NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Report on synoptic assessment of global theoretical NETP potentials

Horizon 2020, Grant Agreement no. 869192

Number of the Deliverable	Due date	Actual submission date
D3.10	**31.10.2023**	**31.10.2023**

Work Package (WP): 3 – Impact assessment

Task: T3.3 Global theoretical NETP potentials that maintain planetary boundaries and deliver on the SDGs

Lead beneficiary for this deliverable: PIK

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Dissemination level: Public

Call identifier: H2020-LC-CLA-02-2019 - Negative emissions and land-use based mitigation assessment

Document history

V	Date	Beneficiary	Author/Reviewer
1.0	2023-10-17	PIK	Constanze Werner; Johanna Braun; Wolfgang Lucht; Dieter Gerten/ Selene Cobo Gutiérrez (ETH), Allanah Paul (BELLONA), Mark Preston Aragonès (BELLONA)
1.1	2023-10-17	PIK	Constanze Werner; Johanna Braun; Wolfgang Lucht; Dieter Gerten

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869192

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Statement of Originality
This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Executive Summary

Globally, 76% of nations have proposed or committed to net zero emission goals for this century. The essence of this concept aligns with the Paris Agreement's aim to balance human-caused emissions with emissions removal. Achieving this equilibrium involves two central elements: "residual emissions," which are emissions remaining despite mitigation efforts, and "carbon dioxide removal" (CDR) techniques. However, scepticism persists about the feasibility of high CDR levels due to complex economic, political, and technological requirements, with significant concerns about potential environmental and social impacts from large-scale deployment of certain negative emission technologies and practices (NETPs). These challenges may threaten Earth system stability, especially considering preexisting anthropogenic pressures and resource competition associated with CDR. Therefore, comprehensive impact assessments of CDR scenarios are required to outline possible pathways of achieving net zero emissions while safeguarding planetary boundaries to maintain Earth system stability and contributing to other societal targets, like the United Nations' Sustainable Development Goals (SDGs).

To address concerns regarding significant trade-offs, WP3 conducted extensive research aimed at assessing the most critical impacts and side effects associated with large-scale deployment of NETPs in regard to Earth system stability, ecosystem functionality, human health, and resource availability. The comprehensive evaluations of NETP impacts and their "sustainable" potential within WP3 were grounded in a diverse array of methodologies, including spatially-explicit, process-based biogeochemical modelling of key environmental functions under NETP deployment (D3.2/3.3/3.7) as well as life cycle analysis addressing diverse impact dimensions (D3.8) and integrated assessment modelling focusing on non-renewable material flows (D3.9), complemented by reviews of state-of-the-art literature for selected marine NETPs (D3.5) and for the potential contribution of Nordic forests to climate stabilization (D3.6).

This deliverable serves to consolidate the WP3 research by (i) presenting an overview of the methods employed, including their objectives, limitations, and explanatory value, (ii) summarizing the most pertinent impacts identified across a range of assessed NETPs and their connections to SDGs and (iii) emphasizing the significance of impacts associated with land-based NETPs, which were found to exhibit robust interconnections with biosphere integrity, the most critical dimension of Earth system stability in conjunction with climate stability. The latter is accomplished through (a) a condensed presentation of the WP3 quantifications for responsible CDR potentials, (b) an additional quantification of land- and calorie-neutral biochar sequestration potentials within an enhanced evaluation, and (c) a literature review focusing on exploitable biomass side streams and the corresponding CDR potentials for Bioenergy with Carbon Capture and Storage (BECCS).

Based on these evaluations, this WP3 synopsis concludes that every NETP assessed (re-/afforestation, forest management, BECCS, biochar sequestration, Direct Air Capture and Carbon Storage (DACCS), enhanced weathering, coastal blue carbon and ocean alkalinization) shows trade-offs with at least one impact dimension. To mitigate the effects of individual stressors from specific NETPs, the CDR portfolio should be diverse under consideration of the NETPs' multidimensional constraints and differences in technology readiness as well as the reliability of CO_2 storage. However, forest restoration stands out with the most co-benefits, aligning with global targets for both nature restoration (e.g., the Kunming-Montreal Biodiversity Framework) and climate stabilization (e.g. the Paris Agreement). Yet, carbon sequestration within forests is reversible and may be threatened by increased fire frequencies under climate change. Also, feasibility of reforestation is intricately linked with large-scale food system transformations. Releasing land for reforestation or other natural climate solutions can most effectively be achieved through a diet shift reducing meat consumption. D3.7 found that a complete transition to the EAT Lancet planetary health diet could release about 736 Mha pasture area to forest

restoration and sequester ~4.3 $GtCO_2eq\ yr^{-1}$ in a 30-year timeframe. Beyond the land use dynamics, natural climate solutions are also strongly interlinked with the food sector by multiple co-benefits including measures to reduce hard-to-abate non-CO_2 GHG emissions in agriculture and applications elevating yields. Facilitated by biochar-mediated yield increases, a land- and calorie-neutral approach to biomass pyrolysis was quantified to sequester ~ 0.2 $GtCO_2eq\ yr^{-1}$ without imposing additional stress on the biosphere or food production. In contrast to these potential synergies, all assessed NETPs relying on biomass feedstocks (wood products, biochar, BECCS) can have severe environmental impacts if based on feedstock production on large-scale and intensively managed plantations. This would add a large new land use sector in a situation where agriculture in its current form is already a major cause of planetary boundary transgressions, likely exacerbating pressure on these boundaries. Thus, the potential for low-impact biomass-based CDR is limited due to constraints imposed by other dimensions of Earth system stability than climate and its quantification is subject to substantial uncertainties, suggesting its realistic potential to be small unless realized in a sustainable, ecologically responsible manner on current agricultural land or by considerately utilizing biomass side streams, both requiring stringent regulation world-wide.

In regard to storage reliability, approaches with geological storage have the potential to become a crucial component for effectively offsetting residual emissions, primarily due to its permanent and reliable carbon storage, while sourcing sustainable biomass for BECCS and clean energy for DACCS prevail as limiting factors. In contrast, CDR from natural climate solutions is saturable and reversible and thus less suitable for compensating residual fossil emissions, but their role in restoring, fostering and protecting the natural carbon sink remains indispensable for Earth system stability.

In conclusion, the findings on NETP impacts and sustainable potentials summarized in this report suggest the careful implementation of a portfolio of NETPs taking the various dimensions of Earth system functioning and SDGs into account in a holistic approach. This comprehensive task faces the challenge to develop deployment strategies that are considerate and robust, yet effective and timely. Nonetheless, it is also crucial to acknowledge the vast range of substantial uncertainties regarding sustainable potentials, i.e. wide ranges in the upper ceiling estimates for reforestation (1.6–4.3 $GtCO_2eq\ yr^{-1}$), land- and calorie-neutral biochar sequestration (0–2.03 $GtCO_2eq\ yr^{-1}$) and BECCS supplied by biomass side streams plus current bioenergy plantings (1.7–7.0 $GtCO_2eq\ yr^{-1}$). In light of these limitations and uncertainties to responsible CDR potentials, the precautionary principle calls for rapid decarbonization and high ambitions to reach lowest possible levels of residual emissions. The smaller the residual emissions are, the lower the demand for CDR, resulting in less pressure to venture into potentially less sustainable NETP applications.

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Introduction

Globally, 76% of nations have put forth proposals, pledges, or legally enacted net zero emission targets for this century (Lang et al., 2023). The concept of "net zero" has undeniably risen to the forefront of climate discussions, becoming the prevailing framework for long-term aspirations in national and corporate climate governance. Fundamentally, the idea of "net zero" aligns with the objectives outlined in the Paris Agreement, which aims to strike a balance between "anthropogenic emissions by sources and removals by sinks of greenhouse gases" (UNFCCC, 2015). This pursuit is rooted in the essential goal of preserving a stable Earth system by limiting climate warming to the lowest level possible, potentially even achieving a reduction in temperatures (compared to current warming levels), aligned with the planetary boundary (PB) for climate change (Richardson et al., 2023). The envisaged equilibrium hinges on two pivotal concepts: "residual emissions," signifying emissions that persist despite mitigation measures, and "carbon dioxide removal" (CDR). CDR encompasses a variety of approaches designed to extract CO_2 from the atmosphere, generating negative emissions to counterbalance residual emissions (negative emission technologies and practices = NETPs). Therefore, the timing of emission reductions and the magnitude of residual emissions, or, in simpler terms, the extent to which greenhouse gas emissions are reduced, directly influence the pressure on CDR efforts.

However, widespread scepticism surrounds the feasibility of achieving high levels of CDR when considering the complex economic, political, and technological prerequisites necessary for the rapid expansion of NETPs (Anderson & Peters, 2016; Lenzi et al., 2018; Nemet et al., 2018). Additionally, concerns have been raised about the potential for severe environmental and social consequences: for example, the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS) utilizing dedicated bioenergy crops could lead to increased land degradation, competition for land resources needed for food production and biodiversity conservation, and heightened demands for irrigation water and fertilizers (Boysen et al., 2017; Humpenöder et al., 2018; Stenzel et al., 2019). Consequently, there is uncertainty regarding the compatibility of high CDR rates, such as the median estimate of 8.8 $GtCO_2$ for BECCS in 2100 within climate stabilization scenarios of Integrated Assessment Models (IAMs) contributing to the IPCC's AR6, with the resilience of the Earth system (Heck et al., 2018). This is especially concerning when considering the existing anthropogenic pressures on key Earth system functions, as evaluated within the PB framework, even in the absence of large-scale NETP deployment (Gerten et al., 2020; Richardson et al., 2023). Moreover, the competition for resources induced by CDR efforts (amongst others land, water and energy), may exert a significant strain on other important societal objectives, such as the United Nations' Sustainable Development Goals (SDGs) (Smith et al., 2019).

To address the concerns about substantial trade-offs, the research in WP3 assessed most critical impacts and side-effects of large-scale NETP deployment in regard to Earth system stability, ecosystem functioning, human health and resource availability. The comprehensive evaluations of NETP impacts and “sustainable” potentials in WP3 build on diverse methodologies encompassing spatially-explicit, process-based biogeochemical modelling of key environmental functions under NETP deployment (D3.2/3.3/3.7) as well as life cycle analysis addressing diverse impact dimensions (D3.8) and integrated assessment modelling focusing on non-renewable material flows (D3.9), complemented by reviews of state-of-the-art literature for selected marine NETPs (D3.5) and for the potential contribution of Nordic forests to climate stabilization (D3.6).

This deliverable synthesizes this work by

(i) providing an overview of the applied methods, their objectives, limitations and explanatory value,
(ii) summarizing the most relevant impacts identified for the range of assessed NETPs and their interlinkages with SDGs,
(iii) highlighting the relevance of impacts from land-based NETPs, as these were found to have the strongest interconnections with biosphere integrity, the second core pillar of Earth system stability alongside climate stability, through
    a. a summary of WP3 quantifications for responsible potentials,
    b. an additional quantification of land- and calorie-neutral biochar sequestration potentials in an enhanced evaluation and
    c. a literature search on exploitable biomass side streams and corresponding BECCS potentials.

Finally, the findings are addressed in the context of residual emissions, highlighting potential consequences of uncertainties and constraints for the diverse roles different NETPs can play in climate stabilization.

1 Assessing NETP impacts and sustainable potentials in WP3

1.1 Methodological and conceptual approaches in WP3

Evaluating the impacts of NETP deployment is a complex field with many intertwined dimensions. To address this, WP3 was designed to encompass a spectrum of the most critical consequences for Earth system stability, ecosystem functioning, human health and resource availability, evaluated through a diverse array of methodologies. These span from process-driven biosphere modelling and life cycle assessments to integrated assessment modelling and focused literature reviews, each developed for specific objectives. This section, along with a structured summary in Table 1, provides a concise overview of their conceptual rationales, the dimensions of impacts considered, the associated limitations and their respective explanatory value.

1.1.1 Process-based biosphere model LPJmL (D3.2/3.3/3.7)

D3.2, D3.3, and D3.7 analyses utilize the dynamic global vegetation model LPJmL (version LPJmL5-NEGEM), which provides spatially explicit simulations of the effects of biomass plantation expansion (BECCS) and reforestation on carbon, water, and nitrogen fluxes and pools. LPJmL simulates the main biogeochemical dynamics within the biosphere in a process-based manner, representing both natural and managed vegetation, including fast-growing second-generation energy crops.

In D3.2, LPJmL5 is used to quantify the biophysical potential of BECCS with feedstock production on currently uncultivated land while considering constraints imposed by four terrestrial PBs: biosphere integrity, land-system change, freshwater use, and nitrogen flows.

As D3.2 demonstrates that the conversion of (semi-)natural land to biomass plantations for NETPs presents a potential exacerbation of the already compromised terrestrial PBs, D3.3 and D3.7 undertake a systematic examination of the CDR potentials by rededicating pasture land to explore potentials within current land use bounds. The assessed scenarios incorporate the expansion of biomass plantations for BECCS and natural forest regrowth (reforestation) accounting for reductions in grazing areas aligned with a global shift towards a sustainable diet (EAT-Lancet planetary health diet). Beyond the quantification of CDR potentials in these scenarios, D3.3 and D3.7 assess environmental consequences of the associated land use changes. The assessment in D3.7 focuses on evaluating the effects on the PBs related to land-system change, nitrogen flows, and freshwater use, for both BECCS and reforestation. Additionally, the evaluation of BECCS is extended to encompass the impact on nitrogen fertilizer application, irrigation water demand and regions experiencing water stress. Accounting for biosphere integrity as the second core boundary next to climate change, the impact on biosphere integrity is separately addressed in D3.3, where impacts on functional biosphere integrity were quantified by evaluating the amount of photosynthetically derived energy available for the biosphere and assessing key biogeochemical and structural variables in relation to their derivation from the natural state.

With LPJmL as a biosphere model, the LPJmL-based impact assessment is restricted to a subset of land-based NETPs, providing insights exclusively into biogeochemical potentials and impacts. Constraints stemming from economic and political factors are addressed solely within stylized scenario storylines, while these scenarios pertain exclusively to certain application pathways rather than encompassing the full range of options for deploying a given NETP (e.g., additional BECCS potentials from biomass side streams, as detailed in Section 2.1). The strength of the assessment, however, lies in the process-based and spatially explicit assessments of CDR potentials and their interconnected impacts on key earth system functions at the global scale.

1.1.2 *Literature search on selected marine NETPs (D3.5)*

D3.5 summarizes important findings from literature concerning the adverse environmental effects of selected marine NETPs and the potential risks associated with CCS involving seabed storage. Blue carbon and ocean alkalinization were chosen for evaluation following the viability assessment in D1.1. The report aims to provide an overview of the key risks and impacts associated with these selected marine NETPs. Thus, it focuses on theoretical risks and observed ecosystem impacts, irrespective of a specific application context.

1.1.3 *Literature search, case study for the Nordic countries (D3.6)*

Focusing on the Nordics and their specific context, D3.6 evaluates forest-related NETPs in terms of their CDR potentials, net climate effect (including albedo changes; potential soil organic carbon losses) and impacts on key ecosystem services (terrestrial biodiversity, water quality, recreational and cultural value). Based on a literature search, available knowledge is synthesized and summarized within one impact evaluation table. While not systematic, the literature search provides an in-depth assessment of the specific conditions in Nordic forests and the related industry based on country-specific climate strategies and reports as well as scientific literature.

1.1.4 *Lifecycle assessment (D3.8)*

D3.8 presents the main findings of a Life Cycle Assessment (LCA) that evaluates the impacts of emissions and resource usage in terms of damage with regard to three categories: human health, ecosystem quality, and resource scarcity. Human health damage is quantified as Disability-Adjusted Life Years (DALYs), representing years of healthy life lost, while ecosystem damage considers local species loss integrated over time, expressed as species·year. Finally, resource scarcity damage accounts for additional costs linked to the extraction of future fossil and mineral resources. All three categories are evaluated across nine damage pathways (e.g., increased respiratory diseases, harm to freshwater species, elevated extraction costs) influenced by 17 impact categories (e.g., global warming, particulate matter, water consumption, mineral resource demands) related to emissions and resource utilization. The CDR component of the eight assessed NETPs (see Table 1) in 24 different application modes contributes by reducing damage through the prevention of climate change-related impacts. However, this benefit can be counterbalanced by negative impacts stemming from emissions (e.g., transportation, electricity requirements, etc.) or resource use (e.g., land use changes, freshwater consumption, gas extraction, etc.) specific to the NETP system.

Within the LCA, NETPs are characterized by average parameters specific to a particular application pathway. Consequently, the evaluation relies on global averages, which may not consistently align with location-specific processes (e.g. varying irrigation demands). Moreover, the choice of specific application modes significantly influences the resulting impacts (e.g. large damage for NETPs based on irrigated biomass plantations). The analytical strength of the LCA, however, stems from the systematic comparison of the sustainability performance among a large number of different NETPs by evaluating them on a per-ton basis of CO_2 removal. This standardized assessment unit allows for the evaluation of various NETPs across the same impact categories, encompassing emissions and resource use throughout their entire lifecycle.

1.1.5 *Integrated Assessment Model TIMES-VTT assessing mineral and metal intensities of NETPs*

In D3.9, the Integrated Assessment Model (IAM) TIMES-VTT is enhanced and applied to simulate quantitative climate stabilization scenarios with a focus on the future demand for critical minerals and metals of clean energy transition technologies as well as NETPs. Thereby, the assessment aims to evaluate potential raw material constraints for the global energy system transition as well as NETP deployment. Preceding simulations of one reference scenario based on Nationally Determined Contributions (NDCs) and two scenarios to limit global warming to 1.5 and 2°C by 2100, the TIMES-VTT database was updated and expanded with regard to mineral/metal intensities of clean energy technologies and NETPs. However, at the time of the analysis, the resource intensities used in the LCA (D3.8) were not yet available for TIMES-VTT modelling and the scarcity of literature on other NETPs allowed for the assessment of metal intensities only for BECCS, biochar sequestration, and Direct Air Capture with Carbon Storage (DACCS; for the latter two only indirect mineral/metal intensities associated with e.g. power needs). While the assessment provides results specific to cost optimization pathways under uncertain assumptions on future technological developments, amongst others with regard to metal recycling rates and mineral/metal intensities, this is the first assessment of global critical raw material needs in economically optimized climate stabilization scenarios within an integrated framework.

Table 1. Methods employed for impact assessment in WP3.

	Method/approach	Objective	NETP	Main assumptions/scenario	Impact dimensions	Major limitations	Explanatory value/method advantage
D3.2	Process-based biosphere model (LPJmL)	Quantify biophysical potential of BECCS with feedstock production on uncultivated land constrained by PBs*	● BECCS	Expansion of biomass-plantations outside current agricultural land while avoiding further transgression of four terrestrial PBs	4 PBs: biosphere integrity, land-system change, freshwater use and nitrogen flows	Biogeochemical assessment without socioeconomic considerations; only potential of BECCS based on biomass plantations outside agricultural land considered; global parameters for technical efficiencies	Global and spatially-explicit simulation of biomass growth and impacts on PBs via process-based modelling
D3.3	Process-based biosphere model (LPJmL)	Quantify impact of reforestation and biomass plantations for BECCS on functional biosphere integrity	● Reforestation ● BECCS	Diet change scenarios in line with EAT-Lancet planetary health diet and rededication of released pasture areas to either reforestation (focus proximity to intact forests) or biomass plantations for BECCS (focus proximity to agr. infrastructure)	Impacts on functional biosphere integrity	Only pasture rededication for reforestation and BECCS assessed; no consideration of other feasibility constraints, i.e. economic or political; global parameters for technical efficiencies	Spatially-explicit and process-based modelling of CDR potentials and impacts on functional biosphere integrity within model at the global level
D3.5	Literature search on selected marine NETPs	Get an overview of most relevant risks/impacts of selected marine NETPs	● Kelp farming ● Ocean liming ● Enhanced weathering	-	Theoretical risks and observed impacts on marine ecosystems	Risks and impacts without consideration of specific application contexts	Overview of relevant risks and impacts in the marine environment
D3.6	Literature search, case study for the Nordic countries (Finland, Sweden and Norway)	Synthesize the potential of forest-based CDR methods in terms of net climate effect and their impacts on regulating, provisioning and cultural ecosystem services	● Reforestation ● Afforestation ● Forest management ● Wood products ● BECCS	-	Terrestrial biodiversity, water quality and recreational value	No systematic literature search but qualitative judgement on impacts based on a selection of publications; no differentiation between natural regrowth and establishment of new plantations	In-depth assessment for the Nordic countries, capturing the specific local conditions; thorough assessment of the net climate effect of forest NETPs and uncertainties; BECCS input beyond energy crops addressed

NETPs:
- ● Reforestation
- ● Afforestation
- ● Forest management
- ● Wood products
- ● BECCS
- ● Biochar
- ● DACCS
- ● Enhanced weathering
- ● Kelp farming
- ● Ocean liming

* D3.2 analysis of reforestation and biochar not considered in this table; preliminary analysis for biochar application revisited in 2.2; reforestation evaluation extended in D3.3/3.7

	Method/approach	Objective	NETP	Main assumptions/scenario	Impact dimensions	Major limitations	Explanatory value/method advantage
D3.7	Process-based biosphere model (LPJmL)	Quantify impact of reforestation and biomass plantations for BECCS on resource demand, water stress and three PBs	Reforestation, BECCS	Diet change scenarios in line with EAT-Lancet planetary health diet and rededication of released pasture areas to either reforestation (focus proximity to intact forests) or biomass plantations for BECCS (focus proximity to agr. infrastructure)	PBs for freshwater use, nitrogen flows and land-system change; water stress and agr. resource demand	Only pasture rededication for reforestation and BECCS assessed; no consideration of other feasibility constraints, i.e. economic or political; global parameters for technical efficiencies	Spatially-explicit and process-based modelling of CDR potentials and interconnected impacts at the global level
D3.8	Lifecycle assessment	Compare the sustainability performance of different NETPs (per t CO2 removed)	Reforestation, Afforestation, Forest management, Wood products, BECCS, Biochar, DACCS, Enhanced weathering, Kelp farming, Ocean liming	NETPs represented by average parameters for one specific application pathway; impacts assessed per unit CDR	Human health, ecosystem quality and resource scarcity assessed as impacts from emissions and resource use	Global averages – partly of location-specific processes (e.g. irrigation demand); selection of specific NETP application pathways strongly influence the impacts (i.e. irrigated biomass plantation)	Comparison of a large number of different NETPs in the same impact categories; covering impacts from emissions and resource use along the entire lifecycle
D3.9	Quantitative climate and energy scenarios modelled with the TIMES-VTT Integrated Assessment Model based on literature search on mineral and metal intensities of NETs and clean energy technologies	Evaluate the future need of selected minerals and metals in clean energy transition pathways under consideration of NETPs' resource demands; identify potential bottlenecks in technology implementation due to resource scarcity; identify data gaps for material us of NETs	BECCS, Biochar (Reforestation/Afforestation, DACCS)**	One reference scenario based on NDCs, two scenarios to limit global warming to 1.5 and 2° by 2100, respectively; assumptions on recycling rates of metals, metal intensity developments in the future amongst others	Impacts on resource scarcity considering silver, cobalt, copper, dysprosium, lithium, manganese, neodymium and nickel	Lack of data for mineral needs of several key NETs (re/afforestation, DACCS) and high uncertainties with regard to future mineral/metal intensity developments and recycling rates; limited information on the metal demands of other than energy sectors; no assessment of uncertainties related to land-based mitigation	First global assessment of mineral demands in clean energy transitions under consideration of NETs, delineation of economically optimal pathways both for Europe and at the global level, under consideration of multiple NET options

NETPs: Reforestation, Afforestation, Forest management, Wood products, BECCS, Biochar, DACCS, Enhanced weathering, Kelp farming, Ocean liming

**Included in TIMES modelling, but no assessed in terms of mineral/metal intensities

1.2 NETP-specific impacts and sustainable potentials

Based on the approaches described in section 1.1, overall 10 NETPs have been assessed in terms of their impacts, focusing on human health and resource scarcity, ecosystem functioning (biosphere integrity) and three further terrestrial PBs (for nitrogen flows, freshwater change, and land-system change), as core pillars for earth system resilience. In the following, key WP3 findings are synthesized for each NETP, combining results from all Deliverables. Additionally, the results are presented in more detail and differentiated by impact category in Table 2 and Table 3. This overview is primarily based on WP3 findings, hence, does not claim to comprehensively cover all impacts related to NETP deployment.

The multiple impact dimensions addressed in NEGEM link to various SDGs, in particular "Zero Hunger (SDG2), "Good Health and Well-being" (SDG3), "Clean Water and Sanitation" (SDG6), "Affordable and Clean Energy" (SDG7), "Industry, Innovation and Infrastructure" (SDG9), "Responsible Consumption and Production" (SDG12), "Climate Action" (SDG13), "Life below Water" (SDG14) and "Life on Land" (SDG15). Interconnections of the WP3 findings with SDGs are highlighted with an arrow in the text (→) as well as in the column headings of Table 2 and Table 3.

1.2.1 Re-/Afforestation

In terms of impacts, it is important to differentiate between reforestation and afforestation. While various definitions exist, a clear distinction should be made between forestation in natural forest biomes vs. (semi-) natural savannah or grassland biomes, as well as between forest restoration or natural regrowth with minimal anthropogenic interference vs. plantation forests with significant timber extraction.

Assisted or natural regrowth of forests could clearly contribute to restoring forest-mediated key earth system functions, in particular climate regulation and the terrestrial carbon sink (Steffen et al. 2015, Richardson et al. 2023). Past deforestation of tropical rainforests is of particular concern, given the strong teleconnections to other regions and high carbon storage. Their large-scale reforestation could shift the status of the PB for land-system change, defined based on remaining forest cover, back into a safe zone, preventing risks of strong and irreversible environmental change caused by past deforestation (see D3.7, → SDG15). Moreover, key biogeochemical properties could be restored by approaching the natural state on reforested areas again, thereby significantly contributing to biosphere integrity, a second core pillar of earth system resilience next to climate stability (see D3.3, → SDG15). At the same time, especially if referring to natural or assisted regrowth of trees, demand for fossil and mineral resources would be low (see D3.8, → SDG12).

In contrast to forest restoration, afforestation with plantations may lead to potential loss of biodiverse rich semi-natural grasslands habitats. With its extensive land use, it was shown to have most negative ecosystem impacts among all NETPs evaluated with LCA as well as the largest negative environmental impacts compared to other forest-related NETPS in the Nordics (see D3.6, D3.8). In addition, road construction and maintenance operations entail negative impacts on human health by fine particulate matter generation (see D3.8, → SDG3) and could contribute to 90% of overall resource demand for this NETP.

Given the extensive land use demand for large-scale forestation, diet change and other land-sparing measures within the food system would be required to enable reforestation within current land use bounds without undermining food security. For forest restoration, the clear environmental benefits call for "the more the better", but potentials strongly depend on the available land. Upon a full transition to a planetary health diet and forest regrowth on freed grazing lands, up to 4.3 Gt CO_2eq yr^{-1} could be sequestered within the first 30 years (see D3.7, → SDG2, 3, & 13). However, CDR from forestation saturates over time and is reversible. Increased risks of forest fires may not only threaten their carbon sink, but also generate fine particulate matter with negative impacts on human health. Finally, reforestation activities should focus on tropical and temperate biomes, as decreased albedo and potential loss of soil organic carbon may significantly counteract the climate effect of CDR in the boreal zone (see D3.6, → SDG13)

1.2.2 Forest management and wood products

Promotion of stable forests through forest conservation has many positive environmental benefits and is associated with strong cultural values (see D3.6, →SDG15). Conversely, intensified forest management and related infrastructure negatively impact biodiversity. Boosting forest growth through fertilization and irrigation may entail additional adverse impacts by impeding freshwater biota through water withdrawals and increased nitrogen leaching amongst others (see D3.6, D3.8). Regarding the net CDR effect, intensified forest management could potentially reduce the carbon sink and overall carbon storage within forests. At the same time, wood products may replace counterfactual materials, e.g. CO_2-intensive construction materials such as steel or fossil energy carriers, thereby creating substitution benefits. This is shown for laminated timber in D3.8, with strong health benefits due to replacement of steel offsetting other damaging factors. This example pinpoints the potential trade-offs associated with "the dual role of the forests in climate change mitigation […]: more intensive harvests can lead to more substitution benefits, but this intensified harvesting will inherently lead to a lower carbon sink and stock in forests. This trade-off needs to be understood better as the role of carbon sinks becomes more important to meet the national targets of net zero, while the demand for biomass for substitution of fossil products in various sectors is similarly on the rise" (D3.6, → SDG12 & 13). Increasing the share of long-lasting wood products compared to short-lasting products (such as pulp and paper) without increasing overall wood harvest has however few direct negative effects while providing (temporary) CDR.

1.2.3 BECCS

WP3 deliverables clearly show that expansion of dedicated biomass plantations for BECCS feedstock production would have detrimental environmental consequences. Given already high anthropogenic pressures on terrestrial PBs today, any conversion of semi-(natural) vegetation to biomass plantations would further undermine other dimensions of earth system stability (see D3.2, → SDG6,14&15). Expansion of biomass plantations within current land use bounds could be enabled by reduced land needs for future food production (e.g. diet changes, → SDG12), but conversion of extensive grazing lands to high output biomass plantations would similarly exacerbate PB pressures (see D3.3, D3.7). The impacts, as well as CDR potentials, depend however strongly on the plantations' management, i.e. fertilization and irrigation schemes. Thus, LCA in D3.8 confirms net health and environmental damage of BECCS despite avoided impacts through CDR effects if based on irrigated bioenergy crops. While minimal inputs on plantations could circumvent most effects on freshwater and nitrogen flows, this would require consequent global political regulation (see D3.7). Besides these feedstock related impacts, hazardous by-products of the CO_2 capturing processes and leakages along the transport and storage of CO_2 may pose risks for freshwater quality and marine fauna (more details under 1.2.5, D3.5, →SDG3&14).

In terms of resource use, however, BECCS provides clear benefits by avoiding extraction of fossil resources through energy generation (see D3.8, → SDG7). Also, BECCS is characterised by low metal and mineral demands in contrast to other clean energy technologies, where future shortages may constrain deployment (see D3.9, → SDG9). It is also important to note, that WP3 focused on quantitative assessment of plantation-based BECCS only, as this is most critical in terms of resource use and impacts. However, use of feedstocks from residue and waste streams, although limited in their availability, could provide BECCS with significantly lower negative environmental impacts (see 2.1). In addition, distinct applications under specific conditions have been identified as environmentally responsible utilization of plantings dedicated to bioenergy use, such as agroforestry (Elagib & Al-Saidi, 2020; Kang et al., 2021) or the cultivation of fast-growing grasses on contaminated land (Nsanganwimana et al., 2014).

1.2.4 Biochar

Impacts of biochar sequestration are strongly driven by the feedstock source as it holds true for all biomass-based NETPs (e.g. 1.2.3). For example, the LCA in D3.8 shows net ecosystem and human health damage (i.e. fully offsetting the CDR-induced prevention of climate change related impacts) when biomass pyrolysis is based on feedstock from irrigated plantations, primarily due to the adverse effects on freshwater ecosystems (→SDG 15) and the potential for water scarcity in food production (→SDG2&3). While scenarios based on dedicated biomass crops indicate substantial pressure on land and agricultural resources (D3.7/D3.8), these impacts could be minimized if the feedstock was sourced from biomass side streams (see 2.1). Furthermore, D3.2 identified a pathway for land- and calorie-neutral biochar production which is further explored in section 2.2. This approach utilizes biochar-mediated yield increases to release cropland for pyrolysis feedstock production, thereby avoiding pressure on land (→SDG 15) and food production (→SDG 2).

Besides yield increases, the incorporation of biochar into agricultural soils provides further co-benefits including enhanced root growth (Xiang et al., 2017), soil organic carbon built-up (Blanco-Canqui et al., 2020) and water use efficiency (Edeh et al., 2020) as well as reduced nitrate leaching and N_2O emissions (Borchard et al., 2019), not addressed in the WP3 assessments. The risks of ecotoxicity of biochar in soils are well known processes that can easily be avoided by standards of clean process operation and certification of biochar quality following guidelines for feedstock sources, e.g. already practiced with the European Biochar Certificate (EBC, 2023). At the larger scale of the global energy market, the pressure of biochar sequestration systems on resource scarcity can be expected to remain relatively low due to fuel and heat generation throughout the pyrolysis process, which can avoid the extraction of gas (→SDG 7) as evaluated in D3.8.

1.2.5 DACCS

The impacts of DACCS are predominantly determined by the energy source it relies upon, given the substantial energy requirements involved (→ SDG7). In line with this, the LCA conducted in D3.8 indicates that the extent to which the CDR-induced prevention of global warming impacts on ecosystems (→SDG 15) and human health (→SDG 3) is counterbalanced is primarily determined by the carbon footprint of the energy source. For example, high temperature liquid sorbent DACCS, which relies on natural gas, emerges as the NETP with the most significant impact on resource scarcity among those assessed. In contrast, low temperature solid sorbent DACCS utilizing geothermal energy demonstrates relatively low pressures on fossil and mineral resources. Furthermore, the IAM evaluation presented in D3.9 demonstrates that the rise in global electricity demand resulting from DACCS deployment may lead to indirect repercussions on the utilization of metals and minerals (~7.5% of the total net power generation in a 1.5°C scenario). Nevertheless, it's noteworthy that in the absence of DACCS, the energy sector's demand for metals was projected to be even greater, primarily driven by a higher demand for stationary electricity storage systems (→SDG 12).

Yet, the impacts of DACCS extend beyond the pressure on the energy market as human health (→ SDG 3) can furthermore be affected by the use of liquid amine in the capture process, where carcinogens such as nitrosamines and nitramines, which result from degradation products, pose a potential threat to freshwater quality (→SDG 6). Moreover, marine ecosystems can be affected during transport and storage of CO_2 under water, as leakages can lead to acidification of the surrounding water with lethal or sub-lethal effects on the marine fauna and bacterial communities (→SDG 14).

1.2.6 Enhanced weathering

The impacts associated with enhanced weathering differ depending on whether basalt or dunite is employed. In the comparative LCA of D3.8, basalt-based enhanced weathering was found to be the most detrimental NETP (among the assessed) in terms of human health due to non-carcinogenic toxicity health effects from the emission of lead, zinc, cadmium and arsenic contained in the mineral (→ SDG3). Furthermore, basalt-based enhanced weathering also shows a particularly high demand for fossil resources due to road transport and mining operations (→ SDG 12), which largely offsets the climate change related benefits of CDR.

Dunite-based enhanced weathering, in contrast, shows reduced material requirements per ton of carbon dioxide removed, resulting in lower impacts associated with fossil fuel usage (→SDG 12). However, applying dunite also leads to more significant health damages related to carcinogenic toxicity due to its higher nickel content (→ SDG3). D3.8 additionally assessed coastal enhanced weathering based on dunite, which could reduce the damage to human health significantly as it avoids the accumulation of toxic metals in agricultural soils.

Additionally, across all enhanced weathering applications, the material is eventually transported to the sea and other aquatic environments, where they can alter the substrate of the ground and the chemistry of water with potential impacts on local flora and fauna (→SDG 14) – disturbances that are, however, highly dependent on the applied quantities of alkaline materials and may diminish via dilution in the environment.

1.2.7 Marine NETPs

Following the prioritization scheme in D1.1, two marine NETPs were evaluated in WP3: coastal blue carbon with the highest technological readiness level among the assessed marine NETPs and ocean alkalinization with the advantage of combating ocean acidification.

While the literature assessment in D3.5 found that the conservation and restoration of natural blue carbon habitats are frequently referred to as "no-regret options" or "win-win solutions", the assessments in WP3 focus on kelp farming as the option with least spatial constraints. Nonetheless, the possibility of competition for suitable areas with other purposes, such as tourism and fisheries, remains (D3.5). At the growth site, environmental impacts emerge due to nutrient removal, leading to reductions in net primary productivity (NPP), carbon export and trophic transfers (→ SDG14). In the D3.8 LCA, this decrease in phytoplankton NPP largely counterbalances the avoided climate-related impacts on ecosystems and human health (→SDG 3). Subsequently, at the storage site, ecosystems are potentially disturbed by increases in acidification, hypoxia, eutrophication and excessive organic carbon inputs (→SDG 14), as summarized in D3.5.

While ocean alkalinization aims to increase the capacity of seawater to absorb CO_2, the high concentration of alkaline material at the application site may pose challenges for marine organisms incapable of effectively accumulating carbon in highly alkaline conditions. Some further risks currently under investigation are the potentially strong fluctuations in pH and seawater pCO_2 impacting plankton growth and calcium hydroxide precipitation threatening coral reefs. Moreover, it remains unknown to what degree the overall changes in primary and secondary production may result in the increased accumulation of contaminants within food chains, with potential implications for human health (→SDG 3). Additional environmental impacts are associated with extensive calcium carbonate mining operations (D3.5) and the energy-intensive oxy-calcination process (D3.8) (→ SDG 12).

1.2.8 Synthesis

As demonstrated by the various approaches to NETP impact assessment in WP3, NETPs deployment may imply significant impacts, here highlighted for human health, resource scarcity and ecosystem functioning (biosphere integrity) plus three further terrestrial PBs, all linking to SDGs. While there is no NETP without negative effects identified in at least one impact dimension, forest restoration is the NETP with most co-benefits, contributing to international targets of nature restoration (e.g. the Kunming-Montreal Biodiversity Framework) and climate stabilization (i.e. the Paris Agreement). However, (i) carbon sequestration is reversible and may be threatened by increased fire frequencies under climate change (UNEP, 2022) and (ii) forest restoration is realisable only in combination with large-scale food system transformations. Forest restoration has to be clearly distinguished from afforestation with plantations, which may cause multiple harmful impacts depending on the previous land cover/use and the forest management. Similarly, all assessed biomass-based NETPs (wood products, biochar, BECCS), can be particularly critical in terms of their impacts if based on feedstock production on large-scale and intensively managed plantations with detrimental effects on the biosphere. But also NETPs which are not directly land-based, i.e. marine NETPs as well as DACCS and enhanced weathering as chemical NETPs can have far-reaching consequences for the biosphere and human health. For DACCS, these negative impacts may only be prevented if the large energy requirements could be met by fossil-free energy. For enhanced weathering, less impacts are expected if based on dunite as compared to basalt, but potential harmful health impacts from toxic metal release would require the identification of more sustainable deployment pathways.

These findings emphasize that the impact of NETP deployment extends beyond climate stabilization and interact critically with multiple other objectives internationally agreed-upon. Therefore, strategies for NETP deployment must take a holistic perspective into account by integrating all impact dimensions. To minimize the impact of individual stressors resulting from single NETPs, it is essential to distribute the burden across a diverse portfolio of NETPs. This holds true not only because of the impacts synthesized here, but also because of NETP-specific feasibility constraints (incl. varying technology readiness level) as well as differences in the durability of stored CO_2. The implications of these NETP specific characteristics in terms of impacts, feasibility and durability are discussed in chapter 3 with regard to different roles NETPs may play in in the context of residual emissions.

Table 2. Effects of land-based NETPs on land, freshwater and nitrogen flows. Increased use of wood products was omitted due to limited coverage within WP3 Deliverables. Reforestation here refers to natural or assisted regrowth of forests in previously deforested areas, while afforestation may refer to plantations within but also outside of natural forest biomes.

Land-based NETP	land	freshwater	nitrogen
Reforestation	Amazon and African rainforests could return to a 'safe' forest cover level, serving as the control variable for the land-system change PB	No additional pressure on water resources as natural regeneration of forests does not require irrigation; minor positive effect on the status of the PB for freshwater use attributed to tree regrowth influencing runoff	Minor positive effect on the status of the PB for nitrogen flows attributed to tree regrowth influencing soil nitrogen turnover
Afforestation	Substantial land use pressure causing the highest ecosystems impacts among the assessed NETPs (see Table 1)		
Forest management		Depletion of base cations in acid sensitive regions in the Nordics through whole-tree harvesting; may lead to soil and surface water acidification in the long term	Intensive fertilization may increase nitrate leaching with potentially detrimental effects for the biodiversity of freshwater biota.
BECCS from energy crops	Significant expansion of arable land (and agricultural intensification) if pastures are replaced by biomass plantations	Nitrosamines and nitramines from degradation products in the CO_2 capture process pose a threat to freshwater quality If based on irrigated bioenergy crops: substantial increase in global water withdrawals for irrigation (i.e. +15% under moderate and +64% under intensive management for ~830 Mha biomass plantations) Areas under moderate and high water stress can increase significantly (by up to 16% and 43%, respectively, for ~830 Mha biomass plantations and moderate management) Increase in areas with transgressions of the freshwater PB (i.e. +44 % for moderate and +101% for intensive management assuming ~830 Mha biomass plantations)	Fertilizer usage and associated environmental impacts can increase significantly depending on biomass plantation management (+61% under moderate and +137% under intensive management on ~830 Mha biomass plantations) Increase in areas with transgressions of the nitrogen PB (i.e. +51 % under moderate and +93% under intensive management assuming ~830 Mha biomass plantations)
Biochar	Pathways for land- and calorie-neutral biomass production feasible through biochar-mediated yield increases, i.e. no additional land required for biochar feedstock production	If based on irrigated bioenergy crops: substantial pressure on water resources impacting ecosystems and human health	

D3.2 D3.5 D3.7 D3.9
D3.3 D3.6 D3.8

Table 3. Effects on NETPs on ecosystems, human health and resource scarcity.

NETP	ecosystem	Human health	Resource scarcity
Reforestation	■ Land-based NETP without added pressure on photosynthetically derived energy for the biosphere – a main pillar of functional integrity ■ Restoring key biogeochemical properties at biome scale by shifting elementary stocks, flows and structures back towards the natural state	■ The primary challenge undermining the health benefits of CDR are NO_X emission and fine particulate matter generated during fires*	■ Relatively low demand for fossil and mineral resources compared to all NETPs assessed*
Afforestation	■ Due to its extensive land use, afforestation has the most significant negative ecosystem impacts among all NETPs evaluated with LCA* ■ Potential loss of biodiverse rich semi-natural grassland habitats; non-native species may invade neighboring pastures** ■ Largest negative environmental impacts compared to other forest related NETPs in the Nordics**	■ Net health impacts (despite CDR benefits) mainly due to formation of fine particulate matter associated with the road construction and maintenance operations* ■ In the Nordics, afforestation of especially former pasture lands is negatively perceived in terms of recreational, touristic, and cultural values**	■ 90%, of the overall impacts on resource availability is attributed to the construction and ongoing maintenance of roads*
Forest management	■ Nitrogen fertilization for enhanced forest growth can reduce biodiversity of understory herbs and shrubs ■ Forest conservation has the most positive environmental impacts compared to other forest related NETPs in the Nordics; conversely, intensified forest management and technical infrastructure has large negative environmental impacts, a.o. threatening biodiversity by loss of old growth and native forests and increased dead wood removal	■ Strong cultural and recreational values associated with forest conservation in the Nordics, however forests with little dead wood are preferred despite its value for biodiversity	
Wood products	■ Net ecosystem damage (despite CDR effect) due to land use pressures and potentially irrigation water use in addition* ■ Increasing the share of long-lasting wood products compared to short-lasting products (such as pulp and paper) has few direct negative effects; however, if increased demand for wood products leads to more intensive harvesting and forest management, negative effects on ecosystem services result (see Forest management)	■ Laminated timber (glulam) shows greatest health benefit among all NETPs evaluated with LCA due to steal replacement completely offsetting other damaging factors*	■ Oriented strand board production has a relatively high resource impact due to its energy-intensive processing*
BECCS	■ If based on irrigated bioenergy crops: net damage of ecosystems (despite CDR effect) due to impact on freshwater species* ■ Geological storage/transport: CO_2 leakages under water can lead to acidification of the surrounding water with lethal or sub-lethal effects on the marine fauna and bacterial communities ■ If based on plantations: substantial reduction in photosynthetic energy available for the Earth system to maintain key biosphere functions ■ If based on plantations: expansion of areas experiencing significant biogeochemical, hydrological, and vegetation changes shifting away from the natural state ■ Effects are variable and depend on the feedstocks (e.g. forestry residues have less impacts than wood from intensified wood harvest)	■ If based on irrigated bioenergy crops: net health damage, mainly attributed to the large water consumption, which translates into potential water shortages that could lead to malnutrition* ■ Without irrigation of bioenergy crops: health benefits, as it counterbalances most impacts by substituting fossil energy* ■ Potential release of carcinogen degradation products in the CO_2 capture process	■ Avoids extraction of fossil resources through energy generation ■ Mineral/metal demand for CCS include Vanadium, Niobium, Nickel, Manganese, Cobalt, Copper, Molybdenum and Chromium, but the deployment of BECCS even on a large scale may not impose significant sustainability issues in terms of metal/mineral use, as the direct impacts are proportionally quite small. Indirect impacts on material use due to the feedstock use may also be estimated rather small.
Biochar	■ If based on irrigated bioenergy crops: net damage of ecosystems (despite CDR effect) due to impact on freshwater species*	■ If based on irrigated bioenergy crops: net health damage due to large withdrawals potentially leading water shortages and malnutrition*	■ Relatively low resource scarcity ranking due to heat generation which avoids the extraction of gas*

■ D3.2 ■ D3.5 ■ D3.7 ■ D3.9
■ D3.3 ■ D3.6 ■ D3.8

NETP	ecosystem	Human health	Resource scarcity
DACCS	■ Offsetting the prevention of global warming impacts on ecosystems mainly driven by carbon footprint of the energy source* ■ Geological storage/transport: CO_2 leakages under water can lead to acidification of the surrounding water with lethal or sub-lethal effects on the marine fauna and bacterial communities	■ Harmful health impacts are not only driven by the energy consumption, but also by the adsorbent and heat pump* ■ Nitrosamines and nitramines from degradation products in the CO2 capture process pose a threat to freshwater quality	■ High temperature liquid sorbent DACCS reliant on natural gas is the most detrimental NETP to resource scarcity among the assessed NETPs, while low temperature solid sorbent DACCS using geothermal energy indicate relatively low pressures* ■ High increase in global demand for electricity has indirect effects on metal and mineral use (app. 7.5% of total net power generation in a 1.5° scenario). However, without DACCS, the metal requirements of the energy sector were simulated to be even higher, due to increased needs for stationary electricity storage systems amongst others
Enhanced weathering	■ Enhanced weathering scenario based on basalt attains the lowest ecosystems benefits among the chemical NETPs, primarily driven by land use associated with the road transport and mining operations* ■ Impacts on the marine flora/fauna due to altering the beach substrate and seawater chemistry in the littoral zone and near-shore	■ Basalt-based EW most detrimental NETP (among the assessed) in terms of human health due to non-carcinogenic toxicity health effects from the emission of the metals contained in basalt* ■ Dunite-based EW indicates larger impacts through carcinogenic toxicity ■ Coastal EW can reduce the health damage significantly compared to application on agricultural soils	■ Dunite-based enhanced weathering – relatively low resource demand compared to all NETPs assessed* ■ Basalt-based EW implies significantly higher pressure on fossil resources due to transport emissions for a larger amount of rocks
Kelp farming	■ Rel. low net ecosystem benefits compared to the other marine NETPs, mainly because of the reduction in phytoplankton NPP offsetting the averted climate impacts* ■ At growth site: nutrient removal reducing NPP, C export, and trophic transfer ■ At the storage site: increases in acidification, hypoxia, eutrophication and organic carbon inputs	■ Only minor net health benefit, as the avoidance of climate-driven health impacts through CDR is largely offset by the reduction in phytoplankton NPP and emissions from powering sea transport and algae cultivation*	■ Competition for limited suitable areas with other uses
Ocean liming	■ Potential challenge for marine organisms unable to concentrate carbon in high alkalinity conditions ■ Risk of calcium hydroxide precipitation, potentially harming coral reefs due to their sensitivity to increased turbidity ■ Varying impacts on pH and seawater pCO2, potentially influencing plankton growth ■ Environmental impacts of extensive mining operations, transportation, and mineral distribution	■ Limited health benefits as most of the CDR benefits are offset by the generation of the electricity used in the oxy-calcination process* ■ Change in primary and secondary production, increasing the accumulation of contaminants in food chains, including cadmium, nickel, chromium, iron and silicon	■ Rel. high impact on resources due to high electricity consumption*

■ D3.2 ■ D3.5 ■ D3.7 ■ D3.9
■ D3.3 ■ D3.6 ■ D3.8

* D3.8 LCA findings refer to a comparative impact assessment where the CDR-induced prevention of climate change-related impacts can be offset by negative impacts stemming from emissions or resource use, ultimately resulting in a nuanced balance of effects that may occur independently across different temporal and spatial scales.

** D3.6 does not differentiate between re- and afforestation, but impacts are here assigned to afforestation to clearly distinguish from findings of D3.2/D3.3/D3.7, where reforestation refers to forest restoration/natural forest regrowth, while D3.6 mostly refers to the establishment of plantations.

2 Quantification of sustainable CDR potentials

The impact assessments summarized in section 1.2 underscore the importance of responsible NETP deployment, emphasizing the need to mitigate the trade-offs between climate mitigation via CDR and other critical dimensions of Earth system stability, ecosystem health, human well-being, and resource availability, while also striving to enhance positive co-benefits wherever possible. In light of the pivotal role of biosphere integrity as one of the two fundamental pillars of Earth system stability, alongside climate stability, it is crucial to scrutinize land-based NETPs and their large-scale implementation, as WP3 assessments highlighted significant interlinkages of these approaches with biosphere integrity.

Carefully evaluating land-based NETPs is not only crucial because of strong interlinkages with biosphere integrity, but also because they have significant contributions to current CDR deployment and are prominent within the scientific literature. With regard to current CDR deployment, managed forests stand out as the most substantial contributor, sequestering approximately 2000 Mt CO_2. This significantly surpasses the second and third-ranking contributors, which are BECCS and biochar sequestration, with 1.82 Mt CO_2 and 0.5 Mt CO_2, respectively (Smith et al., 2023). In contrast, biochar sequestration is the NETP most widely discussed in the scientific literature, potentially suggesting higher relevance in the future (Smith et al., 2023). BECCS and re/-afforestation on the other hand, are the two most relevant (and often only) CDR options in climate stabilization scenarios of IAMs contributing to the IPCC assessment reports (IPCC, 2022). In these economically optimized scenarios, BECCS receives outstanding attention as a cost-efficient NETP providing energy and CDR at the same time. High projected potentials for reforestation, in contrast, are mainly driven by prescribed socio-economic targets and relatively low costs for this CDR approach.

Scientific analyses have repeatedly indicated competition for land and strong impacts on biosphere integrity for these three land-based NETPs. Therefore, this section aims to estimate their "sustainable" potentials by

(i) summarizing quantifications for "sustainable" CDR potentials for land-based NETPs from WP3 assessments,
(ii) providing new quantifications for land- and calorie-neutral biochar sequestration (LCN-BC) and
(iii) closing a gap in the WP3 assessments through a literature search on potentially sustainable biomass potentials from biomass side streams, i.e. residues and waste, for BECCS.

In the following we first outline the additional quantifications (2.1, 2.2) to then combine the results with previous quantifications (2.3).

2.1 Biomass residues and waste streams as feedstock for BECCS

The sustainability of BECCS critically depends on the feedstock (see D3.6). While dedicated plantations are associated with multiple trade-offs, the use of biomass side streams, such as residues and waste, are considered less critical in terms of impacts. As CDR potentials from these feedstocks has not been assessed in WP3 yet, but may provide more sustainable BECCS than from biomass plantations, we here first assess biomass availability from biomass side streams based on literature (Figure 1) and then convert estimated energy content to CDR based on feedstock specific conversion pathways (Figure 2).

2.1.1 Biomass availability

To assess biomass availability from residual biomass and organic waste streams as potential feedstocks for BECCS, we compiled bottom-up estimates from a selection of key publications. Both estimates for current as well as future availability (mostly referring to 2050) were included, differentiating four main feedstock categories (agricultural residues, forestry residues, manure and municipal solid waste). Agricultural and forestry residue estimates may include primary (i.e. generated on site) and secondary (processing) residues, but estimates including tertiary residues (i.e. waste) were excluded to avoid double accounting with municipal solid waste (MSW) estimates.

The following sections summarize findings from the literature search for each feedstock category, focusing on key uncertainties of potential estimates. For all categories, it is important to consider that compiled estimates may refer to different types of potential, complicating a consistent intercomparison: (i) the theoretical potential (no consideration of technological, environmental or economic constraints), (ii) the technical potential (biomass that can be technically removed/collected), (iii) environmental potential (biomass that can be removed/collected without adverse environmental impacts) and (iv) sustainable potential (consideration of both technical and environmental constraints) (Scarlat et al., 2019).

Agricultural residues

The assessed quantifications of crop residue availability usually combine data on (current or future) crop production with crop-specific residue-to-product ratios and maximum sustainable harvest fractions (Kalt et al., 2020). While all terms are associated with high uncertainties, assumptions on maximum sustainable removal rates for residues span a particularly large range. These rates represent the amount of residues that may be removed while maintaining soil quality and preventing soil organic matter loss. Across crops and considered studies, these estimates vary between 0 and 95% removal with most values in the range of 30 to 60% (see e.g. EC, 2017; Scarlat et al., 2010). Next to contradictory assumptions on sustainable removal rates, the included studies may vary in the types of residues and crop considered and whether or not processing residues were included (although their contribution is small in comparison to primary residues), hindering a consistent comparison.

These key uncertainties and inconsistencies lead to a large range of 3 – 66 EJ yr^{-1} within the 10 considered studies. Importantly, the three most recent studies account for competing uses of residues, e.g. for animal husbandry, to determine availability for energetic use (Kalt et al., 2020; Sandström et al., 2022; Searle & Malins, 2015). The spanned range of these three estimates (3.2 – 20.8 EJ yr^{-1}) may thus be considered more realistic in terms of agricultural residue availability as potential feedstock for BECCS.

Forestry residues

Availability of primary forestry residues is typically calculated as current or extrapolated future wood production multiplied with a residue generation rate (i.e. the percentage of residue to wood removal) and the harvested fraction of residues (see e.g. Liu et al., 2020; Smeets et al., 2007). Uncertainties in estimates stem from (i) the assumed wood harvest which may vary with the assumed forest or plantation area, the (ii) residue-to-wood harvest ratio as well as (iii) the harvested fraction of residues, which may be influenced by the technically harvestable or recoverable fraction as well as the assumed sustainable residue removal fraction to prevent soil organic matter loss. Some of the considered studies additionally include processing residues, e.g. mill residues, whose availability is similarly uncertain.

As for agricultural residues, the potential availability of forestry residues within the 7 included studies thus spans a wide range from 4 to 19 EJ yr^{-1}. The two most recent estimates both conclude that availability is < 10 EJ yr^{-1} (Liu et al., 2020; Searle & Malins, 2015). The low estimate from Searle & Malins (2015) may partly be attributed to the exclusion of residues from natural forest logging, given sustainability concerns: In contrast to fertilized plantations, where nutrients may be replenished, residue extraction from natural forests could impede forest growth in the next cycle due to nutrient losses.

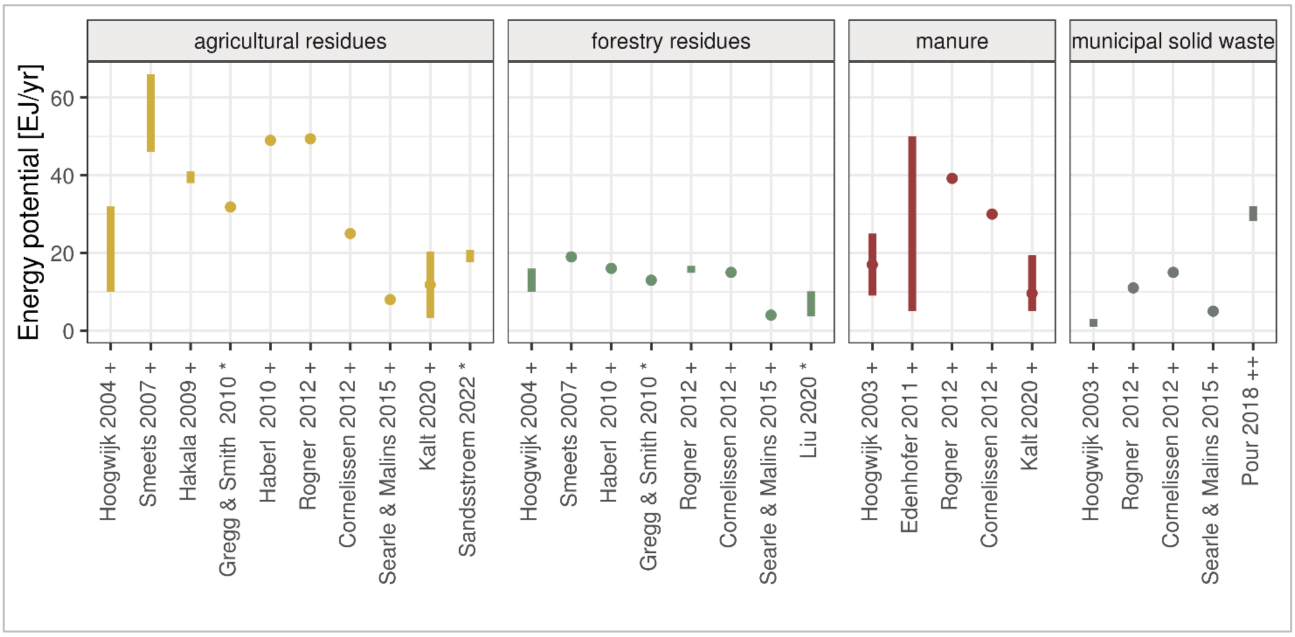

Figure 1: Primary energy potential of biomass side streams that could theoretically be used as feedstock for BECCS. While not always explicitly defined within considered studies, we assume that the energy potential refers to the Higher Heating Value (HHV) for dry matter. If the studies did not report energy potential but weight, the estimates were converted applying HHV values as reported in the appendix A1. Municipal solid waste only refers to the biogenic part. Estimates for current potentials are marked by an asterisk (*), future potentials by a plus sign (+ for 2050; ++ for 2100).

Manure

Calculating manure availability typically requires assumptions on current or future livestock production, the manure production per kg of livestock and the collectible fraction of manure (i.e. how much manure may be technically collected), all of which bear uncertainties. Estimated potentials vary between 5 and 50 EJ yr^{-1} with a particularly high difference between theoretical and technical potentials: Kalt et al. (2020) thus estimate that the theoretical potential is at 19.4 EJ yr^{-1} while only considering intensive livestock systems, where collection is considered techno-economically feasible, reduces the potential to 5 EJ yr^{-1}. In terms of climate change mitigation, energetic use of manure via anaerobic digestion is clearly beneficial, not only because of the potential substitution effects of biomethane, as well as potential capture and storage of released CO_2 (see 2.1.2), but also because CH_4 and N_2O emissions are clearly reduced as compared to conventional manure management (Kalt et al., 2020).

Municipal Solid Waste

The five estimates on global biogenic municipal solid waste (MSW) availability vary in their assumptions on current or future MSW generation and composition, the (future) recycling or compost rates and the collected fraction. Furthermore, some estimates only encompass organic food waste while others refer to all biogenic wastes, resulting in a potential availability range of 1 – 32 EJ yr^{-1}. The particularly high estimates from Pour et al. (2018) may be explained by the assumption that MSW is available for energetic use without considering (increases in) recycling. On the path to a more sustainable circular economy, however, it is desirable to maximize recycling rates, and thus prioritize non-energetic use of biomass to energetic uses in order to optimize cascade utilization. Potential increases in recycling rates as well as desirable reductions in waste generation may thus impact future availability of MSW for bioenergy. Energetic use of the non-recyclable and unavoidable MSW, however, provides strong climate change mitigation benefits through (i) substitution effects (biogas or electricity replacing fossil energy), (ii) reduction in non-CO_2 emissions from unmanaged MSW and (iii) potential storage and capture of CO_2 (see 2.1.2; Pour et al. (2018))

2.1.2 *CDR potentials from biomass residues and waste streams*

Based on the presented estimates of potential available primary energy of biogenic residues and waste, we estimated CDR potentials from combining energetic use of biomass side streams with CCS. For this, we assumed suitable biomass conversion processes depending on the feedstock: conversion to biogas via anaerobic digestion for agricultural residues and manure (Rosa et al., 2021), conversion to biofuel via Fischer-Tropsch (lower estimate) or electricity via combustion (upper estimate) for forestry residues (Chiquier et al., 2022) and conversion to electricity via incineration for MSW (Pour et al., 2018). We assume conversion-process-specific carbon capture rates (67% for biofuel, 90% for electricity and 99.5% for biogas, see appendix A1 for references) and, in line with Rosa et al. (2021), estimate that 1.8–6% of captured carbon is leaked upon transport and injection. Finally, to account for CO_2 emissions through fossil energy use along the supply chain (e.g. for biomass processing and transport), we assume expenditures of 5–10% of the primary energy content of the feedstock (for details on the calculations and parameter values and ranges see the appendix A1; some of the parameters are highly uncertain and calculations serve as rough estimate only).

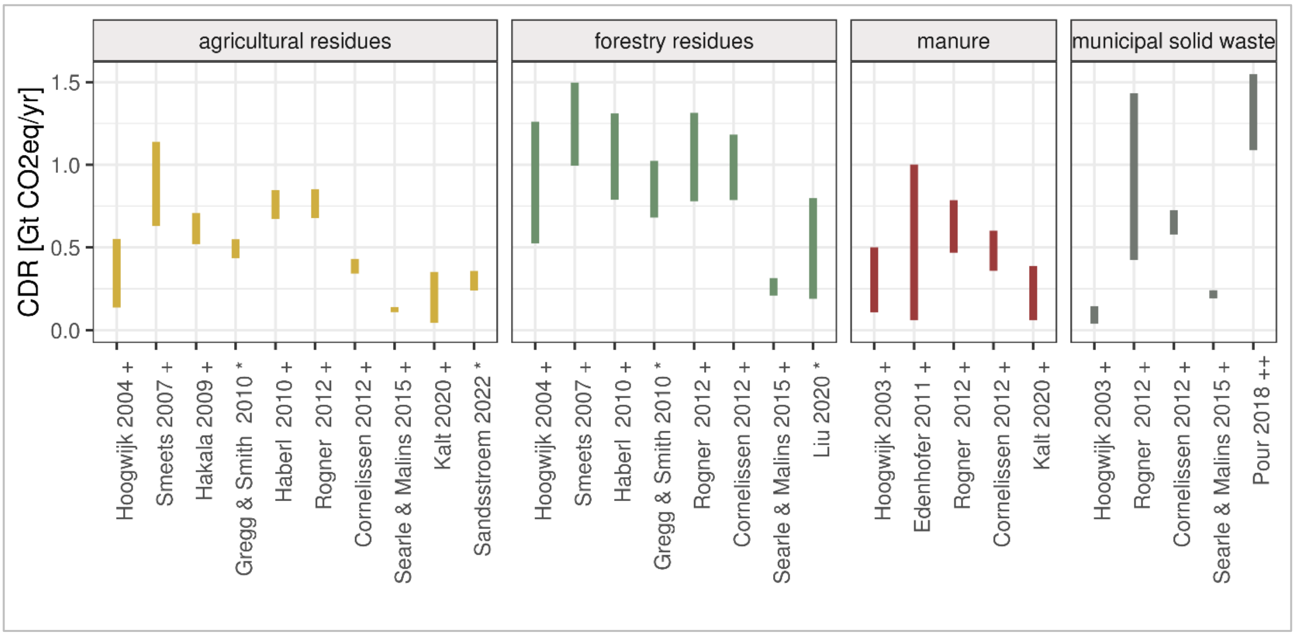

Figure 2: Upper ceiling potentials for CDR from biomass side streams. Agricultural residues and manure are assumed to be used for biogas production, while forestry residues are assumed to be converted to liquid fuels (lower estimate) or electricity (higher estimate). For MSW, incineration is assumed. Details on the calculations and assumed parameters are provided in the appendix. Estimates for current potentials are marked by an asterisk (*), future potentials by a plus sign (+ for 2050; ++ for 2100).

Calculated CDR potentials range between 0 – 1.1 $GtCO_2eq\ yr^{-1}$ for agricultural residues, 0.2 – 1.5 $GtCO_2eq\ yr^{-1}$ for forestry residues, 0.1 – 1.0 $GtCO_2eq\ yr^{-1}$ for manure and 0 – 1.5 $GtCO_2eq\ yr^{-1}$ for municipal solid waste. The high ranges emphasize that the BECCS potentials from biomass side streams are highly uncertain for all types of feedstocks. Importantly, the estimates generally represent the theoretical upper ceiling of potentials, while realistic potentials are likely at the lower end of estimates for two main reasons:

(i) Not all estimates account for competing uses for the same feedstock. However, residues may partly already today be used for other purposes and intersectoral competition may increase in future. For example, the use of agricultural residues for animal husbandry may increase to make livestock production more sustainable (Sandström et al., 2022). Similarly, forestry residues may also be used for material use, e.g. wood-based composites (Braghiroli & Passarini, 2020), which may be preferred over energetic use in line with cascade utilization of biomass. For MSW, increased recycling of materials and waste reduction, e.g. in line with SDG12.3 to half food waste by 2030, may reduce availability. Finally, other biomass-based NETPs, such as biochar, compete for the same resources as BECCS. While CO_2 storage is less reliable, these NETPs may be preferred due to co-benefits and the small-scale applicability.

(ii) The reported potentials account for no or limited feasibility constraints. Social, political, technological and economic barriers may however hinder the exploitation of the potentials. Thus, poor governance, i.e. lack of regulatory control, is likely to lower potentials as it is unlikely that strong governance structures will be present in all countries within the coming decades (Searle & Malins, 2015). Also, high costs and resulting economic unprofitability may be a significant barrier, e.g. for exploiting the energy and climate change potential of manure and municipal solid waste (Kalt et al., 2020; Pour et al., 2018). Finally, the primarily distributed nature of the considered biomass feedstocks poses infrastructural challenges, e.g. in terms of developing feedstock transport networks to BECCS facilities (Rosa et al., 2021). The existing industrial point sources of CO_2 from energetic use of residues and waste, e.g. combustion of black liquor generated within pulp and paper mills or waste incineration in existing plants, could present readily assessible opportunities in this context.

It is also important to note, the net climate change effect of using the considered biomass side streams for BECCS is difficult to assess. While we accounted for CO_2 losses and expenditures along the BECCS supply chain, a careful consideration of the counterfactual case (i.e. not using the materials for BECCS) is important but missing here. For example, even limited removal of agricultural and forestry residues may reduce soil carbon stocks to some degree, which may partly offset the CDR benefits (Kalt et al., 2020). On a different note, energetic use of residues, manure and MSW may also decrease emissions of non-CO_2 gases, thus providing mitigation benefits in addition to fossil substitution and potentially CDR. For example, anerobic digestion of crop residues and manure for biogas production can prevent CH_4 and N_2O emissions (Rosa & Gabrielli, 2023). Integrating the counterfactual case, i.e. reduced or increased emissions as compared to the case of not using the respective feedstocks, is thus crucial for the overall climate change mitigation potential but very challenging to assess.

While not all potential feedstocks from biomass side streams have been covered within this literature analysis (e.g. not all reported forestry residue estimates include processing residues, amongst others from pulp and paper mills), the assessment underlines the high uncertainties in the associated BECCS potentials. Due to competing uses as well as feasibility constraints, the potentials are likely at the lower end of the estimates presented here, i.e. 0.3-5.1 $GtCO_2eq\ yr^{-1}$ for all assessed pathways. Yet, irrespective of these uncertainties, any extensive use of residual and waste streams for BECCS would require comprehensive transformations requiring immediate coordinated actions.

2.2 Land- and calorie-neutral biochar sequestration

Biochar sequestration has been recognized as a readily deployable NETP (Smith et al., 2023) with the potential for minimal environmental impacts and numerous associated co-benefits (Smith et al., 2019). However, as with any biomass-based NETP, the extent of its negative impact is primarily contingent on the choice of feedstock source. In D3.8, the comparative LCA highlighted that the benefits of biochar sequestration in terms of CDR for ecosystems could be offset by land use changes and freshwater withdrawals, particularly when irrigated poplar plantations were used as feedstock. Furthermore, the assessments in D3.3 and D3.7, focusing on the impacts of biomass plantations for BECCS, apply to biochar sequestration as well: establishing large-scale biomass plantations on non-arable land could increase the pressure on agricultural resources, PBs and biosphere integrity, as summarized for BECCS in Table 2 and Table 3.

In contrast, the land and water footprints of biochar feedstock production are minimal when sourced from crop residues or forestry residues, as evaluated in previous research (Woolf et al., 2010). However, estimating the global availability of crop residues carries notable uncertainties, as discussed in section 2.1. Additionally, these residues often face competition for various uses, such as in the context of BECCS. Another option for sustainable feedstock production is through land- and calorie-neutral biochar sequestration (LCN-BC). In this approach, feedstock production takes place within the existing cropland boundaries while sustaining calorie production. Achieving significant yield increases due to improved soil properties following biochar application allows for the production of the same amount of food on reduced land (calorie-neutral). Consequently, a portion of the cropland can be allocated to fast-growing crops designated for biochar feedstock without necessitating additional land (land-neutral).

In our previous evaluation of LCN-BC in D3.2, we found that the relatively low CDR potential we calculated was primarily due to the reliance on exceptionally high yields to meet the biochar demands required for achieving yield increases. When we compared these results to earlier assessments that indicated higher CDR potentials (Werner et al., 2022; Werner et al., 2018), we identified disparities in assumptions related to attainable yield enhancements and pyrolysis parameters. Additionally, we noted greater yield variability in LPJmL5-NEGEM (compared to LPJmL5-NEGEM-Ccycle, see D3.1). In light of these findings, we decided to repeat the evaluation with several adjustments. The assessment summarized here and presented in Werner et al. (2023) features a more stable representation of biomass yields, complemented by a sensitivity analysis that examines the key factors influencing the CDR potential of LCN-BC.

In this evaluation, we used a carbon-centric version of the model, which considers different levels of management intensity rather than explicit fertilizer amounts, to establish a more stable yield range that aligns better with real-world observations. Based on the simulated biomass productivity on cropland areas allocated to biochar feedstock production in the land- and calorie-neutral approach, we quantified the global CDR potential of LCN-BC within the context of biochar-based fertilization (BBF), following the method described in D3.2. Additionally, we conducted a sensitivity analysis to assess the impact of varying assumptions related to feedstock management and pyrolysis conditions (see Werner et al. (2023)). This comprehensive analysis explores a range of factors, including achievable yield increases, feedstock production management intensity, and pyrolysis conditions such as process-specific biochar yields and carbon content in the char (see Appendix).

Our results show that LCN-BC using BBF could sequester an estimated 0 to 2.03 $GtCO_2$ annually (Table 4) within the constraints of cropland boundaries and the need to sustain calorie production. The range depends on all the assessed factors: the level of yield increase achieved through BBF, the assumed pyrolysis parameters, the management intensity of the biomass production system, and the durability of biochar in soils.

Of these variables, the most influential drivers of CDR potential are the level of yield increase achievable through BBF and the management intensity in the feedstock production. Enhancing the effectiveness of biochar application and achieving greater improvements in plant productivity could significantly expand the area suitable for LCN-BC and elevate the CDR potential. For instance, if a 15% yield increase can be attained instead of 10%, the potential could increase by as much as +70–122% (Table 4). In terms of management intensification from marginal (lowest management intensity in LPJmL) to moderate levels (mid-range management intensity in LPJmL), our results indicate a potential increase in CDR by +200–270%. This can be explained by higher productivity as well as an increased extent in suitable area (Figure 3). Therefore, in order to realize more CDR, these optimization measures should be taken into consideration in agricultural practice.

Besides the influence of achievable yield increase and management intensity, our findings highlight the pronounced sensitivity of CDR potentials to the assumption on pyrolysis parameters (i.e. ash supplements to increase biochar yield and carbon content, see appendix). When calculations are based on the optimized parameter set rather than the conservative assumption, the CDR potential increases by 40–75% (Table 4). Therefore, practitioners seeking to enhance carbon sequestration should prioritize settings for their pyrolysis plant/kiln that maximize biochar yield, for example by incorporating ash or rock powder supplements (Buss et al., 2022; Mašek et al., 2019).

While pyrolysis parameters and feedstock production impact the biomass harvest and the suitable area for the LCN-BC approach (Figure 3a), the assumed biochar carbon durability in soils determines the representation of carbon losses over a 100-year period, consequently influencing the ultimate sequestration potential (Figure 3b). Within the evaluated range of 70–80% C remaining after 100 years, this factor emerges as the least influential in determining the overall range of CDR potentials. While this assessment quantified maximum potential on an annual basis, it is not well understood whether soil conditions or sequestration capacities can be negatively impacted by repeated biochar addition and accumulation of pyrogenic carbon.

Table 4. Negative emission potentials of land- and calorie-neutral biochar sequestration calculated for 10% yield increase achieved by biochar-based fertilization given as a mean annual potential and sums over 2025-2100 with results for 5% and 15% yield increases in brackets. The base assumption of a biochar durability of 74% of the biochar carbon remaining in the soil after 100 years is given in bold, whereas the lower range of 70% is shown in plain and 80% in italic font. Table 3 in Werner et al. (2023).

Management	**Annual NE potential [GtCO2]**			**Cumulative NE potential 2025-2100 [GtCO2]**		
	70%	**74% biochar C after 100 years**	*80%*	70%	**74% biochar C after 100 years**	*80%*
Conservative pyrolysis parameters						
Marginal	0.19 (0 – 0.57)	**0.20 (0 – 0.61)**	*0.22 (0 – 0.65)*	14.27 (0 – 43.01)	**15.09 (0 – 45.47)**	*16.31 (0 – 49.16)*
Moderate	0.70 (0 – 1.55)	**0.74 (0 – 1.64)**	*0.80 (0 – 1.78)*	52.49 (0 – 116.59)	**55.49 (0 – 123.26)**	*59.98 (0 – 133.25)*
Optimized pyrolysis parameters						
Marginal	0.35 (0.01–0.78)	**0.37 (0.01–0.82)**	*0.40 (0.01 – 0.89)*	26.55 (0.87 – 57.89)	**28.07 (0.92 – 61.20)**	*30.35 (0.99 – 66.16)*
Moderate	1.04 (0.01 – 1.78)	**1.10 (0.01 – 1.88)**	*1.19 (0.01 – 2.03)*	78.13 (0.94–134.08)	**82.59 (0.99–141.74)**	*89.29 (1.07–153.23)*

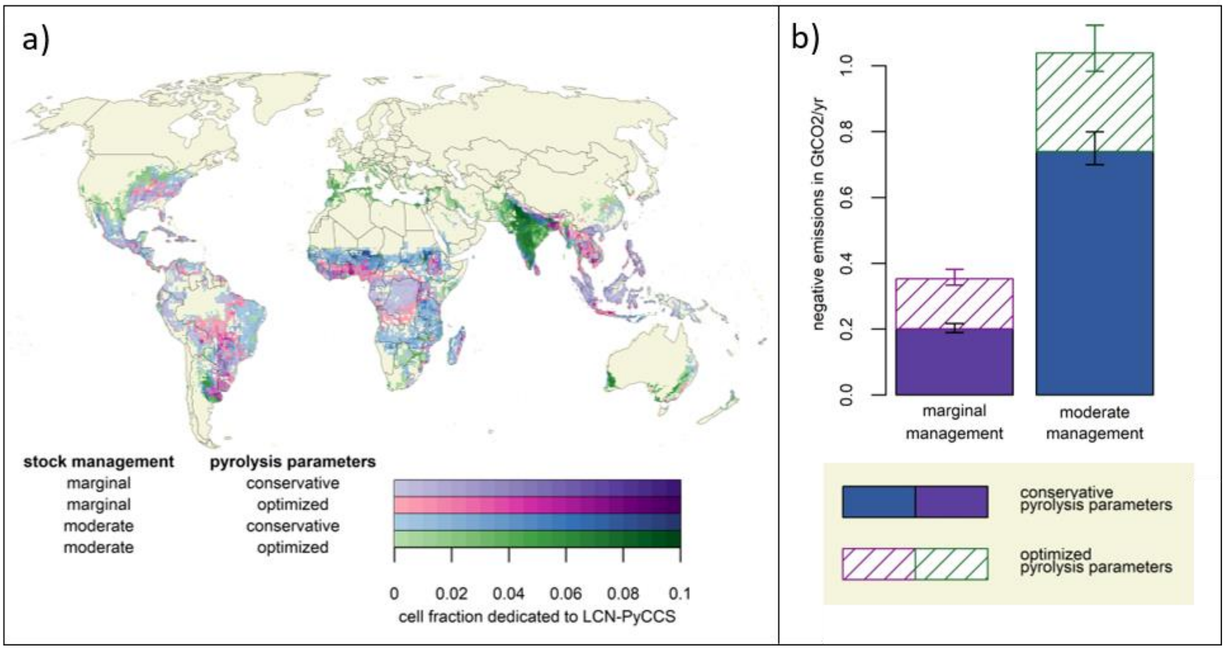

Figure 3. Extents of land suitable for the LCN-BC approach under different assumptions on management intensity and pyrolysis conditions given as cell fractions dedicated to LCN-BC in 2099 (a) and annual global sums of negative emissions averaged over 2025–2099 (b) based on different assumptions of pyrolysis parameters and management of the feedstock producing systems, assuming 10% biochar-mediated yield increase. Combinations of higher potential (highest: moderate stock management plus optimized pyrolysis parameters, green) include the area of combinations with lower potential (lowest: marginal stock management plus conservative pyrolysis parameters, purple). The segments of the bar plots in b) represent the potential under the assumption of 74% biochar carbon remaining in the soil after 100 years, while the error bars show the range for the lower (70%) and higher (80%) durability tested. Figure 3 in Werner et al. (2023).

2.3 Combining quantified potentials in WP3

2.3.1 Quantitative WP3 results on sustainable CDR potentials

For reforestation, BECCS and biochar sequestrations, the evaluations in D3.2, D3.3, D3.7 and section 2.2 aimed to assess and quantify CDR potentials of deployment pathways that minimize the pressure on PBs.

In light of the significant existing human-induced stresses on terrestrial PBs (land-system change, freshwater use, nitrogen flows and biosphere integrity), the conversion of semi-natural vegetation into biomass plantations would only compound challenges related to the overall stability of the Earth system (D3.2). While expanding biomass plantations within current land use boundaries could theoretically be facilitated by reduced land demands for future food production via dietary changes, the conversion of extensive grazing areas into high-yield biomass plantations would concurrently increase pressures on these PBs (D3.3, D3.7). These findings collectively indicate that the expansion of plantation-based BECCS cannot be considered a sustainable solution, given the constraints imposed by PBs and the need to support food production for a growing global population (e.g. cropland areas will likely expand). If a transition towards a less animal-based diet would however enable large-scale forest restoration on current grazing land instead, substantial CDR could be achieved while mitigating pressures on the PBs of land-system change (D3.7) and biosphere integrity (D3.3), among other co-benefits (see 1.2.1). Thus, D3.7 found that a complete transition to the EAT Lancet planetary health diet could release about 736 Mha pasture area to forest restoration and sequester ~4.3 $GtCO_2eq\ yr^{-1}$ in a 30-year timeframe (Figure 4a).

In addition to these synergistic reforestation potentials, D3.2 and section 2.2 expanded on a second application pathway for land-based NETP deployment within the current land use bounds avoiding additional PB pressures: biochar application as part of a LCN-BC approach could remove about 0.2 $GtCO_2eq\ yr^{-1}$ on current croplands without imposing additional stress on the terrestrial PBs or food production, if marginal management without additional water withdrawals or fertilizer applications was assumed (under current technological default and mean response of 10% biochar-mediated yield increases, see Table 4).

2.3.2 BECCS without expansion of dedicated energy crops

While the expansion of dedicated bioenergy plantations may be difficult to reconcile with PBs, integrating existing bioenergy sources with CCS may offer BECCS potential without worsening current PB pressures. Current bioenergy use sourced from conventional bioenergy crops, short-rotation woody crops and forestry plantings amounts to 8, 4 and 13 EJ, respectively (numbers for 2020 in IEA (2021)). For these sources (excluding biomass side streams assessed in 2.1 and current traditional use of biomass), it can be argued that combining them with CCS could enhance sustainability over bioenergy use without CCS. Given the already substantial pressure of first-generation bioenergy crops on food production (i.e. food vs. fuel debate, (Muscat et al., 2020)) and the risk of net negative impact on greenhouse gas emissions from intensively harvested forest plantings compared to natural forest growth (Erb et al., 2018; Peng et al., 2023), we do not consider the expansion of these sources as an option for responsible CDR.

In order to provide a rough estimate for maximum CDR potentials from these sources, we used the conversion, expenditure and leakage rates from the bioethanol production, described in 2.1.2, for dedicated bioenergy crops. For forestry plantings and short rotation coppice we applied the same scheme as for forestry residues (woody biomass, see 2.1.2 and appendix). Based on this, we estimated an upper ceiling CDR potential of 1.3–1.8 $GtCO_2eq\ yr^{-1}$ for which it is important to note that only a portion is likely to be achievable by 2050 (Figure 4b), because the realization of this potential is subject to substantial uncertainties and constrained by various factors spanning social, political, and technological dimensions (Smith et al., 2023). Thus, the feasibility of combining all these biomass streams with CCS remains uncertain.

In addition to applying CCS to bioenergy from current dedicated energy crops or plantings, energetic use of biomass side streams (residues, manure, MSW) could be expanded as outlined in 2.1.2. The compilation of literature estimates for biomass availability and conversion to CDR potentials indicate overall maximum potentials of 0.3–5.2 $GtCO_2eq\ yr^{-1}$. However, while the utilization of biomass side streams faces less sustainability issues than dedicated crops, the exploitation potential is highly uncertain and, due to feasibility constraints as well as competing uses, likely at the lower end of potential estimates. Also, a careful consideration of the counterfactual case, e.g. leaving residues on the field instead of removal, is imperative for determining the overall net climate change mitigation effect. If upper ceiling CDR potentials from current crop- and plantation-based bioenergy are added up to possible CDR potentials from biomass side streams, 1.7-7.0 $GtCO_2eq\ yr^{-1}$ may be removed without additional pressure on PBs. But as stated above, both for current bioenergy from dedicated plants as well as for biomass side streams, realistic potentials are rather expected to be at the lower end due to various feasibility constraints and it is unlikely that the utilization for BECCS could be realized to full potential.

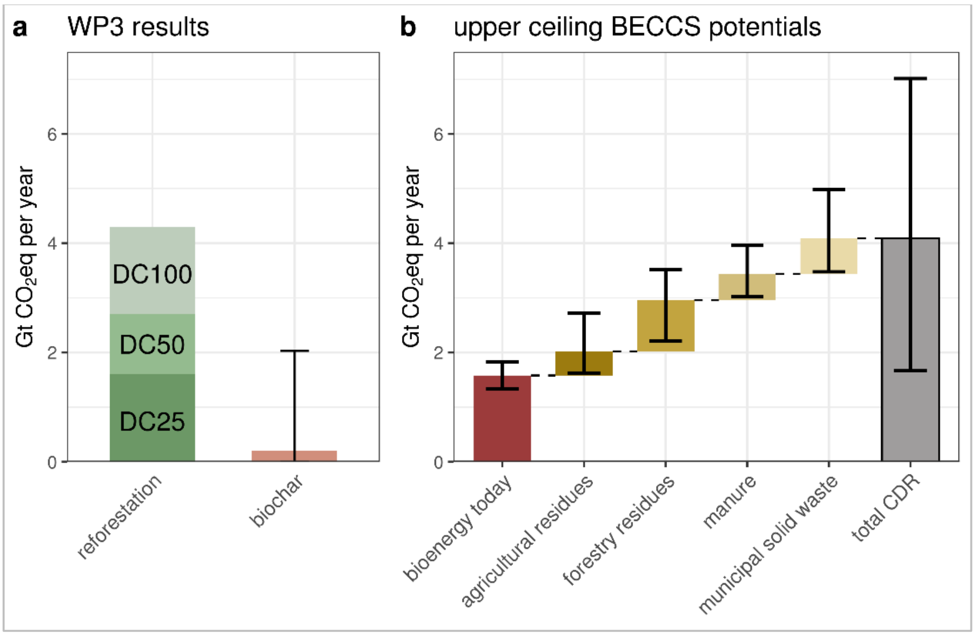

Figure 4: (a) CDR potentials quantified for reforestation on pasture areas upon full or partial transition to a planetary health diet (25, 50 or 100% achievement = DC25/50/100) as well as for land-and-calorie neutral biochar application within current croplands. The biochar range refers to different assumptions regarding biochar-mediated yield increases, management on plantations as well as pyrolysis conditions (b) Upper ceiling BECCS CDR potentials from current plantation-based bioenergy as well as biomass side streams, without considering comprehensive feasibility constraints. The range (error bars) is spanned by (i) different estimates within the literature for biomass availability (referring to biomass side streams) as well as (ii) lower and upper estimates regarding CDR efficiency (see 2.1.2); the bar refers to the median estimate for biomass sides streams and to the mean between the lower and upper estimate for current plantation-based bioenergy. None of the BECCS estimates consider the counterfactual case, i.e. of not using the biomass (e.g. leaving residues on the field) and thus land management/use effects.

3 Responsible NETPs in the context of residual emissions

When examining the theoretical (i.e., not constrained by political, social or practical challenges) upper limits of CDR potential under sustainability constraints, it is informative to contextualize these estimates within the broader role that CDR is expected to fulfill in climate stabilization strategies. In the short term, CDR measures have a theoretical potential to contribute to a reduction in net greenhouse gas emissions. However, their key purpose is to counterbalance residual emissions in net-zero strategies on the long term and eventually achieve global net-negative emissions to return to historical CO2 concentrations (IPCC, 2022). For example, the precautionary “safe” PB for climate change has been set at an atmospheric CO2 concentration of 350 ppm, well below today’s values (Richardson et al., 2023; Rockström et al., 2009).

In this section, we outline critical aspects in deriving estimates of residual emissions in climate stabilization strategies and subsequently discuss the distinct benefits and trade-offs of different NETPs and their responsible deployment in this context.

3.1 Residual emissions in climate stabilization strategies

In theory, the deployment of NETPs compensating for residual emissions is primarily needed to address two key challenges: balancing out residual emissions from sectors that are extremely difficult to fully decarbonize, such as agriculture, and temporarily offsetting residual emissions from hard-to-decarbonize sectors like construction, heavy industry, and heavy transport (Honegger et al., 2021).

Yet, within these sectors, claims regarding residual emissions often center on what society perceivesnecessary, yet difficult to fully eliminate (Lund et al., 2023). Thus, these claims are shaped by societal values, norms, and interests. Livestock agriculture serves as a pertinent illustration of this phenomenon: despite scientific evidence for reduced meat consumption benefitting human well-being and planetary health (Willett et al., 2019), the consistent or even increasing role of animal-based diets is often presented as essential due to projections of population growth, cultural preferences and a perceived lack of alternatives (OECD & FAO, 2020). While measures to reduce emissions from animal farming are being widely discussed, achieving zero emissions in this sector is generally asserted as unfeasible (Honegger et al., 2021; Searchinger et al., 2018). Consequently, many countries anticipate significant residual emissions from agriculture when aiming for net zero emissions (Buck et al., 2023), mainly driven by livestock production (Lund et al., 2023).

However, the majority of government-formulated net-zero strategies lack precision regarding the sectors responsible for residual emissions and are often opaque about the mechanisms for balancing these emissions through CDR (Buck et al., 2023). Currently, there is no standardized approach for quantifying residual emissions in a way that allows for meaningful comparisons between countries. Consequently, it remains often opaque whether the wide range of residual emissions projected by some (Annex 1) countries (7–30% of current emissions remaining in 2050, see Figure 5) is a result mainly of varying local emission reduction potentials, differences in ambition levels or distinct accounting methodologies. On a global scale, even if all countries were to adopt equivalents to the most ambitious scenarios outlined in Buck et al. (2023) – assuming a global mean of 17.9 % emissions remaining in 2050 – substantial residual emissions of approximately 12 $GtCO_2yr^{-1}$ would remain. However, it is anticipated that the actual total of residual emissions from upcoming net zero strategies of countries worldwide may exceed this, especially since less developed countries may assert higher shares of residual emissions (Buck et al., 2023).

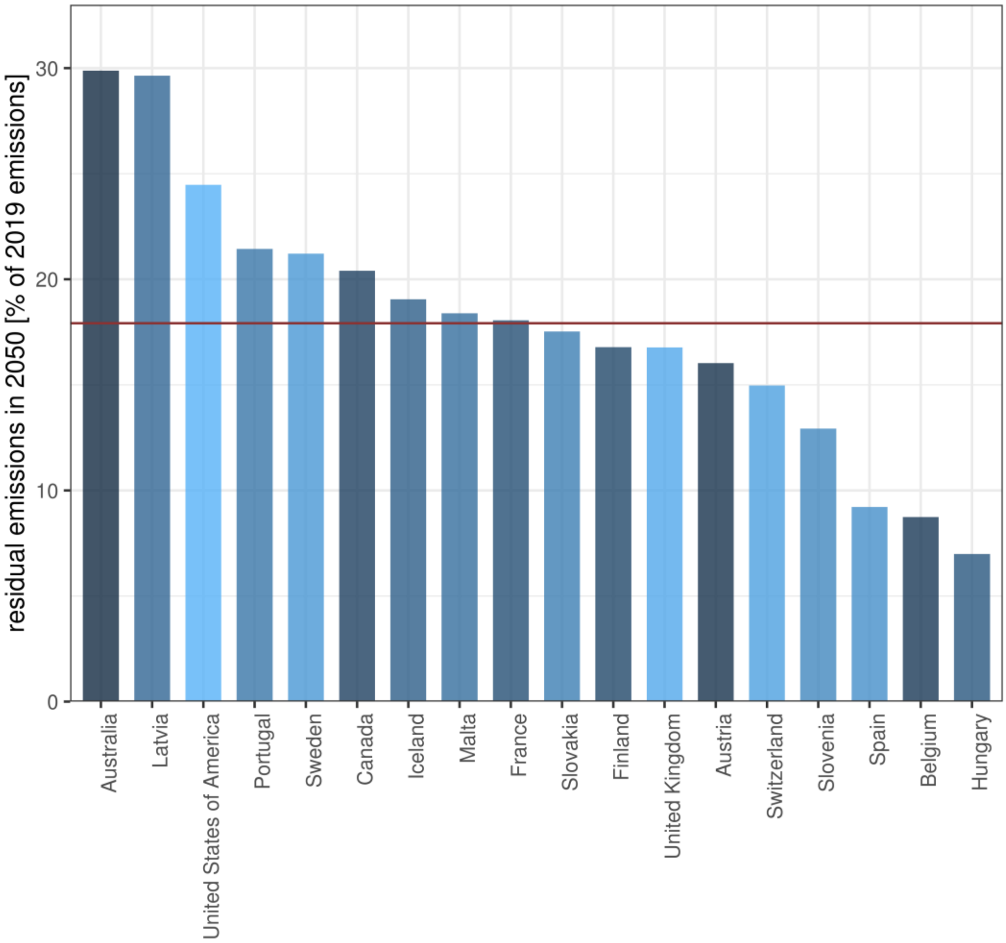

Figure 5: Residual emissions in 2050 projected in net zero emission strategies by selected Annex I countries, adapted from Buck et al. (2023). The red horizontal line indicates the residual emissions for these countries in total if these scenarios were realized (i.e. the mean residual emissions weighted by the country-specific current emission share).

However, the anticipated levels of residual emissions outlined in national long-term strategies often function as aspirational targets and are not always combined with legally binding commitments, thereby diminishing the likelihood of achieving timely and effective emission reductions. This highlights three critical aspects of climate policy: the ambition gap, the legislation gap and the implementation gap. These aspects can be illustrated through consistent scenarios outlined for the energy and industry sectors (excluding LULUCF) by the International Energy Agency (Figure 6) differentiating between

(i) the stated policies scenario (STEPS) demonstrating consequences of existing and stated policies backed by robust implementing legislation or regulatory measures,

(ii) the announced pledges case (APC) assuming all national net-zero emissions pledges are realised in full and on time (incl. policies in countries without net zero pledge assumed to be the same as in the STEPS) and

(iii) the net zero emissions scenario (NZE) designed to show required measures and timing to achieve net-zero energy related and industrial process CO_2 emissions by 2050 (IEA, 2021).

The "ambition gap" becomes evident when comparing the measures necessary for achieving net-zero emissions, as illustrated in the NZE scenario, with the communicated ambitions reflected in the announced pledges (APC). Furthermore, not all of these stated intentions are substantiated by robust implementing legislation or regulatory frameworks required to meet these targets, thereby underscoring the existence of a "legislation gap". Furthermore, there is no assurance that these regulations and governmental programs will effectively translate into the fulfilment of the announced pledges, giving rise to what can be referred to as an "implementation gap" - the divergence between the pledged ambitions and the actual realized emission reductions.

When aiming to reduce the risk of these discrepancies, policy-making would need to couple the timely implementation of targeted policies with the rigorous monitoring of their effectiveness to bridge the legislative and implementation gaps. Yet, addressing the ambition gap is only possible by committing to formulating climate change mitigation strategies that (i) contribute to a global emission budget that aligns with the Paris agreement, taking into account country-specific responsibilities, and (ii) only expect residual emissions that are realistically manageable through responsible CDR measures.

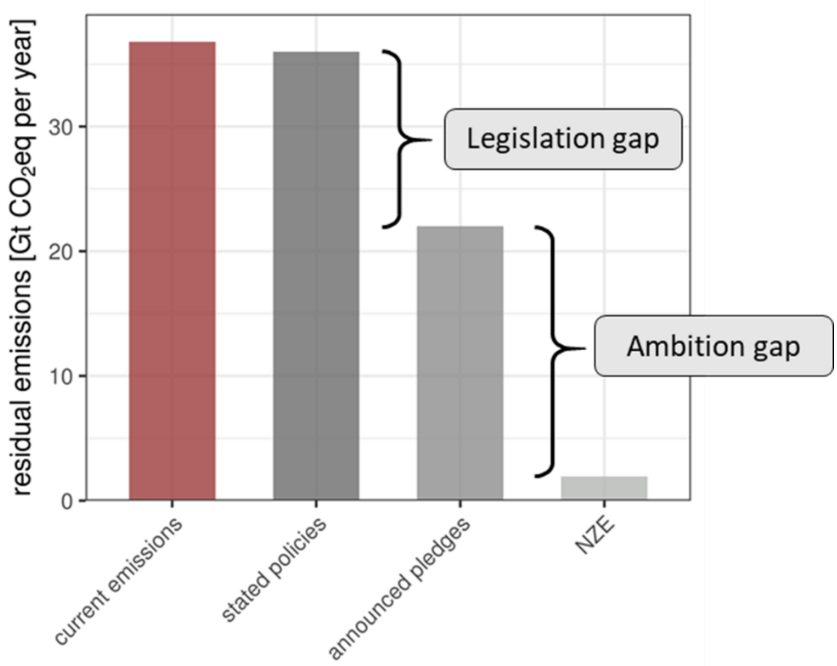

Figure 6. Emissions from the industry and energy sectors (excluding LLUCF) for 2020 (current emissions, red bar) compared to the stated policies scenario (STEPS), announced pledges case (APC) and the net zero emissions scenario (grey bars in respective order) for 2050 from the International Energy Agency (IEA, 2021) illustrating the legislation and ambition gap. The implementation gap would reflect the discrepancy between the actual emissions in 2050 (not displayed here) and the NZE scenario.

3.2 NETPs in the context of residual emissions

Given the prevailing risks (section 1.2) and uncertainties (section 2) related to CDR potentials, responsible climate change mitigation strategies would need to adhere to the precautionary principle and prioritize decarbonization efforts to reduce the dependency on (not entirely secure) removals. Additionally, considering the limited theoretical CDR potentials of low impact discussed in section 2.3 – more likely achievable at the lower end of the spectrum –, responsible NETP deployment requires maintaining low levels of residual emissions. This would minimize the risks of (i) venturing into more aggressive NETP applications that potentially hinder the achievement of SDGs and threaten Earth system stability or (ii) depending on NETPs which fail to materialise.

In regard to the compensation of remaining emissions, different NETPs and application pathways entail specific benefits and risks in terms of CDR durability, the technology-readiness level and the environmental trade-offs and synergies. While chemical NETPs (i.e. DACCS and enhanced weathering) may provide reliable carbon storage, they are still in an early phase of development and uncertainties for sustainable applications remain, as significant threats could be identified for the environment and human health (e.g. toxins from enhanced weathering) as well as substantial pressure on the energy market (e.g. energy demand for DACCS). These factors currently hinder project realization for these NETPs and underscore the imperative need for extensive real-world research and development to validate viable pathways and enable timely upscaling (Smith et al., 2023). The WP3 evaluations have also highlighted the potential for significant ecological risks of marine-based NETPs (section 1.2.7). Consequently, the establishment of sustainable deployment strategies in this domain hinges upon the consolidation of insights from the limited number of existing marine NETP projects (see OceanNETs D1.8, Rickels (2022)) as well as the development of a solid framework for verification and monitoring (see OceanNETs D2.8, (Proelß & Steenkamp, 2022)).

In contrast, the application and effectiveness of BECCS projects are more advanced, as evidenced in its status as the leading novel NETP (i.e. excluding re-/afforestation, soil organic carbon enhancement, wetland restoration, agroforestry, improved forest management and durable wood products) in terms of both the current CDR contribution and the CDR capacity of announced projects (Smith et al., 2023). Nonetheless, the upscaling of BECCS faces considerable challenges due to limited low-impact potential (see section 2.3) and environmental impacts associated with deployment pathways reliant on dedicated energy crops, which potentially pose significant threats to SDGs and Earth system stability (see section 1.2.3). At the same time, BECCS remains a crucial component for effectively counterbalancing residual emissions, primarily due to its permanent and reliable carbon storage (see D6.3, Tanzer et al. (2022)). Thus, preventing negative side effects while harnessing theoretically sustainable potentials for BECCS would require a meticulous approach to the formulation of policies and the structuring of biomass markets to prevent exploitative practices. This would require international agreement at a global scale, in order to avoid that rigorous regulations in one region intensify biosphere exploitation in other regions, or - in the absence of international regulations - restricting use to domestically produced biomass only. In this context, concentrating exclusively on CO_2 and climate change mitigation may fall short of effectively promoting Earth system stability. To prevent additional stress on PBs and SDGs, it can prove more efficient to adopt a comprehensive approach for the design of policies and market frameworks handling BECCS and other biomass-based NETPs. Such an approach should consider a wider array of PB dimensions, with a specific emphasis on ensuring the integrity of the biosphere as the second core pillar of Earth system stability next to climate stability.

The synergistic potential of mitigating climate change while concurrently enhancing biosphere integrity is a major advantage of natural climate solutions (NCS). While potential CDR from reforestation, as the NCS with largest estimated potentials (Griscom et al., 2017), has been quantitatively assessed in WP3, land-based NETPs include further promising NCS, such as agroforestry, conservation agriculture or improved forest management, for example assessed via case studies and upscaling evaluations in the H2020 project Landmarc (e.g. Landmarc D2.6, (Spijker & Picón, 2023)). These may unlock synergies with regard to multiple Earth system dimensions and SDGs. For example, the planting of cover crops between agricultural cultivation cycles may significantly decrease leaching (Nouri et al., 2022), while elevating soil organic carbon stocks (Jian et al., 2020; Poeplau & Don, 2015). The overall estimated climate change mitigation potentials of NCS are high, both resulting from reduced emissions and carbon sequestration within soils and/or vegetation (Griscom et al., 2017; IPCC, 2022), but as for other NETPs implementation may face multiple constraints. Most NCS strongly rely on food system transformations, either to free up land for nature restoration or from management changes on current agricultural lands. The benefit that particularly reduced meat consumption may offer in terms of providing manoeuvring space for NCS is also illustrated by simulated diet change scenarios in D3.3/D3.7 and resulting forest restoration potentials with substantial CDR. However, the practical achievement of dietary changes might encounter obstacles due to societal resistance. In addition, far-reaching transformations of the food sector are also required for getting back into the safe operating space regarding the transgressed terrestrial PBs (Gerten et al., 2020). This, in itself, presents a substantial challenge which is moreover difficult to reconcile with the added pressures on PBs potentially posed by biomass-based NETPs relying on plantations. NCS, in contrast, have the capacity to mitigate pressure on the climate change PB at the same time as other terrestrial PBs (see D3.3/D3.7). While their benefits across multiple dimensions incentivize their implementation, CDR from NCS is saturable and reversible. For example, as mature forests evolve towards an equilibrium of carbon built-up and decay and the carbon storage can quickly be reversed, for example, by fires or other disturbances, reforestation cannot be considered a reliable compensation for residual fossil emissions. Nevertheless, many NCS play an important role in reducing emissions on managed land (e.g. conservation agriculture), especially in the context of non-CO_2 GHG which are difficult to abate and thus particularly relevant for residual emissions. Furthermore, NCS largely contribute to restoring (e.g. reforestation), fostering (e.g. fire management) and protecting (e.g. avoided deforestation) the natural carbon sink that is in itself essential for climate stabilization.

In a broader context, the successful implementation of NETP pathways aimed at counterbalancing residual emissions without exerting undue stress on PBs and SDGs depends on the development of carefully devised strategies with minimized dependence on CDR. Formulating these strategies faces the challenge of effectively managing competition for resources, which includes comprehensive land-use planning and developing distribution schemes for energy and biomass side streams, among other considerations. Additionally, when assessing the net climate effects and impacts of NETPs, it is crucial to account for counterfactual cases. This is particularly pertinent for land-based CDR approaches, involving for example considering carbon storage of biomass or forest plantations versus the potential carbon sequestration of natural vegetation on the same area. Furthermore, inventories and scenarios should be designed to prevent instances of double accounting, e.g. agricultural residues contributing to enhancing soil organic carbon cannot simultaneously be removed for biomass-based NETPs (for an analysis of challenges and needs for coherent accounting see deliverable 6.3; Tanzer et al. (2022)).

The findings of this report show that policy and market design for CDR would need to consider other PBs and SDGs to address human well-being in a stable Earth system beyond climate change mitigation. As WP3 has identified a significant potential for biomass-based NETPs to exert pressure on SDGs and Earth system stability, adopting a holistic approach when developing implementation schemes for these approaches is particularly important. As discussed above the interactions of NETP implementation and food production is multifaceted. Therefore, a promising strategy involves integrating land-based CDR policies with those related to food production, which have strong linkages to health and other SDGs. This integration is exemplified in the D3.3/3.7 scenarios, which illustrate how releasing pasture areas for reforestation through the EAT Lancet planetary health diet can align goals of climate stabilization and healthy diets.

Strong interlinkages could furthermore be found for land-based NETP deployment and biosphere integrity, revealing divergent impacts - detrimental and/or advantageous depending on the NETP. Negative impacts, such as extensive land use changes and increased water stress for BECCS based on irrigated plantations, stand in contrast to potential benefits, including nature restoration through reforestation. These dynamics are critical for Earth system stability, with biosphere integrity being a core PB, second to climate change. When considering responsible CDR deployment, it becomes vital to recognize that the resilience of the Earth system fundamentally depends on two main interdependent pillars, climate and biosphere integrity, which have to be addressed jointly and equitably, not subordinating the latter. So, while meticulous CO_2 accounting and robust verification and monitoring mechanisms are pivotal aspects of responsible CDR deployment, there is increasing evidence that solving these intricate interdependencies extend beyond the scope of CO_2 accounting alone.

Conclusions

It is essential for maintaining a stable Earth system that climate warming is halted at the lowest level possible, or potentially restored to a lower level. However, achieving this global climate stabilization has to take into account other dimensions of Earth system stability, as expressed by the PB framework and other ecological boundaries at more regional scales. This requires looking beyond theoretical potentials for restoring the planet's carbon balance by also considering the repercussions of these NETPs for the integrity of the biosphere, non-carbon biogeochemical cycles, water use and other impacts. While CDR demand, for example to counterbalance residual emissions, may be high, climate policies guiding their implementation have to be formulated in the context of the whole of the Earth system as well as other societal targets like the SDGs.

This report synthesizing WP3 results and extending on further responsible CDR options concludes that:

- there is no NETP without negative effects identified in at least one impact dimension
- forest restoration is the NETP assessed in WP3 with most co-benefits. It contributes to international targets of nature restoration (e.g. the Kunming-Montreal Biodiversity Framework) and climate stabilization (i.e. the Paris Agreement), but is realisable only in combination with large-scale food system transformations
- releasing land for NCS, such as forest restoration, is achievable through a diet shift reducing meat consumption. Such a demand-side measure is not essentially dependent on technological progress but can be influenced by lifestyle choices societies potentially could have some agency over in the required time frame
- all assessed biomass-based NETPs (wood products, biochar, BECCS) can have particularly critical impacts on the biosphere if based on feedstock production on large-scale and intensively managed plantations.

These would add a large new land use sector in a situation where agriculture in its current form is already a major factor in the transgression of PBs, likely exacerbating pressure on these boundaries

- the potential for low-impact biomass-based CDR is limited due to constraints imposed by other dimensions of Earth system stability than climate and its quantification is subject to substantial uncertainties. This suggests that its realistic potential is small unless realized in a sustainable, ecologically responsible manner on current agricultural land or by careful consideration of utilizing biomass side streams, both requiring stringent and consistent global regulation
- CCS-based NETPs have the potential to become a crucial approach for effectively counterbalancing residual emissions, primarily due to their permanent and reliable carbon storage, while sourcing sustainable biomass for BECCS and clean energy for DACCS prevail as limiting factors amongst others
- CDR from NCS is saturable and reversible and thus not reliable for compensation for residual fossil emissions, but their role in restoring, fostering and protecting the natural carbon sink as well as the multiple co-benefits remain indispensable for Earth system stability
- the effects of individual stressors from specific NETPs can be mitigated by diversifying the NETP portfolio – a variety of approaches that does not only consider their multidimensional constraints but also accounts for differences in technology readiness and the reliability of long-term CO_2 storage.

In conclusion, the findings on NETP impacts and sustainable potentials summarized in this report suggest that the careful implementation of a portfolio of NETPs is needed, which takes the various dimensions of PBs and SDGs into account in addition to CDR efficiency/effectiveness. This comprehensive task faces the challenge to develop deployment strategies that are carefully considered and robust, yet effective and timely. Nonetheless, it is also crucial to acknowledge the substantial uncertainties regarding sustainable potentials for all assessed NETPs, as for example discussed in section 2. In light of these limitations and uncertainties to responsible CDR potentials, the precautionary principle calls for rapid decarbonization and high ambitions to reach lowest possible levels of residual emissions. The smaller the residual emissions are, the lower the demand for CDR to achieve net zero, resulting in less pressure to scale up NETP deployment and venture into potentially less sustainable applications.

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)
D3.2	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
D3.5	Literature assessment of ocean-based NETPs regarding potentials, impacts and trade-offs	NIVA	R	PU	M24
D3.6	Case study on impacts of large-scale re-/afforestation on ecosystem services in Nordic regions	NIVA	R	PU	M24
D3.7	Global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices	PIK	R	PU	M36
D3.8	Report on comparative life-cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources	ETH	R	PU	M24
D3.9	Report on assessment of impacts on key non-renewable resource chains: case study on global demand, supply and trade-offs for selected metals and minerals in global mitigation pathways	VTT	R	PU	M25

Appendix

A1 Calculation of BECCS potentials from biomass side streams and current bioenergy

BECCS potentials from biomass side streams and current bioenergy were estimated based on a literature search on biomass availability. The following sections summarize the assumed conversion processes and parameter ranges for subsequent derivation of BECCS estimates, separated by feedstock type. If available, upper estimates on availability were combined with upper estimates of parameters (see below), and lower estimates on availability were combined with lower estimates of parameters (see below), to span the maximum possible range.

Agricultural residues

For agricultural residues, we assume a conversion to biogas via anaerobic digestion following Rosa et al. (2021). For calculation of CDR, we first determine the CO_2 yield per kg dry matter (DM) biomass (parameters are explained within the parameter table below):

$$yield_{CO2} = yield_{CH4} * \frac{\text{biogas\_share}_{CO2}}{(1 - \text{biogas\_share}_{CO2})} * \frac{density_{CO2}}{density_{CH4}}$$

Potential CDR is then estimated from total gross energy content of agricultural residues (total GE; compiled from literature) as follows:

$$CDR = \frac{total\ GE}{HHV} * yield_{CO2} * CEff * (1 - leakage_{CO2}) * (1 - expenditure_{CO2})$$

Parameter	Value	Reference
Higher heating value (HHV)	15.8 kJ/gDM	Wirsenius (2000), averaged over all primary residues
Methane yield (yield_CH4)	0.14 – 0.16 kg CH_4/kgDM	Rosa et al. (2021)
Volumetric CO_2 content in biogas ($\text{biogas\_share}_{CO2}$)	40 %	Rosa et al. (2021)
CO_2 emissions along the supply chain (e.g. for biomass processing and transport) (expenditure_CO2)	5-10 % of the primary energy content	Estimated based on biomass harvest, processing and transport CO_2 emissions for domestic agricultural and forestry residues in Chiquier et al. (2022)
Carbon removal efficiency (CEff)	99.5 %	Rosa et al. (2021)
CO_2 leakage (leakage_CO2)	1.8 – 6 %	Rosa et al. (2021)

Woody feedstocks (forestry residues, forestry planting, short rotation coppice)

For woody feedstocks, we assume conversion to biofuel via Fischer-Tropsch (lower estimate) or electricity via combustion (upper estimate) based on carbon removal efficiencies from Chiquier et al. (2022). CDR is derived from literature estimates on total gross energy content of forestry residues (total GE) as follows (parameters are explained within the table below):

$$CDR = \frac{total\ GE}{HHV} * CinDM * \frac{molar\ mass_{CO2}}{molar\ mass_{C}} * CEff * (1 - leakage_{CO2}) * (1 - expenditure_{CO2})$$

Parameter	Value	Reference
Higher heating value (HHV)	18.75 kJ/gDM	Nurek et al. (2019)
C content in dry matter (CinDM)	48 %	Ma et al. (2018) for woody biomass
CO_2 emissions along the supply chain (e.g. for biomass processing and transport) (expenditure_CO2)	5-10 % of the primary energy content	Estimated based on biomass harvest, processing and transport CO_2 emissions for domestic agricultural and forestry residues in Chiquier et al. (2022)
Carbon removal efficiency (CEff)	66 - 90 % (67: for conversion to bioethanol/biodiesel; 90: for conversion to electricity / combustion)	Conservative estimates from Chiquier et al. (2022)
CO_2 leakage (leakage_CO2)	1.8 – 6 %	Rosa et al. (2021)

Manure

For manure, we assume conversion to biogas via anaerobic digestion following Rosa et al. (2021). As for agricultural residues, CDR is derived from biomass availability estimates (gross energy content, total GE) by first determining the CO_2 yield per kg dry matter (DM) biomass:

$$yield_{CO2} = volumetric\ yield_{CH4} * \frac{\mathrm{biogas}_{\mathrm{share}_{\mathrm{CO2}}}}{\left(1 - \mathrm{biogas}_{\mathrm{share}_{\mathrm{CO2}}}\right)} * density_{CO2}$$

This is then applied to calculate CDR from the energy potential of manure availability estimates:

$$CDR = \frac{total\ GE}{HHV} * yield_{CO2} * CEff * (1 - leakage_{CO2}) * (1 - expenditure_{CO2})$$

Parameter	Value	Reference
Higher heating value (HHV)	15 kJ/gDM	Wirsenius (2000), averaged over dairy and beef battle feces and pig feces and urine
Volumetric Methane yield (volumetric methane yield)	199.9 m^3 CH_4/tDM	Scarlat et al. (2018), averaged over all livestock categories and converted to DM based on total solid content
Volumetric CO_2 content in biogas ($biogas\_share_{CO2}$)	35 - 45 %	Rosa et al. (2021)
CO_2 emissions along the supply chain (e.g. for biomass processing and transport) (expenditure_CO2)	5-10 % of the primary energy content	Estimated based on biomass harvest, processing and transport CO_2 emissions for domestic agricultural and forestry residues in Chiquier et al. (2022)
Carbon removal efficiency (CEff)	99.5 %	Rosa et al. (2021)
CO_2 leakage (leakage_CO2)	1.8 – 6 %	Rosa et al. (2021)

Municipal Solid Waste

For Municipal Solid Waste (MSW), we assume conversion to electricity via incineration as described in Pour et al. (2018).

Pour et al. (2018) refer to overall MSW, including non-biogenic components, but all other compiled estimates on MSW refer to biogenic MSW only. Therefore, we convert the CDR rate per kg MSW as given in Pour et al. (2018) to a CDR rate per kg biogenic MSW as follows:

$$CDR\_per\_biogenicMSW = CDR\_per\_MSW \ * \frac{biogenic\ frac_{MSW}}{biogenic\ frac_{CO2}}$$

CDR from total gross energy content of MSW (total GE, compiled from literature estimates) is then calculated as follows:

$$CDR = \frac{total\ GE}{HHV} * \frac{1}{(1 - moisture_{MSW})} * CDR_{per_{biogenicMSW}} * (1 - leakage_{CO2}) \ * (1 - expenditure_{CO2})$$

For Pour et al. 2018, we estimate total gross energy content of MSW from estimated 4 billion tons of MSW tons in 2100, by subtracting the non-biogenic part, converting the weight to dry matter and assuming a HHV as reported within the table below. Thereby the assumed conversion factors for all included studies are aligned.

Parameter	Value	Reference
Higher heating value (HHV)	17-19.3 kJ/gDM	Searle and Malins (2014), Dashti et al. (2021)
CDR per MSW incinerated (CDR_per_MSW)	0.44 kg CO_2eq / kg MSW (fresh matter)	Pour et al. (2018)
MSW Moisture content (moisture_MSW)	34.2 %	Pour et al. (2018)
Biogenic fraction of captured CO_2 (biogenic frac_CO2)	83 %	Pour et al. (2018)
Biogenic fraction of MSW (biogenic frac_MSW)	63 %	Pour et al. (2018)
CO_2 emissions along the supply chain (e.g. for biomass processing and transport) (expenditure_CO2)	5-10 % of the primary energy content	Estimated based on biomass harvest, processing and transport CO_2 emissions for domestic agricultural and forestry residues in Chiquier et al. (2022)
CO_2 leakage (leakage_CO2)	1.8 – 6 %	Rosa et al. (2021)

Current bioenergy

For estimating potential CDR from currently cultivated dedicated energy crops, we assume conversion to bioethanol with carbon removal efficiencies, expenditure and leakage rates as described for woody biomass. The higher heating values and the carbon content in dry matter are adapted to match the mean values across the three major first generation bioenergy crops (soybean, sugarcane and maize; see table below).

	HHV	C content in DM	
soybean	16.78 MJ/kg	49.09%	Kričká et al. (2018)
sugarcane	18.5	49.6%	Carrier et al. (2011)
maize	18.36	46%	Ambrosio et al. (2017)

For current bioenergy from forestry plantings and short rotation coppice, we apply the same scheme as for forestry residues (woody biomass): for the lower estimate, conversion to biofuel via Fischer-Tropsch and for the upper estimate, conversion to electricity via combustion.

A2 Ranges of the variables describing the operation space of LCN-BC as assessed in 2.2. Table S1 in Werner et al. (2023).

Ranges	Feautures		References
Management of biomass production			
marginal	LPJmL-simulated yields under rainfed conditions		--
moderate	Mid-range between LPJmL-simulated yields under rainfed and irrigated conditionn		--
Pyrolysis paramters			
conservative	Herbaceous:	biochar yield = 23% ash-free DM biomass C in biochar = 39%	Woolf et al. (2021)
	Woody:	biochar yield = 27% ash-free DM biomass C in biochar = 43%	
optimized	Herbaceous:	biochar yield = 31% ash-free DM biomass C in biochar = 53%	Schmidt et al. (2019), Grafmüller et al. (2022)
	Woody:	biochar yield = 35% ash-free DM biomass C in biochar = 61%	
Biochar-mediated yield increases			
base	+10% yield increase (+5–15%)		grand mean of yield responses reported in Melo et al. (2022)
range	+5 and +15 % yield increase		confidence interval of yield responses reported in Melo et al. (2022)
Biochar carbon durability in soils			
Base	74% biochar carbon remaining in the soil after 100 years		annual decay rate of 0.3% per year for biochar with H/C ratios <0.4 (Camps-Arbestain et al., 2015)
Lower	70% biochar carbon remaining in the soil after 100 years		linear regression for 500°C based on Lehmann et al. (2021)
Upper	80% biochar carbon remaining in the soil after 100 years		IPCC (2019)

References

Ambrosio, R., Pauletti, V., Barth, G., Povh, F. P., Silva, D. A. d., & Blum, H. (2017). Energy potential of residual maize biomass at different spacings and nitrogen doses. *Ciência e Agrotecnologia*, *41*, 626-633.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182-183. https://doi.org/10.1126/science.aah4567

Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S., & Acharya, B. S. (2020). Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *GCB Bioenergy*, *12*(4), 240-251. https://doi.org/10.1111/gcbb.12665

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis. *Science of The Total Environment*, *651*, 2354-2364. https://doi.org/10.1016/j.scitotenv.2018.10.060

Boysen, L. R., Lucht, W., & Gerten, D. (2017). Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, *23*(10), 4303-4317. https://doi.org/10.1111/gcb.13745

Braghiroli, F. L., & Passarini, L. (2020). Valorization of Biomass Residues from Forest Operations and Wood Manufacturing Presents a Wide Range of Sustainable and Innovative Possibilities. *Current Forestry Reports*, *6*(2), 172-183. https://doi.org/10.1007/s40725-020-00112-9

Buck, H. J., Carton, W., Lund, J. F., & Markusson, N. (2023). Why residual emissions matter right now. *Nature Climate Change*, *13*(4), 351-358. https://doi.org/10.1038/s41558-022-01592-2

Buss, W., Wurzer, C., Manning, D. A. C., Rohling, E. J., Borevitz, J., & Mašek, O. (2022). Mineral-enriched biochar delivers enhanced nutrient recovery and carbon dioxide removal. *Communications Earth & Environment*, *3*(1), 67. https://doi.org/10.1038/s43247-022-00394-w

Camps-Arbestain, M., Amonette, J. E., Singh, B., Wang, T., & Schmidt, H. P. (2015). A biochar classification system and associated test methods. In J. Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management: Science, Technology and Implementation* (pp. 165-193). Routledge.

Carrier, M., Hugo, T., Gorgens, J., & Knoetze, H. (2011). Comparison of slow and vacuum pyrolysis of sugar cane bagasse. *Journal of Analytical and Applied Pyrolysis*, *90*(1), 18-26. https://doi.org/https://doi.org/10.1016/j.jaap.2010.10.001

Chiquier, S., Patrizio, P., Bui, M., Sunny, N., & Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways [10.1039/D2EE01021F]. *Energy & Environmental Science*, *15*(10), 4389-4403. https://doi.org/10.1039/D2EE01021F

Dashti, A., Noushabadi, A. S., Asadi, J., Raji, M., Chofreh, A. G., Klemeš, J. J., & Mohammadi, A. H. (2021). Review of higher heating value of municipal solid waste based on analysis and smart modelling. *Renewable and Sustainable Energy Reviews*, *151*, 111591. https://doi.org/https://doi.org/10.1016/j.rser.2021.111591

EC. (2017). *Sustainable and optimal use of biomass for energy in the EU beyond 2020. Annexes of the Final Report. European Comission.*

Edeh, I. G., Masek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties - New insights and future research challenges. *Science of The Total Environment*, *714*. https://doi.org/10.1016/j.scitotenv.2020.136857

Eisen, M. B., & Brown, P. O. (2022). Rapid global phaseout of animal agriculture has the potential to stabilize greenhouse gas levels for 30 years and offset 68 percent of CO2 emissions this century. *PLOS Climate*, *1*(2), e0000010. https://doi.org/10.1371/journal.pclm.0000010

Elagib, N. A., & Al-Saidi, M. (2020). Balancing the benefits from the water–energy–land–food nexus through agroforestry in the Sahel. *Science of The Total Environment*, *742*, 140509. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.140509

Erb, K.-H., Kastner, T., Plutzar, C., Bais, A. L. S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., Pongratz, J., Thurner, M., & Luyssaert, S. (2018). Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, *553*(7686), 73-76. https://doi.org/10.1038/nature25138

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., & Schellnhuber, H. J. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability*, *3*(3), 200-208. https://doi.org/10.1038/s41893-019-0465-1

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., . . . Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645-11650. https://doi.org/10.1073/pnas.1710465114

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, *8*(2), 151-155. https://doi.org/10.1038/s41558-017-0064-y

Honegger, M., Poralla, M., Michaelowa, A., & Ahonen, H.-M. (2021). Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies [Policy and Practice Reviews]. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.672996

Humpenöder, F., Popp, A., Bodirsky, B. L., Weindl, I., Biewald, A., Lotze-Campen, H., Dietrich, J. P., Klein, D., Kreidenweis, U., Müller, C., Rolinski, S., & Stevanovic, M. (2018). Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters*, *13*(2), 024011. https://doi.org/10.1088/1748-9326/aa9e3b

IEA. (2021). *Net Zero by 2050. A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050

IPCC. (2019). *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use*.

IPCC. (2022). *Climate Change 2022. Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

Jian, J., Du, X., Reiter, M. S., & Stewart, R. D. (2020). A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology and Biochemistry*, *143*, 107735. https://doi.org/https://doi.org/10.1016/j.soilbio.2020.107735

Kalt, G., Lauk, C., Mayer, A., Theurl, M. C., Kaltenegger, K., Winiwarter, W., Erb, K.-H., Matej, S., & Haberl, H. (2020). Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food-system pathways. *Environmental Research Letters*, *15*(3), 034066. https://doi.org/10.1088/1748-9326/ab6c2e

Kang, K., Klinghoffer, N. B., ElGhamrawy, I., & Berruti, F. (2021). Thermochemical conversion of agroforestry biomass and solid waste using decentralized and mobile systems for renewable energy and products. *Renewable and Sustainable Energy Reviews*, *149*, 111372. https://doi.org/https://doi.org/10.1016/j.rser.2021.111372

Krička, T., Matin, A., Voća, N., Pospišil, A., Grubor, M., Šaronja, I., & Jurišić, V. (2018). Changes in nutritional and energy properties of soybean seed and hull after roasting [journal article]. *Research in Agricultural Engineering*, *64*(2), 96-103. https://rae.agriculturejournals.cz/artkey/rae-201802-0007.php

http://dx.doi.org/10.17221/29/2016-RAE

Lang, J., Hyslop, C., Yeo, Z. Y., Black, R., Chalkley, P., Hale, T., Hans, F., Hay, N., Höhne, N., Hsu, A., Kuramochi, T., Mooldijk, S., & Smith, S. (2023). *Net Zero Tracker*. https://zerotracker.net/

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. A., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in Climate Change Mitigation. *Nature Geoscience*. https://doi.org/10.1038/s41561-021-00852-8

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., & Minx, J. C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature*, *561*, 303-305. https://doi.org/10.1038/d41586-018-06695-5

Liu, W., Hou, Y., Liu, W., Yang, M., Yan, Y., Peng, C., & Yu, Z. (2020). Global estimation of the climate change impact of logging residue utilization for biofuels. *Forest Ecology and Management*, *462*, 118000. https://doi.org/https://doi.org/10.1016/j.foreco.2020.118000

Lund, J. F., Markusson, N., Carton, W., & Buck, H. J. (2023). Net zero and the unexplored politics of residual emissions. *Energy Research & Social Science*, *98*, 103035. https://doi.org/https://doi.org/10.1016/j.erss.2023.103035

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., & Fang, J. (2018). Variations and determinants of carbon content in plants: a global synthesis. *Biogeosciences*, *15*(3), 693-702. https://doi.org/10.5194/bg-15-693-2018

Mašek, O., Buss, W., Brownsort, P., Rovere, M., Tagliaferro, A., Zhao, L., Cao, X., & Xu, G. (2019). Potassium doping increases biochar carbon sequestration potential by 45%, facilitating decoupling of carbon sequestration from soil improvement. *Scientific Reports*, *9*(1), 5514. https://doi.org/10.1038/s41598-019-41953-0

Muscat, A., de Olde, E. M., de Boer, I. J. M., & Ripoll-Bosch, R. (2020). The battle for biomass: A systematic review of food-feed-fuel competition. *Global Food Security*, *25*, 100330. https://doi.org/https://doi.org/10.1016/j.gfs.2019.100330

Nemet, G., F. , Callaghan, M., W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W., F., Minx, J., Rogers, S., & Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003. https://doi.org/10.1088/1748-9326/aabff4

Nouri, A., Lukas, S., Singh, S., Singh, S., & Machado, S. (2022). When do cover crops reduce nitrate leaching? A global meta-analysis. *Global Change Biology*, *28*(15), 4736-4749. https://doi.org/https://doi.org/10.1111/gcb.16269

Nsanganwimana, F., Pourrut, B., Mench, M., & Douay, F. (2014). Suitability of Miscanthus species for managing inorganic and organic contaminated land and restoring ecosystem services. A review. *Journal of Environmental Management*, *143*, 123-134. https://doi.org/https://doi.org/10.1016/j.jenvman.2014.04.027

Nurek, T., Gendek, A., & Roman, K. (2019). Forest residues as a renewable source of energy: Elemental composition and physical properties. *BioResources*, *14*(1), 6-20.

OECD, & FAO. (2020). *OECD-FAO Agricultural Outlook 2020-2029*. https://doi.org/doi:https://doi.org/10.1787/1112c23b-en

Peng, L., Searchinger, T. D., Zionts, J., & Waite, R. (2023). The carbon costs of global wood harvests. *Nature*. https://doi.org/10.1038/s41586-023-06187-1

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33-41. https://doi.org/https://doi.org/10.1016/j.agee.2014.10.024

Pour, N., Webley, P. A., & Cook, P. J. (2018). Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). *International Journal of Greenhouse Gas Control*, *68*, 1-15. https://doi.org/https://doi.org/10.1016/j.ijggc.2017.11.007

Proelß, A., & Steenkamp, R. (2022). *Report on the Future Regulation of Ocean-based NETs* (OceanNets Deliverable, Issue. https://oceanrep.geomar.de/id/eprint/57225/

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., . . . Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/doi:10.1126/sciadv.adh2458

Rickels, W. (2022). *Database and report on currently already existing or announced ocean NETs projects, including a world map of projects* (OceanNets Deliverable, Issue. https://oceanrep.geomar.de/id/eprint/57043/

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., . . . Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*.

Rosa, L., & Gabrielli, P. (2023). Achieving net-zero emissions in agriculture: a review. *Environmental Research Letters*, *18*(6), 063002. https://doi.org/10.1088/1748-9326/acd5e8

Rosa, L., Sanchez, D. L., & Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe [10.1039/D1EE00642H]. *Energy & Environmental Science*, *14*(5), 3086-3097. https://doi.org/10.1039/D1EE00642H

Sandström, V., Chrysafi, A., Lamminen, M., Troell, M., Jalava, M., Piipponen, J., Siebert, S., van Hal, O., Virkki, V., & Kummu, M. (2022). Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nature Food*, *3*(9), 729-740. https://doi.org/10.1038/s43016-022-00589-6

Scarlat, N., Fahl, F., Dallemand, J.-F., Monforti, F., & Motola, V. (2018). A spatial analysis of biogas potential from manure in Europe. *Renewable and Sustainable Energy Reviews*, *94*, 915-930. https://doi.org/https://doi.org/10.1016/j.rser.2018.06.035

Scarlat, N., Fahl, F., Lugato, E., Monforti-Ferrario, F., & Dallemand, J. F. (2019). Integrated and spatially explicit assessment of sustainable crop residues potential in Europe. *Biomass and Bioenergy*, *122*, 257-269. https://doi.org/10.1016/j.biombioe.2019.01.021

Scarlat, N., Martinov, M., & Dallemand, J.-F. (2010). Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Management*, *30*(10), 1889-1897. https://doi.org/https://doi.org/10.1016/j.wasman.2010.04.016

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., & Matthews, E. (2018). Creating a sustainable food future.

Searle, S., & Malins, C. (2015). A reassessment of global bioenergy potential in 2050. *GCB Bioenergy*, *7*(2), 328-336. https://doi.org/https://doi.org/10.1111/gcbb.12141

Searle, S. Y., & Malins, C. J. (2014). Will energy crop yields meet expectations? *Biomass and Bioenergy*, *65*, 3-12. https://doi.org/https://doi.org/10.1016/j.biombioe.2014.01.001

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., & Turkenburg, W. C. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, *33*(1), 56-106. https://doi.org/https://doi.org/10.1016/j.pecs.2006.08.001

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Impacts of Land-Based Greenhouse Gas Removal Options on Ecosystem Services and the United Nations Sustainable Development Goals. *Annual Review of Environment and Resources*, *44*(1), 1-32. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., . . . Minx, J. C. (2023). *The State of Carbon Dioxide Removal - 1st Edition*. https://www.stateofcdr.org

Spijker, E., & Picón, C. G. (2023). *County case study scaling scenario final report*. https://static1.squarespace.com/static/5f7b27859c352b2444f4cbd9/t/64a41113da6ba17623c7395d/1688473876685/D2.6+-+Report+only.pdf

Stenzel, F., Gerten, D., Werner, C., & Jägermeyr, J. (2019). Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C. *Environmental Research Letters*, *14*(8), 084001. https://doi.org/10.1088/1748-9326/ab2b4b

Tanzer, S. E., Preston Aragonès, M., Serdoner, A., & Dhakshinamoorthy, A. (2022). *Global governance of NETPs - global supply chains and coherent accounting (D6.3)*.

UNFCCC. (2015). *Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev.1*. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
Werner, C., Lucht, W., Gerten, D., & Kammann, C. (2022). Potential of Land-Neutral Negative Emissions Through Biochar Sequestration. *Earth's Future*, *10*(7), e2021EF002583. https://doi.org/10.1029/2021EF002583
Werner, C., Lucht, W., Kammann, C., & Braun, J. (2023). Land-neutral negative emissions through biochar-based fertilization – assessing global potentials under varied management and pyrolysis conditions [in review]. *Mitigation and Adaptation Strategies for Global Change*.
Werner, C., Schmidt, H. P., Gerten, D., Lucht, W., & Kammann, C. (2018). Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C. *Environmental Research Letters*, *13*(4), 044036. https://doi.org/10.1088/1748-9326/aabb0e
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., . . . Murray, C. J. L. (2019). Food in the Anthropocene: the EAT Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447-492. https://doi.org/10.1016/S0140-6736(18)31788-4
Wirsenius, S. (2000). *Human use of land and organic materials: modeling the turnover of biomass in the global food system* Chalmers University of Technology]. Gothenburg, DK. https://publications.lib.chalmers.se/records/fulltext/827.pdf
Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56. https://doi.org/10.1038/Ncomms1053
Xiang, Y., Deng, Q., Duan, H., & Guo, Y. (2017). Effects of biochar application on root traits: a meta-analysis. *GCB Bioenergy*, *9*(10), 1563-1572. https://doi.org/10.1111/gcbb.12449