NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices

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Executive Summary

Large-scale implementation of land-based negative emission technologies and practices (NETPs) such as Bioenergy with Carbon Capture and Storage (BECCS) and afforestation is commonly projected in economically-optimized climate change mitigation scenarios, but might shift anthropogenic pressures to the biosphere. Our previous analysis (D3.2) demonstrated that conversion of (semi-)natural land to NETPs would further undermine terrestrial planetary boundaries (freshwater use, nitrogen flows, land-system change and biosphere integrity), i.e. other crucial dimensions of Earth system stability next to climate change. To prevent such further deterioration of an already stressed biosphere, a fundamental transformation of the food system to reduce agricultural land requirements is essential, thereby enabling land-based NETPs within current land use bounds.

In this context, diet changes towards less livestock products are promising, as large reductions in pasture area could be achieved while at the same time not counteracting food security, especially if accompanied by increases in healthy plant-based products. To contribute to developing future land use pathways which deliver maximum gain with regard to a multidimensional sustainability space, we here systematically analyze carbon dioxide removal (CDR) potentials on pastures in line with potential reductions in grazing areas upon global transition to a sustainable diet (EAT-Lancet planetary health diet). Differentiating between conversion to either biomass plantations for BECCS or reforestation, we concurrently assess the impacts of such large-scale pasture rededication on (i) agricultural resource demand, (ii) local water stress and (iii) terrestrial planetary boundaries. For the latter, we here focus on freshwater use, nitrogen flows and land-system change, while the D3.3 report complements the analysis with an in-depth assessment of impacts on biosphere integrity.
For spatially-explicit quantification of both CDR potentials and interconnected impacts, we employ the dynamic global vegetation model LPJmL with simulation of coupled carbon, water and nitrogen fluxes and pools for both natural vegetation and agricultural areas. Building on the model developments of LPJmL5-NEGEM (see D3.1 and D3.2), the representation of biomass plantations has been enhanced to enable, amongst others, differentiation between three management intensities (intensive, moderate, minimal) in terms of irrigation and fertilizer application as well as resulting impacts on yields, water flows and the nitrogen cycle.

Based on spatially-explicit simulation of grazing dynamics, we estimate that reduced grazing demand in line with a transition to the EAT-Lancet planetary health diet could reduce global pasture area by ~800 Mha for either assisted regrowth of natural forests or conversion to biomass plantations for BECCS. Area rededications of such extent would correspond to ~25% of current pasture area and compare to ~50% of current arable land.
Conversion of these areas to biomass plantations for BECCS is simulated to remove ~14.4 $GtCO_2eq\ yr^{-1}$ (9.7-18.5) for a biomass-to-electricity conversion, or ~8.9 $GtCO_2eq\ yr^{-1}$ (5.9-11.3) for a biomass-to-liquid conversion. The latter aligns with the median BECCS rates simulated in economically optimized climate stabilization scenarios included in IPCC's AR6 for the year 2100, which may however also include BECCS based on other feedstocks than dedicated plantations.
Such large-scale expansion of biomass plantations would however result in a drastic increase in global fertilizer application (~+60%) and irrigation water withdrawals (~+15%), assuming moderate management intensity on plantations, thereby creating a strong competition for agricultural resources with potentially severe impacts on food security. As a result of the increased water withdrawals for irrigation on biomass plantations, areas under high water stress are simulated to increase by ~40% at the global level. These socio-economic impacts on water and food security are accompanied by increases in areas with transgressions of environmental boundaries for nitrogen and water (by ~50% and ~45%, respectively). Both CDR levels and impacts strongly depend on the management on biomass plantations, underscoring the challenging trade-off between CDR provision and other sustainability goals: Increased irrigation and fertilization can enhance CDR but could exacerbate pressures on resource demand, water stress and environmental boundaries. Minimal management, i.e. assuming rainfed and

unfertilized plantations only, reduces global CDR by one third but may mitigate most, albeit not all, side-effects – yet, requiring strong and comprehensive political regulations.

Reforestation on pastures provides less CDR per rededicated pasture area than BECCS, with a simulated CDR of ~4.3 $GtCO_2eq\ yr^{-1}$ for pasture area reductions in line with a full transition to the planetary health diet. This corresponds to roughly half of estimated maximum CDR potential from reforestation found in literature, but exceeds median net CDR rates on managed land projected for 2050 in economically optimized climate stabilization scenarios included in IPCC's AR6 that mostly assume less stringent transformations of the food sector. While the simulated aboveground carbon accumulation rates upon forest regrowth in this assessment are well validated against literature, soil carbon increments are highly uncertain and may be underestimated here. Also, the yearly sequestration rate refers to a 30-year timeframe of regrowth, emphasizing the limited carbon storage potential in forests with decreasing CDR rates over time until eventual saturation of the forests' CO_2 sink, as well as potential risks of sequestered CO_2 being released back to the atmosphere due to natural disturbances, amongst others.
In contrast to BECCS, however, reforestation would not increase pressures on water stress and environmental boundaries for nitrogen and water. On the contrary, reforestation on pastures would serve both climate stabilization and nature restoration, thereby synergistically contributing to getting back into a safe operating space with regard to multiple planetary boundaries. As shown here, both the Amazon and the African rainforest would be shifted back into a "safe" zone of forest cover, as the control variable for a planetary boundary for land-system change. Similarly, the complementary report D3.3 shows significant benefits for biosphere integrity. The combination of diet changes with reforestation on spared land may thus provide an important cornerstone for contributing to both international targets of nature restoration (e.g. the Kunming-Montreal Biodiversity Framework; the Bonn Challenge to restore 350 Mha of forests; the three billion tree pledge in the context of the EU) and climate stabilization (i.e. the Paris Agreement), without negatively impacting food availability.

Overall, our results underpin that reducing land use within the food system may enable high CDR potentials, making diet changes to fewer animal products an effective strategy for mitigating climate change. Expanding the focus beyond the carbon cycle, our results also stress that a multidimensional perspective on sustainability and Earth system stability favors reforestation on pastures, at least when talking about large-scale conversions and if extensive management on biomass plantations cannot be ensured globally. While the analysis shows the strong dependence of land-based CDR potentials on a sustainability transformation of the food system, large-scale diet shifts or other land-sparing measures would require collectively coordinated efforts of high ambition. With regard to diet changes, the current trend points to the opposite direction, i.e. increases in livestock consumption at the global level, and would require strong engagement from countries with above-average consumption of livestock products, among them many EU countries.

With regard to climate stabilization, risk minimization within multi-dimensional sustainability calls for rapid and stringent decarbonization with overall minimal reliance on CDR as (i) BECCS from dedicated plantations might have severe side-effect even if realized within current land use bounds, (ii) biogenic carbon storage, amongst others in forests, is reversible and limited and (iii) other novel NETPs such as Direct Air Capture or enhanced weathering might be difficult to upscale.

Our results emphasize the importance of multi-dimensional sustainability assessments for CDR and land use strategies in the EU and beyond, considering all planetary boundaries as well as socio-economic effects. Development pathways would thus need to integrate urgently needed (i) food system transformations, (ii) nature restoration as well as (iii) climate stabilization. For this, the global perspective outlined in the presented report needs to be combined with analyses on the specific conditions within EU countries as aimed for within the NEGEM project.

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1 Introduction

Climate stabilization might require, in addition to rapid and stringent decarbonization, large-scale carbon dioxide removal (CDR) as simulated in most economically optimized mitigation scenarios (IPCC, 2022). Land-based negative emission technologies and practices (NETPs) such as Bioenergy with Carbon Capture and Storage (BECCS) and afforestation might however shift anthropogenic pressures to the biosphere (Creutzig et al., 2021; Creutzig et al., 2015; Heck et al., 2018; Humpenöder et al., 2018; IPCC, 2019a). While contributing to climate stabilization, conversion of (semi-)natural land for CDR would further undermine terrestrial planetary boundaries, i.e. other dimensions of Earth system stability, as shown in our previous analysis (D3.2; Braun, Werner, et al. (2022)). This comes at the backdrop of a global biodiversity crisis (IPBES, 2019) and the international call for increased protection and restoration of nature as agreed upon e.g. in the recent Kunming-Montreal global biodiversity framework. Considering that extractive human land use is already the major cause for planetary boundaries transgressions (Benton et al., 2021; Campbell et al., 2017), land-based CDR which does not add pressures on the biosphere requires transformations in the food system to free up land for climate stabilization within current land use bounds (see D3.2).

Providing sufficient food for an additional 2 billion people until 2050 without *increases* in agricultural land and resource use is however already a significant challenge in itself. Any rededication of cropland is particularly difficult to reconcile with food security, as arable land demand may rather increase in most world regions even assuming sustainable intensification and yield increases (Bajželj et al., 2014; FAO, 2018; Tilman et al., 2011). Not expanding cropland areas for food production within the next decades thus already implies highly ambitious political and technological efforts. Global pasture area, covering twice as much land as cropland (Klein Goldewijk et al., 2017), has however started to decline by ~200 Mha between the years 2000 and 2020 (FAO, 2023a) and may potentially further decrease significantly in future through (i) increased efficiency in husbandry (Kalt et al., 2020) and (ii) possible diet changes towards less livestock products (Bajželj et al., 2014; Braun, Stenzel, et al., 2022; Hayek et al., 2021; Smith et al., 2013; Stehfest et al., 2009; Theurl et al., 2020; Wirsenius et al., 2010). Grazing intensification on some pastures to spare others has thus been shown to exhibit significant potentials to free up pastures potentially usable for CDR (Kalt et al., 2020), but increased grazing and potentially overgrazing may have adverse impacts on soil carbon pools (Bai & Cotrufo, 2022).

Diet changes have been identified as a major factor influencing future land-based CDR potentials (Erb et al., 2012) and may be particularly promising given the (i) large pasture reduction potentials (Stehfest et al., 2009; Wirsenius et al., 2010) and (ii) the potential co-benefits for terrestrial planetary boundaries, as well as water and food availability (Braun, Stenzel, et al., 2022; Cassidy et al., 2013; Foley et al., 2011; Gerten et al., 2020; IPCC, 2019a). Regarding the latter, dietary changes toward less livestock products are recognized as one important cornerstone for increasing food availability vis-à-vis limited resources given the unfavourable resource conversion efficiency from plant matter to animal products (several feed calories are needed to produce one calorie of animal product; Foley et al. (2011); Berners-Lee et al. (2018); Godfray et al. (2010)). If accompanied by increases in healthy plant-based products and more distributional justice, such diet shifts may thus contribute to achieving food security. Jointly addressing multiple sustainable development goals (SDGs), a planetary health diet has been proposed by the EAT-Lancet commission which is designed to meet the daily nutritional requirements of individuals while at the same time contributing to planetary health, i.e. compliance with planetary boundaries. Emphasizing the consumption of plant-based products (including whole grains, fruits, vegetables, nuts and legumes), while reducing the intake of animal-based foods (particularly red and processed meat), a global transition to such a diet could benefit both health and environment (Springmann et al., 2016; Willett et al., 2019) thereby unlocking synergies with multiple SDGs (Chen et al., 2022).

In the context of CDR, land sparing compatible with such a diet transition may allow for conversion of pasture areas to provide CDR without increasing anthropogenic land use nor compromising food availability. Nevertheless, rededication of large areas to competing uses (rewilding; biomass plantations for BECCS) has to be carefully evaluated with regard to potential CDR, impacts on planetary boundaries, water stress as well as resource competition with the food system. Numerous studies estimated climate change mitigation potentials from food system transformations, including diet changes, and resulting potentials for regrowth of natural vegetation on freed land (e.g. Hayek et al., 2021; Herrero et al., 2016; IPCC, 2022; Stehfest et al., 2009; Theurl et al., 2020). Also, there have been a range of studies with integrated assessment models investigating future climate change mitigation scenarios under more sustainable food systems (e.g. Humpenöder et al., 2022; Soergel et al., 2021). Yet, to our knowledge there is no global study with systematic comparison of competing uses on pastures in terms of CDR contribution and interconnected impacts, grounding on detailed process-based representation of the biosphere. To contribute to developing future land use pathways, which deliver maximum gain with regard to a multidimensional sustainability space, a systematic analysis on CDR potentials on pastures and the resulting socio-economic and environmental impacts is however crucial. This report therefore seeks to answer the following questions:

1) How large are CDR potentials from rededicating pastures to biomass plantations for BECCS or reforestation, assuming pasture area reductions in line with a full or partial transition to the EAT Lancet planetary health diet?
2) What would be the resulting impacts of these pasture conversions on agricultural resource demand, terrestrial planetary boundaries and water stress?

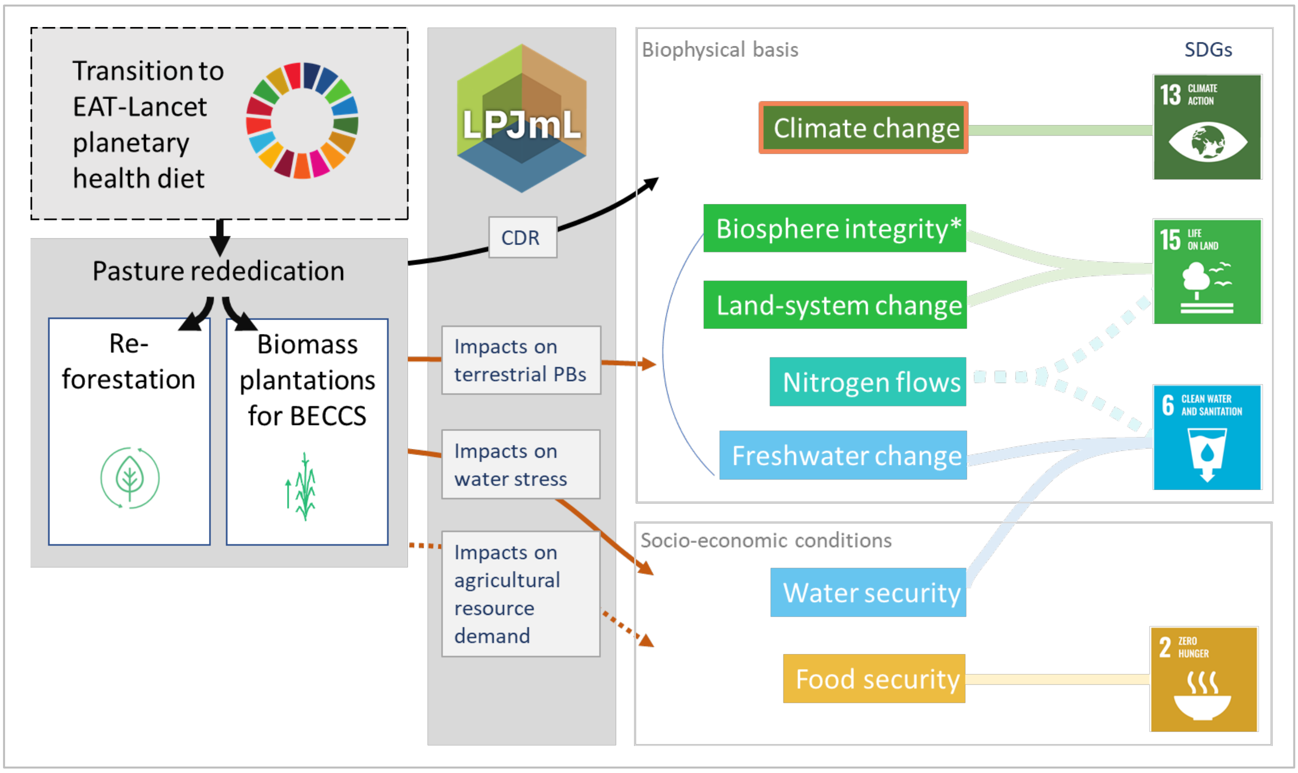

*Figure 1: Overview on study design and the addressed sustainability dimensions. Interactions between the analyzed planetary boundaries (CDR for climate stabilization; impacts on terrestrial planetary boundaries) and SDGs are visualized with connecting lines (direct connections with SDG targets are shown with solid lines, indirect connections with dotted lines). *Impacts on biosphere integrity are analyzed in D3.3.*

We employ the dynamic global vegetation model LPJmL (Schaphoff, von Bloh, et al., 2018; von Bloh et al., 2018) to simulate spatially explicit effects of pasture rededication on coupled carbon, water and nitrogen fluxes and pools. This allows for both process-based simulation of net CDR volumes (see 3.1) and interconnected impacts (see 3.2, 3.3 and 3.4). We differentiate between pasture reductions compatible with a full as well as partial transition to the EAT Lancet planetary health diet and a conversion to biomass plantations for BECCS with either minimal, moderate or intensive management intensity and reforestation. The latter is here defined as assisted regrowth of natural vegetation for restoration of natural carbon pools, acknowledging that carbon accumulation in natural forests is likely higher over the long-term and more resilient to changing climate conditions as compared to forest plantations (Erb et al., 2018; Lewis et al., 2019). In line with a “food first” paradigm, we assume that sustainable intensification and the assumed diet changes are sufficient to increase food production on remaining agricultural areas to feed a growing world population. Yet, to evaluate potential indirect effects on food security via resource competition, we analyze changes in demand for arable land, fertilizer and irrigation water implied by the pasture rededication scenarios (see 3.2).

As a central element for human prosperity, the report then focuses on potential changes in water stress, with water security as a core SDG (see 3.3). Building on the analysis of socio-economic impacts, the impacts on terrestrial planetary boundaries are evaluated (see 3.4 and Figure 1 for interconnections with SDGs). Planetary boundaries aim to delineate a safe operating space for humanity by defining limits to human alteration of nine key Earth system processes (Rockström et al., 2009b; Steffen et al., 2015). Next to e.g. climate change, as a core boundary which is clearly transgressed, four main terrestrial planetary boundaries have been proposed, amongst others for freshwater use, biogeochemical flows (nitrogen and phosphorus), land-system change and biosphere integrity. The latter is recognized as a second core planetary boundary for Earth system stability (Steffen et al., 2015) and D3.3 (Werner et al., 2023) extensively discusses metrics to compute related impacts. As a complement to this in-depth analysis for impacts on the biosphere, we here focus the analysis on freshwater use, nitrogen flows and land-system change and their respective sub-global definitions. With planetary boundaries building the biophysical foundation for achieving SDGs, including water and food security, the scenarios’ synergies and trade-offs are discussed to evaluate their impact with regard to multidimensional sustainability.

2 Methods

After a description of LPJmL as the modelling basis (see 2.1), we detail how we derive spatially explicit pasture rededication scenarios corresponding to full or partial transition to the EAT Lancet planetary health diet (see 2.3). We further specify both the calculation of net CDR and the analysis of impacts on water stress and three terrestrial planetary boundaries (see 2.5).

2.1 LPJmL

[The contents of this section are identical to those of the corresponding section in the complementary Deliverable 3.3]

For the quantification of CDR potentials and environmental impacts, we apply the dynamic global vegetation model (DGVM) LPJmL, a well-established tool to assess climate and land use change impacts on the terrestrial biosphere, agricultural/biomass production, as well as the carbon, nitrogen and water cycle (Schaphoff, von Bloh, et al., 2018; von Bloh et al., 2018). LPJmL represents biogeochemical processes of the biosphere at a daily time step and a spatial resolution of 0.5° x 0.5° in a process-based, spatially-explicit manner (Figure 2). In our analysis, we employed the LPJmL5-NEGEM version, which was prepared in subtask 3.1.1 as detailed in D3.1 and further adapted for fertilization dynamics on biomass plantations for the assessments in D3.2. Since the latter report, we have revised the parametrization of herbaceous biomass plantations to better reflect key aspects of plant physiology and nitrogen recovery (see Text S1 and corresponding Table S 1). Note that these model improvements and other crop calibration in LPJmL are based on current crop performance and do not represent new breeds, emerging farming technologies or precision agriculture. For further information on the representation of biogeochemical dynamics and their validation, please refer to Schaphoff, von Bloh, et al. (2018), Schaphoff, Forkel, et al. (2018) and von Bloh et al. (2018).

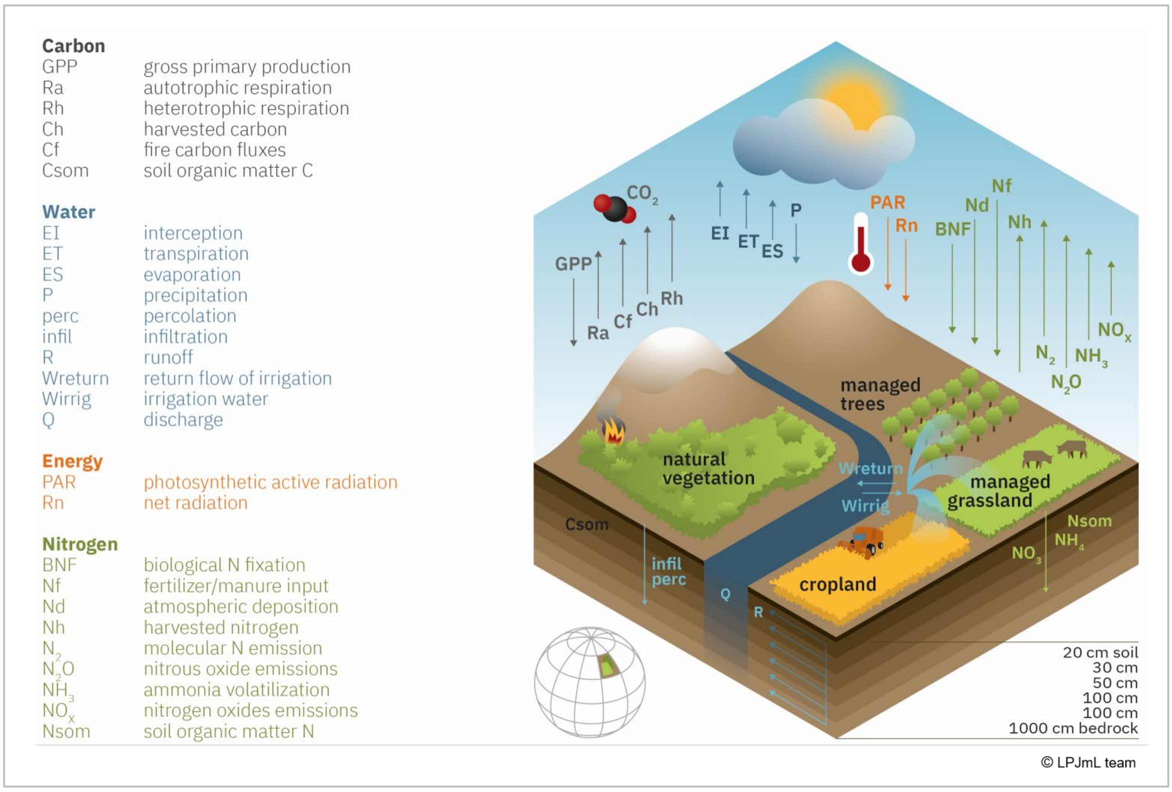

Figure 2: Schematic illustration of major processes represented in LPJmL.

LPJmL simulates key ecosystem functions of vegetation through representing 11 natural plant functional types (PFTs), 13 crop functional types (CFTs) including managed grassland, and three fast-growing second-generation energy crops. These bioenergy functional types (BFTs) are further categorized as herbaceous type (fast-growing perennial grass parametrized based on observations for Miscanthus) and woody types (eucalypt, poplar, and willow based on the climate zone).

While the model simulates competition among natural plant functional types (PFTs) for light, water and nutrients, the distribution of crops and pasture is determined by a scenario-specific land use input that specifies the extent of irrigated versus rainfed areas. Irrigation water demand is internally computed for each cell and crop functional type (CFT) based on soil water deficit, with withdrawals from local renewable freshwater resources (river discharge, lakes and reservoirs) taking into account inefficiencies of prescribed irrigations systems (surface, sprinkler or drip irrigation) and constraints of local water availability after reductions through water withdrawals for households, industry and livestock (Jägermeyr et al., 2015). While the soil water deficit is dynamically modelled depending on daily climate input, soil type and crop species, the inefficiency of drip, sprinkler or surface irrigation systems is assumed to be fixed.

LPJmL5-NEGEM further includes a representation of the nitrogen cycle that considers nitrogen-limited plant growth and ecosystem productivity by adjusting photosynthesis and respiration rates depending on the availability of nitrogen (von Bloh et al., 2018). The plant’s uptake of nitrogen is determined by soil mineral nitrogen concentrations, soil properties, fine root mass, and plant demand for nitrogen. Inputs to the nitrogen pools in the soil (NO_3^- and NH_4^+, and nitrogen of soil organic matter) are generated by decomposition of plant biomass, biological nitrogen fixation, atmospheric deposition and fertilization, the latter being prescribed by the input data for the scenario. By dynamically simulating the major flows of nitrogen, the model accounts for the mineralization of soil organic matter, immobilization, (de-)nitrification, and plant uptake within the nitrogen pools and represents losses to the atmosphere through (de-)nitrification or volatilization, as well as nitrate losses to renewable freshwater resources in runoff and leaching.

2.2 Diet Change Scenarios

To estimate possible reductions in pasture extent in line with a global transition to the EAT Lancet planetary health diet, we first calculate the global proportion by which current grass feed could be reduced. Based on spatially explicit simulation of livestock densities and grazed biomass in LPJmL, we then rededicate current pasture areas to either biomass plantations or reforestation so that the rededicated areas correspond to the calculated grazing reduction.

(i) Reduction in grazed biomass corresponding to the EAT Lancet planetary health diet

At the global level, the EAT Lancet diet implies a 70% reduction in ruminant meat consumption ($target_{meat}$) and an 8% increase in milk consumption ($target_{milk}$) in comparison to current consumption levels as reported by FAO for 2017 (FAO, 2023b; Willett et al., 2019). However, globally grazed biomass contributes significantly more to meat than to milk production: 70% of global grass feed is used for ruminant meat production ($grass\_share_{milk}$) and only 30% for milk production ($grass\_share_{meat}$) (Herrero et al., 2013). The global proportion by which current grass feed could be reduced is then calculated by weighting the changes in ruminant meat and milk consumption with the contribution of global grass feed to milk and meat production:

$$Grass\_reduction = target_{milk} * grass\_share_{milk} + target_{meat} * grass\_share_{meat}$$

This results in 46% reduction in grass feed implied by a shift from current consumption patterns to the EAT Lancet diet (referring to dry matter). In addition to a scenario where the transition to the EAT Lancet diet is fully achieved (DC100), we also simulate scenarios with only partial transition to an EAT Lancet diet, i.e., where only half (DC50) or a quarter (DC25) of the grazing reduction is achieved (see Figure 3). Note that a reduction in ruminant meat and milk production would also imply reductions in crop feed, as mixed crop-livestock systems are more common than grazing systems (Herrero et al., 2013). We did not explicitly account for these additionally spared cropland areas for feed production, but instead implicitly assumed that these areas will contribute to increasing production of plant-based products for a growing population. Also, we did not explicitly simulate changes in animal- and plant-based products for the EAT-Lancet diet beyond changes in ruminant products as our study focuses on potentials on current pastures.

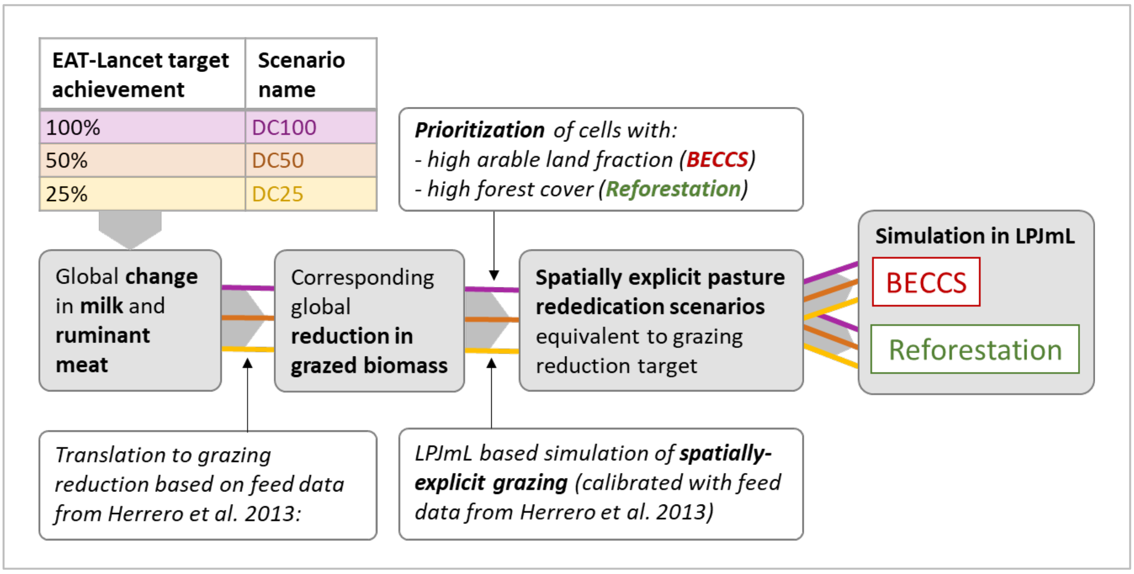

*Figure 3: Overview on the approach to generate spatially-explicit scenarios of pasture conversion to either biomass plantations for BECCS or reforestation. For BECCS scenarios, each DC (**d**iet **c**hange) scenario is simulated for three different management intensities on biomass plantations (see Table 1).*

(ii) Spatially-explicit simulation of grazing in LPJmL

Recently, LPJmL has been expanded with a livestock module which simulates impacts of grazing on the carbon and nitrogen cycle by accounting for both feed quantity and quality (Heinke et al., 2022). Spatially-explicit livestock densities can be prescribed and have been derived from Herrero et al. (2013), who provide grass use data for 29 world regions partitioned into 8 livestock production systems. For each production system in a world region, the livestock density was calibrated so that simulated grazed biomass best matches the data from Herrero et al. (2013) in the year 2000.

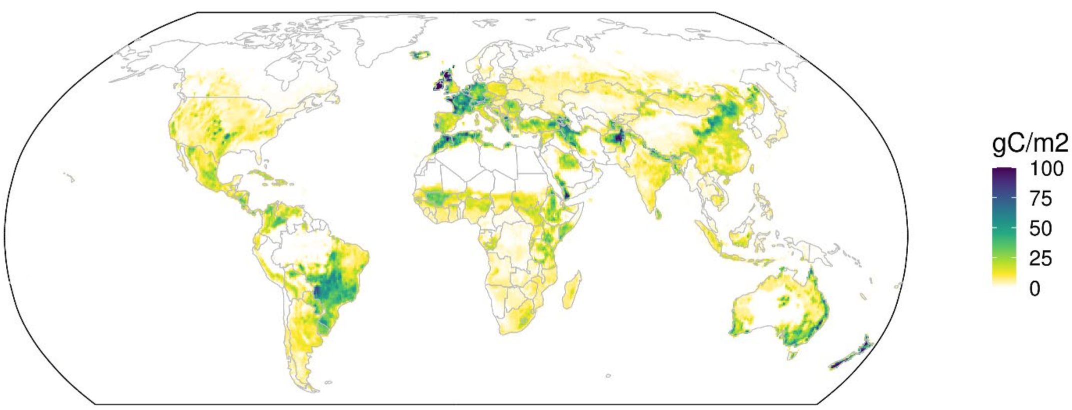

Figure 4: Simulated annual uptake of carbon from livestock on pastures for 2017 land use and climate. The legend was cut at 100 gC m^{-2} for better visualisation.

Resulting simulated grazing intensities are shown in Figure 4, with particularly high grazing rates in Brazil's Cerrado, parts of Europe, amongst others Ireland, Western Asia, South-Eastern Australia and New Zealand. Globally, simulated grazed biomass amounts to 2.6 Gt dry matter for the pasture extent in 2017 (assuming a carbon content of 0.424 (Heinke et al., 2022)), which is in good agreement with the 2.3 Gt dry matter estimated in Herrero et al. (2013) for 2000.

2.3 Spatially explicit pasture rededication scenarios

We simulate rededication of current (2017) pasture extents corresponding to the calculated potential grazing reduction upon diet change. In this, we rely on the simulated spatially explicit grass feed uptake to account for the fact that rededication of pastures with high grazing rates would result in stronger feed and thus animal product reductions than rededicating the same area within a minimally grazed rangeland. Thus, a grazing reduction by 46% must not equal a reduction in pasture area extent by the same proportion. Cells for pasture rededication are prioritized according to different storylines for the BECCS and reforestation scenarios, which are described in the following. Additionally, we describe the management scenarios for biomass plantations as well as the calculation of net CDR for both BECCS and reforestation.

2.3.1 BECCS

Prioritization scheme for pasture rededication

For conversion to biomass plantations, we prioritize pastures in cells with highest cropland fraction. This mirrors the high infrastructure needs for transport and processing of biomass for BECCS and the resulting economic advantages of building upon existing infrastructure. Additionally, a high cropland fraction indicates agro-ecological suitability for growth of bioenergy crops. Rededication of pastures thus starts in cells with the highest cropland fraction and then continues iteratively for the cells with the next highest share. This procedure stops when cumulative grazed biomass within all rededicated cells corresponds to a reduction in grazing in line with the diet change scenario.

Management scenarios for BECCS from dedicated biomass plantations

We assume herbaceous biomass plantations because the current representation in LPJmL suggests that the herbaceous BFT has a considerable economic advantage over the woody type, owing to its higher yields and capacity for annual income generation. To capture the importance of water and nutrient management on plantations for both CDR and impacts, we developed three management scenarios spanning the range from intensive to moderate and minimal management intensity (see Table 1). Each of the EAT-Lancet achievement scenarios (DC100, DC50, DC25) is combined with each of these management scenarios, resulting in overall nine BECCS scenarios.

Table 1: Management scenarios for BECCS. CO_2 removal efficiency refers to losses along the BECCS supply chain (see D3.2) for either a biomass-to-electricity (B2E) or biomass-to-liquid pathway (B2L). N = Nitrogen.

management scenario	irrigation	fertilization	CO_2 removal efficiency	
			B2E	B2L
intensive	irrigation share as for crops, but min. 30% of rededicated cell area	2 x N harvest under unlimited N conditions	0.923	0.669
moderate	irrigation share as for crops, but max. 30% of rededicated cell area	1 x N harvest under unlimited N conditions	0.836	0.603
minimal	rainfed	0	0.795	0.583

With regard to irrigation, we assume surface level irrigation to reduce simulated losses through evaporation compared to sprinkler systems, which would be economically less viable for species with high leaf cover like Miscanthus. Furthermore, irrigation is only allowed in cells where it would increase the yield by at least 30% in all scenarios. This excludes irrigation on 9% of global pasture areas. In all other cells, we set the cell-specific share of irrigated biomass plantations in the *moderate* management scenario to the average irrigation share across all crops within the same cell, but to maximum 30%. This mirrors current irrigation infrastructure and needs, while at the same time assuming that irrigation of food crops remains the priority. In the DC100 scenario, this corresponds to a mean irrigation share over all rededicated cells of 7%. In contrast, for the *intensive* management scenario, we assume the same irrigation share as for crops within the same cell but at least 30% of biomass plantation area as suggested for the irrigation scenario in Stenzel et al. (2021). This reflects a world with strong expansion of irrigation infrastructure to boost yields and corresponds to a mean irrigation share on biomass plantations of 25% across all rededicated cells in the DC100 scenario. Finally, the *minimal* management scenario assumes rainfed plantations only.

For fertilization, the application rates of nitrogen on biomass plantations were obtained from a preparatory LPJmL simulation of nitrogen harvest on biomass plantations under unlimited nitrogen supply (see Table 1). In the scenario of *moderate* management intensity, the rate of nitrogen fertilization was set to the cell-specific harvested nitrogen in this preparatory run, assuming that removed nitrogen has to be replenished by fertilizer to maintain nitrogen reserves within the soil. This approach is in line with recommendations for Miscanthus' nutrient requirements within the literature (Cadoux et al., 2012). The thus obtained median nitrogen fertilization rate across cells with available data from an extensive dataset with Miscanthus site studies (98 kg N/ha for rainfed and 116 kg N/ha for irrigated) is comparable to the median fertilizer applications reported (90 kg N/ha) for these site studies (Li et al., 2018). For an *intensive* management intensity, we assume fertilizer applications equalling twice the nitrogen harvest from the preparatory run for a scenario aiming to boost yields while neglecting resulting higher nitrogen losses to the environment. Based on the highest fertilization rate found for Miscanthus in Li et al. (2018), we however capped the cell-specific fertilizer rates at a maximum of 280 kg N/ha in all scenarios. As there have been mixed results on the fertilizer response of Miscanthus, with some studies showing no effect, no nitrogen fertilizer application is assumed under *minimal* management intensity. This however implies tolerating decreases in soil nitrogen reserves leading to soil degradation on the long-term (Cadoux et al., 2012).

Calculation of net CDR

Net CDR from BECCS was calculated for each of the management and diet change scenarios by multiplying yearly harvested carbon (H, converted to CO_2) with a CO_2 removal efficiency along the BECCS supply chain ($CEff$) and subtracting (i) land use change emissions (LUC) and (ii) additional nitrous oxide emissions (N_2O):

$$netCDR = H * CEff - LUC - N_2O$$

All CDR results refer to mean yearly rates over a 30-year timeframe with mid-century climate (see 2.4). For CEff, we assumed three scenarios for biomass-to-electricity (B2E) conversion (high, medium and low efficiency) from the MONET framework with a detailed representation of the BECCS supply chain (Chiquier et al., 2022) and linked these to the plantation management scenarios (see Table 1 and D3.2 for an overview on assumptions regarding CO_2 capture rates, transport distance and carbon footprint of electricity amongst others). As an alternative, we estimated CEffs for a less efficient biomass-to-liquid (B2L) conversion, which might however play an important role for providing renewable energy for the transport sector (Leblanc et al., 2022). We built corresponding scenarios of low, medium and high CEffs assuming CO_2 capture rates of 66, 68.7 and 71% (Chiquier et al., 2022) and adjusting the CEffs for B2E according to these lower capture rates (Table 1). Note however, that a B2L pathway would also imply changes in processing and transport of biomass amongst others, which might change the emissions along the BECCS supply chain and which may be consistently modelled within the MONET framework in future. Land use change emissions from conversion of pastures to biomass plantations were calculated based on simulated mean annual changes in soil, litter and vegetation carbon pools as compared to the counterfactual case of sustaining pasture areas under the same climate conditions. Similarly, changes in N_2O emissions were determined in comparison to this counterfactual scenario and thus result from additional fertilization (depending on the management scenario) and changes in nitrogen turnover within the soil. Upstream emissions from fertilizer production have not been consistently accounted for.

2.3.2 Reforestation

Prioritization scheme for pasture rededication

Given the importance of intact forest landscapes for conservation (Betts et al., 2017), we prioritize reforestation on pastures in regions with high share of remaining forest cover. Thereby, reforested cells could serve as corridors connecting forested areas, which may improve resilience in both reforested land and adjacent intact forests (Littleton et al., 2021). To minimize fragmentation, cells are ranked according to remaining forest cover within the cell itself and the eight neighboring cells (Gerten et al., 2020). Reforestation of pastures thus starts in the cell with highest ranking and then continues iteratively to the cell with the next highest ranking. This procedure stops when cumulative grazed biomass within all rededicated cells corresponds to a reduction in grazing in line with the diet change scenario. As for BECCS we simulate scenarios corresponding to full (DC100) as well as partial transition to the EAT Lancet diet (DC25; DC50).

Due to reductions in albedo upon reforestation (e.g. Bonan, 2008; Pongratz et al., 2011; Sonntag et al., 2016; Vogt et al., 2022 (D3.6)) in the boreal zone and a resulting net warming effect, the described procedure only targets pastures in the temperate and tropical zone, but excludes reforestation in the boreal zone. This is in line with assumptions within the literature on forest restoration opportunities for climate change mitigation (Griscom et al., 2017; Littleton et al., 2021). Climate effects of changes in albedo as well as aerosol emissions were however not explicitly considered, but calculations focus on CDR.

Calculation of net CDR

To simulate CDR potentials from reforestation, we compared carbon pools in vegetation ($vegC$), litter ($litC$) and soil ($soilC$) between the scenario (sc) with reforestation on pastures in line with a diet change target and the agricultural reference (ref) with unchanged land use patterns:

$$netCDR = (litC_{ref} + soilC_{ref} + vegC_{ref}) - (litC_{sc} + soilC_{sc} + vegC_{sc})$$

We did not account for potential additional CO_2 emissions from forestry activities, but these have been shown to be negligible as compared to sequestered carbon (Chiquier et al., 2022).

As we deliberately defined reforestation as the restoration of natural forest ecosystems (i.e. assuming native species and excluding harvesting, fertilization and irrigation), natural vegetation was simulated to regrow on reforested areas, undergoing establishment and competition among plant functional types as implemented in a process-based manner within LPJmL. This represents a practice of “abandoning” pastures and leave it to undergo natural processes without human intervention. Due to the absence of an explicit reforestation module, LPJmL cannot represent planted tree saplings of a pre-defined functional type and of higher age. Instead, the model simulates the competition of various plant types leading to a slower establishment and thus limited carbon accumulation within the first decades. Further improvement is required to enhance the delayed establishment, even when considering the approach of natural forest regrowth. A comparison to literature on aboveground carbon accumulation rates in young natural forests (Cook-Patton et al., 2020) showed that the respective simulated rate is underestimated by a factor of ~2. We therefore assume that carbon pools after 60 years of simulation are reached within 30 years, and show that the thereby implied aboveground carbon accumulation rates match well both modelled rates in Cook-Patton et al. (2020) and 2019 IPCC defaults (IPCC, 2019b) across biomes and continents (see Figure S 1). For only one out of 33 temperate and tropical forest biomes, the simulated median rate on rededicated pastures was out of the range provided in Cook-Patton et al. (2020) based on an ensemble machine-learning model building on an extensive field measurement dataset. Furthermore, the simulations closely align with the observations collected by Cook-Patton et al. (2020) regarding the biome-specific median increment of carbon found on former pasture (see Figure S 2). The applied approach of doubling the simulation length allows for a more consistent modelling of sequestration rates and environmental impacts, which differs from the approach in D3.2 where only sequestration rates were adjusted in postprocessing. While natural fire disturbances are simulated in LPJmL, additional disturbances, such as pests or extreme weather events, and their impacts on sequestered carbon have not been accounted for.

2.4 Simulation setup

[The contents of this section are identical to those of the corresponding section in the complementary Deliverable 3.3]

All simulations of pasture rededication to biomass plantations for BECCS or reforestation were preceded by a 10,000-year spin-up of potential natural vegetation with 1901-1930 climate (input combining GSWP3 data with a bias-adjusted version of ERA5, Lange (2019)) to bring vegetation distribution and related carbon and nitrogen pools into equilibrium (see Figure 5). This was followed by a transient simulation of historical land use change from 1500 to 2017, with prescribed land use patterns as well as fertilizer and manure rates from Ostberg et al. (2023).

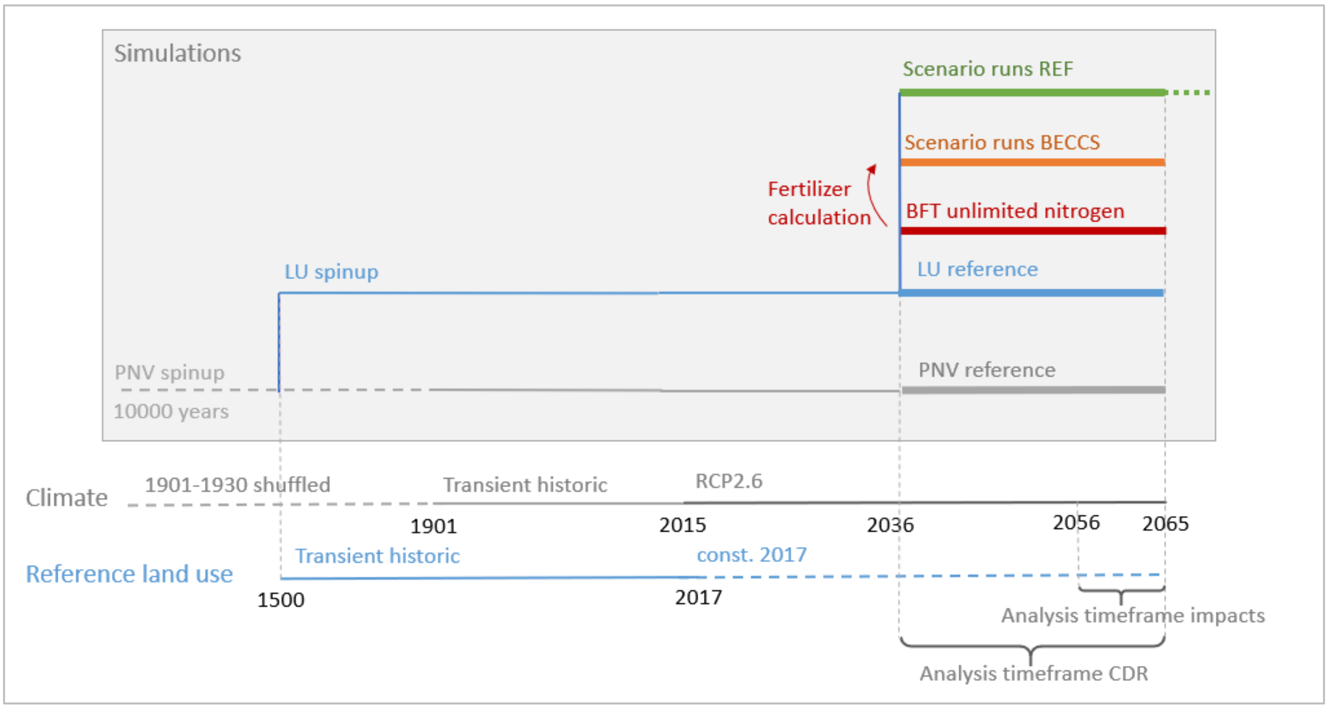

Figure 5: LPJmL simulation protocol. PNV = potential natural vegetation; LU = land use; BFT = bioenergy functional type (here: for representation of Miscanthus).

For simulations of mid-century CDR potentials from rededicated pastures to either biomass plantations for BECCS or reforestation, we adapted the 2017 land use pattern according to the scenarios (see above) and kept this pattern constant for 2036-2065 climate. As a reference for calculation of CDR and impacts, we simulated, for the same timeframe and climate, the counterfactual case of keeping 2017 land use constant over time (LU reference, see Figure 5) and potential natural vegetation (PNV reference, see Figure 5), amongst others for simulation of natural biome extents, incl. forest areas. Future climate inputs are based on a bias-correct version of data from the GFDL-ESM4 model for RCP2.6-SSP2 prepared by Lange and Büchner (2021), assuming climate change mitigation compatible with the Paris Agreement. While yearly CDR is averaged over a 30-year mid-century timeframe, the impacts of pasture rededication were calculated for the last 10 years of the respective analysis timeframe to better account for the committed impacts, which may be less pronounced in the first years after conversion. For calculation of CDR for reforestation, the simulation was extended by 30 years for a better match with literature on carbon sequestration rates (see 2.3.2).

2.5 Impact Analysis

For evaluation of the impacts implied by the scenarios of pasture rededication to biomass plantations or reforestation, we analyze potential increases in agricultural resource use and interconnected changes in water stress as well as three terrestrial planetary boundaries (freshwater use, nitrogen flows and land-system change).

2.5.1 Water stress index

We calculate water stress as described in Stenzel et al. (2021), using a well-established metric (Alcamo et al., 2003; Gosling & Arnell, 2016): the proportion of total human water withdrawals compared to water availability in discharge. For this, we compute the water stress index (WSI) for each 0.5° x 0.5° cell as monthly mean over 10 years of mid-century climate (2056-2065) based on the percentage of withdrawals for households, industry and irrigation compared to total discharge:

$$water\ stress\ index = \frac{domestic + industrial + irrigation\ water\ withdrawals}{total\ discharge}$$

Discharge and irrigation water withdrawals for both cropland and biomass plantations are simulated in a process-based manner within LPJmL, whereas domestic and industrial water withdrawals were taken from Flörke et al. (2013) (until 2000, thereafter assumed to be constant). Yearly mean water stress is derived by averaging over all months of the year. Cells are classified as highly water stressed if computed yearly mean WSI is > 40% (Vörösmarty et al., 2000) and as moderately water stressed for a WSI >20% but ≤40% (Stenzel et al., 2021). Cells with a monthly discharge < 0.03 mm are omitted (Stenzel et al., 2021).

2.5.2 Planetary boundaries

As a complement to D3.3 with an assessment of impacts on the biosphere, we here focus the analysis on impacts on freshwater use, nitrogen flows and land-system change and their respective sub-global definitions (for more detailed descriptions of the computation see D3.2).

Freshwater Use

The sub-global control variable for freshwater use as defined in Steffen et al. (2015) refers to the maximum allowed amount of river flow reduction as to sustain aquatic ecosystems. Such environmental flow requirements were determined for each grid cell based on discharge in the PNV reference and the variable monthly flow (VMF) method (Pastor et al., 2014; Steffen et al., 2015) (for flow regime dependent classification and thresholds for river flow reductions see Table 2; cells with discharge < 1 m^3/s were omitted). Transgressions of these environmental flows may result from anthropogenic water withdrawals and/or from reductions in runoff through changes in land cover.

Nitrogen flows

As proposed in Steffen et al. (2015), we focus on limits to surface water eutrophication as a major concern regarding anthropogenic modifications of the nitrogen cycle. Following de Vries et al. (2021) and Schulte-Uebbing et al. (2022), we define nitrogen boundaries for each cell based on critical nitrogen concentrations in runoff (through surface and subsurface runoff and leaching N flows) from agricultural and natural land to surface waters as dynamically simulated within LPJmL. Based on national surface water quality standards and objectives as well as ecotoxicological studies on nitrogen pollution, critical nitrogen concentrations in surface waters have been set to 1 mgN l^{-1} (as precautionary boundary) to 2.5 mgN l^{-1} (as upper end of the uncertainty) (de Vries et al., 2013). Assuming that on average 50% of nitrogen flowing into surface waters is retained or sedimented (Schulte-Uebbing et al., 2022), the thresholds of nitrogen concentrations in runoff are thus set to 2-5 mgN l^{-1}. To specifically capture anthropogenically increased nitrogen loads, we subtracted nitrogen loads from a simulation with potential natural vegetation and preindustrial nitrogen deposition (1850), thereby excluding any potential transgressions due to natural processes as simulated in LPJmL. Our approach intends to focus on the agricultural impact on surface water eutrophication by considering nitrogen losses from soils, exclusively. Point sources such as sewage and aquaculture are not accounted for.

Land-system change

Following the definition in Steffen et al. (2015), biome-specific limits to land-system change were applied based on remaining forest cover to acknowledge the importance of forests in climate regulation. Because of substantial climate feedbacks through changed evapotranspiration (tropical forest) and albedo (boreal forest) with potential impacts beyond the region of forest loss, these thresholds are stricter for tropical and boreal forests (see Table 2 with biome-specific thresholds). Pristine forest cover was estimated based on the reference simulation with potential natural vegetation (see 2.4) and cells were assigned to tropical, temperate, and boreal forest based on foliage projected cover of simulated plant functional types (see Figure S 3 for a map with simulated biomes). The remaining forest cover for each biome and continent was then determined by subtracting pasture and cropland areas from pristine forest cover.

Table 2: Control variables and planetary boundaries for three terrestrial Earth system processes. N = nitrogen.

Earth System Process	**Control Variable**	**Planetary Boundary (zone of increasing risk) and sub-global assessment unit**	**References**
Freshwater Use	River flow reduction as % of potential mean monthly river flow (MMF)	low-flow months: 25% (25-55%); intermediate-flow months: 40% (40-70%) high-flow months: 55% (55-85%), assessed at the grid cell level considering upstream-downstream effects	Steffen et al. (2015); Pastor et al. (2014)
Nitrogen Flows	N in runoff to surface water as proxy for dissolved inorganic N concentrations in surface water	2 mgN l^{-1} (2-5 mgN l^{-1}), at grid cell level (0.5°x0.5°)	de Vries et al. (2013); de Vries et al. (2021); Schulte-Uebbing et al. (2022)
Land-System Change	Area of forested land as % of potential forest for each biome	Tropical: 85% (85-60%) Temperate: 50% (50-30%) Boreal: 85% (85-60%), assessed for each continent and biome	Steffen et al. (2015)

3 Results

3.1 Net CDR potentials from rededicating pastures

A full or partial transition to the EAT-Lancet planetary health diet could allow for conversion of 194, 388 and 836 Mha of pastures to biomass plantations for the DC25, DC50 and DC100 scenario, respectively, or alternatively for reforestation on 161, 325, and 736 Mha of pastures, at the global level (see Figure 6). This corresponds to rededication of ~5% (DC25) to ~25% (DC100) of global pasture areas (in year 2017), and compares to ~10% (DC25) to 50% (DC100) of global croplands (in year 2017). While the EAT Lancet planetary health diet was calculated to imply a reduction in grazed biomass of 46%, pasture areas decrease only roughly half as much, as areas with above-average grazing intensities were selected for rededication in both allocation schemes. For biomass plantations, cells with a high share of arable land were prioritized (for economic and infrastructure reasons; see methods). This leads to rededicated pastures in regions with already intensive agriculture and mostly high population density first (see yellow areas in Figure 7a), further expanding into less intensively used areas in the higher pasture rededication scenarios. In contrast, reforestation starts in regions with highest remaining forest cover (for restoration of intact forest landscapes; see methods), thus expanding from pristine areas amongst others in the (sub-) tropics and mostly sparsely populated regions to areas with higher historical deforestation rates (see Figure 7a). These different allocation schemes also explain why the assigned global areas differ for biomass plantations and reforestation.

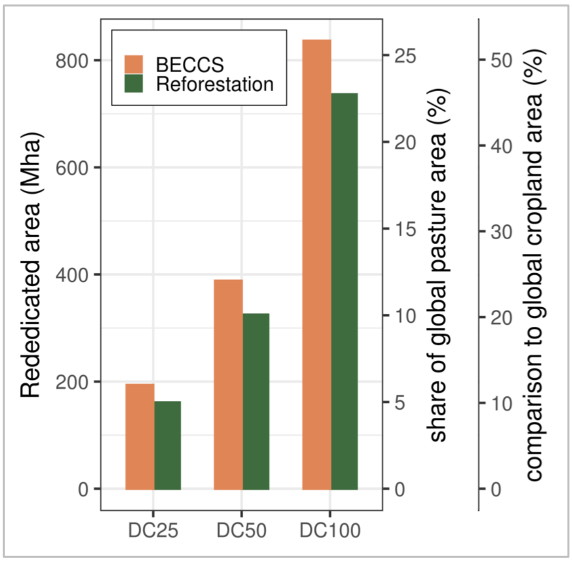

Figure 6: Global pasture areas rededicated to biomass plantations for BECCS or, alternatively, to reforestation in line with partial or full transition to an EAT-Lancet planetary health diet. Right axes show (i) the rededicated pasture area share and for contextualization (ii) the share of global cropland the areas would correspond to.

For BECCS with moderate management, simulated net CDR per area on rededicated pastures is highest in eastern China and US, as well as tropical Southeast Asia, where high precipitation levels boost productivity on rainfed plantations (see Figure 7b; for simulated net CDR in the minimal and optimal management scenarios see Figure S 4). Depending on the management and diet change scenarios, 12-25% of the originally harvested CO_2eq on biomass plantations are offset through land use change emissions (i), and 4-15% through additional N_2O emissions from fertilization (ii). Additional supply chain losses through fossil fuel use and the carbon capture and storage process (iii) range between 8 and 21% of the originally harvested CO_2eq for a more efficient B2E pathway and 33-42% for a B2L pathway, resulting in overall CO_2 removal efficiencies between 48-66% for B2E and 27-43% for B2L (see Figure S 5 for detailed breakdowns of net CDR calculation for all scenarios). Despite these inefficiencies, net CDR rates from biomass plantations for BECCS are generally higher as compared to respective CDR potentials from reforestation. For reforestation, pasture conversion is simulated to not always lead to net CDR both in temperate and tropical biomes (see red cells in Figure 7b), implying that aggregate soil, litter and vegetation carbon pools decrease as compared to pastures. It has been shown that pastures can have particularly high soil carbon pools with ~90% of sequestered carbon stored belowground and that light grazing, in contrast to heavy grazing, may increase soil organic carbon (Bai & Cotrufo, 2022). A transition from pastures to woody vegetation may lead to decreases in the accumulated soil carbon pools, at least within the first decades after tree establishment when growth in aboveground biomass may not compensate for potential losses in soil carbon (Conant et al., 2001;

Cook et al., 2014; Friggens et al., 2020; Kirschbaum et al., 2008; Shen et al., 2023). Nevertheless, this model behavior needs further investigation and testing, as site studies generally report overall increases in carbon stocks through forest regrowth on former managed grasslands, or the other way round, forest conversion to pastures generally represents a loss in overall carbon pools (Conant et al., 2001; de Koning et al., 2003; Fearnside & Imbrozio Barbosa, 1998; Silver et al., 2004). Recovery of soil carbon accumulation rates and vegetation carbon built-up after reforestation might thus take too long in LPJmL.

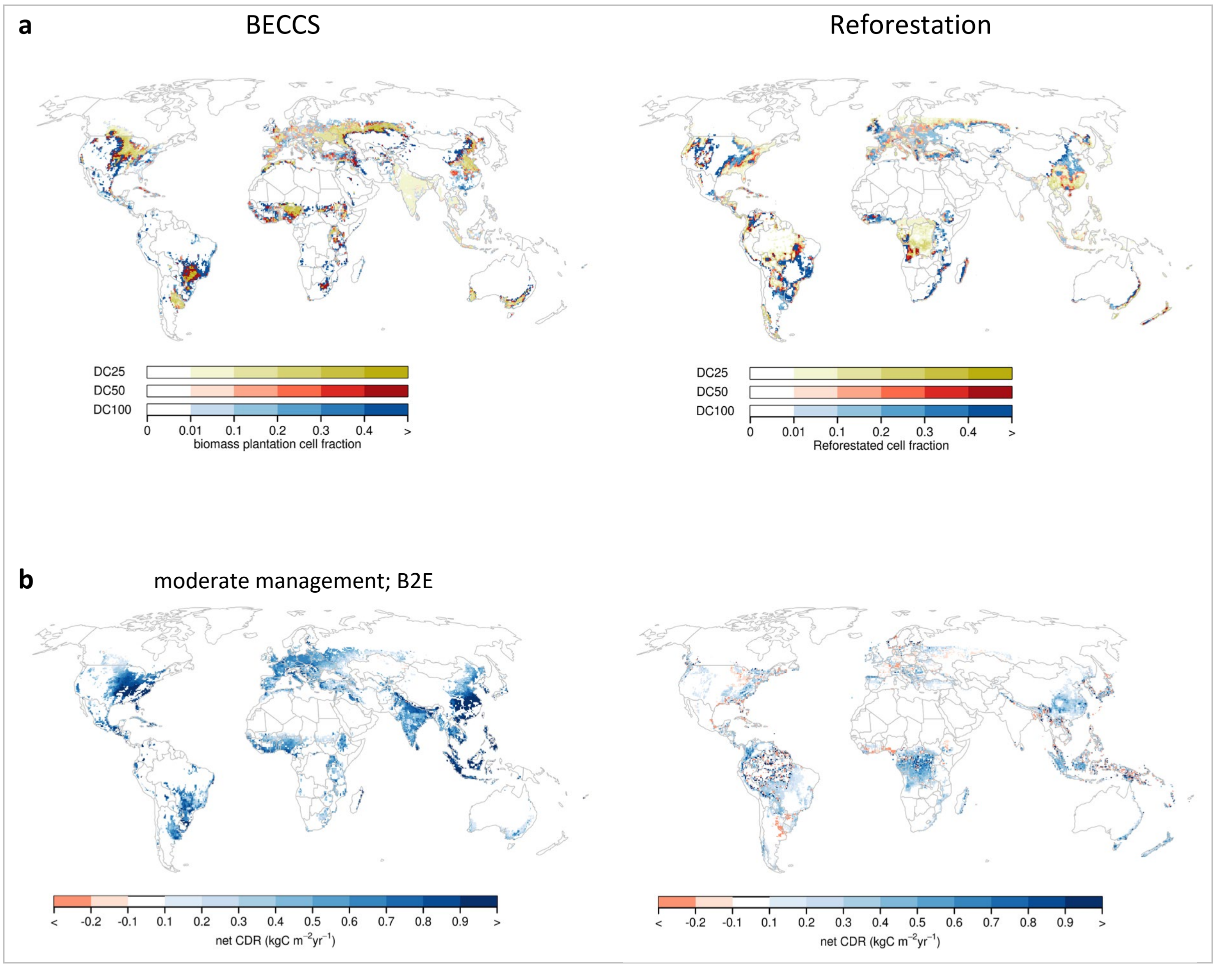

Figure 7: Simulated scenarios of rededicating pastures to biomass plantations for BECCS (left) or reforestation (right) in line with diet changes. (a) Geographic distribution of rededicated cell fractions corresponding to a 25% (yellow), 50% (red) and 100% (blue) transition to the EAT-Lancet planetary health diet. (b) Simulated net CDR per area for all cells with rededicated pastures in the 100% scenario. For BECCS, this refers to the moderate management scenario and biomass-to-electricity conversion (B2E; see methods). Negative net CDR (= net CO_2 emissions instead of removal) are displayed in red.

At the global level, a partial or full transition to the planetary health diet and associated reductions in pasture requirements could allow for the realization of high levels of CDR from BECCS or reforestation within current land use bounds. Establishment of biomass plantations on ~200Mha of pasture areas in line with a partial transition to the planetary health diet (DC25) may provide 3.3 $GtCO_2eq\ yr^{-1}$ in the moderate management scenario (1.7 – 4.4 for minimal and optimal management) for the more efficient B2E pathway, and 2.0 GtCO2eq yr^{-1} (1.0 – 2.8) for a B2L pathway (see Figure 8a). For a full diet transition, this potential may be increased to up to 14.4 $GtCO_2eq\ yr^{-1}$ (9.7 – 18.5) for B2E and 8.9 $GtCO_2eq\ yr^{-1}$ (5.9 – 11.3) for B2L. Compared to CDR levels simulated in economically optimized climate mitigation scenarios included in the 6th Assessment Report of the

IPCC (IPCC, 2022), the DC25 scenario is broadly in line with median BECCS rates in 2050, whereas the more comprehensive diet change scenarios better align with AR6 rates in 2100 (see Figure 8b). Note that this comparison serves contextualizing purposes only, as (i) the Integrated Assessment Models (IAMs) covered in AR6 do not only assume biomass sources from additional dedicated biomass plantations and partly include additional feedstocks from agricultural and forestry residues as well as logs from managed forests (Hanssen et al., 2020; Rose et al., 2022) and (ii) the here presented scenarios assume large-scale and comprehensive diet shifts towards less livestock products, in contrast to most IAM scenarios.

For reforestation, the global numbers are generally lower than for BECCS, but in the lower scenarios still within the range of the B2L BECCS pathway (see Figure 8a). A full transition to the EAT-Lancet diet may allow for removal of up to ~4.3 GtCO2eq yr^{-1} on reforested pastures, or 1.6 and 2.7 GtCO2eq yr^{-1} for the DC25 and DC50 scenario, respectively. While net removal from managed land (integrating re-/afforestation and deforestation amongst others) in 1.5°-2°-compatibleAR6 scenarios span a wide range, median net CDR in 2050 is comparable to the rates simulated in the DC50 scenario, while the most ambitious DC100 scenario is broadly in line with median AR6 rates in 2100 (Figure 8b). Land sparing and net reforestation in AR6 scenarios may however not only result from diet changes but also from productivity increases amongst others. Also, simulated reforestation rates may be underestimated due to too slow tree establishment and soil carbon loss in some cells (see above and discussion). Yet, exclusion of cells with net emissions upon reforestation only leads to a minor CDR increase by 0.5 GtCO2eq yr^{-1} to 4.8 GtCO2eq yr^{-1} in the DC100 scenario.

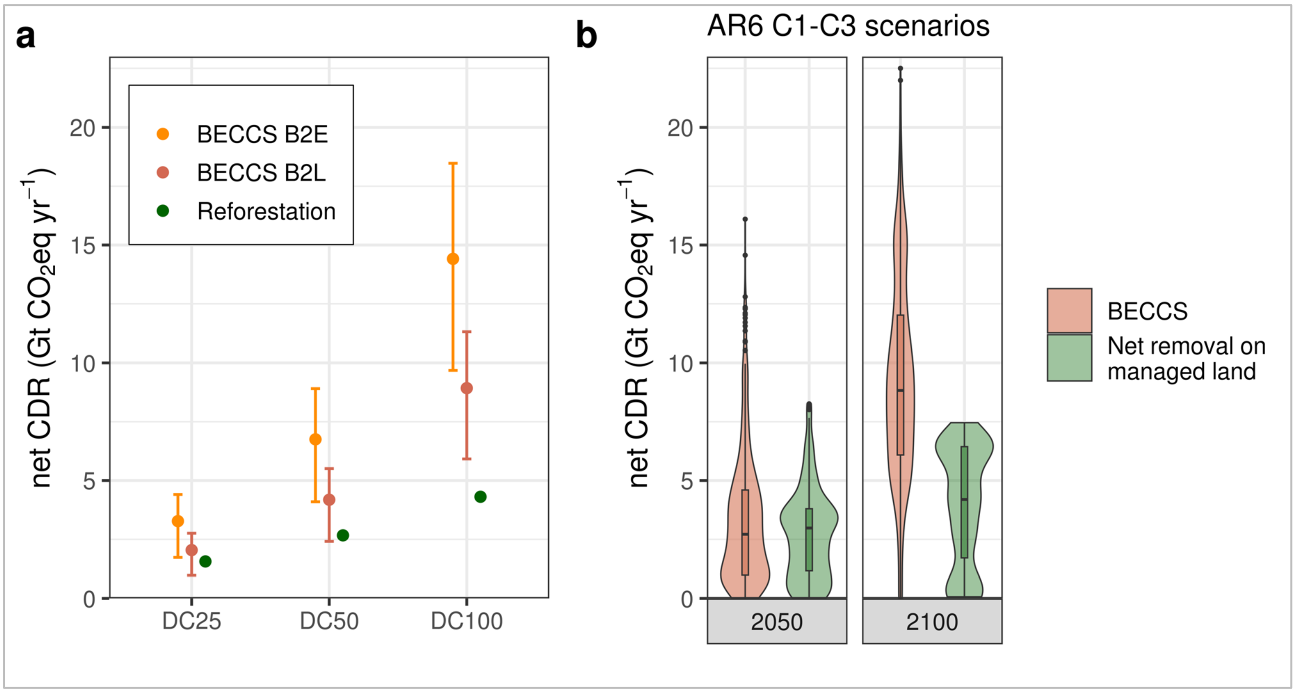

Figure 8: Global net CDR potential for BECCS and reforestation on pasture areas in line with full or partial transition to a planetary health diet (a). For BECCS, CDR rates for both a biomass-to-electricity pathway (B2E) and a biomass-to-liquid (B2L) pathway are displayed, referring to the moderate management scenario. Error bars delineate the range spanned by the minimal and intensive management scenarios. In (b) projected CDR rates for BECCS and managed land (net; integrating deforestation and re-/afforestation) from 1.5°-2°-compatible scenarios (categories C1-C3) included in the IPCC AR6 report (IPCC, 2022) are displayed for contextualization. Boxplots show medians and interquartile ranges, and kernel probability density of projected CDR rates is additionally displayed.

3.2 Impacts on agricultural resource demand

While BECCS from rededicated pasture may provide more CDR per area, thus more efficiently contributing to climate stabilization, increases in agricultural resource demand through expansion of biomass plantations could be severe, depending on the extent of rededicated pasture area. In contrast, arable land extent is not affected in the reforestation scenarios, and, as a result of the diet change mediated reductions in pasture areas, fertilizer demand is simulated to slightly decrease (although synthetic fertilizer is overall minor on pastures as compared to arable land inputs). This section therefore focuses on BECCS only and the scenarios' implications for agricultural resource demand.

Biomass plantations require arable land, thus increasing the global cropland area needed to grow food, feed, fiber and fuels. The DC100 scenario compatible with a full transition to a planetary health diet implies an expansion corresponding to half (52%) of current cropland (Figure 9). Such an increase of arable land within few decades would require unprecedented rates of cropland expansion, equivalent to the global cropland expansion within the last ~120 years. The less stringent DC scenarios still imply cropland expansion as seen within the last ~60 years (DC50; 388 Mha) and ~25 years (DC25, 194 Mha), respectively. Land use conversion from pasture to cropland generally represents an intensification of land use, especially in the case of high output biomass plantations. This is mirrored in simulated increases in water and nitrogen demand as well as in environmental variables (see 3.4).

The DC100 scenario would increase global water withdrawals for irrigation by 15% under moderate management (share of irrigated area for biomass plantations as for crops within the respective cell but max. 30%), and up to 64% under intensive management (min. 30% of biomass plantations area irrigated). The effects are respectively less strong for the DC25 and DC50 scenarios (3 and 7% under moderate management; 16 and 31% under intensive management; see Figure 9). While establishing rainfed plantations only (as assumed in the minimal management scenario), may allow to prevent increases in water withdrawals, this would require strong and universal political frameworks ensuring zero irrigation irrespective of potential economic benefits.

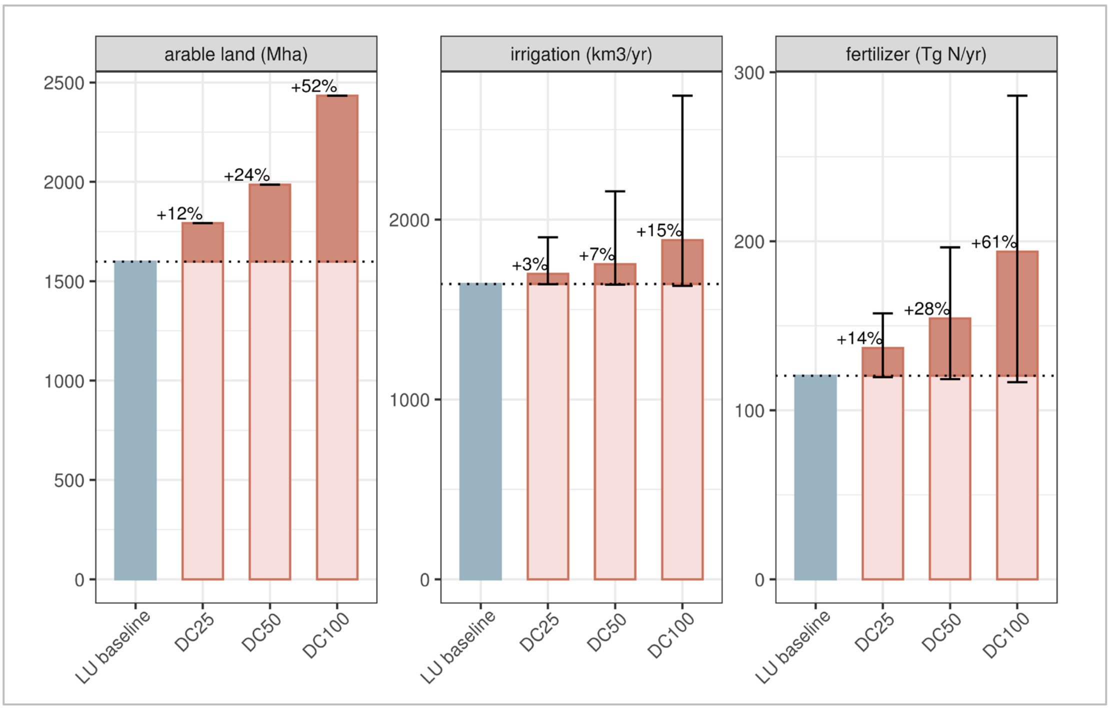

Figure 9: Changes in agricultural resource demand (arable land, water withdrawals for irrigation and fertilizer application) for three BECCS scenarios corresponding to partial or full transition to an EAT Lancet planetary health diet. Red bars depict simulated resource demand for the moderate management scenario; the error bar shows the range from minimal to intensive management on biomass plantations. Blue bar shows resource demand for agricultural land use in 2017.

Fertilizer use may increase even more drastically than water withdrawals: by 61% for the DC100 scenario and moderate management. If yields are to be optimized at the cost of a lower nitrogen use efficiency, i.e. more losses to the environment, fertilizer requirements could even rise by up to 137% as simulated for intensive management (Figure 9). Fertilizer use may be kept constant or even slightly decrease if biomass plantations receive no fertilizer at all and replace pasture areas that have received low amounts of synthetic fertilizer. While some field studies show no significant increase in Miscanthus yields upon fertilization (Cadoux et al. (2012); see 2.3.1), (i) this would lead to depletion of soil nitrogen reserves on the long-term and (ii) would require, as for irrigation, strong regulations as to prohibit fertilization on biomass plantations. The moderate management scenario, where applied N fertilizer equals the amount of N removed by harvest under unlimited N supply, thus seems more plausible and is well in line with a global assessment of fertilizer requirements on biomass plantations for low warming targets (~48 TgN yr^{-1} for a global biomass harvest of ~ 3.8 Pg C yr^{-1} ≈ 13 gN/kgC (Li et al., 2021); here: 33.8 TgN yr^{-1} for a global biomass harvest of 3.01 Pg C yr^{-1} ≈ 11.2 gN/kgC for DC50 and moderate management). The analysis thus shows that both nitrogen and water demand likely strongly increase upon global expansion of biomass plantations, although the magnitude clearly depends on the management on biomass plantations and its regulation.

3.3 Impacts on water stress

Such strong increases in agricultural resource demand would have strong socio-economic impacts. For water, the ratio of freshwater withdrawal to available freshwater resources has been proposed to quantify water stress i.e. the level of anthropogenic pressure on freshwater resources (see 2.5.1). Water scarcity is already today a major issue in many parts of the world, and may be worsened by climate change and increases in population (Gosling & Arnell, 2016). We here analyzed the changes in water stress under mid-century climate from rededicating biomass plantations to pastures, all else being equal.

Both areas under moderate and high water stress increase significantly, by up to 16% and 43%, respectively, for the DC100 scenario and moderate management on biomass plantations (by 6/11% and 8/21% in the less ambitious DC50 and DC25 scenario; see Figure 10). Notably, areas under *high* water stress, with more than 40% of locally available freshwater resources abstracted, show particularly strong increases. Higher shares of irrigated biomass plantations as simulated in the intensive management scenario could even increase areas under moderate and high water stress by up to 78 and 151%, respectively (Figure 10). While the magnitude of increased water stress is again clearly dependent on management (see 3.2), even under minimal management (implying rainfed plantations only), water stress is simulated to increase in some regions, i.e. Eastern China and the Mediterranean (Figure 11). This is due to simulated decreases in runoff from plantations as compared to pastures, and resulting decreases in water availability in rivers.

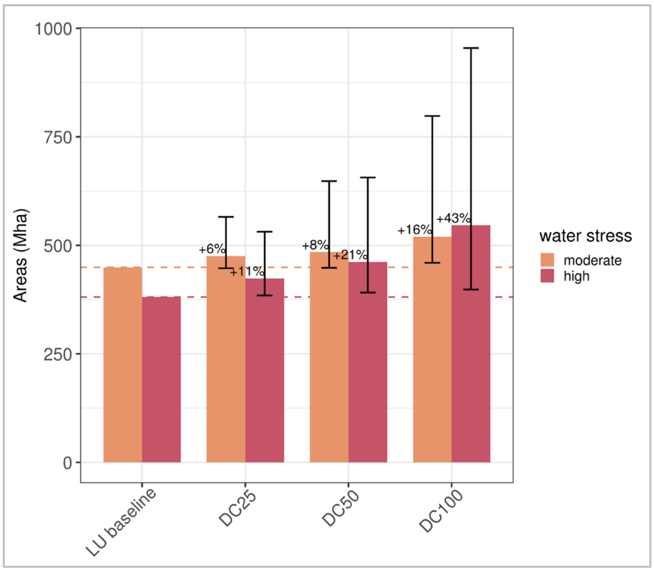

Figure 10: Areas under moderate (water stress index > 0.2 / ≤0.4) and high water stress (water stress index > 0.4) in BECCS scenarios as compared to the land use reference (2017) under mid-century climate (2056-2065) with the relative change indicated as percentage next to the uncertainty bars indicating the range between minimal and intensive management intensity.

Under moderate management, regions affected most strongly by increased water stress include India, Northeast China and the Mediterranean. Additional strong water stress increases under intensive management are simulated in African tropical savanna climate, Southern Australia, the Russian steppe, the Great Plains in the US and Southeast Brazil. The affected cells are partly located in regions with relatively little irrigation today, where irrigation of >30% of biomass plantation area as assumed under intensive management has a high effect.

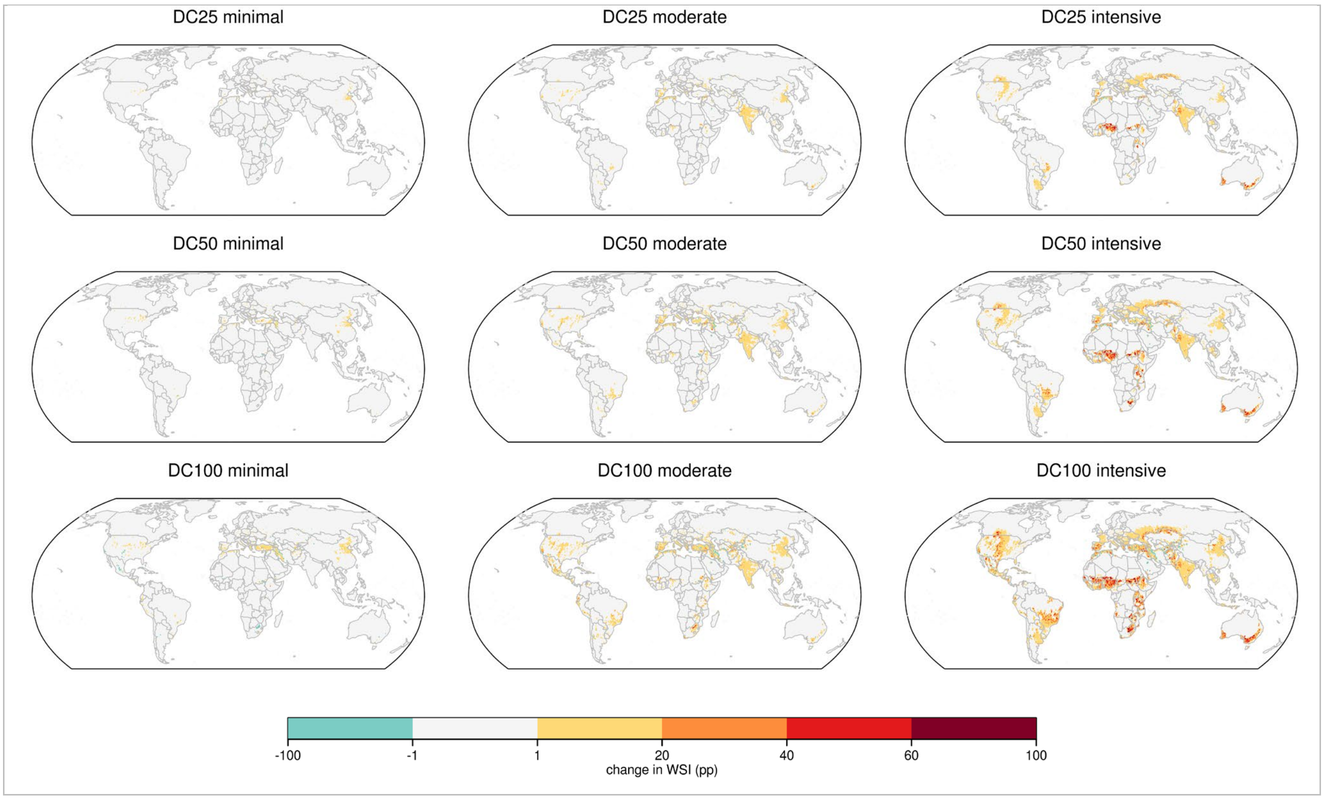

Figure 11: Geographic distribution of changes in the water stress indicator (WSI), in percentage points (pp), from rededicating pastures to biomass plantations.

As the reforestation scenarios on pastures do not imply changes in irrigated areas, water stress is generally not aggravated as compared to the land use reference (<2.5% increase in areas under moderate or high water stress for DC100; only in a few cells runoff and thereby water availability is decreased through reforestation). While not contributing to solving current water stress issues, at least no additional pressures are simulated in an already water-stressed world. This contrasts the additional pressures as simulated for BECCS scenarios.

3.4 Impacts on planetary boundaries

Both impacts on resource demand and water stress address socio-economic impacts resulting from rededicating pastures to biomass plantations or forests. This section focuses on environmental impacts based on the planetary boundaries (PB) concept, by analyzing the effects on land-system change, freshwater use and nitrogen flows (for a complementary analysis of effects on biosphere integrity, see D3.3).

3.4.1 BECCS

For BECCS scenarios, we analyzed simulated effects on freshwater use and nitrogen flows only, as the status of the land-system change boundary does not change per definition: one type of anthropogenic land use is converted to another, but remaining forest cover, the control variable for land-system change, remains unchanged.
Under moderate management intensity on biomass plantations, both areas with nitrogen and freshwater transgressions increase drastically by 51 and 44 %, respectively, for the largest expansion of biomass plantations compatible with pasture area reductions in line with a full transition to a planetary health diet (23/17% and 12/7% for the DC50 and DC25 scenario; see Figure 12). Intensive management would amplify the additional pressures: Areas with nitrogen transgressions are simulated to increase by up to 93% and freshwater by up to 101% for the DC100 scenario. Even under minimal management, i.e. unfertilized rainfed plantations only, geographic extent of both nitrogen and freshwater transgressions is expanding. This due to (i) acceleration of nitrogen turnover on biomass plantations as compared to pastures with resulting increased N losses in leaching, and (ii) decreased runoff from biomass plantations leading to reductions in river flows in some cells. The latter is observed mainly in Eastern China and the Middle East (see Figure 13).

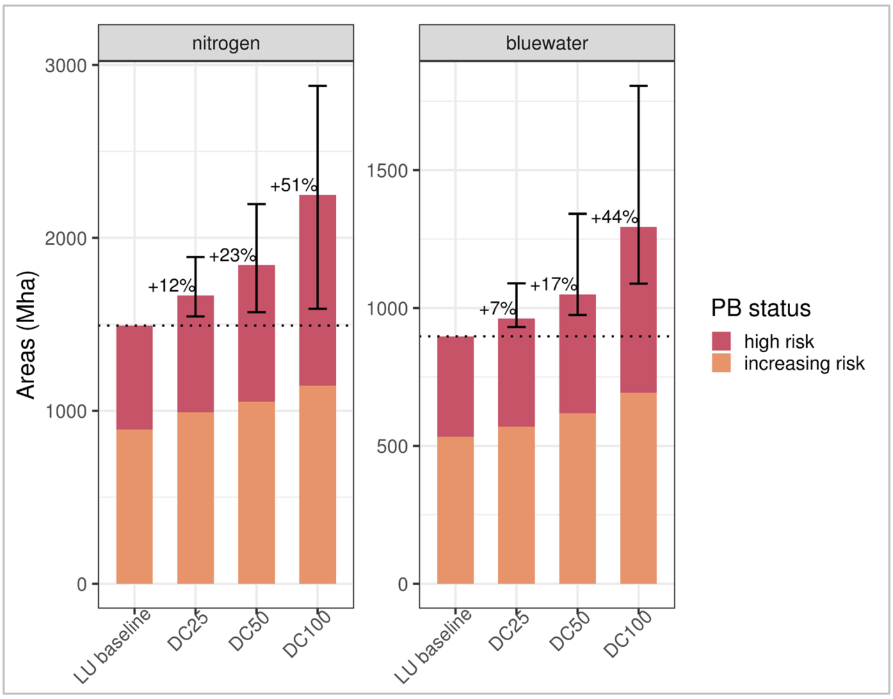

Figure 12: Impact of BECCS scenarios on areas with transgressions of the nitrogen and freshwater use boundaries. The baseline refers to the reference with unchanged 2017 land use.

While these pressure-increasing effects clearly dominate, there are some cells in Western Europe, the Great Plains in the US and Brazil where the pressure on the nitrogen boundary decreases under minimal management, as nitrogen input is reduced as compared to pastures. Moderate and intensive management scenarios result in hotspots of increased PB pressures, with some regions where both the status of the nitrogen and freshwater PB is aggravated, such as simulated in Western Africa, Southern Brazil, the Mediterranean and Southern Russia, amongst others (Figure 13). These additional transgressions come at the backdrop of already largescale transgressions caused by current agriculture (see dark grey areas in Figure 13 for water and/or nitrogen transgressions). Clearly, the magnitude of additional pressures depends on the management on biomass plantations and its regulation (see above).

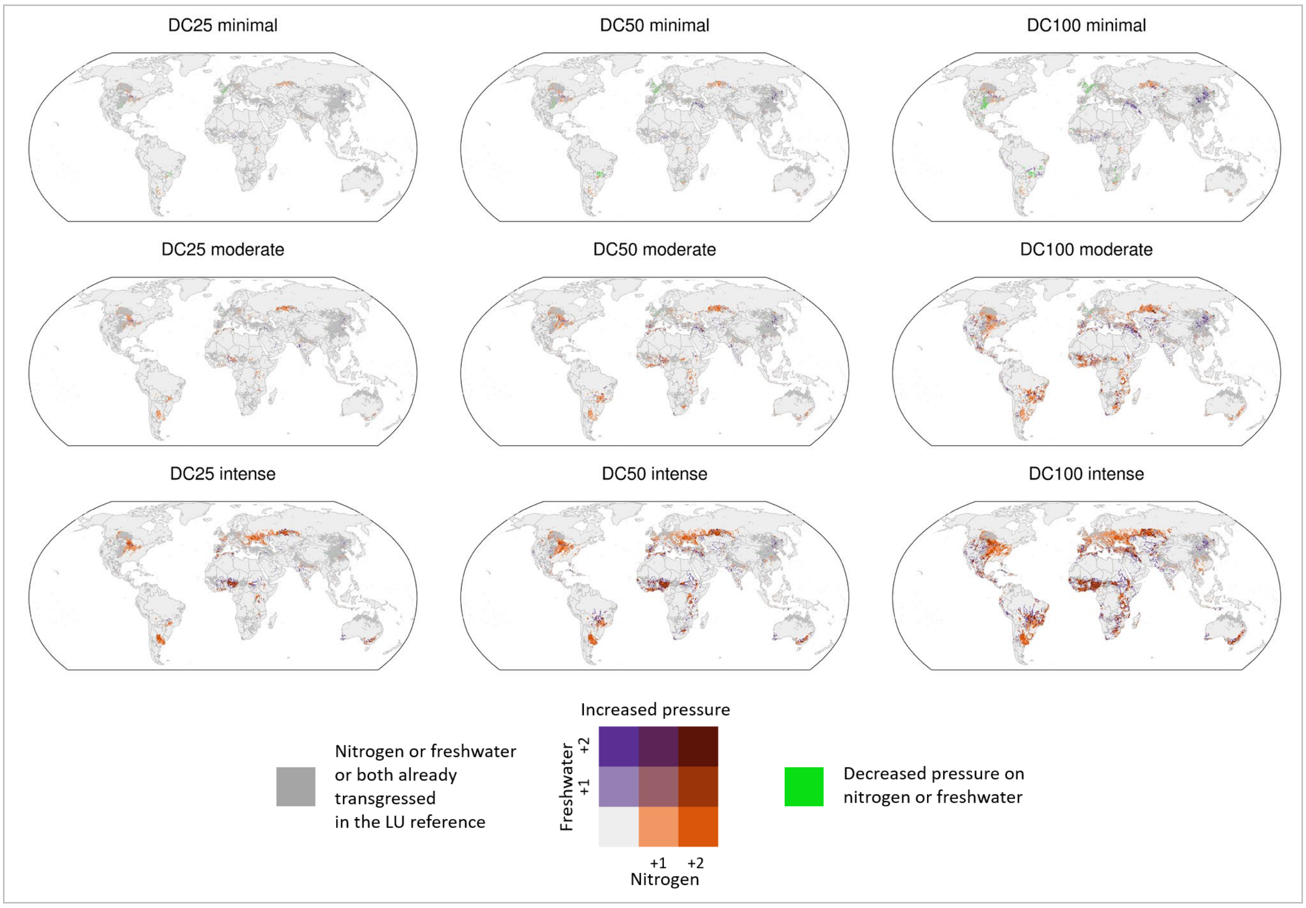

Figure 13: Spatially explicit effects of rededicating pastures to biomass plantations on the status of freshwater and nitrogen boundaries. The bivariate scale shows increases in pressure on the freshwater and/or nitrogen boundary as compared to the land use reference. +1 = planetary boundary status worsens by one step: either a shift from a safe level to increasing risk level, or from increasing risk level to high risk level; +2 = planetary boundary status worsens by two steps: from safe to high risk level. Green areas indicate cells where conversion of pastures to biomass plantations improve the nitrogen and/or freshwater status.

3.4.2 Reforestation

In contrast to the BECCS scenarios, the reforestation scenarios are simulated to have minor positive effects on the status of the freshwater and nitrogen PB status, due to the reductions in pasture areas and resulting minor decreases in fertilizer inputs as well as regrowth of trees and resulting changes in runoff and soil nitrogen turnover: Global areas with PB transgressions decrease by ~4% and ~1.5% for nitrogen flows and freshwater use in the DC100 scenario, respectively (see Figure S 6 for spatially-explicit effects for the three DC scenarios). In addition, unlike conversion of pastures to biomass plantations, reforestation on pastures in the sense of assisted regrowth of natural vegetation could improve the status of the land-system change PB by partly restoring forest cover. Thus, reforestation in line with a full transition to a planetary health diet may release pressure on the land-system boundaries. In particular tropical forest biomes, where past deforestation has pushed the land-system change PB status into a zone of increasing risk, may shift back into the safe zone, as simulated for both South-American and African tropical forest in the most ambitious diet change scenario (see Figure 14). As it has been shown that the Amazon rainforest may be approaching a tipping point potentially resulting in large-scale tree die-back (Boulton et al., 2022), such an increase in resilience might be of particular importance. But also for the less ambitious scenarios and all other major forest biomes, the partial restoration of historic forest extent may contribute to increased forest resilience. Similarly, reforestation on pastures is simulated to positively impact biosphere integrity, as analyzed and discussed in Deliverable D3.3, by bringing vegetation structure and biogeochemical flows closer to their natural states.

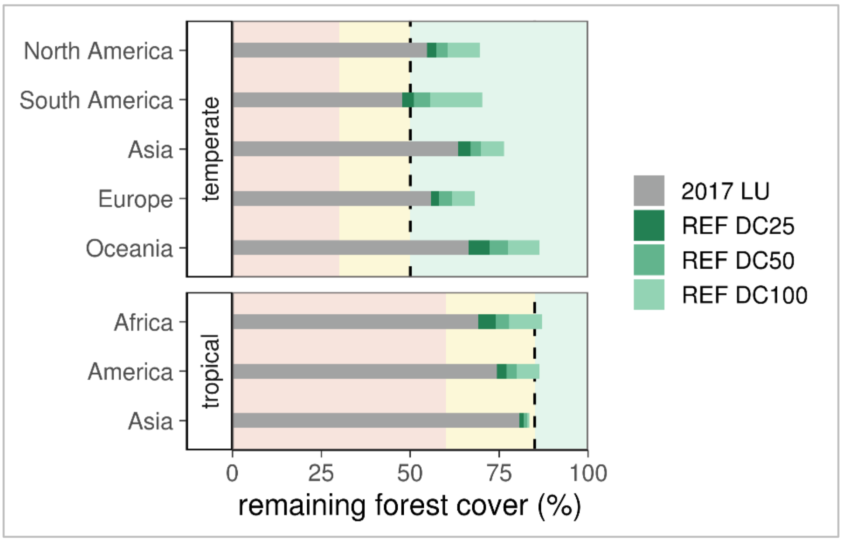

Figure 14: Impact of reforestation scenarios (REF) on biome-specific land-system change relative to PB thresholds. Background color indicates the safe, increasing risk and high-risk zone according to the biome-specific thresholds defined in Steffen et al. (2015); the dashed line indicates the planetary boundary, set at the "safe" end of the zone of increasing risk (Steffen et al., 2015). For tropical and boreal biomes, the thresholds are stricter, given stronger climate feedbacks and teleconnections of these biomes.

4 Discussion

We employed the global biosphere model LPJmL to estimate CDR volumes and impacts from rededicating pastures to biomass plantations for BECCS or reforestation. The results emphasize the importance of joint analyses of both CDR potentials and socio-economic and environmental impacts for an integrated evaluation of potential land use futures. In the following sections, we first discuss and contextualize simulated CDR rates as well as impacts. We then discuss the interconnections with food security and SDGs to evaluate synergies and trade-offs of pasture conversion within a multidimensional sustainability space. All results have to be interpreted against the background of the uncertainties inherent to global modelling of the biosphere. Whereas simulated carbon, water and nitrogen fluxes have been thoroughly validated (e.g. Schaphoff, Forkel, et al., 2018), further model development is ongoing, particularly in terms of the soil water balance and temporal soil carbon dynamics upon reforestation. These further developments may lead to updates of the results over time.

4.1 Simulated CDR rates and impacts

According to our spatially-explicit scenarios, reduced grazing demand in line with a transition to the EAT-Lancet planetary health diet could free up to ~800 Mha of pastures for either biomass plantations or reforestation, corresponding to roughly 25% of current global pasture areas. This is less than simulated in Stehfest et al. (2009) for a transition to a healthy diet similar to the EAT-Lancet diet (1360 Mha), but this can be attributed to the fact that we here prioritized conversion of pastures particularly suitable for CDR with above-average livestock intensities (see 3.1). Still, the size of rededicated areas would correspond to half of current cropland areas and is higher than the median reduction in pastures modelled between 2020 and 2100 in economically optimized climate stabilization scenarios included in IPCC's 6th Assessment Report (AR6; IPCC, 2022) (676 Mha; interquartile range: 153-910 Mha). The fact that pastures decline strongly in most of these mitigation scenarios emphasizes that land sparing within the food system, through diet changes and/or increased efficiency within husbandry and grazing intensification, is a central assumption for attaining climate targets.

We here performed a systematic analysis to elucidate synergies and trade-offs of pasture rededication for CDR based on spatially-explicit and process-based simulation of both CDR and interconnected impacts. Yet, this exploration does not account for political, economic or institutional feasibility of such large-scale diet changes and corresponding rededication of pastures. The results should thus be interpreted considering that they imply highly ambitious, integrated and coordinated actions towards primarily plant-based diets thus reversing current trends towards increased consumption of livestock products at the global level.

<u>BECCS</u>

Biomass plantations for BECCS on rededicated pasture areas are simulated to remove ~14.4 $GtCO_2eq\ yr^{-1}$ (9.7-18.5) for a biomass-to-electricity conversion, or ~8.9 $GtCO_2eq\ yr^{-1}$ (5.9-11.3) for a biomass-to-liquid conversion. The latter is roughly equivalent to simulated median BECCS rates in 2100 in AR6 climate stabilization scenarios (IPCC, 2022), which however do not exclusively rely on biomass feedstocks from dedicated plantations, but also from residues and, in a few models, logs from managed forests (Hanssen et al., 2020; Rose et al., 2022) (see 3.1). CDR at that magnitude compares to slightly less than the global net carbon sink in oceans for biomass-to-liquid conversion (2.9 GtC = 10.64 $GtCO_2$) and even to twice the current global net carbon sink on the entire land surface (1.9 GtC = 6.97 $GtCO_2$) for the biomass-to-electricity conversion (Friedlingstein et al., 2022). Creating an additional anthropogenic sink of that magnitude may thus be considered a planetary-scale form of bio-geoengineering (Heck et al., 2016).

The large-scale expansion of biomass plantations would drastically increase fertilizer application (~+60%) and irrigation water withdrawals (~+15%) assuming a moderate management on plantations, thereby creating a strong competition for agricultural resources with potentially severe impacts on food security (see 4.2). Concerning water security, the implied expansion in irrigated areas is simulated to increase areas under high water stress by ~40%, amongst others in India, Eastern China and the Mediterranean. This is in line with a previous study with an earlier LPJmL version without nitrogen dynamics which showed that additional water stress from irrigated biomass plantations for climate stabilization at 1.5°C could even exceed the avoided increase in water stress from climate change (Stenzel et al., 2021). This could only be circumvented if sustainable water management was implemented globally (i.e. preservation of environmental flows and implementation of advanced on-field water management). The respective scenario suggests that this could limit the increase in additional areas under high water stress to 20% for a biomass plantation extent of 600 Mha (Stenzel et al., 2021).

In addition to socio-economic impacts on water and food security, areas with transgressions of environmental boundaries for nitrogen and water would increase by ~50% and ~45%, respectively. This underpins previous studies on severe side-effects of biomass plantations on nitrogen losses and unsustainable water withdrawals, at least in the absence of complementary environmental protection measures (Heck et al., 2018; Humpenöder et al., 2018). Both CDR levels and impacts are strongly dependent on the management on biomass plantations: More irrigation and fertilization may boost achievable CDR, but at the same time amplify negative impacts on resources, water stress and environmental boundaries. This emphasizes the severe trade-off between CDR provision from dedicated biomass plantations for BECCS and other sustainability targets (Humpenöder et al., 2018). Minimal management, i.e. assuming rainfed and unfertilized plantations only, reduces global CDR but may mitigate most, albeit not all, side-effects, but would require global political regulations. Converting less pasture areas to biomass plantation would reduce the magnitude of negative side effects and CDR potential, but the direction of impact would remain the same, increasing to some extent the pressure on an already severely disrupted Earth system.

<u>Reforestation</u>

Reforestation on rededicated pastures would provide less CDR per rededicated pasture area than BECCS, with a simulated CDR of ~4.3 $GtCO_2eq\ yr^{-1}$ for a full transition to the planetary health diet, i.e. conversion of 736 Mha. This simulated CDR potential corresponds to only roughly half of estimated maximum CDR potential from reforestation (Cook-Patton et al., 2020; Griscom et al., 2017). While we validated aboveground carbon accumulation rates based on data from Cook-Patton et al. (2020); (IPCC, 2019b) with an overall good match (see 2.3.2), belowground and soil carbon changes are highly uncertain (Cook-Patton et al., 2020; Hayek et al., 2021). Therefore, these pools have been partly neglected in previous assessments (Bernal et al., 2018; Griscom et al., 2017). According to site studies, soil carbon pools may decrease upon reforestation of pastures (see literature in 3.1), but slow recovery of soil carbon accumulation rates and vegetation built-up after reforestation in LPJmL requires further evaluation. Further, we here explicitly excluded the natural background carbon sink, by only accounting for additional carbon storage as compared to the counterfactual case of maintained pastures under elevated CO_2 and increased nitrogen deposition. This distinction between the natural resilience response of the biosphere and additional anthropogenic CDR is crucial (Nolan et al., 2021) but sometimes neglected, which may partially explain why simulated reforestation CDR rates per hectare are at the lower end of the literature range (Bernal et al., 2018; Cook-Patton et al., 2020; Griscom et al., 2017).

Unlike BECCS, reforestation would not fuel a competition for agricultural resources with food provision nor exacerbate global water stress and transgressions of environmental boundaries for nitrogen and water. Instead, reforestation on pastures could significantly help to restore nature by alleviating pressures on planetary boundaries for both land-system change and biosphere integrity (for the latter see D3.3). Thus, the most ambitious diet change scenario might move both the Amazon and the African rainforest back into a “safe” zone of remaining forest cover, as a control variable for land-system change. As summarized in the literature, reforestation may provide multiple co-benefits for Nature’s Contributions to People and SDGs, including enhancing biodiversity by creating wildlife corridors, regulation of air and water quality, enhancing precipitation through increased moisture recycling and flood and erosion control, the latter gaining importance vis-à-vis increased frequency of extreme events under climate change (Griscom et al., 2017; Seymour et al., 2022; Smith et al., 2019). Large-scale forest restoration as realisable upon transition to the EAT-Lancet planetary health diet would thus jointly address international targets regarding both climate change mitigation and nature restoration: The simulated DC50 scenario implying reforestation on 325 Mha is close to reaching "The Bonn Challenge", an international initiative aiming to bring 350 Mha of degraded or deforested areas into restoration until 2030[1]. In the context of Europe, this synergy between climate stabilization and nature restoration is addressed by EU's pledge to plant three billion additional trees by 2030, aiming to increase carbon storage in biodiversity-friendly forests. Full transition to the EAT-Lancet diet would even imply to reach halfway towards the 30 by 30 target, i.e. conserving 30% of the world's land and ocean areas by the year 2030 as agreed upon within the Kunming-Montreal Global Biodiversity Framework as part of the Convention on Biological Diversity: expanding protected areas by 736 Mha would increase protected areas from 16.6% today (UNEP-WCMC et al., 2020) to ~22% of global land surface. To reach such ambitious targets, financial incentives for restoring and preserving forests would have to come from high-income and high-emitting nations (Hayek et al., 2021), particularly for tropical forest restoration, where high benefits for both carbon storage and biodiversity protection coincide (Soto-Navarro et al., 2020).

Given the synergies of nature restoration for multiple planetary boundaries, particularly biosphere integrity as a core pillar of planetary stability next to climate (see D3.3), rewilding of even larger pasture areas would be beneficial. Assuming more drastic diet changes up to a vegan diet could allow renaturation of all pasture areas thus expanding from a focus on forest ecosystems to also include restoration of savanna and grassland ecosystems. As shown by Hayek et al. (2021), shifting to plant-based diets by 2050 could allow for overall removal of 332-547 GtCO_2, corresponding to 99–163% of the remaining CO_2 emissions budget consistent with a 66% chance of limiting warming to 1.5 °C. Over 70% of this potential would result from rewilding pastures (the remainder from crop feed reductions). The same authors also quantify the potential overall removal on abandoned pastures to be ~245 GtCO_2 for a transition to the EAT-Lancet diet. According to our simulations, roughly half of this overall potential is assumed to be reached after 30 years (~130 GtCO_2).

The existence of an upper limit to reforestation potentials emphasizes the inherent limit to forest carbon storage: With increasing forest maturity, CDR rates decrease until eventual saturation of the forests CO_2 sink, usually within less than a century (Chiquier et al., 2022). Reforestation is thus not suitable to compensate for residual hard-to-abate emissions in the long-term, which have been projected at ~18% of current emissions in the most ambitious scenarios from Annex I countries (industrialized countries and economies in transition) (Buck et al., 2023). Also, carbon stored in forests is exposed to natural disturbances, such as droughts and wild fires, which may increase with climate warming. As put by Nolan et al. (2021), reforestation is thus "at risk from the problem they are attempting to solve". In contrast to BECCS, with CO_2 storage in geological reservoirs considered as permanent, CDR from reforestation is reversible and would require sustained management to prevent sequestered carbon from being released back to the atmosphere (Chiquier et al., 2022; Tanzer et al., 2022 (D6.3)).

4.2 Interactions with the food system

Impacts of the food system on CDR and climate change mitigation

The food system is a key determinant of land availability for CDR, with diet changes – next to sustainable intensification and food waste reductions, – being particularly impactful (see above). On the other hand, diet changes could also reduce the need for CDR by significantly reducing non-CO_2 emissions. We here focused on CDR from pasture rededication, and did not analyze the resulting additional climate change mitigation potentials from emission reductions in line with the assumed diet changes. Herrero et al. (2016) showed however, that a

[1] https://www.bonnchallenge.org

low meat diet could additionally reduce process emissions (primarily CH_4/N_2O from enteric fermentation and manure) by about 1-2 $GtCO_2eq\ yr^{-1}$.

Impacts of CDR on food security

There have been multiple studies on the potential negative effects of stringent global climate change mitigation policies for large-scale BECCS and/or afforestation on food security, resulting from increased land rent due to the additional competition (Fujimori et al., 2022; Hasegawa et al., 2018; IPCC, 2019a; Kreidenweis et al., 2016). At the same time, diet changes and further sustainability transformations within the food system have been shown to prevent such food price increases by in turn reducing pressure on land (Soergel et al., 2021). We here a priori assumed that pastures would be abandoned in line with simulated diet change scenarios, but more research is needed to gain understanding on how to best incentivize such diet changes without negative effects on food security. Also, we performed a systematic scenario analysis to better understand the isolated effect of rededicating pastures to either reforestation or biomass plantations for BECCS, and did not model indirect effects on food security. While exploring the economic spill-overs of changes in demand for agricultural commodities is clearly out of the scope of a vegetation model, the simulated increases in agricultural inputs for the BECCS scenarios would likely increase water and fertilizer prices. This increased competition for agricultural inputs could drive food prices up and thereby exacerbate global food security.

Diet changes and food security

Diet changes towards less animal products generally have a positive impact on global food availability (Berners-Lee et al., 2018). While not explicitly modelled, the assumed EAT-Lancet diet would not only free pasture areas, but also allow for partial reallocation of crop feed to direct human consumption or for growth of plant-based alternatives on freed cropland, thereby increasing food availability (Braun, Stenzel, et al., 2022; Cassidy et al., 2013). Nevertheless, livestock may provide valuable nutrients particularly in pastoralist societies and subsidence farming systems (Garnett, 2013). Thus, approximately 10% of the world's meat supply is sourced from extensive rangelands, sustaining the livelihoods of several hundred million pastoralists (Jenet et al., 2016). Pastoralist societies typically exist in arid and semi-arid climate zones, where rainfall is too low to support traditional agriculture (i.e. regions within non-forest ecosystems and with minimal cropland). As we prioritized cells with a high cropland share (BECCS) and high forest cover in neighbouring cells (reforestation), the rededication scenarios are thus expected to imply minimal effects on pastoralist systems and mostly target commercially used pastures.

Planetary boundaries as a biophysical basis for food production

The simulated scenarios of pasture rededication impact terrestrial planetary boundaries in opposite directions. While reforestation may contribute to restoring Earth system functioning with regard to biosphere integrity (see D3.3) and land-system change, expansion of biomass plantations for BECCS would exacerbate the pressures on biosphere integrity (see D3.3), freshwater use and nitrogen flows. This comes against the backdrop of current agriculture being the major cause of terrestrial planetary boundary transgressions (>80% contribution) and a major contributor to climate change (~25%) (Campbell et al., 2017). The food system is however not only a prime cause for planetary boundary transgressions but at the same also at risk of the consequences of these very transgressions: (i) Stable climate conditions is crucial for agricultural production and the stability of the Holocene allowed for the development and flourishment of agriculture (Rockström et al., 2009a); increases of extreme weather events can multiply yield losses and crop failures (e.g. Lesk et al., 2022). (ii) The biosphere supports agriculture production in multiple ways, amongst others by species creating and maintaining healthy soils, pollinating plants or controlling pests, by purifying water and providing protection against extreme weather events, and by impacting rainfall patterns, amongst others (FAO, 2019). While the higher CDR rates from BECCS might help to better dampen climate change effects on food security, the further deterioration of the biosphere might negatively affect food production in other ways (Pilling et al., 2020). This highlights that (i) food security is highly intertwined with the biophysical SDGs and (ii) that the planetary boundaries constitute the foundation for reaching SDGs, among them food security. In this context, reforestation has the clear advantage of synergistically contributing to getting back into a safe operating space with regard to multiple planetary boundaries.

5 Key findings and policy relevant messages

[The contents of this section have been aligned with the corresponding section in the complementary Deliverable 3.3]

Reduced grazing demand in line with a transition to the EAT-Lancet planetary health diet could free up ~800 Mha of pastures for either biomass plantations or reforestation, corresponding to roughly 25% of current global pasture areas. Biomass plantations for BECCS on these rededicated areas could remove ~14.4 $GtCO_2eq$ yr^{-1} for a biomass-to-electricity conversion, or ~8.9 $GtCO_2eq$ yr^{-1} for a biomass-to-liquid conversion. The latter is roughly equivalent to simulated median BECCS rates in 2100 in AR6 climate stabilization scenarios (IPCC, 2022), which however also include other biomass feedstocks than dedicated energy crops.
Such large-scale expansion of biomass plantations would however drastically increase global arable land (~+50%), irrigation water withdrawals (~+15%) and fertilizer application (~+60%) assuming a moderate management on plantations, thereby creating a strong competition for agricultural resources with potentially severe impacts on food security. Concerning water security, the implied expansion in irrigated areas would increase areas under high water stress by ~40%. In addition to socio-economic impacts on water and food security, areas with transgressions of environmental boundaries for nitrogen and water would increase by ~50% and ~45%, respectively. As a complement to this analysis, D3.3 shows that large-scale conversion of pastures to biomass plantations would exacerbate pressures on the biosphere by reducing the energy available for natural ecosystems and increasing areas subject to major or severe biogeochemical, hydrological and vegetation-structural shifts. CDR levels and impacts are strongly dependent on the management on biomass plantations: more irrigation and fertilization may boost achievable CDR, but at the same time amplify negative impacts on resources, water stress and environmental boundaries. This emphasizes the severe trade-off between CDR provision from dedicated biomass plantations for BECCS and other sustainability targets. Options such as precision farming, the use of nitrification inhibitors, application of microbiome technologies or breeding of species with enhanced tolerance towards water and nitrogen stress could potentially alleviate these trade-offs but their assessment was beyond the scope of this assessment. Minimal management, i.e. assuming rainfed and unfertilized plantations only, reduces global CDR but may mitigate most, albeit not all, side-effects, but would require universal political regulations. While converting less pasture areas to biomass plantations would reduce the negative side-effects and CDR potential in magnitude, the direction of the impacts would remain the same, thereby to some degree increasing the pressure on an already severely disturbed Earth system.

Assuming comprehensive pasture reductions in line with a full transition to the EAT-Lancet planetary health diet, reforestation on rededicated pastures would provide less CDR per rededicated pasture area than BECCS, with a simulated CDR of ~4.3 $GtCO_2eq$ yr^{-1}. This is higher than the median projected net removal on managed land for 2050 in 1.5°-2° compatible scenarios of IPCC's AR6, which mostly assume less stringent food system transformations, and similar to the median rates in 2100 (IPCC, 2022). In contrast to BECCS, however, no competition for agricultural resources with food provision would emerge and the pressures on water stress as well as environmental boundaries for nitrogen and water, would – if not decrease – at least not increase. Furthermore, reforestation on pastures could significantly contribute to restoring nature, thereby reducing pressures on planetary boundaries for both land-system change and biosphere integrity (for the latter see D3.3). Notably, the most ambitious diet change scenario might shift both the Amazon and the African rainforest back into a "safe" zone of deforestation, as a control variable for land-system change.

6 Conclusions and further steps

Our results underpin that reducing land use within the food system may enable high CDR potentials, making diet changes to fewer animal products an effective strategy for mitigating climate change (Stehfest et al., 2009). While dedicating pastures to biomass plantations for BECCS would allow for more CDR (with a higher level of permanence) than reforestation, this would come at the cost of drastic trade-offs with food and water security as well as terrestrial planetary boundaries. Against the backdrop of already severe and wide-spread terrestrial planetary boundary transgressions today (Gerten et al., 2020), these negative side effects might lead to the "cure being worse than the disease". As an alternative, CDR from reforestation is less efficient per area, thus requiring more ambitious diet changes to reach similar CDR rates as BECCS. It would however allow to synergistically achieve multiple sustainability targets, by simultaneously contributing to both climate stabilization and nature restoration. Given that land is a finite and scarce resource, this multifunctional use of land could provide an integrated strategy to combine several goals within the same territory (WBGU, 2020). It thereby also responds to the recent call of members from both the International Panel on Climate Change as well as the International Panel on Biodiversity and Ecosystem Services to address the intertwined climate and biodiversity crisis jointly (Pörtner et al., 2023). Expanding the focus beyond the carbon cycle, our results thus stress that a multidimensional perspective on sustainability and Earth system stability favors reforestation on pastures, at least when talking about large-scale conversions and if extensive management on biomass plantations cannot be ensured globally.

The combination of diet changes with reforestation on spared land may provide an important cornerstone for the urgent U-turn to reverse current planetary boundary transgressions (Gerten et al., 2020) without negatively impacting food availability. A respective sustainability transformation of the food system, combining diet changes with reductions in food losses and waste and sustainable intensification, would however require unprecedented ambitions and coordination. With regard to diet changes, the current trend points to the opposite direction, i.e. increases in livestock consumption at the global level (FAO, 2023b), and would require strong engagement from countries with above-average consumption of livestock products, among them many EU countries.

At the same time, ambitious international efforts are needed to reach the CDR levels – next to stringent decarbonisation – needed to reach net zero greenhouse gas emissions for climate stabilization (Smith et al., 2023). CDR from reforestation is reversible and not sufficient to compensate for projected residual emissions (Buck et al., 2023), particularly on the long run, as carbon sequestration in forests saturates within a few decades. Yet, diet changes and associated land sparing could significantly reduce the need for novel NETPs, such as direct air capture and storage, enhanced weathering or BECCS (Smith et al., 2023), which are still under development but would allow for permanent storage of CO_2. With regard to BECCS, other biomass sources than dedicated biomass plantations, e.g. agricultural and forestry residues, biogenic point sources or manure (Hanssen et al., 2020), may play an important role for climate stabilization without the severe side-effects of dedicated biomass plantations – however significant uncertainties are associated with the relatively high contribution projected in most economically optimized mitigation scenarios (Hanssen et al., 2020). As biomass plantations are however not only considered for CDR but also for an increase in bioenergy supply, this would also imply a reduction in the reliance on bioenergy along with a stronger reliance on other renewable energy sources. Given that (i) biogenic carbon storage, amongst others in forests, is reversible and limited, (ii) BECCS from dedicated biomass plantations might have severe side-effects and (iii) other novel NETPs might be difficult to upscale (Nemet et al., 2018), early and rapid decarbonization with minimal reliance on CDR should however be prioritized under all means (Ho, 2023).

As a contribution to evaluate land use futures under multi-dimensional sustainability objectives, we here systematically assessed the CDR potentials and impacts from rededicating pastures. Our results emphasize the importance of such multi-dimensional sustainability assessments for CDR and land use strategies in the EU and beyond. Climate policies should thus carefully consider the effects on all planetary boundaries as well as socio-economic effects within the EU and globally, avoiding potential adverse effects on the biosphere (Searchinger et al., 2022). Development pathways would thus need to integrate urgently needed (i) food system transformations, (ii) nature restoration as well as (iii) climate stabilization to align European production and consumption with planetary boundaries (Sala et al., 2020). For this, the global perspective outlined in the presented report needs to be combined with analyses on the specific conditions within EU countries as aimed for within the NEGEM project. Combined with complementary NEGEM assessments on political, social and technological feasibility of different NETPs, the results of this systematic analysis will feed into the integrated assessment of several NEGEM climate stabilization pathways with TIMES-VTT, amongst others for designing and quantifying an ambitious climate stabilization scenario with a focus on “Nature conservation and Biodiversity“ (see Lehtilä et al. (2022) (D8.6)). The insights provided by this deliverable and its complementary counterpart D3.3. will also be integrated within the synoptic report D3.10, synthesizing the key findings of WP3 on CDR potentials under consideration of impacts on planetary boundaries and SDGs. Additionally, Deliverable D3.4 will focus on assessing the effects of climate extremes on NETP potentials, expanding beyond the current emphasis on low emission climate scenarios in the presented studies.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D3.1	Upgraded LPJmL5 version	PIK	R	PU	M12
D3.2	Global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries	PIK	R	PU	M24
D3.3	Global NETP assessment of impacts utilising concepts of biosphere integrity	PIK	R	PU	M36
D7.1	MONET-EU tool	ICL	R	PU	M12
D7.2	Extended MONET-EU	ICL	R	PU	M17

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Appendix

S1. Revised parametrization of the herbaceous BFT

Within the NEGEM project, we have continuously worked on enhancing the representation of the above described carbon, nitrogen and water flows for the BFTs in LPJmL as a contribution to the core objective of NEGEM to assess realistic potentials of (biomass-based) NETPs. As part of these efforts, we have made some adaptations to the plant physiology and nitrogen distribution of the herbaceous BFT (see Table S 1). Specifically, we have adjusted the specific leaf area (i.e. the leaf extent per accumulated mass) to fit the reported value for Miscanthus in the TRY database, setting it to 39 $mm^2 mg^{-1}$ dry matter (Kattge et al., 2020). In addition, we have modified the relation of leaf to root biomass from 0.75 to 2.50 to represent the high-growing Miscanthus, rather than regular C4 grass of significantly lower height. The adapted value falls within the narrow corridor of the complete coverage of different value ranges reported in the literature (Guo et al., 2016; Rakić et al., 2021; Trybula et al., 2015) (Table S 1).
In terms of biomass decay, we have further suppressed the natural turnover of leaf biomass to the litter pool in the model, as this biomass is typically harvested in managed systems. Opposed to the former harvest routine depending on carbon accumulation, the harvest has been set to a single event per year (Table S 1) to better represent the common practice (Li et al., 2018). Moreover, we have adapted the C/N ratio of the aboveground biomass to match the measurements by Heaton et al. (2009), using the interannual variance to determine minimum, median, and maximum ratios in the model (Table S 1). Finally, we have also adjusted the nitrogen recovery rate based on measurements of the nitrogen content in standing biomass from the same publication, setting it to 32% for green harvest and 70% for brown harvest (Heaton et al., 2009). However, this assessment exclusively assumes green harvest as it is reported a common practice (Li et al., 2018) and allows for processing to biofuels (Winkler et al., 2020).

Table S 1. Adjustments of parameters of the herbaceous bioenergy functional type.

Parameter	Default value	Adjusted value	Literature
Specific leaf area	23 $mm^2 mg^{-1}$ dry matter	39 $mm^2 mg^{-1}$ dry matter	10–70 $mm^2 mg^{-1}$ dry matter (Cheng et al., 2020) 11–99 $mm^2 mg^{-1}$ dry matter (Kattge et al., 2020)
Ratio of leaf biomass to root biomass	0.75	2.50	1.04–1.31 at emergence (Trybula et al., 2015) 4.55-8.33 at maturity (Trybula et al., 2015) 2.31–4.54 (Guo et al., 2016) 1.43–2.50 (Rakić et al., 2021)
turnover	$\frac{1}{365}$ leaf mass per day	none	
Harvest date	Determined by carbon accumulation	*Northern hemisphere:* 1. Oct. for green harvest 1. Feb. for brown harvest *Southern hemisphere:* 1. Apr. for green harvest 1. Aug. for brown harvest	*Northern hemisphere:* All months covered without distinction for green and brown harvest in Li et al. (2018) October for green harvest (Winkler et al., 2020) March for brown harvest (Winkler et al., 2020)
C/N ratio in leaves	Median: 34.0 minimum: 17.4 Maximum: 66.9	Median: 90 minimum: 34 maximum: 132	34–132 (Heaton et al., 2009)
N recovery	70%	Green harvest: 31.80% brown harvest: 70.12%	31.80–70.12% (Heaton et al., 2009)

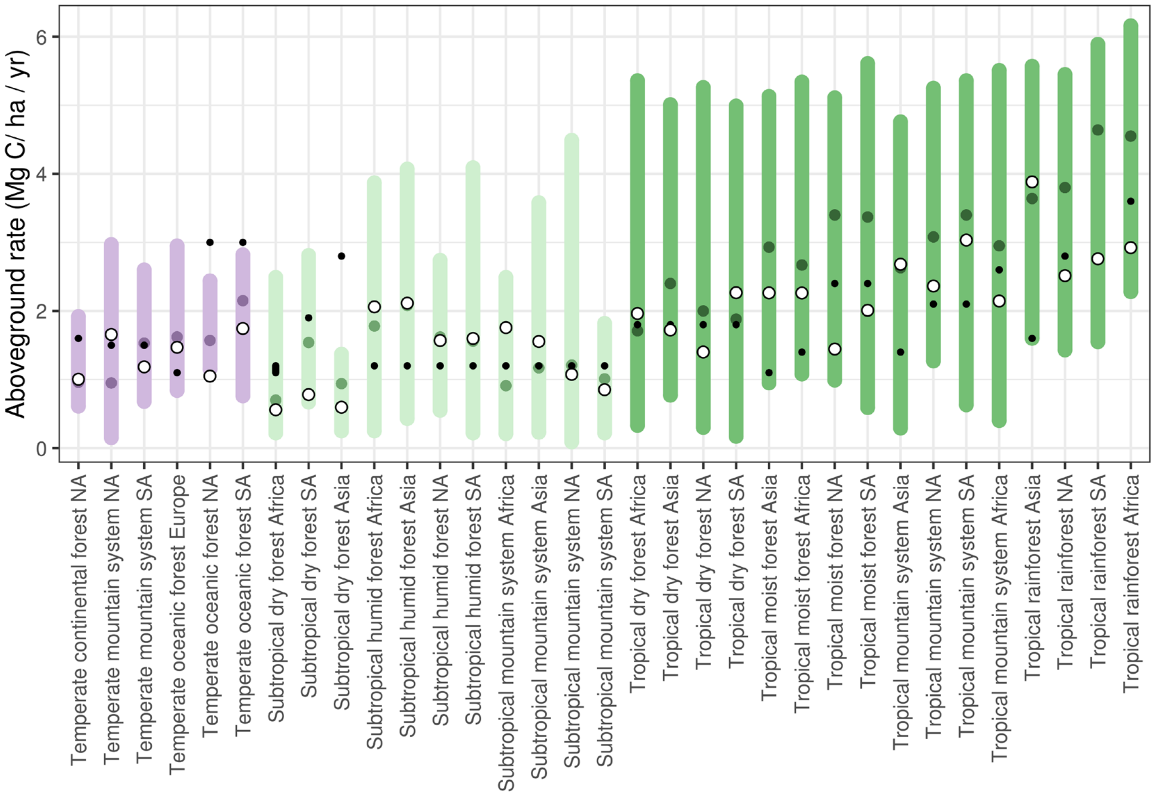

Figure S 1: Comparison of simulated median aboveground carbon accumulation rates (open circles) per ecozone to (i) IPCC (2019b) defaults (filled black circles) and (ii) predicted rates from Cook-Patton et al. (2020) (coloured circles for the average and coloured bars for the range between minimum and maximum simulated rate). Simulated rates refer to the assumption that carbon pools after 60 years of simulation with LPJmL are reached within 30 years to compensate for too slow establishment rates. NA = North America; SA = South America.

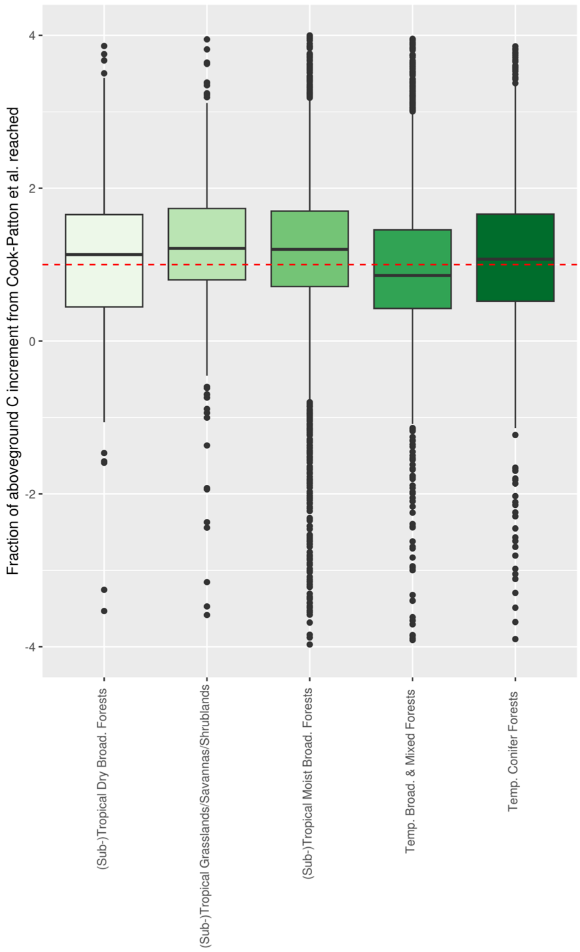

Figure S 2 The fraction of aboveground carbon increment given for reforestation on pastures for five biomes in Cook-Patton et al. (2020) reached by LPJmL simulations over 60 years. The dotted red line highlights the value of 1 which represents a complete resemblance of the observed data.

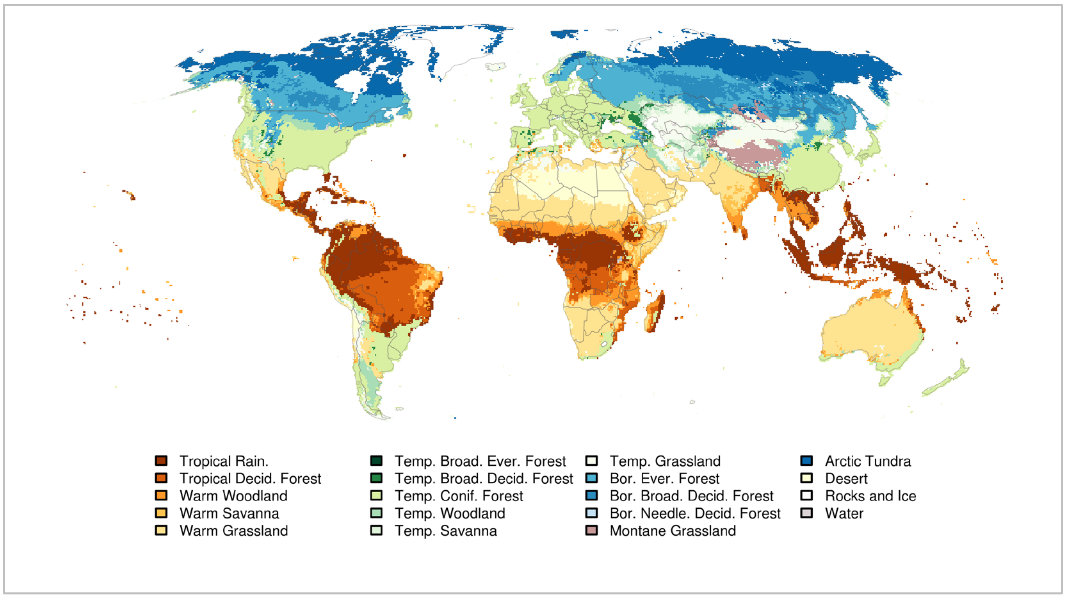

Figure S 3: Biomes based on simulated distribution of plant functional types in LPJmL (for potential natural vegetation under 2036-2065 climate for RCP2.6-SSP1).

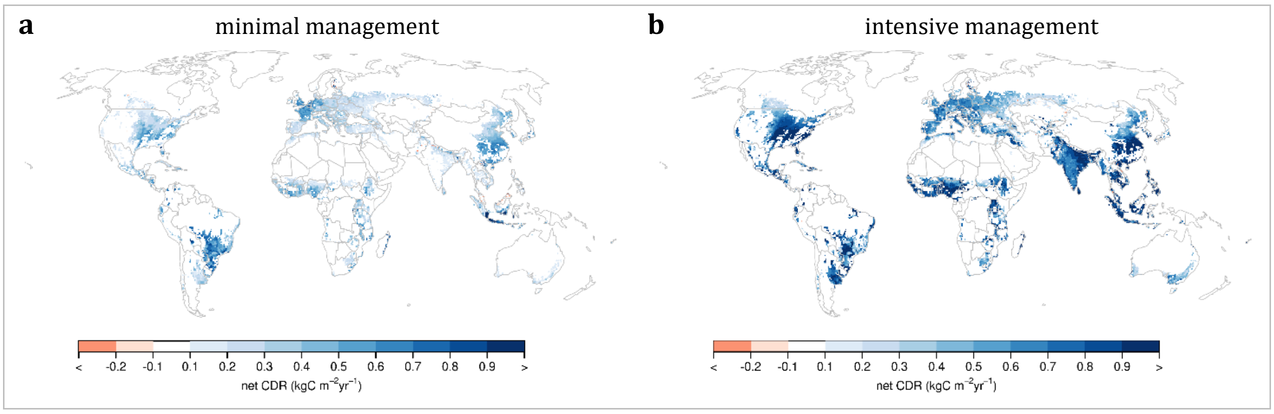

Figure S 4: Simulated net CDR from biomass plantations for BECCS assuming (a) minimal management and (b) intensive management, as well as a B2E pathway.

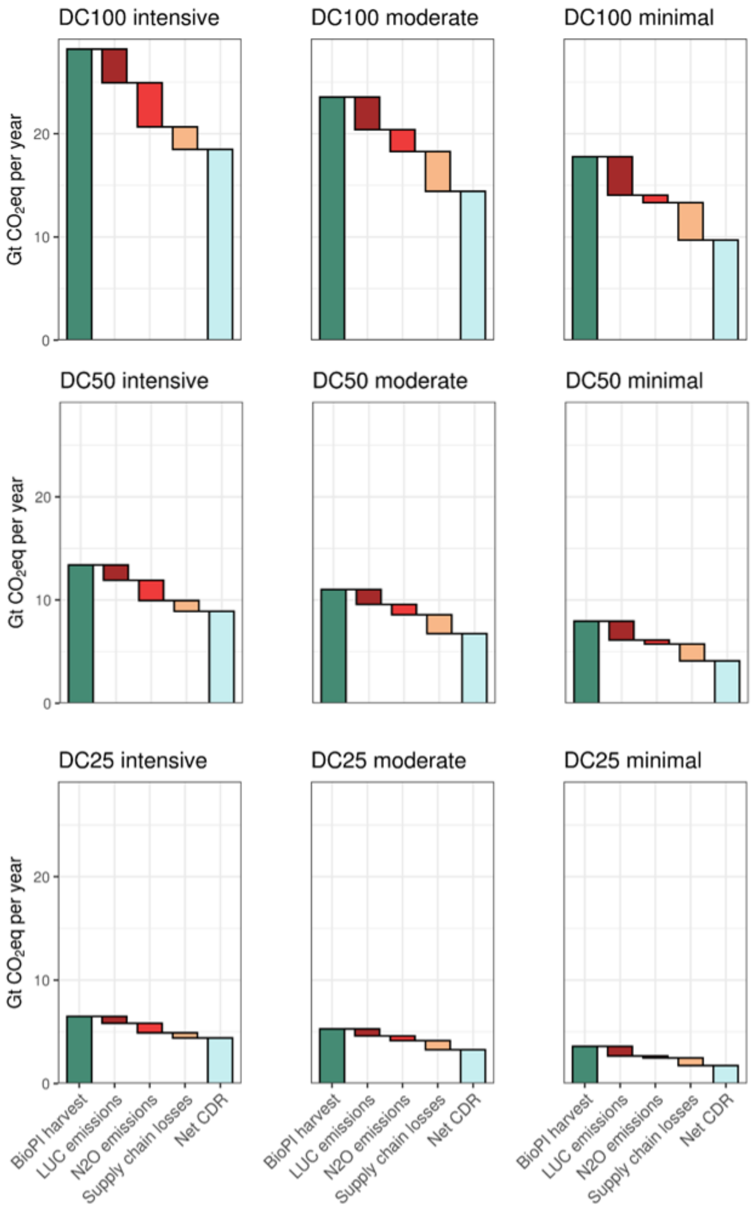

Figure S 5: Calculation of global net CDR from rededicated pastures to biomass plantations for BECCS, for partial or full transition to EAT-Lancet diet (DC25, DC50, DC100) and three management scenarios (intensive, moderate and minimal). Harvested CO_2eq are reduced by land use change emissions through reduced carbon pools on plantations (dark red), additional N_2O emissions through fertilization on plantations (in CO2eq; red), and C02 losses along the BECCS supply chain through fossil fuel use and in the carbon capture and storage process (orange, here for a B2E pathway; see methods).

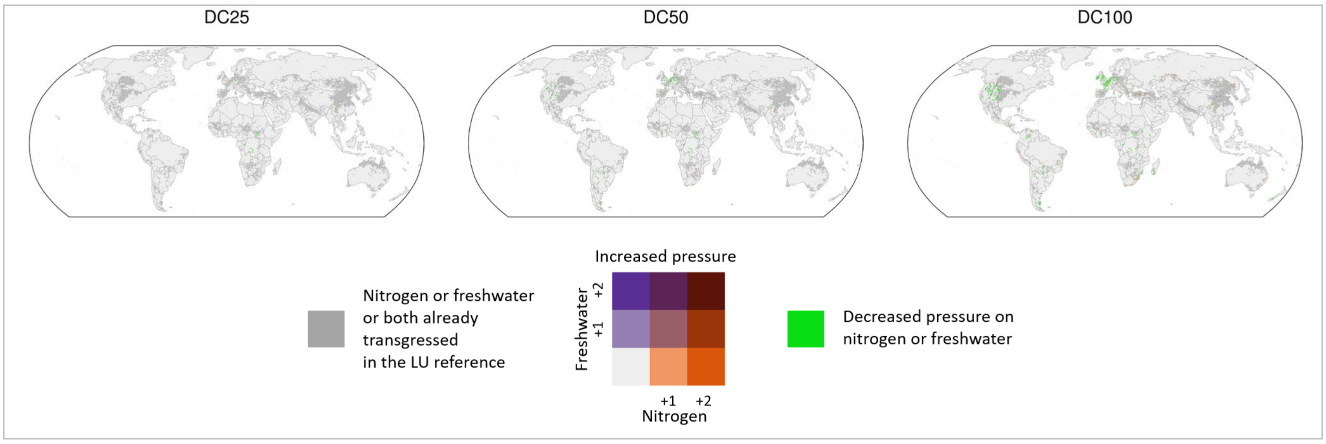

Figure S 6: Spatially explicit effects of reforestation on pastures on the status of freshwater and nitrogen boundaries. The bivariate scale shows increases in pressure on the freshwater and/or nitrogen boundary as compared to the land use reference. +1 = planetary boundary status worsens by one step: either a shift from a safe level to increasing risk level, or from increasing risk level to high risk level; +2 = planetary boundary status worsens by two steps: from safe to high risk level. Green areas indicate cells where conversion of pastures to forests improve the nitrogen and or freshwater status.