NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Extended MONET-EU

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Executive Summary and policy relevant messages

A recent IPPC report indicates that immediate and rapid reductions in greenhouse gas (GHG) emissions is required to limit global warming to 1.5°C and calls for global efforts across all sectors. The report also assigns a crucial role for Negative emission technologies and practices (NETPs), which have potential to offset emissions from the heat, power and industrial sectors by removing CO_2 from the atmosphere. However, Integrated Assessment Models (IAMs) extensively feature, bioenergy and carbon capture and storage (BECCS), Direct Air CO_2 Capture and Storage (DACCS) and afforestation as potential carbon dioxide removal (CDR) options. The reliance on a single or restricted portfolio of NETPs to reach these global mitigation targets not only triggers potential irreversible ecosystems impacts but also hinders the simultaneous implementation of other carbon mitigation strategies.

MONET-EU is a spatio-temporal explicit model aiming at providing a whole-system analysis of a least cost portfolio of CDR pathways, in a ten-yearly time-steps, subject to a range of sustainability and bio-geophysical constraints. Specifically, CDR targets are specified at country or at regional level (EU), and sustainability limits — land and biomass supply availability[1], maximum water stress— are imposed in the model. In addition, maximum deployment constraints are specified for each CDR option. In its initial formulation, MONET-EU included exclusively BECCS within its technological database. Hence, this work aims to extend the model database to include other NETPs, specifically afforestation/reforestation (AR), solid and liquid sorbent DACCS systems and biochar production via slow pyrolysis.

In addition, as part of the activities carried out in WP7, the default MONET-EU input data for biomass yields based on statistical databases as described in D7.1, have been replaced by climate- and scenario-specific yields simulated by the process-based biosphere model LPJmL (Lund-Potsdam-Jena managed land). This allowed to explore further the impacts of climate change on the yields of the feedstock for biomass based NETPs, i.e., BECCS and AR, which were previously not considered in MONET. Finally, to investigate the contribution of these NETPs in reaching regional and country level CDR targets with the European Union, we applied the MONET-EU framework to a range of policy scenarios, characterized by a varying degree of collaborations between EU states. Specifically, we assumed that EU countries would either meet their national CDR target in isolation, or that each country would contribute to meet the regional CDR target based on its geophysical, economic, and technical capabilities.

The results show that the cost-optimal way to meet the Paris Agreement, strongly relies on international cooperation, especially when the availability of biomass resources is restricted, i.e., the imports of biomass outside the EU is not permitted. When nations act in isolation, not only the deployment of these technologies at scale is more costly, but some of the EU countries are not able to meet their own targets, due to lack of access to CO_2 storage or limited biomass and land availability. Finally, the study also reveals an overall preference for BECCS, which starts to be deployed at scale and in different countries already in 2020 owning to its lower removal costs compared to other technologies, followed by afforestation, while the role of DACCS is more prominent during the second half of the century. Similarly, due to its lower removal efficiency compared to the other NETPs, biochar deployment is very limited across the timescale, contributing with less than 1% to the total CO_2 removed by 2100.

[1] Note that the model doesn't assume variations in feedstock yields or land use changes in the future.

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1. Introduction

According to the International Panel for Climate Change (IPCC), limiting global warming to 1.5°C will require large-scale deployment of NETPs to remove CO_2 from the atmosphere, which enables the offset of residual emissions in hard-to-abate sectors, and also the recovery of emission overshoot. NETs cover a wide range of technologies with diverse development levels, economics, and scale; with mitigation potentials varying across time and geographical scale.

Global mitigation pathways descending from IAMs, currently rely on few (BECCS and more recently afforestation and DACCS) CDR technologies to achieve the mitigation targets. Literature evidence (Smith *et al.*, 2015; Heck *et al.*, 2018) has warned that to avoid irreversible negative impacts on natural ecosystems, the inclusion and evaluation of a larger range of NETs is crucial. Hence, the aim of this work is to extend the MONET-EU framework as it was first conceived by Fajardy and al. (Fajardy and Mac Dowell, 2017; Fajardy, Chiquier and Mac Dowell, 2018) to include other NETPs such as afforestation/reforestation, Direct Air CO_2 Capture and Storage (DACCS) and biochar.

To this end, this deliverable builds on the Member-State specific NETPs database (D4.1) developed in Task 4.1. as well as in Task 1.1, where techno-economic data on an extensive portfolio of NETPs have been collected and analyzed (D1.1). Specifically, both commercially available DACCS archetypes involving CO_2 separation using liquid solvents and solid sorbents, are being considered. This deliverable also draws on the biogeophysical database constructed in Task 4.2., containing data on land availability, biomass feedstock potential as well as main sustainability constraints with each EU member state. The afforestation model accounts for different forest growth based on ecological zones and tree species (i.e., broadleaves and conifers) and for a set of forestry operations including forest establishment (i.e., land establishment, herbicide application, seedling plantation and fertilizer application), forest management (i.e., thinning operations), and forest road construction and maintenance. Finally, biochar pathways entail the adoption of the biomass feedstocks already parameterized in the model database, which allow to identify potential land and biomass competing issues among different NETPs pathways.

Section 2 of this report presents the main modelling assumptions adopted to parameterize each of these technologies within MONET-EU. We will first provide a qualitative discussion on the main features of each option, followed by a techno-economic analysis of the selected NETPs archetypes. For consistency, each option will be evaluated in terms of whole system costs and CO_2 removal efficiency, accounting, respectively, for the costs and potential carbon leakages associated with each step of the NETPs supply chains. To validate the new model configuration, section 3 will discuss the application of MONET-EU within 3 policy scenarios. Each of these scenarios identify the optimal portfolio of CDR technologies required to meet removal targets consistent with the Paris Agreement in the EU. However, a key distinction in these scenarios is the way in which the EU member meet these targets, i.e. either through collaboration or in isolation.

2. Extension of MONET-EU: modules description

The following section presents a techno-economic analysis of the NETPs included in the extended version of MONET-EU, in addition to the BECCS to power pathway. Specifically, in previous modelling versions, the conversion technology considered as the archetypal BECCS technology is a 500 MW dedicated pulverised biomass thermal power plant, combined with post-combustion amine-based CO_2 capture. Other BECCS pathways, such as the adoption of CCS in biorefineries have not yet been included in the model. Note that this represents a limitation of the present study, since previous work conducted within this project, specifically in Task 1.4, have concluded that the deployment of BECCS within existing industries could lead to lower cumulative costs than BECCS to power pathways. Key features of the MONET framework as well main modelling assumptions associated with BECCS pathway can be found in D7.1.

2.1 Afforestation/Reforestation (AR)

AR is one of the first CDR options proposed and discussed by the international climate community. It is also one of the best-established CDR option so far. AR is defined by the IPCC as the "direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources". Specifically, afforestation refers to the conversion of land that has not been afforested in recent history, commonly for a period of at least 50 years, whereas reforestation refers to the conversion of land that was previously deforested.

This NETP involves planting trees or facilitating the natural regeneration of trees on land that has not been forest for some length of time. Growing forests capture CO_2 from the atmosphere *via* photosynthesis Sequestrated CO_2 is then accumulated in the form of carbon in above-ground biomass and transferred in part to below-ground biomass, deadwood, litter and forest soils. The following section present the main assumptions that have been adopted for parameterizing AR in MONET-EU.

The estimation of forests carbon (C) (and CO_2) stock is a key element for the quantification of AR CO_2 sequestration potential: forests C stock is usually broken down into three main components: tree/biomass (*i.e.,* above-ground and below-ground biomass), dead organic matter (*i.e.,* litter and dead wood) and soil C stocks.

Figure 1 shows the system framework adopted in MONET-EU to characterize AR. Specifically, the models is composed of 5 integrated sub-models: 1) a forest growth model, 2) a forest management cycle model, 3) a biogenic carbon sequestration model and 4) its associated "fire-penalty" model, and 5) a forestry operations model. Specifically, CO_2 (and N_2O) and cost balances are carried out for each step of the forestry operations model. Spatial resolution of AR's whole-system model is at the climato-ecological level − ecological zones[2] − within each country in the EU (EU-27 & UK) (de Rigo *et al.*, 2016). Further details on each of these modules and their interactions can be found in the appendix.

[2] An ecological zone is defined as “a zone or area with broad yet relatively homogeneous natural vegetation formations, similar (not necessarily identical) in physiognomy”(FAO, 2001)

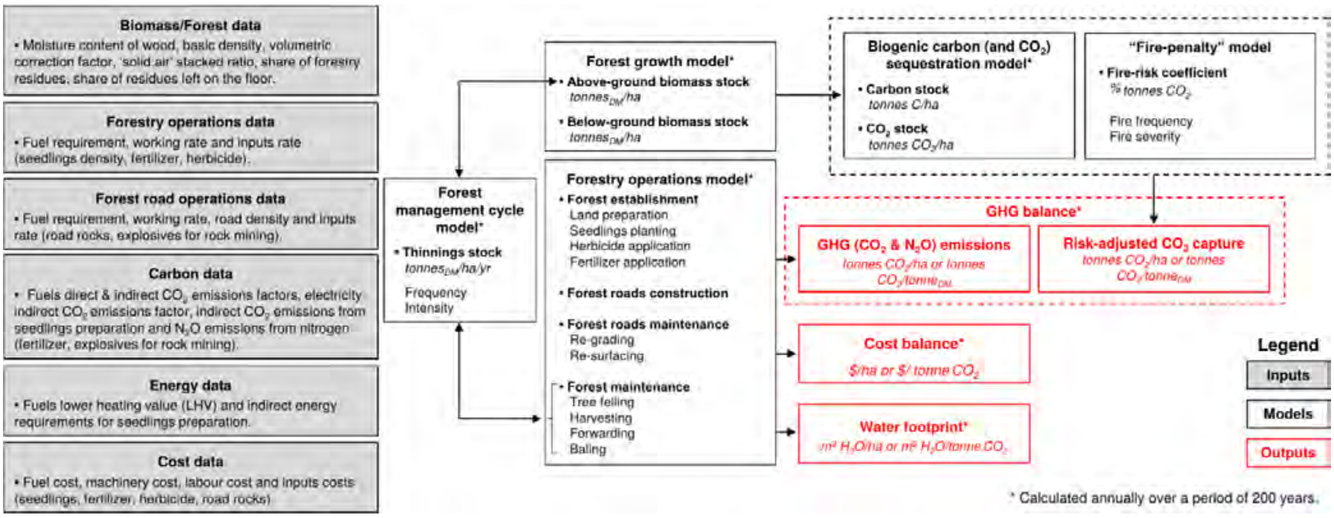

Fig 1. Schematic representation of the AR's whole-system model, outlining the interactions between 5 integrated sub-models: 1) a forest growth model, 2) a forest management cycle model, 3) a biogenic carbon (C) (and CO_2 sequestration model), and 4) its associated "fire-penalty" model, and 5) a forestry operations model

CO_2 removal efficiency

Overall, AR total GHG balance, i.e., its CO_2 removal potential, is the difference between the risk-adjusted CO_2 sequestration from forest growth (see appendix for detailed discussion on CO2 sequestration potential of forests), and the total GHG emissions generated within the different stages of AR projects: site establishment, forest roads construction and annual maintenance, and annual forestry (thinning) operations. Specifically, MONET-EU accounts for direct GHG emissions from the combustion of fuels and direct N_2O emissions arising from the application of nitrogen-based fertilizer during the forest establishment.

Importantly, MONET-EU assumes that the energy systems are being progressively decarbonized from 2020 in line with the IPCC P2 mitigation scenario, as such, it is assumed that carbon neutral electricity is available in the EU by 2050 while fossil fuels are completely replaced by biofuels by 2080[3]. Figure 2 depicts the resulting GHG emission balance of AR projects in the UK following these assumptions. It can be notice that, while thinning practices account for more 35% of total GHG emissions in 2020, i.e. 1.5 t_{CO2}/ha, the contribution of forestry operations are drastically reduced by 2080, due to the overall decarbonization of the energy systems.

[3] Data have been extracted from the publicly available IIASA database: https://tntcat.iiasa.ac.at/

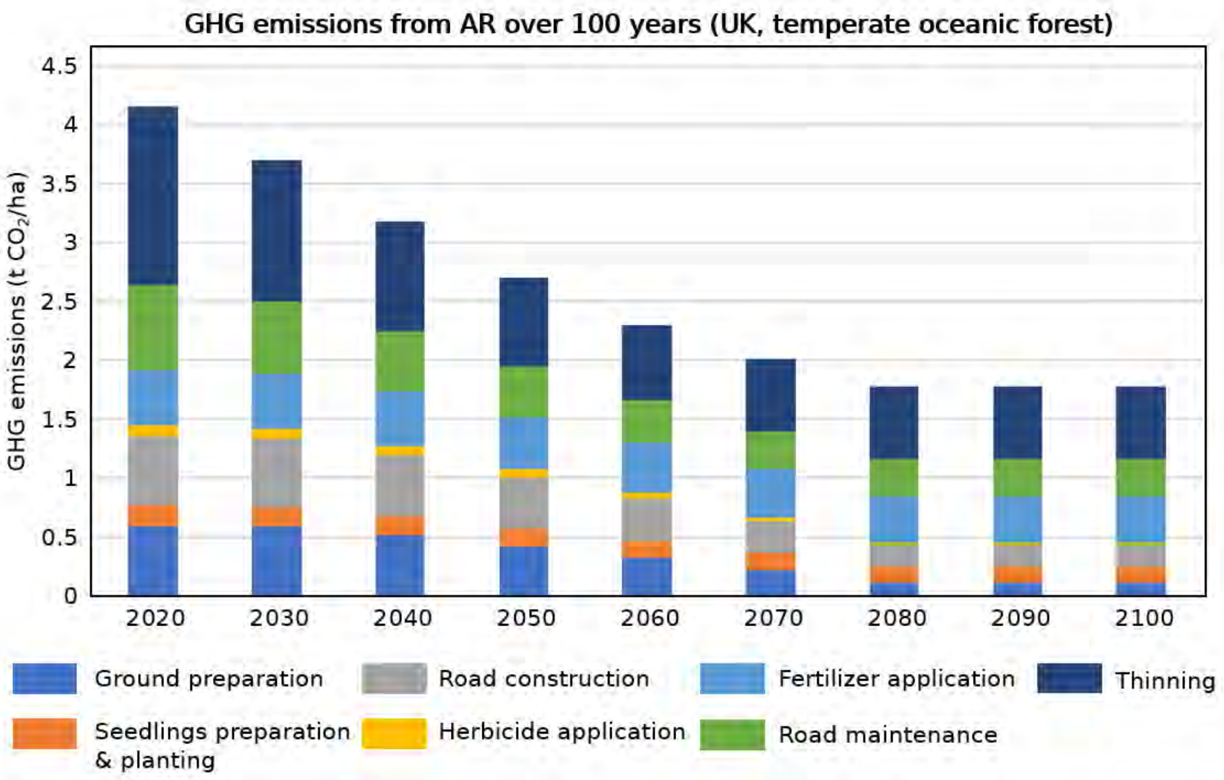

Figure 2. Breakdown of the GHG emissions of AR over 100 years following energy systems decarbonization projected by the IPCC P2 scenario, assuming net-zero electricity by 2050 and fossil fuels phase-out by 2080.

Techno-economic assessment

Similar to the carbon balance, the overall removal cost of AR accounts for the following cost parameters:

- the cost of energy, such as fuels and electricity which is country specific
- the cost of machinery, such as trucks or excavator for land preparation, harvester and forwarder for harvesting operations, or other machinery for road construction and maintenance
- the cost of labour, such as ground worker, forest worker, road operator, etc
- and the cost of feedstocks, materials, such as agrochemicals, seedlings or road rocks.

AR's initial investment, due to the establishment of the forest and the construction of forest roads, is levelized with the use of a capital recovery factor (CRF), itself calculated with an interest rate of 8% and a financial lifetime of 30 years. Other annual costs (*i.e.,* forest and forest roads maintenance) are summed up each year. Fig 3 depict the cost breakdown of AR projects in the UK, which is assumed to be characterized mostly by a temperate oceanic climate (TO) (88%). For illustrative purposes the ecological zone of temperate mountain (TM) system is also shown.

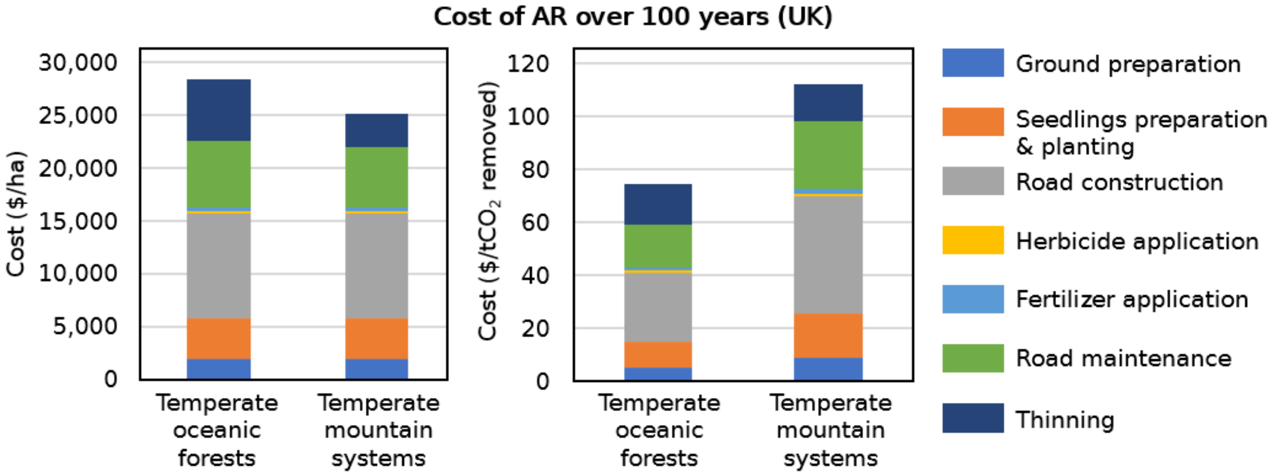

Figure 3. Breakdown of the removal cost for AR projects based on the existing ecological zones in the UK. Cost values are presented in 2018 US dollars

2.2 Direct Air CO_2 Capture and Storage (DACCS)

With DACCS, CO_2 is directly captured from the atmosphere using a range of sorbents or solvents, and then transported and injected into geological formations. Figure 4 depicts the supply chain configuration of DACCS included in the MONET-EU as well as main carbon and water and primary energy (wind and solar) flows.

Two archetypal DACCS plants are currently being developed at the demonstration-scale and have been implemented in the model. The first one, developed by Carbon Engineering Ltd (DACCS-CE), captures CO_2 directly from the air with a potassium hydroxide (KOH) sorbent in the air contactor and stores it as a carbonate (K_2CO_3) (Ishimoto *et al.*, 2017; Keith *et al.*, 2018). The sorbent is then regenerated by reacting K_2CO_3 with a calcium hydroxide ($Ca(OH)_2$) in the pellet reactor. $Ca(OH)_2$ is obtained in the slacker by hydrating calcium oxide (CaO), which itself is produced by calcining calcium carbonate ($CaCO_3$) in a kiln, at 900°C. The high-temperature heat required by the regeneration process is currently supplied by natural gas, while the emissions arising from fuel combustion are being captured by the absorber. The second one, developed by Climeworks (DACCS-CW), captures CO_2 with an amine functionalised sorbent on a filter. Once the filter is saturated, it is heated to 100°C, and the CO_2 is released and collected. The low-temperature heat of the regeneration process can be provided by the electricity grid.

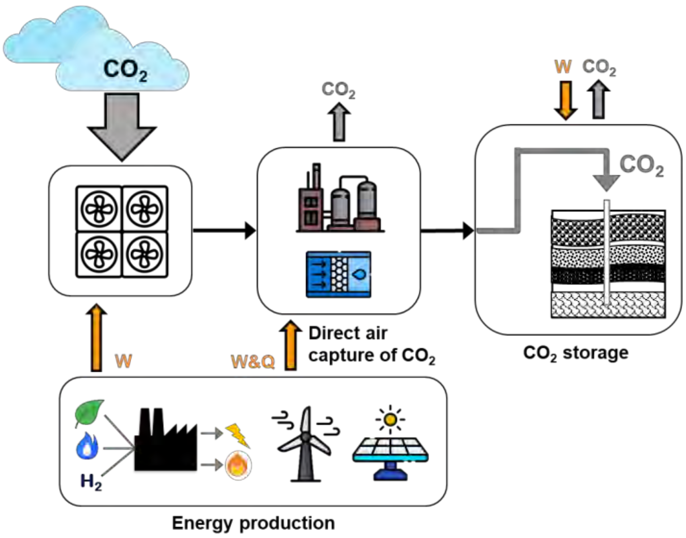

Figure 4. Schematic representation of DACCS supply chain included in MONET

For both DACCS plant archetypes power from the electricity grid is required for the continuous operation of the plant, including fans, liquid pumping and CO_2 compression. Similarly to BECCS plants, we assume that DACCS plants are built and operating in the vicinity of geological formations that are suitable for CO_2 storage, at a distance of 100 km.

DACCS's total energy requirements include direct energy requirements from the combustion of natural gas (DACCS-CE) or from the consumption of electricity (DACCS-CE and DACCS-CW). In addition, the model also accounts for the indirect energy requirements (embodied energy) from the production of natural gas (DACCS-CE), the production of electricity, and the transport and storage of CO_2.

CO_2 removal efficiency

DACCS's CDR potential is equal to the difference between DACCS's CO_2 captured at the DACCS plant (both from the atmosphere and from the combustion of natural gas in the case of DACCS-CE archetype) and DACCS's direct and indirect emissions from the combustion of natural gas and from the use of electricity for the continuous operation of the plants.
Figure 5 shows the impact of the energy sector (specifically the power sector) decarbonisation on the DACCS's CDR efficiency for both DACCS archetypes (DACCS-CE and DACCS-CW). Considering the current — 2020 — carbon intensity of national (and sub-national) electricity grids, DACCS-CE archetype's efficiency ranges between 44–88%, whereas the one of DACCS-CW archetype ranges between 79–92%, as figure 5 shows. However, when assuming a complete decarbonization of the power grid in the EU by 2050, these values drastically improve (see lower panel of Figure 5), particularly in the case of DACCS-CE systems.

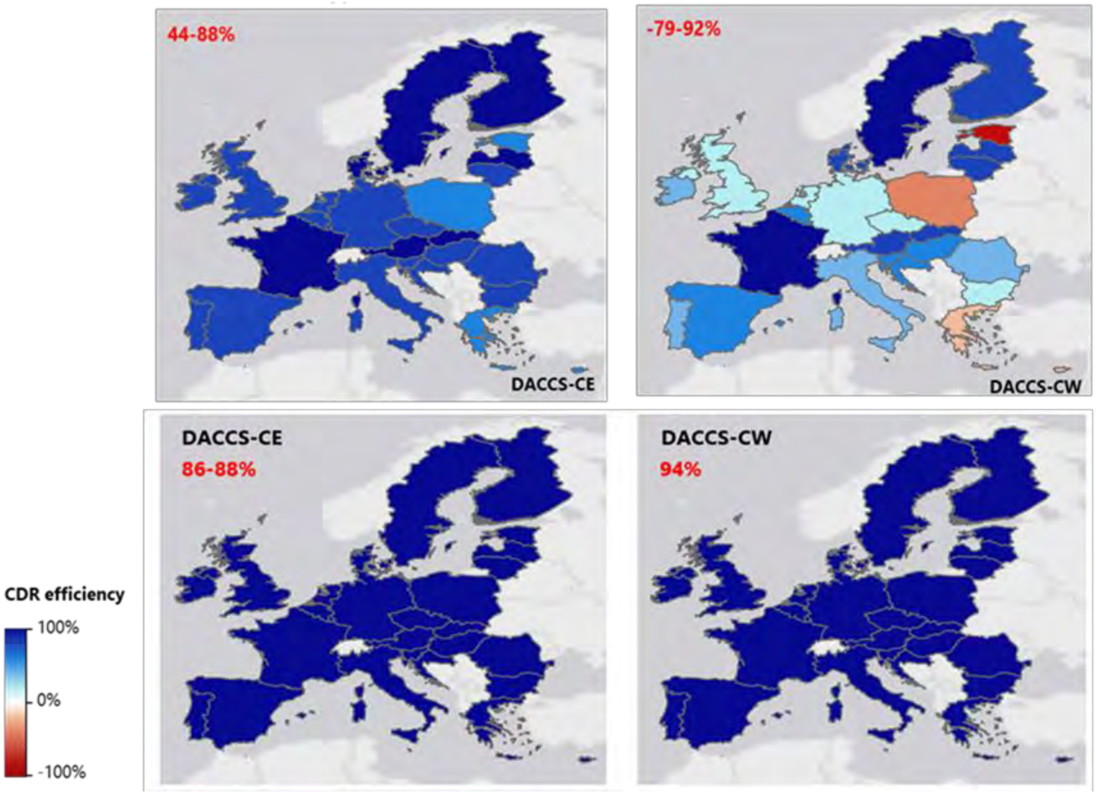

Figure 5. Removal efficiencies of DACCS-CE and DACCS-CW. Based on current (top panel) and future (lower panel) carbon intensity of the electricity grid in the EU

Techno-economic assessment

Because of the low atmospheric concentration of CO_2 (approximately 412 ppm), DACCS is very energy intensive: DACCS's total energy requirements, including the separation of CO_2 from the air and the compression of CO_2, have been reported 4 times greater than conventional CCS's total energy requirements (Herzog, 2021). Given these actors, and the low maturity of the technology, DACCS's cost is still uncertain and expensive, ranging between \$30-1,000/t_{CO2}. The following cost components have been included in the cost model for both DACCS archetypes:

- the energy cost such as electricity and natural gas
- the CAPEX and OPEX (including labour, operating and maintenance costs) of the plant
- Transport and storage costs, assuming an average Co2 transport distance of 100 Km

DACCS's CAPEX has been levelized assuming an interest rate of 8% and a financial lifetime of 30 years. For the DACCS-CE archetype, CO_2 capture cost comprises energy (natural gas and electricity), CAPEX and OPEX. When parametrizing this NETP pathway, we conservatively assume that DACCS-CE capture cost, including the energy cost, is twice more than what has been suggested in the literature, i.e., around \$ 300/tCO_2 while maintaining constant the ratio of CAPEX/OPEX. This, results into a non-levelized CAPEX of \$4,030/tCO_2 captured, and an annual OPEX of \$116/tCO_2/yr. By contrast, DACCS-CW is based on modular process and the plant itself is operated in a two time-steps. As a result, DACCS-

CW are characterized by lower capital costs but higher operation and maintenance costs. Therefore, after excluding the energy (electricity only) cost, the levelized CAPEX and the OPEX account both for 50% of the remaining cost of CO_2 capture. This results into a non-levelized CAPEX of $4,066 captured, and an OPEX of $361/t$CO_2$/yr captured. Figure 6 shows the cost breakdown of both plants' archetypes.

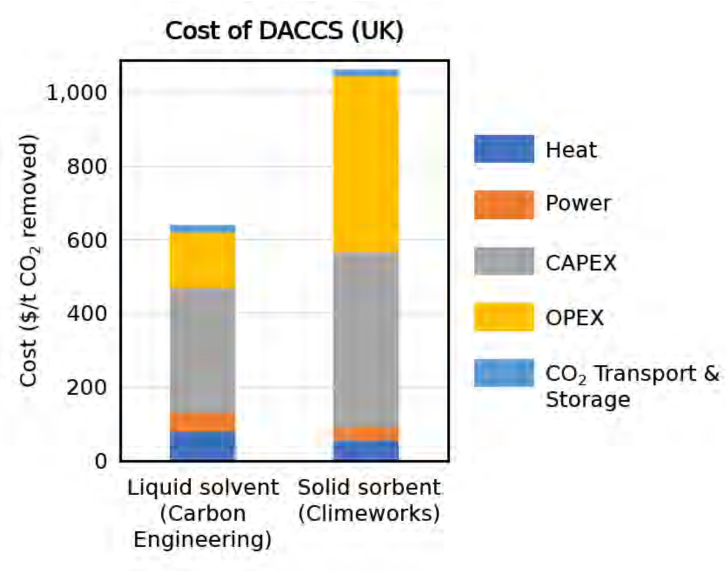

Figure 6. Cost breakdown of DACCS-CE and DACCS-CW archetypes included in MONET-EU. In the example we use energy cost for the UK

2.3 Slow pyrolysis for biochar production

Biochar is a carbon rich material produced through the pyrolysis of biomass. Biogenic waste materials suitable for biochar production include crop residues, food and forestry wastes, and animal manures. Biochar's climate-mitigation potential relates to its ability to permanently store organic carbon, owning to its highly recalcitrant nature (Woolf *et al.*, 2010), which slows the rate at which photosynthetically fixed carbon (C) is returned to the atmosphere. The C fraction of biochar can fluctuate between 25% to 70% mainly depending on the ash content (and, to a lesser extent, H and O content) of the feedstock, with wood waste and animal manure on the upper and lower bound of this range, respectively. Biochar produced from residues of crops and grasses is generally more degradable than that from wood, which is attributed to inert properties of various feedstocks, such as the high lignin content.

Biochar also yields several potential co-benefits including the production of syngas and bio-oil (Patrizio *et al.*, 2021). The latter can be used for on-site heat applications or as a fossil fuel substitute, after post-treatment. Similarly, syngas can be used to produce electricity and/or heat for on-site purposes, e.g., biomass drying.
Various pyrolysis technologies yield different proportions of biochar and syngas. In general, pyrolysis maximizes biochar production at temperatures between 300-700 °C (slow pyrolysis) and maximizes condensable vapors production, *i.e.,* bio-oil, at higher process temperature (fast pyrolysis).

The boundaries of the biochar production system adopted in MONET-EU are illustrated in **Error! Reference source not found.** and include the biomass cultivation, harvest and transport activities, the biochar production process *via* slow-pyrolysis and its transport and application into the soil.

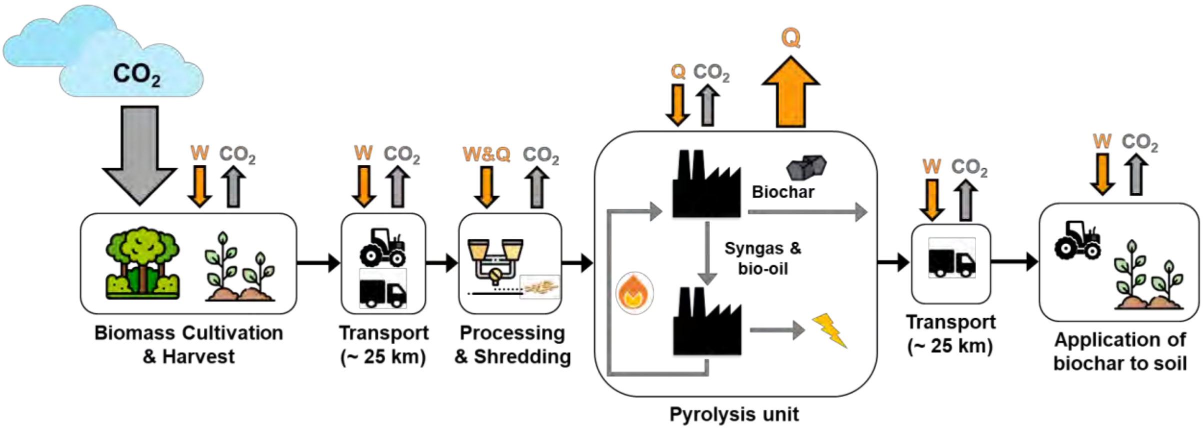

Figure 7. Schematic representation of biochar supply chain included in MONET-EU

As mentioned before, pyrolysis plants can yield different proportions of biochar, syngas and bio-oil, which could then be sold for profit, thus generating revenues to the plant operators. In order to account for the different services that slow-pyrolysis pathways can provide, the following plant archetypes have been parametrized in the model:

- Farm scale plant, using 2000 t_{DM}/yr, dedicated to the production of biochar only
- Medium scale facility, using 16000 t_{DM}/yr, where the bio-oil resulting from the pyrolysis of the biomass is sold for other applications, e.g., low grade heat or fossil fuel replacement. Hence, here bio-oil represents a low-carbon alternative to natural gas.
- Large scale plant, using 185,000 t_{DM}/yr, where the syngas being produced in the pyrolysis process is converted to electricity (in this case we assumed a conversion efficiency of 38%) and subsequently sold to the grid at current electricity market price.

CO_2 removal efficiency

The overall carbon efficiency of biochar is lower than for other technologies such as BECCS and DACCS, since on average, only half of the biogenic carbon contained in the biomass feedstock is sequestered in biochar after the pyrolysis process. Moreover, in addition to the carbon leakages occurring along the biomass supply chain, e.g., during biomass transport and preprocessing, the carbon content of biochar also degrades with time once applied to soil. However, issues of permanence of the carbon sinks, are not yet included in this version of the model.

Techno-economic assessment

The following cost parameters have been accounted for in the economics of biochar production:

- the cost of energy, such as fuels (e.g., diesel), electricity or natural gas incurred during biomass cultivation and preparation activities
- the cost of machinery, such as tractor for field preparation and for biomass cultivation and harvest, or for biochar application on soil, or trucks for biomass and biochar transport
- the cost of labour, such as farmer or pyrolysis plant operators
- other variable costs such as the cost of feedstocks, materials, such as agrochemicals, or rhizomes (Miscanthus) and cuts (Willow).

The pyrolysis CAPEX is levelized with the use of a capital recovery factor (CRF), itself calculated with an interest rate of 8% and a financial lifetime of 20 years.

Figure 8 presents a cost breakdown of biochar production in the UK based on the main plant archetypes presented in previous section. It can be observed that the cost of producing biochar is 60% lower in the case of large pyrolysis facilities, owning to the combined effects of the revenues associated with electricity production (which is being sold to the grid) and the economy of scale effect which favor large scale projects (Shackley *et al.*, 2011)

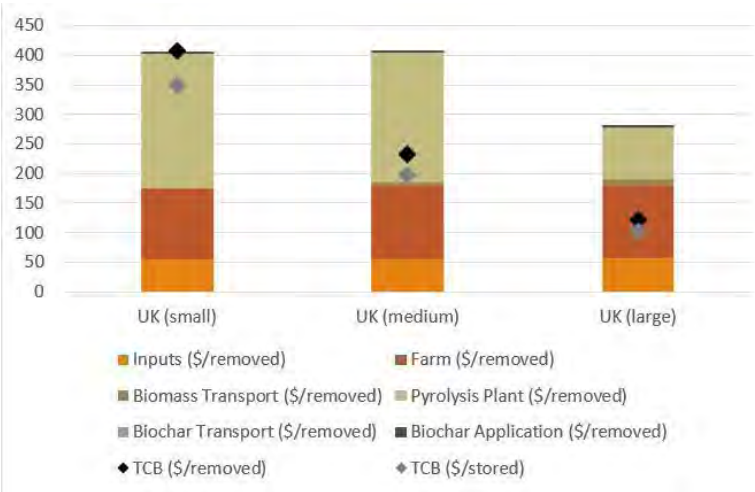

Figure 8. Cost breakdown of slow-pyrolysis plant archetypes included in MONET-EU. TCB: total cost of biochar production in terms of US 2018 dollar per ton of CO2 removed and stored.

3. Updated biomass yields

Following the enhancement of MONET-EU with other NETPs, for the purpose of this work, data on biomass yields already contained in the model database have been updated with simulated crop yields descending from the dynamic global vegetation model (DGVM) LPJmL (Lund-Potsdam-Jena managed land), in co-operation with WP3 (LPJmL model described in D3.1).

LPJmL is a process-based model that simulates climate and land use change impacts on the terrestrial biosphere, agricultural production, and the carbon and water cycle. LPJmL operates in daily time steps and at a spatial resolution of 0.5° x 0.5°, simulating key ecosystem processes in direct coupling with the carbon and hydrological cycles. Detailed descriptions and validations of the biogeochemical dynamics can be found in Schaphoff et al. (Schaphoff *et al.*, 2018)

In addition to the representation of vegetation by nine natural plant functional types (PFTs) and 13 crop functional types and managed grassland, LPJmL includes three types of fast-growing second-generation energy crops parametrized as Eucalyptus in tropical climates and poplar and willow in temperate climates for woody types and C4 grass for herbaceous energy crops (Beringer, Lucht and Schaphoff, 2011; Heck *et al.*, 2016).

3.1 Data transfer from LPJmL to MONET-EU

Potential yields of the following crop functional types have simulated using LPJmL5-NEGEM Ccycle without nitrogen dynamics:

a. **bioenergy C4 grass**: LPJmL's bioenergy C4 grass doesn't differentiate between switchgrass and Miscanthus as it is parametrized as a functional type representing various species. However, the simulated yields show the best match with observations of Miscanthus yields.
b. **short rotation coppice plantations**: in tropical regions, the simulated yields represent Eucalyptus; in all other regions, the simulated yields represent willow and poplar (no differentiation)

In addition, separated simulations for rainfed and irrigated plantation have been conducted. In the case of irrigated plantations, water supply is assumed to be unlimited and is supplied based on daily soil water deficit. The resulting net irrigation requirement correspond to the amount of water required in the upper 50 cm soil to avoid crop water limitation. The corresponding soil-plant interactions are simulated in daily timesteps for each plant functional type or crop functional type (i.e. bioenergy C4 grass) and cell-specific soil and climate conditions.

Additionally, drip-irrigation-specific application requirements are determined based on conveyance efficiencies and application requirements, which take into account the system-specific inefficiencies. The resulting gross irrigation requirement is requested for withdrawal, if supply falls below demand. Importantly, as this irrigation approach is demand-driven and not based on actual farming practice (that might be below, above or close to the actual demand) we approach yields under optimum management (especially with no N limitation).

The simulation covers the period between 1979-2018, assuming plantations starting in 1979 and base on monthly high-resolution gridded multivariate climate dataset CRU TS 4.03[4]. Outputs from LPJmL have been subsequently aggregated to NUTS1 level, consistent with the spatial resolution of MONET-

[4] Harris et al. (2020): https://doi.org/10.1038/s41597-020-0453-3)

EU, considering area-weighted quantiles of the simulated yields and corresponding water withdrawals based on marginal land availability in the EU, taken from the geophysical database presented in D4.2

As for irrigation water demand, the following two LPJmL derived outputs are provided, as shown in Figure 9, for bioenergy C4 grass and short rotation coppice plantations respectively:

- Irrigation water withdrawals = gross irrigation water requirements/demand
- Blue water consumption

Figure 10 represents an example of output descending from LPJmL. Specifically, Figure 10 a) depicts the marginal land availability in the EU which formed the basis of the analysis, while Figure 10 b) and 10 c) show the resulting simulated yields for irrigated and rainfed Miscanthus.

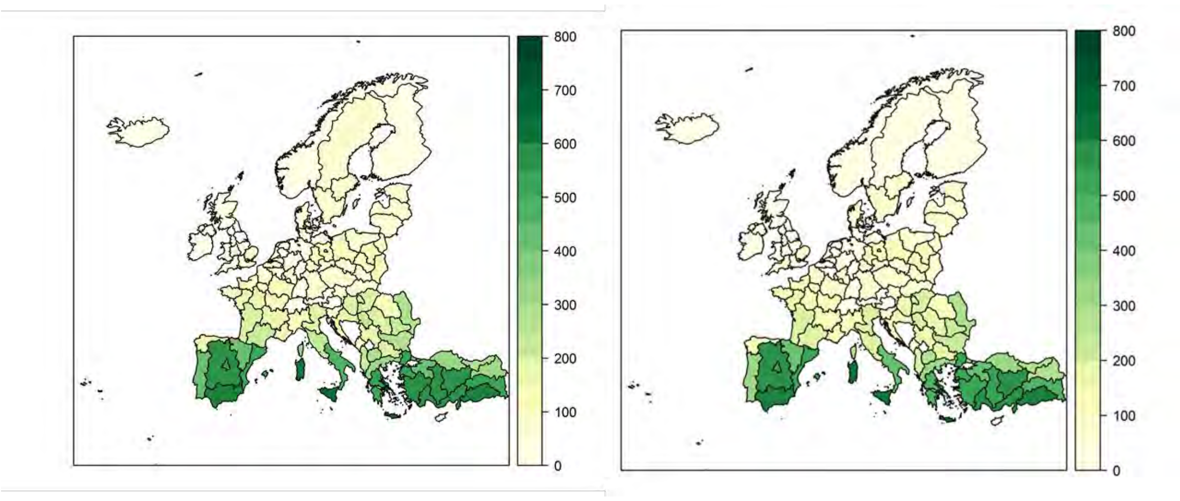

Figure 9. Gross irrigation water demand (left) and blue water consumption (right) for Miscanthus in the EU. Data are in mm/yr and represent simulated median values

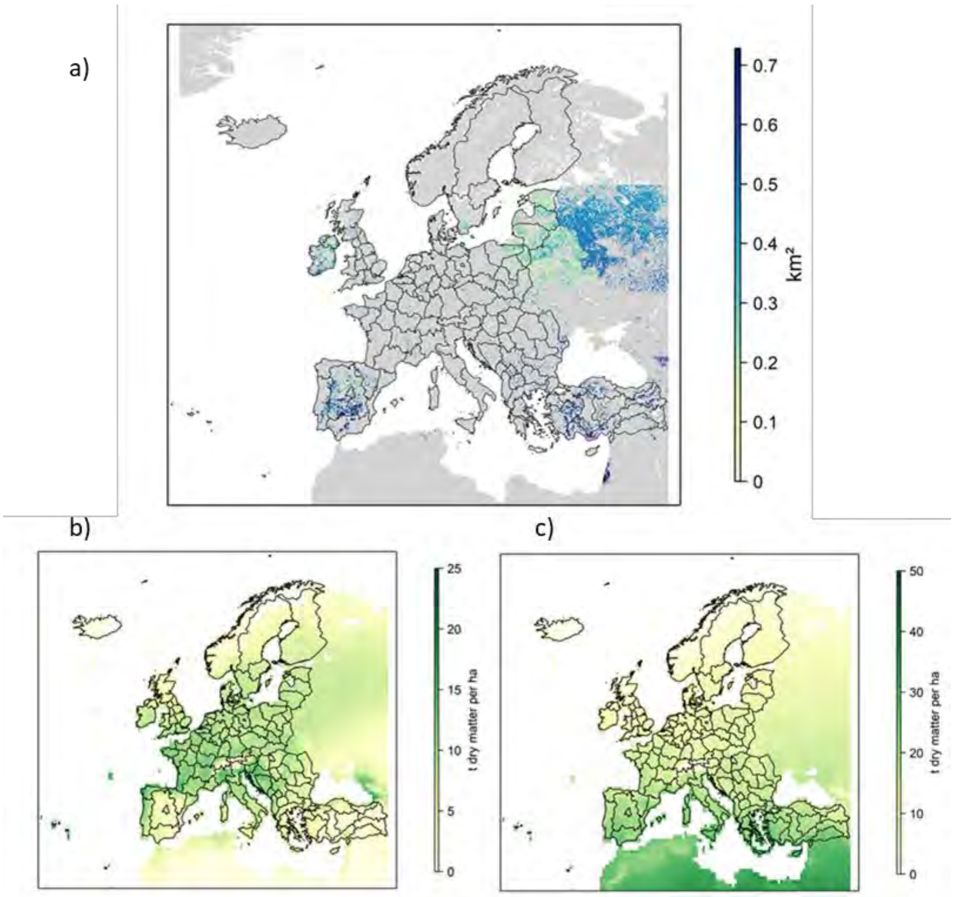

Figure 10. a) Marginal land availability in the EU and simulated yields for irrigated (b) and rainfed (c) Miscanthus

4. Results and discussion

4.1 Modelling constraints

MONET-EU is a linear optimisation problem (LP), that determines the optimal co-deployment of CDR pathways — AR, BECCS, DACCS, and biochar — consistent with the Paris Agreement's objectives of 1.5°C. In addition, the following modelling constraints apply:

CDR targets constraints

Cumulative CDR targets are specified throughout the whole planning horizon (2020-2100) according to the Paris Agreement's 1.5°C objectives. More specifically, the IPCC P3 scenario — a middle-of-the-road scenario, in which societal and technological development follows historical trends — is used in our reference scenarios. Owing to the complexity and sophistication of IAMs, spatial resolution is necessarily limited, with the world usually represented with a limited number of regions. Further, the different levels of CDR deployed in IAMs are the result of global and cost-optimal mitigation pathways, and thus do not reflect on the responsibility of any individual nation for climate change or its capability to address it. In this study, we apply a responsibility-based burden sharing principle, which have been reviewed and discussed in Task 4.3 (D4.3) to determine the proportion of the global CDR targets that should be allocated at the national scale (Raupach *et al.*, 2014). The global CDR target is therefore distributed in proportion to each nation's cumulative historic GHG emissions (see figure 11). For the EU, this corresponds to 20.5% of cumulative CDR target, equal to 83 Gt_{CO2} to be removed from the atmosphere by 2100.

Expansion of CDR solutions constraints

Operation conditions, specific to each CDR pathway, and including lifetime, expansion rate for AR, are specified in the model. BECCS and DACCS plants are assumed to have a lifetime of 30 years, and pyrolysis plants 20 years, and are operating at base-load capacity. Conversely, AR has an "unlimited" lifetime, as, once established, forests need to be maintained in perpetuity to avoid any reversal of CO_2 emissions back to the atmosphere.

A maximum build rate for new-built BECCS plants of 1 GW/yr at the national scale is assumed, based on the literature surveyed on energy system and climate modelling. Considering an average 500 MW BECCS plant, and a capture rate of 90%, this results in an average CO_2 capacity of 4.2 $MtCO_2$/yr/plant, and an average biomass feedstock capacity of 2.7 Mt_{DM}/yr/plant. This is equivalent to a maximum increase in the CO_2 capture rate for BECCS of 8.4 Mt_{CO2}/yr within each EU country, and a maximum biomass feedstock capacity of 5.4 Mt_{DM}/yr with each EU country.

To ensure fair comparison across CDR technologies, a maximum build rate for new-built DACCS plants of 8.4 $MtCO_2$/yr is also used. Thus, the combination of BECCS and DACCS can increase the CO_2 capture rate by 470.4 $MtCO_2$/yr at the EU scale. Similarly, a maximum build rate for new-built pyrolysis plants (for biochar production) of 5.4 Mt_{DM}/yr/plant is also used.

Finally, a maximum AR deployment rate of 47 Mha/yr was reported in the IPCC P2 scenario—qualified as a sustainable development scenario — between 2030–2040 (maximum deployment rate in all four

IPCC illustrative scenarios). Adjusted at the EU forest's scale, this is equivalent to 36.5 kha/ yr within each EU country.

Geological CO_2 storage constraints

BECCS and DACCS plants are deployed in the vicinity of geological CO_2 storage — a distance of 100 km — with sufficient CO_2 storage capacity for the lifetime of the technology. CO_2 is assumed to be safely and permanently stored. Maximum CO_2 storage capacity for BECCS and DACCS are specified, owing to region-specific limits.

4.2 Case study description

In this analysis, we investigated the optimal deployment of BECCS, DACCS, biochar and AR in the EU by 2100 within the following scenarios:

- Business as Usual (BAU): here it is assumed that all NETPs are being deployed, subject to the deployment constrained described above, to meet the EU CDR target. Specifically, each country is set to meet is own emission target by 2100, based on the responsibility burden sharing principle (Figure 11).

- Optimistic scenario: here, all technologies can be deployed, similar to the BAU scenario. In addition, instead of meeting national-level target in isolation, these countries can meet the cumulative CDR pledge together, based on their shared emission target (in this case equal to the removal of 83 Gt_{CO2} by 2100). To achieve this goal, they can also trade bio-geophysical resources. Specifically, biomass for BECCS and biochar production can be produced locally or imported from any other region in the EU.

- Pessimistic scenario: in this case, not only each country needs to meet its own removal target in isolation, but it is also assumed that only land based NETPs are available within the 2020-2100 period, i.e., DACCS technology never reaches commercialization. Hence, this scenario represents a pessimistic case in which NETPs are limited and there is no cooperation between countries to achieve a common goal.

With the aim of quantifying the effect of different agricultural practices on the overall deployment of these technologies, the analysis also considers the adoption of both woody and grass energy dedicated crops. These crops are assumed to be grow on marginal land, following the assumptions adopted by LpJml model (see section 3 of these report). Finally, this case study considers the use of EU biomass only, which can be either cultivated and used locally, or traded between EU countries, using the most carbon efficient mode of transport. Biomass imports from outside the EU are not allowed.

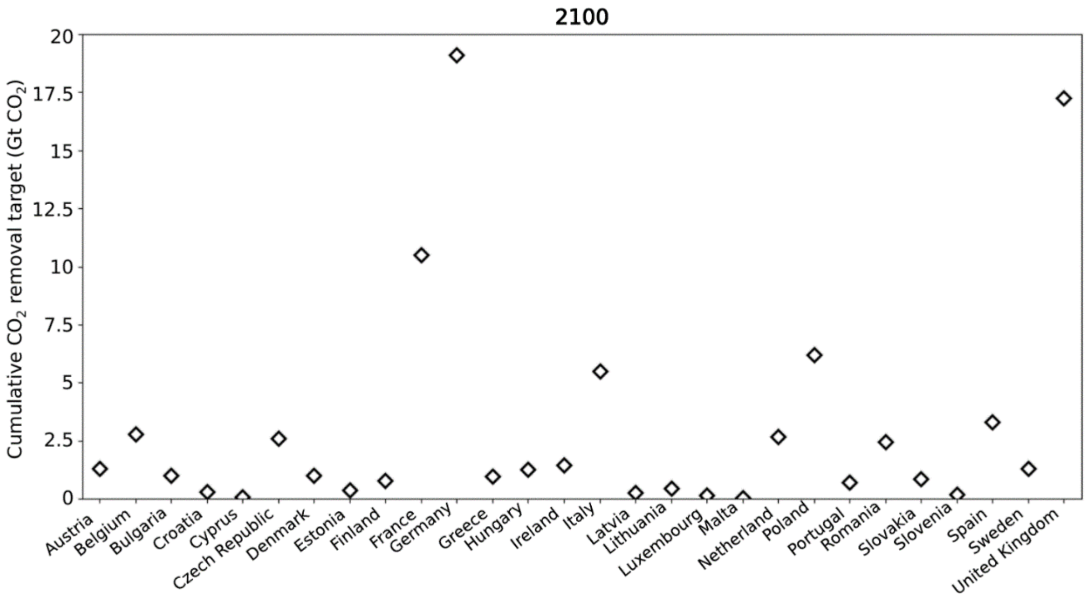

Figure 11. Cumulative CO_2 removal target for each country in the EU based on responsibility burden sharing principle.

4.3 Results

In this section we present a non-exhaustive selection of MONET-EU model outputs based on the scenarios and modeling constraints presented above.

Figure 10 presents the contribution of each NETP, *i.e.*, BECCS, biochar, DACCS and AR, in reaching EU level CDR targets within each scenario. It can be noticed that, at the beginning of the simulation period, BECCS represents the least cost CDR option: by 2040, around 12.5 Gt_{CO2} are being removed by BECCS in both optimistic and pessimistic scenarios, with smaller removal contributions, i.e., ~ 2 Gt_{CO2} from AR. However, in the BAU scenario, other technologies such as DACCS start to be deployed already in 2040. This is because, the deployment of land based NETPs is limited by geophysical constraints such as land availability and biomass yields. Hence, when regions are set to meet their own CDR target as in the case of the BAU scenario, investing in DACCS technologies become essential already by mid-century, to compensate for the constrained deployment of BECCS and AR.

It should also be noted that before 2080 and in all scenarios investigated, the amount of CO_2 being removed by NETPs is always higher than what is being imposed by the CDR targets, especially at the beginning of the simulation period. This indicates that, given the geophysical limitations associated with some technologies, such as afforestation, which takes around 20 years to become efficient in removing CO_2 and then it quickly saturates, a successful and least cost strategy for NETPs deployment relies in planning and anticipation.

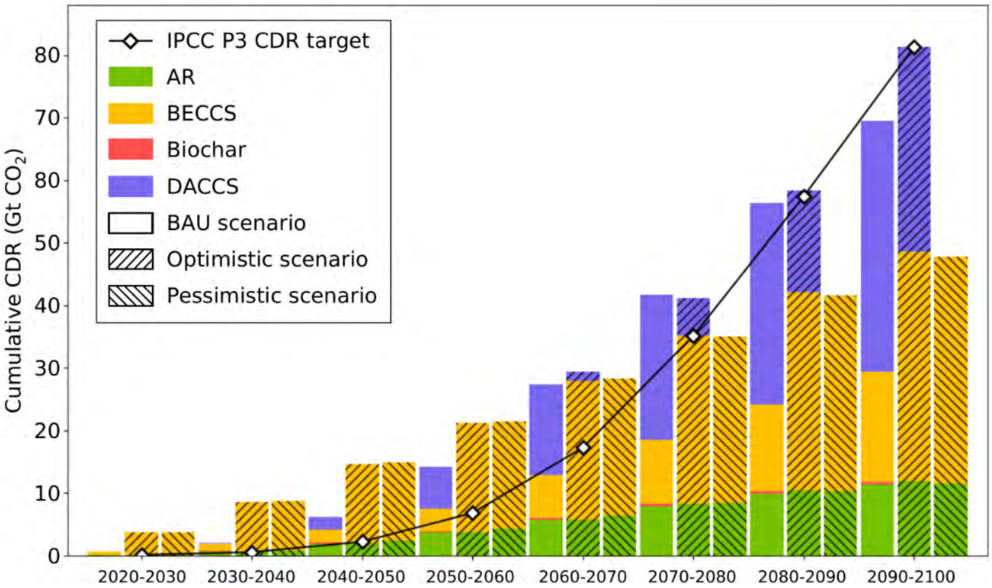

Figure 12. P3 Cost-optimal CO_2 removal, from 2020 to 2100, for each CDR option in the EU. BAU: country level CDR targets, Optimistic: EU level CDR target (cooperation) and Pessimistic: country level CDR targets without DACCS. Cost-optimal CDR pathways are primarily comprised of BECCS, and then AR.

Moreover, after 2080, reaching the targets becomes unfeasible both in the pessimistic and in the BAU scenarios, due to the presence of technical constraints. In fact, if DACCS fails to be deployed (pessimistic scenario), the targets imposed at the end of the century are missed by 3.3 Gt_{CO2} (representing 29% of the cumulative target in 2100), owning to the scarcity of biomass resources which cannot be compensated by imports from outside the EU. This, in turn, restricts the maximum deployment of BECCS and biochar. In addition, in both the pessimistic and the BAU cases, a market for negative emissions fails to materialize, and hence countries cannot collaborate to reach these targets by trading carbon removal credits.

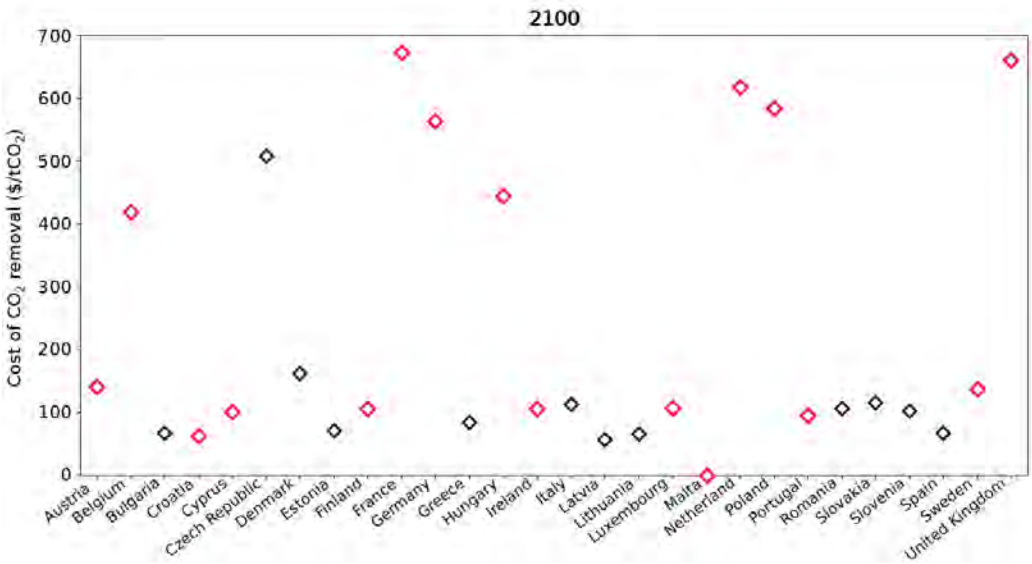

Figure 13. Cost of CO_2 removal by 2100, in each EU country. diamond shapes indicate whether a country fails (red) to meet or achieves (black) its own emission target.

In the BAU case, the average cost of CO_2 removal in the EU is 235 $\$/t_{CO2}$ by the end of the century. As shown in figure 13 high removal costs are observable in France, the UK, the Netherlands and Austria, which, owning to geophysical constraints, i.e., insufficient amount of land for AR projects ad of biomass resources for BECCS and biochar, have to rely on costly technological options, i.e., DACCS, to achieve high removal rates by the end of the Century. The limited availability of domestic CO_2 storage in most of the EU countries, restricts the deployment of technical CDR, i.e., DACCS and BECCS, even further. Hence, in the absence of a shared transnational CO_2 infrastructures, most of EU countries fail to meet their end of the century targets (Figure 13), even with a wide range of NETPs being available.

Combining these results with the statistic on biomass use by country depicted in Table 1, it is also possible to appreciate the trades in biomass between EU associated with the deployment of land based NETPs by 2100. It can be noticed that Spain and Poland are the countries where the majority of biomass is being cultivated, thanks to a combination of high biomass yields and extensive amounts of marginal land available for crop cultivation, i.e., 6.86 Mha and 2.35 Mha respectively, representing around 40% of all marginal land available in Europe. This notwithstanding, the absence of geological storage for CO_2 storage is an important technical barrier to the deployment of BECCS and DACCS in these regions.

Table 1. Cumulative biomass uses within each EU country by 2100. It can be noticed that, with some exceptions, Miscanthus is always preferred over willow owing to its higher yield.

	Biochar *Miscanthus*	**BECCS** *Willow* **(Mt/yr)**	**BECCS** *Miscanthus*
Austria	71.30	0	2.85
Belgium	52.47	0	475.99
Bulgaria	0	0	0
Croatia	0.38	41.35	78.15
Cyprus	0	0	0
Czech Republic	71.30	0	17.56
Denmark	0	31.08	11.57
Estonia	0	0	0
Finland	0	0	0
France	71.30	0	387.54
Germany	71.30	54.63	241.83
Greece	5.27	0	773.15
Hungary	71.30	23.82	7.49
Ireland	71.30	0	181.14
Italy	0	0	619.78
Latvia	0	77.16	0
Lithuania	0	294.86	0
Luxembourg	1.12	0	0
Malta	0	0	0
Netherlands	71.30	0.21	0.34
Poland	71.30	508.93	609.30
Portugal	71.30	0	0
Romania	0	0	567.30
Slovakia	0	83.76	1.73
Slovenia	0	0	31.05
Spain	38.41	0	5703.73
Sweden	71.30	0	38.89
United Kingdom	71.30	0	421.53

5. Conclusions

With the aim of extending the MONET-EU model to include a portfolio of NETPs that could be realistically deployed with the EU, this deliverable has relied on the Member-State specific NETPs database (D4.1) developed in Task 4.1. as well as in Task 1.1 (D1.1). Specifically, both commercially available DACCS archetypes involving CO_2 separation using liquid solvents and solid sorbents, have been included in the model database. This deliverable also draws on the biogeophysical database constructed in Task 4.2., containing data on land availability, biomass feedstock potential as well as main sustainability constraints with each EU member state. The afforestation model accounts for different forest growth rates based on ecological zones and tree species (i.e., broadleaves and conifers) and for a set of forestry operations including forest establishment (i.e., land establishment, herbicide application, seedling plantation and fertilizer application), forest management (i.e., thinning operations), and forest road construction and maintenance. Finally, biochar pathways entail the adoption of the biomass feedstocks already parameterized in the model database, which allow to identify potential land and biomass competing issues among different NETPs pathways.

To validate the model, we applied the MONET-EU framework to a range of policy scenarios, characterized by a varying degree of collaborations between EU states. Specifically, beside a business-as-usual scenario (BAU) where each EU country acts in isolation to meet its own national target, we also consider the case in which the EU acts as a whole, i.e. countries collaborate to meet a EU level removal target. An important caveat of this analysis is that, in translating the regional target to country allocations, we selected a representative equity principle, based on the findings of D4.3. As pointed out by Matthews et al., far from being science-based decisions, national allocations are largely subjective choices made by individual countries, i.e. based on the principle of self-differentiation (Meinshausen *et al.*, 2015; Matthews *et al.*, 2020). This notwithstanding, the aim of the proposed case study is to investigate the implication of two contrasting approaches to reach a collective emission target, rather than proposing prescriptive country-specific CDR deployment pathways. Further analysis in D7.3. will be dedicated to exploring the implication of adopting other national allocation principles stemming from the analysis conducted in D4.3. In addition, D7.3. will consider the adoption of other emission targets descending from the IPCC scenarios and discuss their implication on the required level of CDR deployment over time.

The results of the analysis show that the cost-optimal way to meet the Paris Agreement, strongly relies on international cooperation, especially when the availability of biomass resources is restricted. In fact, when nations act in isolation, not only the deployment of these technologies at scale is more costly, but some of the EU countries are not able to meet their own targets, due to limited biomass and land availability. Such collaborative approach will rest upon the availability of a shared, cross-border CO_2 transport and storage infrastructure. Given the increasing number of CCS projects in Europe moving towards becoming operational by 2030, there is a crucial need to support this progress also from a market perspective.

In addition, to enable and support collaboration between EU countries, NETs should be integrated into an international market for negative emissions trading, in which nations capable of generating CDR surplus, relatively to their individual CDR targets, could provide this as a service to other nations with lower biomass and resource availability. In such market, CDR surplus would generate negative emissions credits (NECs), that could be traded between nations, thus enable meeting the Paris

Agreement target in the most cost-efficient manner. Specifically, we found that a negative emissions market would allow "dependent NEC beneficiary" nations — nations that could not meet their national CDR targets domestically — to successfully deliver their share of the Paris Agreement's CDR objectives. How, and at which price should NECs be allocated from a nation to another represents an open question.

Finally, we argued that the later a market for negative emissions trading would be implemented, the more expensive delivering the Paris Agreement's CDR objectives would be. Imminent action towards the establishment and deployment of a multi-regional, or possibly international, geopolitical and economic framework for NE trading, and robust institutions to enable monitoring, verification and accreditation of this NE trading, will therefore be key in delivering the Paris Agreement's CDR objectives.

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	Report	CO	6
D1.2	Comprehensive sustainability assessment of terrestrial biodiversity NETPs	ETH	Report	PU	12
D4.1	NETP database	ICL	Excel spreadsheet	PU	9
D4.2	Bio-geophysics database	ICL	Excel spreadsheet	PU	12
D4.3		ICL	Report	PU	17

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7. Appendix

7.1 Overview of AR model in MONET-EU

Forest growth model

Within the forest growth model, forest growth curves are characterized by ecological zone and forest type (broadleaves/conifers), to account for geographic, climatic and ecological variations. Both the above-ground biomass − the vegetation above the soil, such as stems, branches, foliage or bark −, with and without forest management, and the below-ground biomass are included in the forest growth model.

Forest stands are subject to a non-intensive forest management − with reduced or minimum human intervention. The purpose of forest management activities is to maximize and maintain the C (and CO_2) sequestration potential of the forest by clearing the forest of old and/or sick trees so that younger trees are allowed to grow more vigorously and with more space.

Forest growth depends on many parameters, such as climate, species, forestry practices - themselves observing important geographic variations (Harald Aalde *et al.*, 2006). The above-ground biomass stock of reference can be defined as a sigmoid curve, which is typical in even-aged stands in the absence of forest management (without human intervention). In MONET, the above-ground biomass stock B_{Ref}^{AG} (tonnes$_{DM}$.ha^{-1}) has been parametrized by adopting the IPCC default biomass stock B_{Ref} (tonnes$_{DM}$.ha^{-1}) and net biomass growth rate G_{Ref} (tonnes$_{DM}$.ha^{-1}.yr^{-1}) of natural forests (See Table 9.1). Finally, B_{Ref}^{AG} is calculated for each ecological zone *gez* and each year *yr* over the forest growth period:

$$\forall\ gez, yr\ \leq\ T_{Ref}(gez), \qquad B_{Ref}^{AG}(yr, gez) = \frac{L_{Ref}(gez)}{1 + \exp\left(-k_{Ref}(gez)\left(yr - x_{0,Ref}(gez)\right)\right)}$$

with:

$$T_{Ref}(gez) = \frac{B_{Ref}(gez)}{G_{Ref}(gez)}$$

$$L_{Ref}(gez) = B_{Ref}(gez)$$

$$x_{0,Ref}(gez) = \frac{T_{Ref}(gez)}{2}$$

$$k_{Ref}(gez) = \frac{\ln\left(\frac{a_{Ref}}{100 - a_{Ref}}\right)}{x_{0,Ref}(gez)}$$

where:

- T_{Ref} is the growing period of reference (years),
- L_{Ref} is the maximum biomass stock of reference (tonnes$_{DM}$.ha^{-1}),
- $x_{0,Ref}$ is the mid-point of the reference sigmoid curve (years),
- a_{Ref} is the asymptotic coefficient of the reference sigmoid curve (-), whose default value is set to 99,
- and k_{Ref} is the slope coefficient of the reference sigmoid curve (tonnes$_{DM}$.ha-1.yr^{-1}), such as:

$$\frac{d\ AGBio_{Ref}}{dt}\left(yr = x_{0,Ref}(gez), gez\right) = \frac{k_{Ref}(gez)}{4}$$

At the end of the growing period of reference, the above ground biomass stock reaches its maximal value (*i.e.*, $B_{Ref}^{AG} = L_{Ref}$) and saturate after about 44 years (median). However, this implies that the forest must be maintained in perpetuity in in order to preserve its climate benefit as well.

The managed above-ground biomass stock derives from the above-ground biomass stock of reference discussed above, subject to the different phases of the forest management cycle (FMC): the establishment, initial, full-vigour, mature, and old-growth phases. Forest growth phases are usually determined based on the Mean Annual Increment (MAI) − the average rate of merchantable volume of biomass growth − and its Maximum Mean Annual Increment (MMAI). In the context of (biogenic) CO_2 removal, however, both merchantable and non-merchantable biomass stocks are considered, including both above-ground biomass and below-ground biomass stocks, and evaluated in terms of total biomass dry-mass.

In the context of climate mitigation, AR is deployed while prioritizing C (and CO_2) sequestration potential over timber production. Therefore, the FMC model introduced here is only comprised of thinning operations (no harvesting operations), so that the forest C (and CO_2) stock are maintained and maximized.

It is assumed that: 1) the frequency of thinning operations decreases with time − from every 5 years during the full-vigour phase to every 15 years during the old-growth phase −, and 2) the intensity is set as 10% of the above-ground biomass stock at any time.

A schematic of the FMC workflow is described in Figure S1 and is defined for each ecological zone *gez* and for each year *yr* over a default period of 200 years, where:

- $yr_{E,END}$ is the last year of the establishment phase (years),
- $yr_{I,END}$ is the last year of the initial phase (years),
- MAG_{BT}^{AG} is the mean annual growth (MAG), before thinning ($\text{tonnes}_{DM}.\text{ha}^{-1}\text{yr}^{-1}$),
- $MMAG_{Ref}^{AG}$ is the maximum mean annual growth ($\text{tonnes}_{DM}.\text{ha}^{-1}\text{yr}^{-1}$),$AT$ is the annual thinning stock ($\text{tonnes}_{DM}.\text{ha}^{-1}$),
- $\%_T$ is the thinning share of the above-ground biomass stock (%),
- B_{BT}^{AG} is the above-ground biomass stock, before thinning ($\text{tonnes}_{DM}.\text{ha}^{-1}$),
- $yr_{last\ FVT}$ is the year during which the last thinning of the full-vigour phase occurred (years),
- and $yr_{last\ MT}$ is the year during which the last thinning of the mature phase occurred (years).

$yr_{E,END}$ and $yr_{I,END}$ default values are respectively 5 and 15 years.

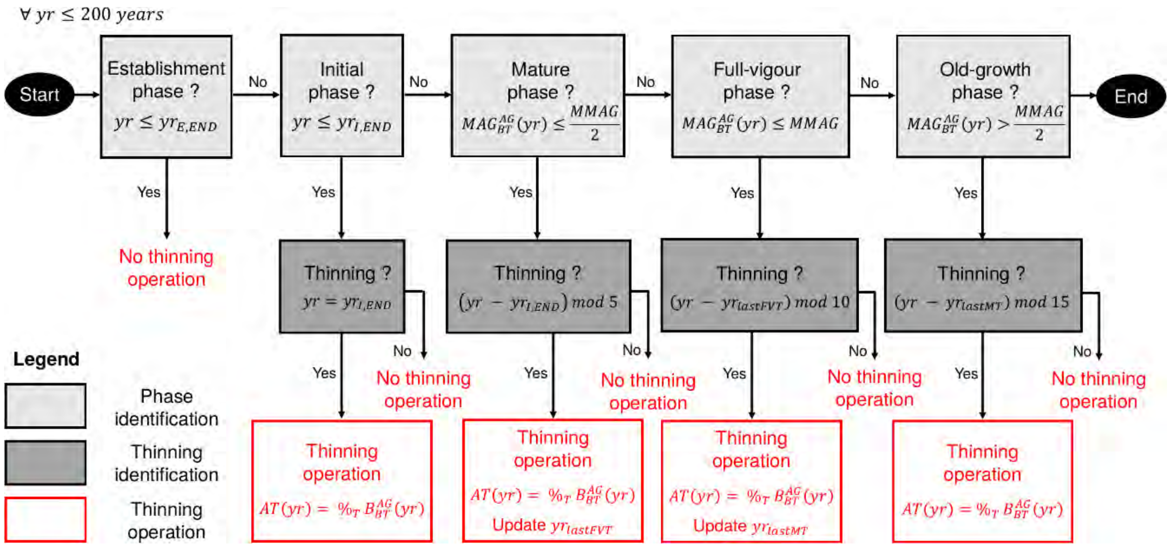

Figure S1. Schematic of the forest management cycle (FMC) workflow. This has been used for determining thinning operations' frequency and intensity.

The below-ground biomass stock B_{AT}^{BG} can be estimated from the above-ground biomass stock with the use of a "root-to-shoot" ratio. A "root-to-shoot" ratio usually depends on climate, tree species, soil type and declines with stand age and/or productivity.

Extreme range values of 0.09–1.16 tonnes root$_{DM}$.(tonnes shoot$_{DM}$)$^{-1}$ have been reported in the literature, although average range values of 0.20–0.56 tonnes root$_{DM}$.(tonnes shoot$_{DM}$)$^{-1}$ might be more likely (Harald Aalde *et al.*, 2006).

In our study, the "root-to-shoot" ratio R evolves with the amount of above-ground biomass stock (before thinning) B_{BT}^{AG}. Specifically, R is characterised by ecological zones *gez*, tree species *sp* and by the amount of above-ground biomass stock aB_{BT}^{AG} and calculated as follows:

$$R\left(gez, sp, B_{BT}^{AG}(yr, gez)\right) = \begin{cases} R_1(gez, sp) \times \ln\left(R_2(gez, sp) \times B_{BT}^{AG}(yr, gez) + 1\right), & R_2(gez, sp) \neq 0 \\ R_1(gez, sp), & R_2(gez, sp) = 0 \end{cases}$$

where R_1 and R_2 coefficients are the coefficients interpolated[5] from the IPCC provided in Table A1 and Table A2.

Finally, the total biomass growth curve B^{Total} is defined for each ecological zone *gez*, each tree species *sp* and each year *yr* over a default period of 200 years and is calculated as follows:

$$B^{Total}(yr, gez, sp) = B_{AT}^{AG}(yr, gez) + B_{AT}^{BG}(yr, gez, sp)$$

[5] $R_1$and R_1were obtained by solving a non-linear curve-fitting (data-fitting) problem in least-squares sense in Python 3.7 (function scipy.optimize.leastsq).

Table A1 IPCC default "root-to-shoot" ratio, characterised by ecological zone, forest type and above-ground biomass stock (Harald Aalde *et al.*, 2006)

Climate domain	Ecological zone	Above-ground biomass (tonnes$_{DM}$ ha^{-1})	Root-to-shoot R (tonne root$_{DM}$ (tonne shoot$_{DM}$)$^{-1}$)	
Tropical	Tropical rainforest		0.37	
	Tropical moist deciduous forest	< 125	0.20	
		> 125	0.24	
	Tropical dry forest	< 20	0.56	
		> 20	0.28	
	Tropical shrubland		0.40	
	Tropical mountain system		0.27	
Subtropical	Subtropical humid forest	< 125	0.20	
		> 125	0.24	
	Subtropical dry forest	< 20	0.56	
		> 20	0.28	
	Subtropical steppe		0.32	
	Subtropical mountain system		No estimates*	
Temperate	Temperate oceanic forest, Temperate continental forest, Temperate mountain system	Conifers	< 50	0.4
			50-150	0.29
			> 150	0.2
		Broadleaves	< 75	0.46
			75-150	0.23
			> 150	0.24
Boreal	Boreal coniferous forest, Boreal tundra woodland, Boreal mountain system	< 75	0.39	
		> 75	0.24	

* Used IPCC tropical mountain systems values

Table A2. Interpolated root-to-shoot R1 and R2 values

Climate domain	Ecological zone	R1 (tonnes root$_{DM}$ tonne shoot$_{DM}$$^{-1}$)		R2 (tonne$_{DM}$$^{-1}$)	
Tropical	Tropical rainforest*	0.37		-	
	Tropical moist deciduous forest	801		0.00029	
	Tropical dry forest	33		0.01113	
	Tropical shrubland*	0.40		-	
	Tropical mountain system*	0.27		-	
Subtropical	Subtropical humid forest	848		0.00028	
	Subtropical dry forest	474		0.00126	
	Subtropical steppe*	0.32		-	
	Subtropical mountain system*	0.27		-	
Temperate	Temperate oceanic forest, Temperate continental forest, Temperate mountain system	Conifers	25	Conifers	0.02159
		Broadleaves	24	Broadleaves	0.02275
Boreal	Boreal coniferous forest, Boreal tundra woodland, Boreal mountain system	25		0.04466	

* Used IPCC "root-to-shoot" value

Biogenic carbon sequestration model

Growing forests capture CO_2 from the atmosphere via photosynthesis. The sequestrated C contained in the above-ground biomass is then partially transferred to the below-ground biomass, dead organic matter and soil. All together these constitute biogenic C pools (H Aalde *et al.*, 2006; Harald Aalde *et al.*, 2006). The resulting C stock can be calculated by considering a carbon content factor C_f, which is specific of tree species, age, size and ultimately climate. Hence, in MONET, the total biomass carbon stock (after thinning) C_{AT}^{Total} derives from the total biomass stock B^{Total}. C_{AT}^{Total} is defined for each ecological zone *gez*, each tree species *sp* and each year *yr* over a default period of 200 years and parametrised with the IPCC default values for C_f (Harald Aalde *et al.*, 2006), as shown below:

$$C_{AT}^{Total}(yr, gez, sp) = B_{AT}^{Total}(yr, gez, sp) \times C_f(gez, sp)$$

Finally, the total biomass CO_2 stock CO_{2AT}^{Total} derives from the conversion of C to CO_2, based on the ratio of molecular weights (44/12):

$$CO_{2AT}^{Total}(yr, gez, sp) \ = C_{AT}^{Total}(yr, gez, sp) \times \frac{44}{12}$$

Permanence of biogenic CO_2 sequestration

Forests are vulnerable to natural and human disturbances such as drought, hurricanes, forest fires and pests, or to human-induced reversals, such as active deforestation. With climate change, this vulnerability could even be exacerbated (Fuss *et al.*, 2018). Consequently, the permanence of biogenic CO_2 sequestration is less reliable than the one of geological CO_2 sequestration, such as in the cases of BECCS or DACCS.

Because the impact of natural disturbances on forest stands can be catastrophic, both in terms of biodiversity or financial losses − specifically in the context of timber production − how the risk of natural disturbances should be anticipated and integrated in forest management has been increasingly investigated. However, the focus has been predominantly set on maximising timber productivity and economic value, with or without carbon sequestration benefits, such as carbon price or carbon tax, and scarcely on minimizing biomass and resulting CO_2 sequestration losses (Stainback and Lavalapati, 2004; Couture and Reynaud, 2011; Hu, Stainback and Li, 2016).

A few risk-accounting methods have been introduced, specifically for hurricanes or wildfires (McNulty, 2002; Hurteau, Hungate and Koch, 2009; Chuvieco *et al.*, 2014; Szpakowski and Jensen, 2019), although most of the literature focuses on wildfires. In spite of the increasing widespread use of remote-sensing − the use of satellites to search for and collect geo-spatial data −, these risk-accounting methods remains site-, region-, or at most, country-specific. For instance, the Landscape Fire and Resource Management Planning Tools (LandFire) Program in the USA has been providing national geo-spatial datasets (partially or completely based on remote-sensing) on vegetation distribution, fire regime and other fuel characteristics. The NASA Land Use and Land Cover Program has also been releasing the MODIS Active Fire Products and Burned Area Products, ones of the most complete datasets at the global scale, but

The fire risk model adopted in MONET derives from a risk-accounting methodology developed in Hurteau *et al.* (Hurteau, Hungate and Koch, 2009) which defines a wildfire-penalty coefficient R_{fire}, which can be applied at the global scale. R_{fire} is built upon wildfires' severity − the potential biomass loss given a fire occurrence − and periodicity − the probability of a fire event occurring during a specified time period.

CO_2 sequestration potential

AR's CO_2 sequestration potential CO_{2AT}^{Seq} is defined for each ecological zone *gez*, each tree species *sp* and each year *yr* over a default period of 200 years and is estimated with the use of R_{fire}, characterised by ecological zone *gez:*

$$CO_{2AT}^{Seq}(yr, gez, sp) = (1 - R_{fire}(gez)) \times CO_{2AT}^{Total}(yr, gez, sp)$$

AR CO_2 sequestration potential can be further aggregated at the regional scale:

$$CO_2^{Seq}(yr, sr) = \frac{\sum_{sp,gez} CO_{2AT}^{Seq}(yr, gez, sp) \times \%_{sp}(sp, sr) \times \%_{gez}(gez, sr)}{\sum_{sp,gez} \%_{sp}(sp, sr) \times \%_{gez}(gez, sr)}$$

Where:

- CO_2^{Seq} is AR CO_2 sequestration potential in sub-region *sr* and year *yr* (tonnes CO_2 captured.ha^{-1}),
- $\%_{sp}$ is the share of each tree species *sp* in sub-region *sr* (%),
- and $\%_{gez}$ is the share of each ecological zone *gez* in sub-region *sr* (%).

The maximal CO_2 sequestration potential of at the EU member state level scale is illustrated in Fig. S.2. AR's CO_2 sequestration potential is not affected by wildfires in boreal and temperate climates, whereas it decreases by 23--29% in warmer areas such as Italy, Spain and Portugal and well as Greece and Croatia.

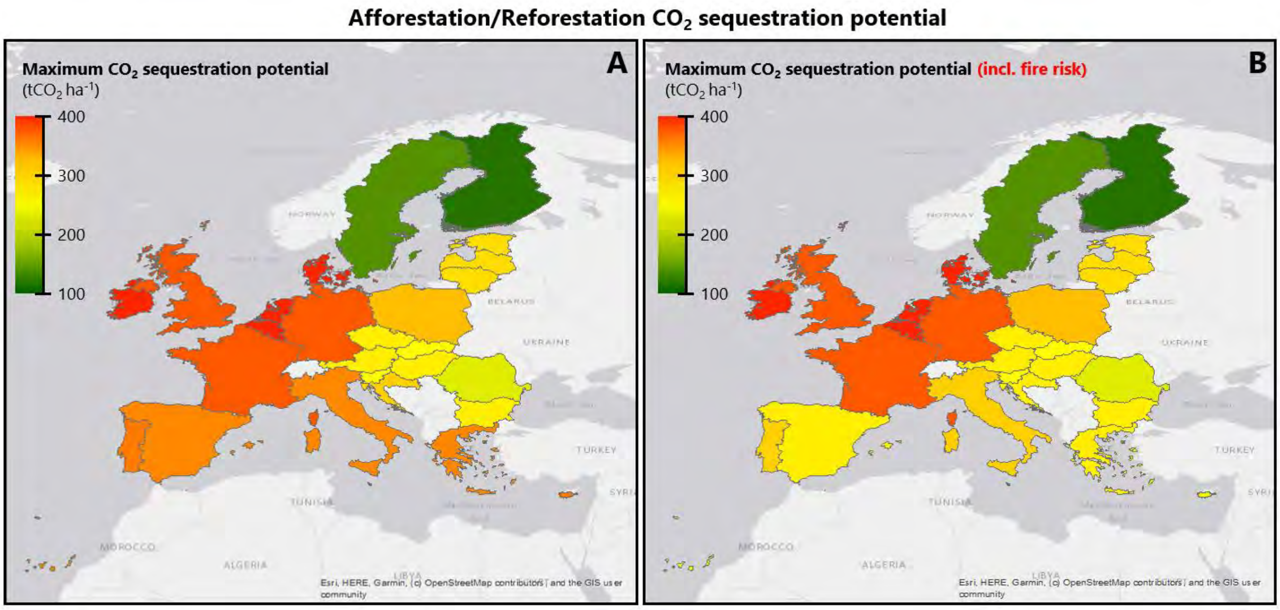

Figure S2. Maximum CO_2 sequestration potential of AR projects when excluding or including the risk of wildfires (A and B respectively).