NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Comprehensive sustainability assessment of terrestrial biodiversity NETPs

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Executive Summary and policy relevant messages

Terrestrial Negative Emission Technologies and Practices (NETPs) seek to enhance the natural CO_2 sequestration capacity of the land-based carbon sinks (above- and belowground biomass and soil).

Here we followed the life cycle assessment methodology to derive a set of Key Performance Indicators (KPIs) that allowed us to evaluate the following terrestrial NETPs:

- Afforestation/reforestation (A/R) in tropical, temperate, and boreal ecological zones.
- Manufacturing of wood products: glued laminated timber (glulam) and medium density fiberboard (MDF).
- Use of biochar as a soil amendment product and as a sand replacement in building materials. Some of the defined biochar scenarios consider the capture and storage of the CO_2 generated in the pyrolysis process (CCS).

We assessed the biophysical potential of Soil Carbon Sequestration (SCS) on global marginal land and identified the cultivation of *P. euphratica* (poplar) in West Africa as an optimal SCS strategy. Hence, the scenarios based on wood products and biochar rely on this crop. Promoting the deployment of NETPs in developing countries could boost job creation, and therefore have positive implications for sustainable development.

Our results reveal that A/R is the most appealing terrestrial NETP in terms of Carbon Dioxide Removal (CDR) efficiency – defined as the ratio between the net amount of CO_2 that is removed from the atmosphere and the sequestered CO_2 –, attaining values between 0.85 and 0.99. In general, A/R generates the lowest environmental impact across the studied impact categories, excluding land use, which varies significantly with the ecological zones. Moreover, the climate-related health impacts and externalities prevented by A/R are greater than the non-climate health impacts and externalities they generate throughout their life cycle.

The production of MDF – which requires chemicals like melamine and urea formaldehyde resins – led to the lowest CDR efficiency (0.20) and unfavorable KPI values. The wood scenario based on glulam, with a CDR efficiency of 0.51, obtains better results. However, we do not recommend focusing future research efforts within the NEGEM project on this NETP, given the uncertainty associated with the permanence of the carbon stored in the wood products.

The CDR efficiency of the biochar scenarios ranges between 0.44 and 0.73, depending on whether CCS is integrated into the pyrolysis process, the biochar application, and its lifetime. The CO_2 emissions that are avoided by substituting natural gas heat with the excess heat generated in the pyrolysis process are substantial (0.19-0.67 tonne/tonne sequestered CO_2). Hence, integrating this NETP into heat-demanding systems could help advance its deployment, although its cost is still high compared to the wood products and A/R NETPs.

The main limitation of this work is that we did not investigate how the surface albedo changes affect the climate change impacts of terrestrial NETPs at a local/regional scale. Future research should address this question. On the other hand, terrestrial NETPs are constrained by site-dependent environmental conditions and land availability, and they are vulnerable to unexpected disturbances (fires, pests, etc.) and climate change. Therefore, CDR pathways should consider them in concert with other NETPs.

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A/R. Afforestation/Reforestation.

AR1. Reforestation of tropical rainforest scenario.

AR2. Afforestation of boreal tundra woodland scenario.

BC1. Biochar scenario with sand replacement and no CCS.

BC2. Biochar scenario with soil application and CCS, biochar LT: 500 years.

CCS. Carbon Capture and Storage.

CDR. Carbon Dioxide Removal.

DALY. Disability-Adjusted Life Year.

FU. Functional unit.

GEZ. Global Ecological Zone.

Glulam. Glued laminated timber.

KPI. Key Performance Indicator.

LT. Lifetime.

MDF. Medium Density Fiberboard.

NETPs. Negative Emission Technologies and Practices.

SCS. Soil Carbon Sequestration.

SOC. Soil Organic Carbon.

TRL. Technology Readiness Level.

WP1. Glulam production scenario.

WP2. MDF production scenario.

Introduction

The Negative Emission Technologies and Practices (NETPs) that sequester carbon in soil and biological stocks, driven by plant uptake of atmospheric CO_2 *via* photosynthesis, are referred to as terrestrial NETPs in this document. In NEGEM deliverable 1.1,[1] we identified afforestation/reforestation (A/R), building with wood, enhancing soil carbon sequestration (SCS) and biochar amendment as the most promising terrestrial NETPs, based on these three Key Performance Indicators (KPIs): the Technology Readiness Level (TRL) – a scale from 1 to 9 that rates the maturity of a given technology –, Carbon Dioxide Removal (CDR) potential and cost (Table 1).

Table 1. Terrestrial NETPs with a high level of potential deployment[1]

	TRL	Max CDR Gtonne/yr	Cost (2019€) €/tonne CO_2
Afforestation/reforestation	8-9[2]	0.5-3.6[3]	5-47[3]
Building with wood	8-9[4]	0.5-1[4]	Negligible[4]
Soil carbon sequestration	6-7[4]	2-5[3]	0-93[3]
Biochar amendment	4-6[4]	0.5-2[3]	28-112[3]

Afforestation involves the conversion of land that has not been covered by forest in the preceding 50 years to forested land, whereas reforestation takes place on land that has been deforested within the last 50 years.[5] Although managed forest plantations are usually monocultures,[6] sustainable A/R practices should prioritize native mixed species, which provide extra ecosystem functions[7] with positive effects on biodiversity.[6]

The climate benefits of using wood products as construction materials stem not only from the temporal storage of carbon in the product, but also from the substitution of other materials.[8] Glued laminated timber (glulam) – which can replace steel as a structural material –,[9] and cross-laminated timber – a wood panel product that can substitute concrete –,[10] are particularly appealing engineered wood products.

Enhancing SCS in vulnerable soils with low carbon stocks can also bring co-benefits such as improved soil fertility, water retention and reduced soil erosion.[11] Among the land-use management portfolio of SCS strategies (e.g., no-tillage agriculture, growing diverse cover crops, organic matter amendment, or restoring wetland hydrology),[8] planting perennial species – which increase the biomass (above- and belowground) and soil organic carbon (SOC) stocks – could be an effective SCS method for marginal lands.[12]

Similarly, the use of the biochar generated in biomass pyrolysis processes as a soil amendment product has been reported to reduce soil greenhouse gas emissions and increase crop yields.[3,8] However, the carbon sequestration capacity of biochar is highly variable; its long-term stability depends on the feedstock quality, the pyrolysis process, and the soil and climate conditions.[13] Thus, successful CDR would require strict application standards and monitoring. Alternatively, biochar could be used in building materials, replacing sand.[14]

Previous studies have evaluated the environmental performance of A/R,[15–18] biochar systems[19–22] and building with wood,[23] with a strong focus on the climate change impact assessment. This work aims at a more comprehensive analysis of the implications of terrestrial NETPs. We applied a set of technical, environmental, and socioeconomic KPIs to assess the sustainability performance of the following NETPs:

- A/R based on mixed tree stands native of tropical, temperate, and boreal climates.
- Wood products: glulam and Medium Density Fiberboard (MDF) produced from poplar.
- Biochar (with and without the capture and storage of the CO_2 produced in the pyrolysis process). The soil application of biochar (produced from poplar) with different degradation rates, and its use as a sand replacement in building materials were evaluated.

SCS was not evaluated as an individual NETP, but the carbon sequestered throughout the lifetime (LT) of the modeled plantations due to the land-use change was quantified in all the assessed scenarios.

1. Methodology

Here we describe the life cycle modeling approach and the methodological framework developed to quantify the SCS potentials of specific plant species, which were used to define and model the scenarios based on wood products and biochar.

1.1 Life cycle assessment and KPIs

We conducted a life cycle assessment – the evaluation of inputs, outputs and potential environmental impacts – [24] of the chosen terrestrial NETPs following the methodology described in Figure 1. An attributional modeling approach[25] was selected, and the functional unit (FU) – the reference unit that quantifies the performance of the studied systems – was defined as one tonne of CO_2 effectively sequestered within the timeframe of the analysis (100 years).

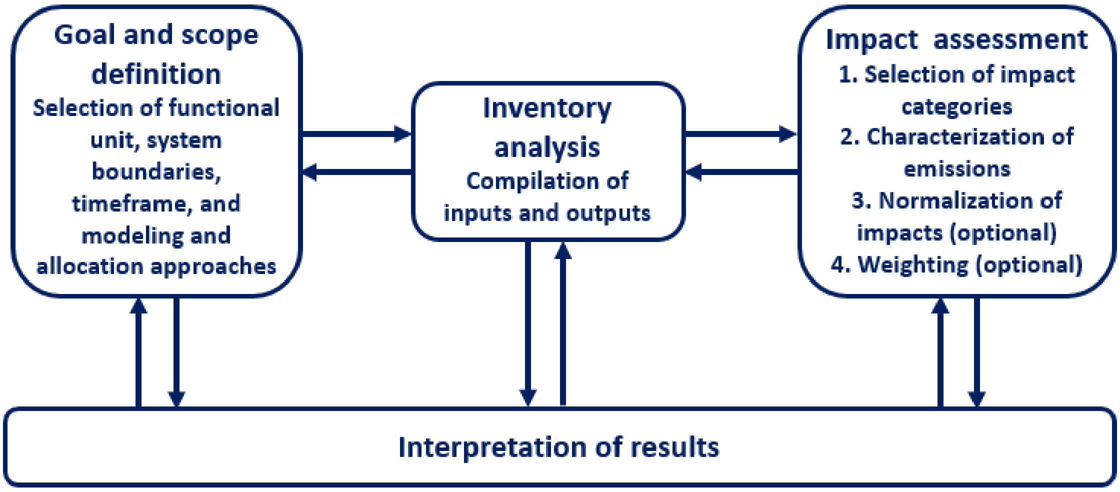


Figure 1. Overview of the life cycle assessment phases (adapted from ISO 14040[24]).

We assumed that the forest plantations are not subject to unexpected events such as pests and fires that could release the sequestered carbon back into the atmosphere. Likewise, we considered that the manufactured wood products and the building materials where the biochar is stored have a long lifespan and remain functional within the technosphere during the considered time horizon. On the other hand, in the scenarios where biochar is used for soil amendment, we quantified the amount of carbon that is degraded to CO_2 within the first 100 years after it is applied to the soil.

Under the assumption that the secondary functions of the studied NETPs – i.e., the products and services they provide in addition to CDR – substitute equivalent functions provided by other systems, the system boundary expansion method was applied.[16] In the wood product scenarios, we consider that 1 m^3 of glulam avoids the production of 428.6 kg of steel,[26] whereas MDF replaces gypsum fiberboard (on a volume basis) as a panel material. In the biochar scenarios, the excess heat generated by burning the byproducts of the pyrolysis process replaces heat produced in the combustion of natural gas. When biochar is used in building materials, such as concrete or bitumen, it substitutes fine aggregates composed of sand.

The life cycle models, built on data extracted from the Ecoinvent 3.5 database,[27] were implemented in SimaPro 9.1.0.8,[28] and allowed us to calculate the KPIs relative to the FU. The CDR efficiency (η_{CO_2}, Equation 1) was defined as the ratio between the net amount of CO_2 that is removed from the atmosphere within the selected time horizon – computed as the sequestered CO_2 (S_{CO_2}) minus the overall life-cycle CO_2 emissions (E_{CO_2}), – and S_{CO_2}. The avoided CO_2 KPI (A_{CO_2}, Equation 2) reflects the CO_2 emissions that are prevented by replacing other services and products, estimated with the amount of service or product *i* (i.e., steel, gypsum fiberboard, heat or sand) that is substituted per tonne of sequestered CO_2 (SF_i), and the CO_2 emissions related to that service or product ($EF_{CO_2,i}$).

$$\eta_{CO_2} = \frac{S_{CO_2} - E_{CO_2}}{S_{CO_2}} \quad (1)$$

$$A_{CO_2} = \sum_{i \in I} SF_i \cdot EF_{CO_2,i} \quad (2)$$

The environmental KPIs were quantified with the Environmental Footprint impact assessment method (EF 3.0).[29] These KPIs reflect the CDR impacts on the following 16 categories: climate change, ozone depletion, ionizing radiation, photochemical ozone formation, particulate matter, human toxicity (carcinogenic and non-carcinogenic), acidification, eutrophication (freshwater, marine and terrestrial), freshwater ecotoxicity, land use, water use, use of fossil resources and use of minerals and metals.

Two socioeconomic KPIs were computed, namely the impacts on human health and externalities. The human health impacts, expressed in DALYs (Disability-Adjusted Life Years), were estimated with the ReCiPe2016 endpoint method.[30] The externalities – i.e., the monetized environmental impacts, expressed in 2019€ – were calculated applying the conversion factors proposed by Weidema[31] to the endpoint level impacts – damage to human health, ecosystems and resource availability – estimated with the ReCiPe2016 method.

1.2 Biophysical potential of SOC sequestration on global marginal land

1.2.1 Framework description and scope

We developed a framework to quantify the global biophysical CDR potentials of terrestrial NETPs through soil carbon sequestration (SCS) induced by specific plant species (woody or herbaceous). Central to the framework is its flexibility in goal and scope definition for identifying areas of interest based on the selection of land cover classes (e.g. cropland, marginal land, forest land, etc.), soil properties (e.g. carbon content in the soils), geographic and environmental boundaries. The framework allows selecting candidate plant species and categories (e.g. fibers, trees, energy crops, food/feed, etc.) —here referred to as “biopumps” – representing industrial crops with SCS and feedstock potentials for various bioeconomy pathways, eventually enabling temporary carbon storage throughout the supply chains.

The framework aims at facilitating the mapping of target areas and their matching with various biopumps, considering environmental tolerances to a variety of climatic and edaphic variables. The mapping is carried out using georeferenced products and geographic information system software. The identified matches are coupled with a SOC model to assess net SCS potentials and determine the best combinations most likely to enhance SCS over the long-term, as compared to the baseline situation of the target areas. We developed an R code to automate the tasks of: a) matching biopumps to target areas based on the created pedoclimatic databases, and b) computing SCS and carbon eroded by water.

In our case study we applied the framework on marginal land at a 30 arcsec (1 km) resolution at a global scale and conducted the simulations over the 2020-2100 time horizon. A key defining factor was the assessment of SOC-deficiency land covers, entailing initial SOC stocks limited to a maximum of 50 tonne SOC/ha (≤30 cm topsoil), as those being likely to attain higher sequestration potentials.[32]

1.2.2 Target area definition, mapping and identification

We defined target areas based on key studies,[33–35] including land areas that are currently unused or underused by agriculture due to an aggregation of socio-economic and environmental (biophysical) limitations or human-induced land degradation, but which could potentially be suitable for sustainable biomass production. Based on the definition, we identified global marginal land by combining georeferenced data (detailed in the Appendix Table1) from:

1. i) Global land cover map by the European Space Agency of the year 2018, featuring 22 land cover classes defined in the FAO Land Cover Classification System,[36] to select marginal lands.
2. ii) FAO's Global Soil Organic (GSOC v1.5) map[37] for the year 2017, to exclude SOC stocks >50 tonne SOC/ha.
3. iii) World Database on Protected Areas (WDPA v1.6),[38] to exclude officially protected areas, and
4. iv) FAO Dominant Type of Problem Lands, complemented by the Harmonized World Soil Database (HWSD v1.21),[39] to exclude areas unsuitable for biomass growth.

The marginal lands were consolidated into target areas at a manageable scale to conduct SOC computation, based on geographies and environmental boundaries set by the combination of climate zones, as defined in FAO's Global Ecological Zones (GEZs)[40] (19 in total), and administrative geo-political world regions (22 in total). The pedoclimatic conditions (e.g. monthly climate data, clay content, soil depth, etc.) were recorded for the consolidated and averaged target areas with the same world region and GEZ, to inform the SOC model.

The preliminary identified marginal lands cross-referenced with SOC stocks <50 tonne SOC/ha were bare areas (~2020 Mha) and sparsely vegetated (<15%) (~690 Mha) —excluding agricultural, non-forestry, and non-natural ecosystems with high vegetation or biodiversity. We added recently abandoned agricultural land, corresponding to cropland transition (here over the period 2010-2018) to mosaic cropland/(semi-)natural vegetation, grasslands, sparse vegetation, bare areas, mosaic herbaceous cover or shrubland (~4Mha). The biophysically suitable areas (excluding protected areas), however, comprised in total ~28 Mha (1% from preliminary marginal lands). The majority of the identified target areas per region were located in Asia, Northern Africa, and South America. Europe accounts for only 0.1% of the total target areas, largely present in the Southern European region corresponding to GEZ subtropical dry forest.

1.2.3 Biopump selection and identification of environmental tolerances

Initially, 164 crops (dominated by perennials) were considered, including those from the EU H2020 MAGIC project.[41] Data on their SCS potential and yield were compiled from diverse data sources. We pre-selected 50 biopumps based on a semi-quantitative analysis by scoring them on three main criteria: SCS potentials, primary yield productivity and marginal land adaptability. The short-listed biopumps were recorded into a database (associated with 432 plant species) specifying their climatic and soil tolerances retained from the ECOCROP database,[42] to evaluate their suitability to grow on identified and consolidated target areas, and likewise to inform the SOC model (e.g. plant-based carbon inputs).

1.2.4 SOC sequestration and losses from soil carbon erosion

We used the Rothamsted C (RothC v26.3) 5-pool model,[43,44] which was applied to a wide range of climates and world regions in combination with GIS products,[45–47] and is recommended by the FAO as a standard SOC model for national comparisons (at a 30 arcsec resolution).[48] RothC computes the soil organic matter from known carbon inputs and predicts the net SOC stock changes over the long-term at monthly time steps. The decay processes depend on the following input data: soil clay content [%], average monthly climate data (temperature [°C], precipitation and evapotranspiration [mm]), annual organic carbon inputs, land use (arable, forest and grass cover) and management, and soil depth [cm]. Carbon inputs specific to each pool (except for inert organic matter) are described by a rate constant parametrized for grassland, crop and forest land. Near-present climate data (1979 to 2013) was retrieved from the CHELSAv1.2 database[49,50] and evapotranspiration CGIAR's High-Resolution Global Soil-Water-Balance[51] (detailed in Appendix Table 1). The annual averaged soil loss by water erosion was computed with the RUSLE2015 equation,[52] translated into eroded soil organic carbon, as proposed by Lugato et al.[53]

1.2.5 Suitable biopumps with high SCS potentials

The actual matching areas with biopumps (i.e., biophysically suitable target areas where at least one biopump can grow) represent 0.56 Mha. In total, 17 biopumps associated with 67 species were identified as being compatible with target areas within 12 world regions and 11 GEZ. Top biopumps with highest SCS potentials were Hemp (*C. sativa spp. indica)*, Neem (Melia azedarach), Cup plant (*S. perfoliatum*)*,* Poplar (*P. euphratica*), Acacia *(A. erioloba* or *A. ataxacalntha*), Miscanthus *(spp.)*, Switchgrass (*P. maximum*), Topinambour (*H. annuus*).

1.2.6 Perspectives for SOC sequestration

The study demonstrated that the applicability of the biopump-NETPs highly depends on the local environmental conditions, i.e., the biophysical constraints and carbon losses due to soil erosion by water. These key elements determine the land availability for biomass production and thus the actual negative emission potentials of SCS. The maximum CDR of the marginal land (with SOC <50 tonne C/ha) case study and their matching biopumps amounted to ~5 Mtonne CO_2 over the 2020-2100 time horizon. This value is significantly below the magnitude of the global CDR required to limit warming to 1.5 ºC.[54]

In the next steps, we envision to explore how the CDR potentials are affected by considering areas with SOC stocks >50 tonne C/ha, extending the biopump list by including all the originally identified crops, assessing the sensitivity due to the carbon input variability associated with different yield performances, and considering the effects of climate change on long-term SOC computation (e.g., using averaged monthly climate data from the CMIP6 RCP SSP1.26 climate trajectories). As part of Work Package 3, we will address the whole carbon balance (i.e., including biomass carbon stocks) and conduct an environmental assessment of specific biopump cultivation and bioeconomy scenarios.

2. Scenario definition

Six A/R scenarios were analyzed, each of them corresponding to a specific GEZ within a given climate domain (Table 2). The litter carbon stocks due to land-use conversion and the above- and below-ground biomass carbon stocks estimated by the IPCC[5,55] were used to quantify the sequestered CO_2.

All the A/R scenarios consider the production of the tree seedlings (1500 trees/ha),[56] and the planting operations, but the construction and maintenance of the forest roads (7.5 m/ha)[57] were only included in the afforestation scenarios, under the assumption that the road infrastructure already exists if the land has been recently deforested.

We defined best- and worst-case scenarios for each climate zone; the reforestation scenarios that do not require new road infrastructure were analyzed in the GEZ capable of sequestering more carbon within each climate domain, whereas afforestation – which will lead to higher impacts due to the road construction and maintenance activities – was assumed to take place in areas with a lower carbon sequestration capacity.

Table 2. Afforestation/reforestation scenarios

Scenario	Climate domain	Ecological zone
1. Reforestation	Tropical	Rainforest
2. Afforestation	Tropical	Dry forest
3. Reforestation	Temperate	Coniferous forest
4. Afforestation	Temperate	Broadleaf forest
5. Reforestation	Boreal	Coniferous forest
6. Afforestation	Boreal	Tundra woodland

The scenarios focusing on wood products and biochar are based on *P. euphratica* (poplar), a perennial coppice with a 21-year rotation period. Among the multiple combinations of plant species, GEZ and world regions analyzed (refer to section 1.1), the cultivation of *P. euphratica* in the tropical shrubland of Western Africa was identified as the most promising SCS strategy in terms of the net sequestered SOC; although the net SOC sequestered (i.e. gross SOC sequestered minus SOC eroded by water) per unit area is modest (1.57 tonne/ha), given the large extension of this marginal area (0.3 Mha), it could sequester up to 0.47 Mtonne of SOC, ahead of the cultivation of acacia in the tropical desert of Australia and New Zealand, whose maximum sequestration potential is 0.42 Mtonne of SOC (Table 3).

Table 3. Top three combinations of regions, GEZ and species in accordance with their maximum SOC sequestration capacity

Region	GEZ	Species	Common name	Area (ha)	Net SOC (tonne/ha)	Net SOC (Mtonne)[1]
Western Africa	Tropical shrubland	*Populus euphratica*	Poplar	302,508	1.57	0.47
Australia/ New Zealand	Tropical desert	*Acacia erioloba*	Acacia	154,422	2.73	0.42
Australia/ New Zealand	Tropical shrubland	*Zea mays ssp. mays*	Maize	44,766	3.44	0.15

[1] Over the studied 2020-2100 time horizon.

The marketable and non-marketable wood of *P. euphratica* sequesters 2.81 and 3.72 tonne C/ha/yr, respectively. The life cycle inventory provided by Peters et al.[19] was adapted to quantify the activities, inputs and emissions associated with the cultivation of poplar. The distance from the biomass plantation to the pyrolysis and wood production facilities is assumed to be 15 km. We modeled two scenarios based on the manufacturing of glulam and MDF from poplar wood. In the first one, glulam is produced from the marketable wood, whereas the non-marketable wood is used to produce MDF. All the wood is used to produce MDF in the second scenario.

In the biochar scenarios, the poplar wood chips are subjected to a slow pyrolysis process at 450 ºC, where 50% of the biomass carbon is stored in the biochar.[19] The pyrolysis byproducts (gas and tars) are burned to provide the heat required in the pyrolysis process, generating excess heat. The inventory data for the pyrolysis process and the biochar application were adapted from Peters et al.[19]

A total of six biochar scenarios were considered (Table 4): two scenarios where the biochar substitutes sand in building materials, and four scenarios where the biochar is applied to the soil. The latter consider biochar LTs of 500 and 1000 years,[58] which – assuming a constant carbon degradation rate – lead to the emission of 20% and 10% of the sequestered carbon as CO_2 within the selected 100-year time horizon, respectively. When biochar is used as an aggregate replacement, it remains sequestered within the building material during the considered timeframe.

Following the assumptions made by Peters et al.,[19] the circular systems where biochar is used to amend the poplar plantation soil benefit from a ~7% increase in poplar yield. Consistent with the reduced pollutant emissions related to the soil application of biochar that are reported in the literature,[3] we consider that the nitrogen present in the biochar does not lead to additional nitrate or N_2O emissions.[19]

As shown in Table 4, three biochar scenarios include the capture and storage (CCS) of the CO_2 produced in the combustion of gas and tars. The efficiency of this CO_2 capture process is 90%,[59] and it relies on the absorption of CO_2 in a monoethanolamine solution. The captured CO_2 is subsequently desorbed with a fraction of the generated excess heat (3.22 GJ/tonne).[59] The electricity required to capture and compress the CO_2 to 150 bar is 164.63 kwh/tonne.[59] The data used to model the CO_2 transport and storage phases were taken from Koornneef et al,[60] and the global 2018 electricity mix was assumed to power the pyrolysis and CCS processes.[61]

Table 4. Biochar scenarios

Scenario	Biochar LT in the soil (years)	CCS
1. Sand substitution	–	No
2. Sand substitution	–	Yes
3. Soil application	500	No
4. Soil application	500	Yes
5. Soil application	1000	No
6. Soil application	1000	Yes

3. Key findings

The CDR efficiency (η_{CO_2}) and the avoided CO₂ (A_{CO_2}) KPIs of the studied scenarios are depicted in Figure 2. All the A/R scenarios have a higher η_{CO_2} than the wood product and biochar scenarios. The reforestation of the tropical rainforest is the most efficient of the assessed NETPs (η_{CO_2}= 0.99), but η_{CO_2} drops to 0.85 in the boreal tundra woodland afforestation scenario, which has a lower carbon sequestration capacity per unit area. The production of MDF from poplar wood attains the lowest η_{CO_2} (0.20), whereas the production of glulam emits less CO₂ throughout its life cycle and achieves a higher η_{CO_2} (0.51). The η_{CO_2} of the biochar scenarios range between 0.44 and 0.73. It is higher in the biochar scenarios with CCS (0.67-0.73) because they require less biomass to sequester the same amount of CO₂ as the scenarios without CCS, and therefore their life cycle emissions are lower.

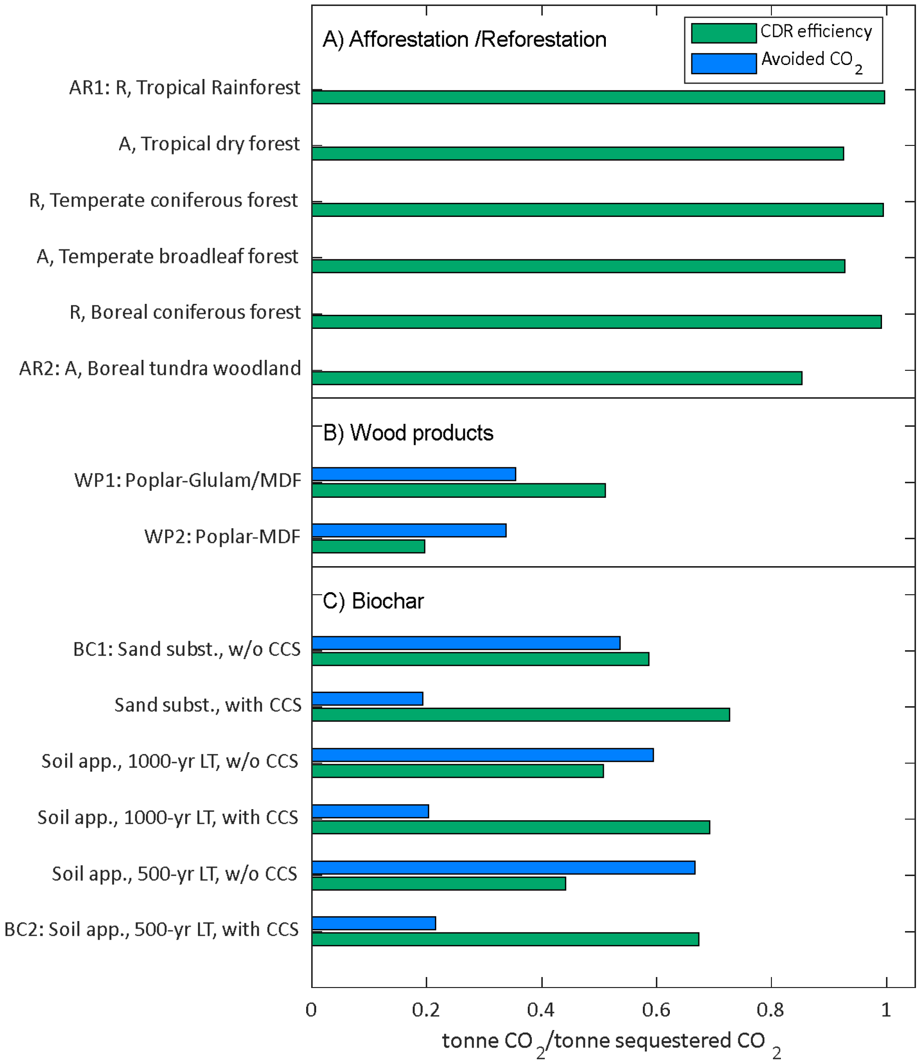


Figure 2. Technical KPIs: CDR efficiency and avoided CO₂.

The prevented CO₂ emissions in the wood product scenarios due to the substitution of gypsum fiberboard and steel (A_{CO_2}=0.34-0.35 tonne CO₂/tonne sequestered CO₂) are moderate compared to the A_{CO_2} values of the biochar scenarios without CCS (0.54-0.67 tonne/tonne sequestered CO_2), where the excess heat replaces the heat generated in the combustion of natural gas. On the contrary, in the biochar scenarios with CCS, part of the heat is used to desorb the CO_2 captured in the monoethanolamine solution, and A_{CO_2} decreases to 0.19-0.22 tonne/tonne sequestered CO_2.

The heating credits determine the climate change impacts of the biochar scenarios; as Figure 3 shows, the biochar scenarios without CCS attain the best results in the climate change impact category (between -1,089 and -1,067 kg CO_2-eq/tonne sequestered CO_2); although their biomass consumption is higher and hence their life cycle emissions are greater than those of the biochar scenarios without CCS (whose climate change impacts range between -887.8 and -854.4 kg CO_2-eq/tonne sequestered CO_2), they are outweighed by the larger heating credits. The avoided CO_2 emissions and the avoided climate change impacts increase as the biochar lifetime decreases because more biomass is needed to sequester the same amount of CO_2, generating more heat in the pyrolysis process.

The climate change impacts of A/R range between -995.8 and -990.6 kg CO_2-eq/tonne sequestered CO_2 in the reforestation scenarios, and -919.5 and -837.2 kg CO_2-eq/tonne sequestered CO_2 in the afforestation scenarios. The best climate change KPI is attained in the tropical domain, and the worst in the boreal areas. Given the lower sequestration capacity of the boreal GEZs, more tree seedlings, planting operations and road infrastructure are needed per unit area, leading to more impact. It is worth noting that in the boreal areas, the majority of the carbon is sequestered in the soil, as opposed to the other climate zones, where most of the carbon is stored in the biomass.

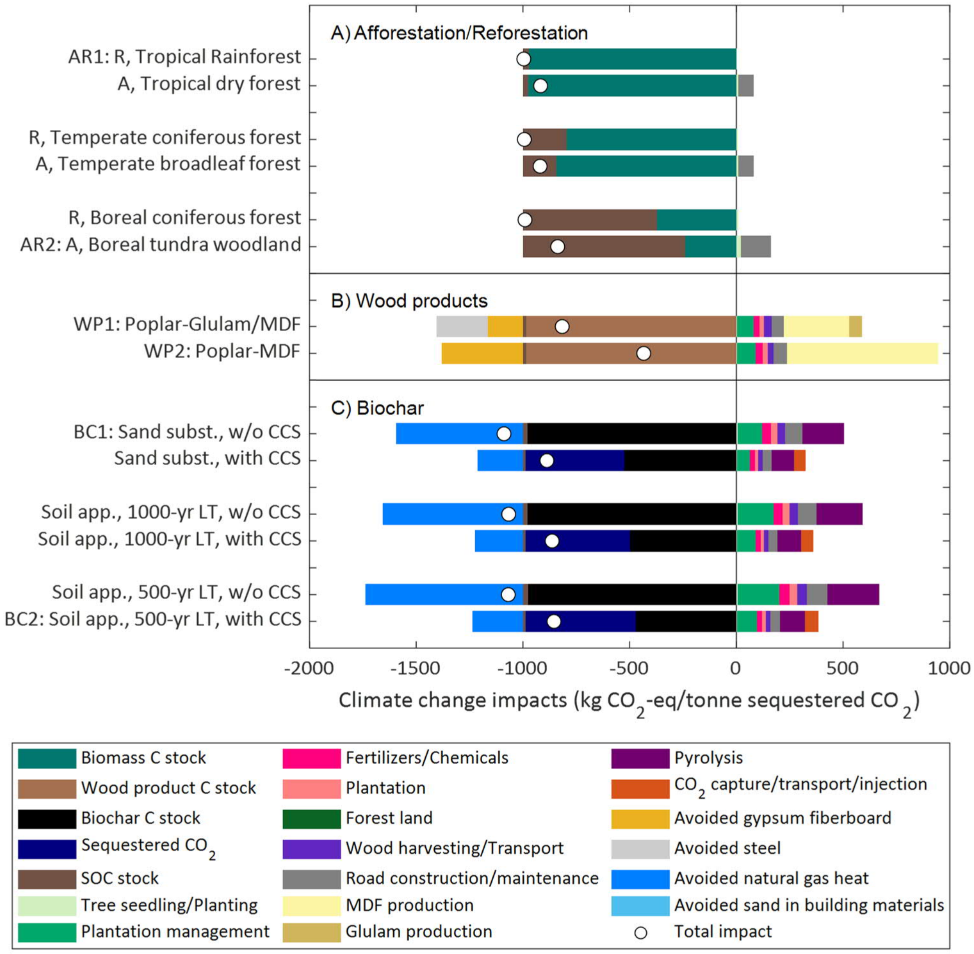


Figure 3. Climate change KPI and contribution to climate change impacts.

The highest climate change impacts occur in the scenarios where wood products are manufactured (-816.1 and -434.1 kg CO_2-eq/tonne sequestered CO_2). Most of the impacts are due to the production of MDF, which requires products like melamine and urea formaldehyde resins, with high carbon footprints.

The other environmental KPIs are presented in Figure 4. Only the results of the best and worst scenarios in terms of climate change impacts are shown for each type of terrestrial NETP. The production of MDF is the worst-performing NETP for most of the studied impact categories. The carcinogenic toxicity impacts of MDF are particularly relevant – one order of magnitude higher than those of the biochar scenarios –, and they are mainly related to the emission of formaldehyde. However, the avoided impacts associated with steel production in the glulam scenario lead to negative impacts in the freshwater eutrophication, ecotoxicity, non-carcinogenic toxicity and minerals and metals use categories. On the other hand, the scenarios relying on poplar can avert non-carcinogenic toxicity impacts because of the metals present in the soil that the biomass takes up.

The A/R scenarios attain low impacts (mostly due to the road construction and maintenance phase) across the studied impact categories, excluding land use; the land required by the afforestation of boreal tundra woodland is between four and seven times greater than that of the biochar scenarios.

The biochar scenarios without CCS attain the highest impacts in the ionizing radiation (linked to the electricity used in the pyrolysis process), water use, and freshwater and marine eutrophication categories. The latter are due to the higher biomass consumption of these scenarios, which leads to larger water and fertilizer inputs. Conversely, the avoided heating credits of the biochar scenarios without CCS can prevent impacts in the ozone depletion (primarily because of the bromotrifluoromethane emitted in the natural gas extraction phase) and fossil resource use categories.

The rise in temperatures and the altered precipitation patterns associated with climate change increase the risk of certain diseases (e.g., malnutrition, malaria, diarrhea) and natural disasters.[62] As Figure 5a shows, the deployment of terrestrial NETPs prevents climate-related health impacts in the six selected scenarios. Nevertheless, only in three of them – reforestation of tropical rainforest, afforestation of boreal tundra and glulam production – the prevented health impacts outweigh the other adverse health side-effects linked to pollutant emissions and water consumption that occur throughout the NETPs' life cycle. The net health impacts range between $-9.1 \cdot 10^{-4}$ and $-4.7 \cdot 10^{-4}$ DALYs/tonne sequestered CO_2 in the A/R scenarios. The avoided toxicity impacts linked to the replacement of steel are also substantial in the glulam scenario, whose net health impacts amount to $-8.0 \cdot 10^{-4}$ DALYs/tonne sequestered CO_2.

The unintended harmful health impacts of the reforestation scenarios are negligible. Although the particulate matter generated in the road construction and maintenance operations of the afforestation scenarios cannot be overlooked, they are low compared to the other scenarios. The water consumed to irrigate the poplar plantation – which reduces freshwater availability, causing human health damage – and the formation of fine particulate matter – mainly related to the electricity used in the pyrolysis process and the melamine formaldehyde resin used to manufacture MDF – are the main contributors to the detrimental health effects of the scenarios generating net health impacts. The toxicity impacts linked to the production of MDF are also noteworthy. The scenario producing solely MDF leads to the highest net health impacts ($1.2 \cdot 10^{-3}$ DALYs/tonne sequestered CO_2).

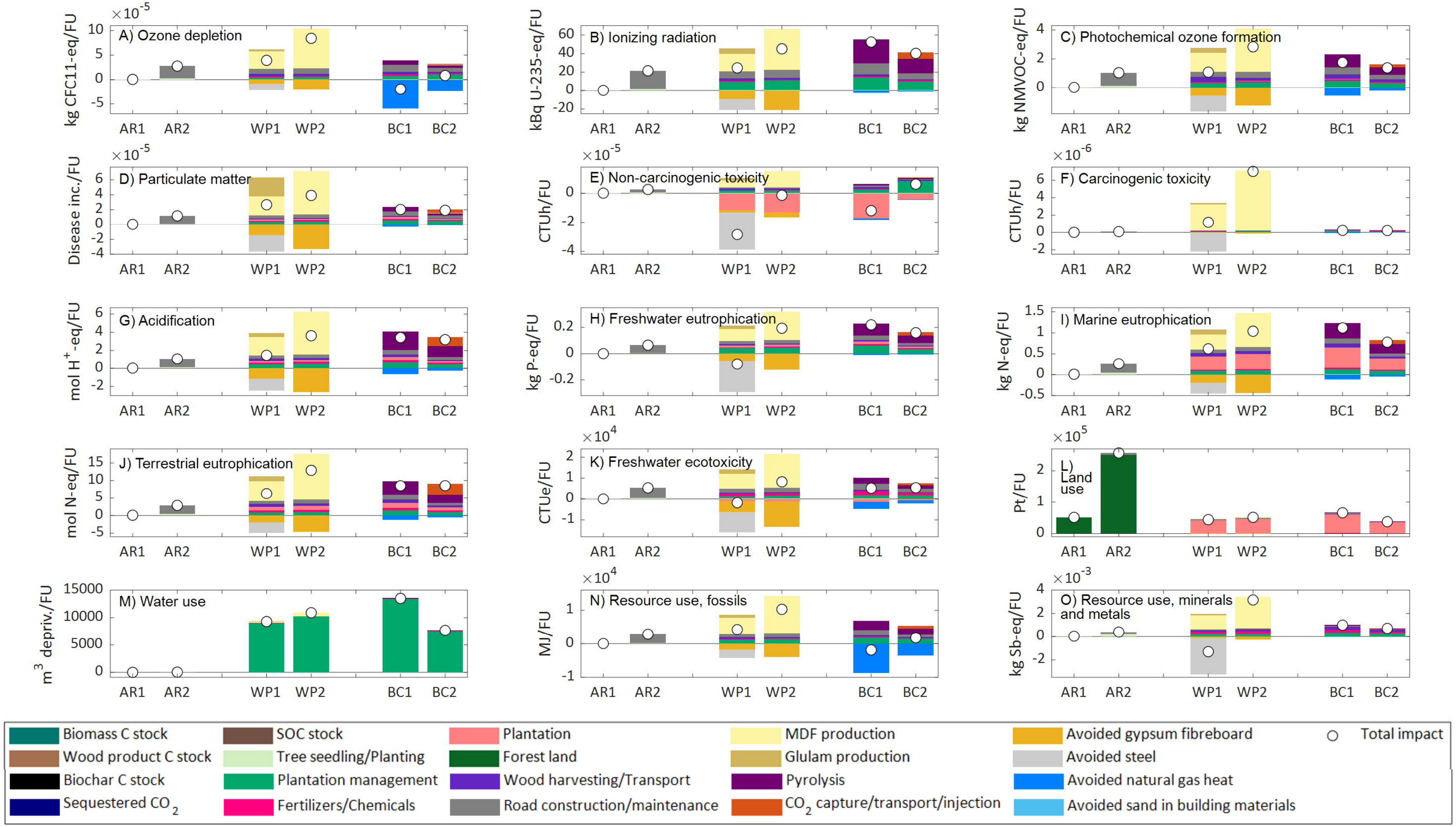


Figure 4. Environmental KPIs and contribution to impacts. Selected scenarios: AR1 (reforestation of tropical rainforest), AR2 (afforestation of boreal tundra woodland), WP1 (production of glulam/MDF), WP2 (production of MDF), BC1 (biochar replaces sand, w/o CCS), BC2 (soil application of biochar, 500-year LT, with CCS).

As shown in Figure 5b, out of the six selected scenarios, only the monetized impacts of reforesting the tropical rainforest are negative (-73 €/tonne sequestered CO_2). In this scenario, the prevented externalities could counteract the CDR costs (5-47 €/tonne sequestered CO_2).[3]

The externalities of the other scenarios vary between 8 and 257 €/tonne sequestered CO_2, with the bounds corresponding to the glulam and MDF production scenarios, respectively. Damage to ecosystems is the main endpoint impact contributing to the externalities across the selected scenarios, excluding MDF production, whose human health impacts represent the largest share of the externalities. Land use is the principal cause of ecosystems damage, closely followed by water consumption in the scenarios where poplar is irrigated.

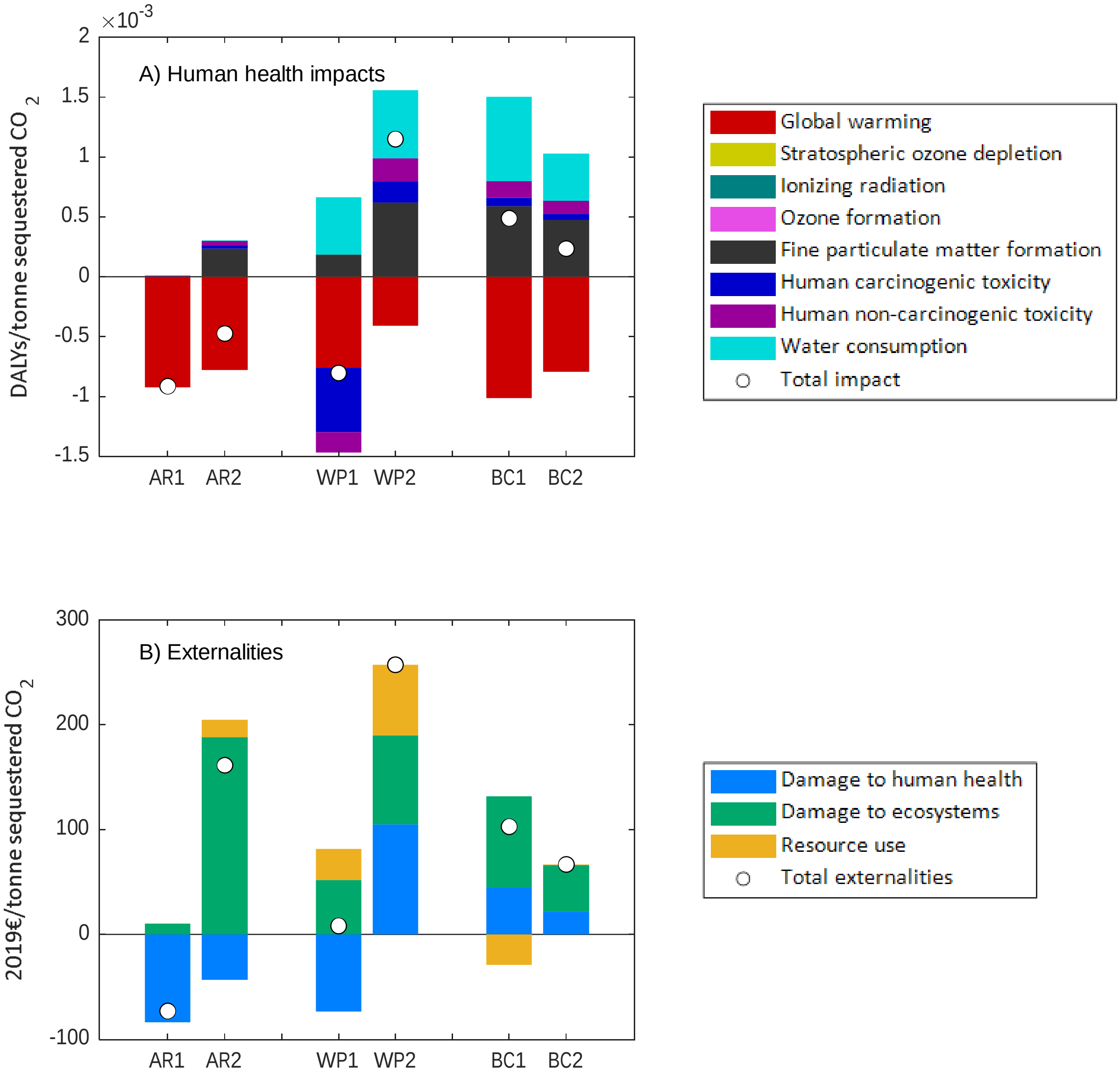
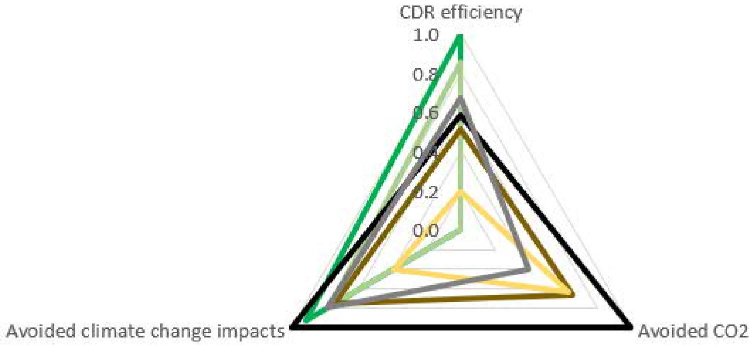


Figure 5. Socioeconomic KPIs. A) Human health impacts and contribution of impact categories. B) Externalities and contribution of endpoint impacts. Selected scenarios: AR1 (reforestation of tropical rainforest), AR2 (afforestation of boreal tundra woodland), WP1 (production of glulam/MDF), WP2 (production of MDF), BC1 (biochar replaces sand, w/o CCS), BC2 (soil application of biochar, 500-year LT, with CCS).

The normalized KPIs of the selected scenarios were calculated by dividing the KPI values of each scenario by the maximum KPI value within each category. They are represented in Figure 6. It illustrates the benefits of the A/R scenarios and the worse performance of the wood products, showcasing that none of the studied scenarios performs better than the others in all the impact categories.

A) KPIs to maximize



B) KPIs to minimize

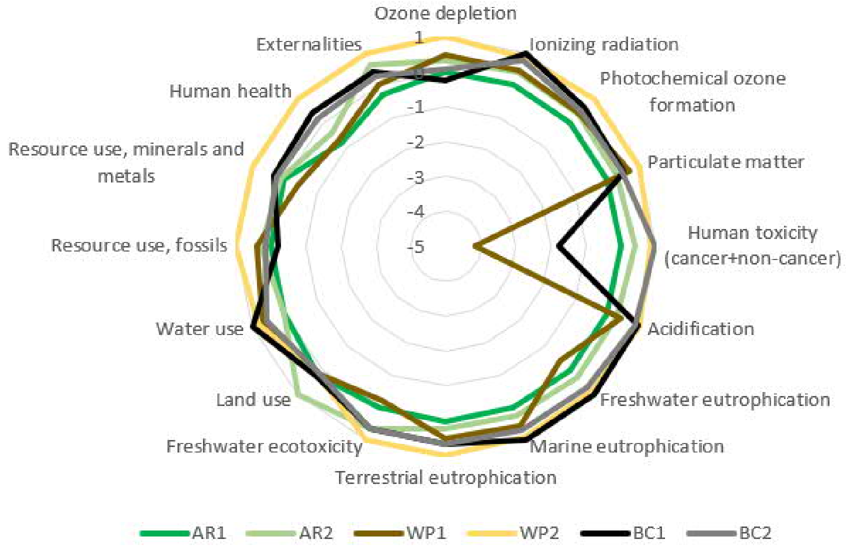


Figure 6. Normalized KPIs. A) KPIs that the NETPs aim at maximizing. B) Other KPIs that should be minimized. Selected scenarios: AR1 (reforestation of tropical rainforest), AR2 (afforestation of boreal tundra woodland), WP1 (production of glulam/MDF), WP2 (production of MDF), BC1 (biochar replaces sand, w/o CCS), BC2 (soil application of biochar, 500-year LT, with CCS).

4. Conclusions and further steps

Here we analyzed the environmental and socioeconomic implications of alternative terrestrial NETPs (A/R, wood products and biochar). We identified A/R as the most promising terrestrial NETP in terms of CDR efficiency and the assessed environmental and socioeconomic KPIs. Other NETPs attain lower scores in certain KPIs (climate change, ozone depletion, non-carcinogenic toxicity, freshwater eutrophication, and fossil, mineral and metal resource use), yet they generate more impact throughout their life cycle; i.e., their better performance is due to the avoided credits.

The main environmental impact of the A/R practices is linked to their extensive land use, which depends on the location's capacity to sequester carbon in the biomass and soil and varies greatly across ecological zones. Land use can lead to detrimental consequences on the local biodiversity if other ecosystems prevail in the area. By contrast, A/R can prevent health impacts and externalities, which constitutes a significant advantage over the other terrestrial NETPs.

In general, the wood products performed poorly across the studied impact categories, chiefly because of the production of MDF. Finding other applications for the non-marketable wood, such as the generation of bioenergy, could help improve the environmental profile of these NETPs. However, given the uncertainty associated with the lifetime of these products (and therefore with the permanence of the carbon stored in the wood), future research efforts in the context of the NEGEM project should focus on other NETPs.

The use of biochar as a soil amendment product also entails the risk of releasing part of the sequestered carbon as it reacts with atmospheric oxygen. We found that using biochar to replace fine aggregates in building materials could circumvent this problem and reduce the collateral impacts generated in the biomass cultivation phase (because less biomass is required to sequester the same amount of CO_2), although we did not consider the implications of the end-of-life treatment for the stored carbon. Analyzing the market's capacity to absorb biochar could ascertain the feasibility of deploying this NETP at a large scale. Nevertheless, the main factor that hinders the implementation of this NETP is the high cost of the pyrolysis process[63] compared to A/R and building with wood.

One key aspect that will determine the performance of the terrestrial NETPs is that the avoided climate change impacts could be offset by surface albedo changes, which are highly location-dependent.[64] Future works should incorporate the albedo effects into the life cycle assessment.

Terrestrial NETPs are constrained by the local environmental conditions and available land – agricultural activities and biodiversity conservation should be prioritized over terrestrial CDR –, and they are vulnerable to unexpected events such as droughts and fires. Therefore, they should not be considered in isolation, but as part of the portfolio of NETPs. Contrasting the findings presented here with the results of the sustainability assessments performed for other NETPs in NEGEM Work Package 1 could help design optimal CDR strategies.

To prepare this report, the following deliverable has been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.1	Justification of NETPs chosen for the NEGEM project	ETH	R	CO	6

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Appendix: Data sources

Table A1. List of data sources used in the SCS framework

Data	Type	Spatial resolution	Reference	Version/ year	Link
Georeferenced					
World administrative areas (country and sub-national boundaries)	Vector	N/A	Global administrative areas (GADM) maps and data[65]	GADM v3.6, 2018	https://gadm.org/download_world.html
World Regions layer package	Vector	N/A	Esri ArcGIS Data & Maps (2020)	2013	https://www.arcgis.com/home/item.html?id=a79a3e4dc55343b08543b1b6133bfb90
Latitudes and longitude grids	Vector	N/A	Esri ArcGIS Data & Maps (2020)	2014	https://www.arcgis.com/home/item.html?id=ece08608f53949a4a4ee827fd5c30da1
Global Soil Organic Carbon Map	Raster	1 km	FAO GSOC[37]	GSOC v1.5	http://54.229.242.119/GSOCmap/
Global Land Cover Map	Raster	300 m	European Space Agency Climate Change Initiative (ESA-CCI) products, based on FAO's Land Cover Classification System v.3 (LCCS3) [36]	2010 and 2018	https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=form
Global protected areas	Vector	N/A	UN Environment Programme World Conservation Monitoring Centre[38]	WDPA v1.6	https://www.protectedplanet.net/en
Soil and terrain properties	Raster	1 km	Harmonized World Soil Database[39]	HWSD v1.21	http://www.fao.org/geonetwork/srv/en/main.home
Near present (historic) climate	Raster	1 km	Climatologies at High resolution for the Earth's Land Surface Areas[49,50]	CHELSA v1.2, 1979 to 2013)	https://chelsa-climate.org/downloads/
Global climate zones	Vector	N/A	FAO's Global Ecological Zones (GEZ)[40]	GEZ 2010 product, second edition	http://www.fao.org/geonetwork/srv/en/metadata.show?currTab=simple&id=47105
Global soil erosion	Raster	25 km	Global soil loss map[66]	GloSEM v1.1	https://esdac.jrc.ec.europa.eu/content/global-soil-erosion
Actual evapotranspiration	Raster	1 km	CGIAR's High-Resolution Global Soil-Water Balance[51]	2019	https://cgiarcsi.community/data/global-high-resolution-soil-water-balance/
Non-georeferenced					
Key climate and soil requirements of crops	N/A	N/A	FAO Crop Ecological Requirements (ECOCROP) database[42]	2018	https://github.com/supersistence/EcoCrop-ScrapeR
Yield	N/A	N/A	Crops: FAOSTAT,[67] lignocellulosic plants,[68] grasses (literature)	2010-2018	http://www.fao.org/faostat/en/#data/QC