050.