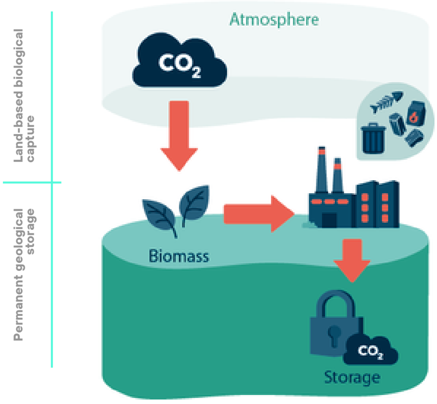


BioCCS

A process that can remove carbon or reduce CO_2 emissions

Expected permanence	millennia
Reversal risk	low
Uncertainty in amount of initially captured carbon	medium
Uncertainty in amount of carbon stored over time	low
Ease of MRV	high
Key co-benefits	Energy production (heat, electricity, fuels)

Advantages

CHEAP RETROFITTING

CCS can be applied to existing point sources of biogenic CO_2, such as paper mills, ethanol plants and biomass power/CHP plants. This makes it cheaper, whilst contributing to energy security.

PERMANENT STORAGE

Sequestered carbon is stored permanently with low risk of reversal.

MRV

Protocols for monitoring, reporting and verification already exist.

PRODUCTION OF USEFUL BY-PRODUCTS

Energy in the form of heat, electricity or fuels are produced during the biomass conversion. This decreases the energy footprint of BioCCS and can offer additional revenue streams.

What is BioCCS and how does it store carbon?

Biomass with carbon capture and storage (BioCCS) converts the CO_2 sequestered in biomass into energy, fuels, or other uses. The carbon released during this process is captured and stored in permanent geological storages. The selected biomass source and conversion pathway differ depending on the BioCCS project at hand, which in turn influences the CDR potential. The biomass source may be forest or agricultural residues, pulp and paper industry, wood pellets, solid municipal waste or dedicated crops, whilst conversion pathways involve biological or thermochemical processes. In this sense each BioCCS plant is unique, involving a specific feedstock, supply chain, CO_2 capture process and downstream processes.

Biomass used in BioCCS is often “zero-rated” meaning the carbon the biomass captured while growing is considered to be emitted upon harvest (accounted for under LULUCF emissions accounting). Any biogenic CO_2 captured from biomass conversion in a BioCCS plant is automatically considered a negative emission. Existing point source biogenic CO_2 emissions can also be captured.

There are currently 19 bioenergy production facilities around the world either in operation, piloting or under construction. Some prominent projects in the field include Drax and Stockholm Exergi with the intention of capturing 8 Mt CO_2/yr and 0.8 Mt CO_2/yr respectively followed by permanent geological storage.

Relevant regulatory frameworks: Biomass feedstock sourcing should comply with EU Renewable Energy Directive guidelines for sustainable biomass.

Challenges

HIGH VALUE CHAIN EMISSIONS

Long distances between biomass source, processing and storage sites result in higher emissions along the entire value chain.

IMPERFECT CARBON CAPTURE RATES

Not all carbon from bioenergy conversion can be directly captured (capture rates ca. 90-99%).

PLANETARY BOUNDARY PRESSURE

Large-scale deployment from dedicated bioenergy crops severely conflicts with planetary boundaries and biodiversity goals. Biomass crops require vast amounts of water, fertiliser and land, competing with food security, whilst raising food prices.

LONG CARBON PAYBACK TIMES

Carbon debt payback time can be long depending on biomass source.

HIGH INDIRECT GHG EMISSIONS

Associated deforestation and indirect land-use change emissions can be high. Since the demand for food and feed crops remains, more food and feed is produced elsewhere and just displaces where emissions occur.

LEAKAGE POTENTIAL

Potential leakage during biomass transport, particularly if biomass used and produced in different regions.

What is the sustainable potential of BioCCS to sequester carbon?

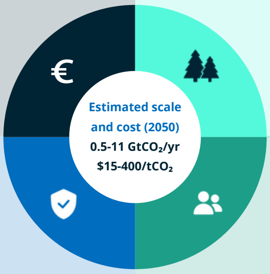
Economic performance

CapEx
Lower costs for retrofitted plants.
OpEx
High costs to process CO_2 and transport to storage site. Costs are lower for highly concentrated CO_2 streams within BioCCS plants.

Environmental performance

Land-use change, biosphere integrity, freshwater impacts and nutrient flows are impacted less by non-dedicated energy crops or by utilising biomass side-streams (agricultural/forestry residues).

Water and land requirements are higher for plantation-based BioCCS.



Resource security

Lower energy constraints if the energy produced in biomass conversion can be utilised.

Additional dedicated energy crops for biomass production require new land conversion and water for irrigation.

Social and governance performance

Potential need for international biomass transport and impact on food systems due to additional land area requirements.

Unfavourably perceived by stakeholders.

Current unknowns and future research perspectives

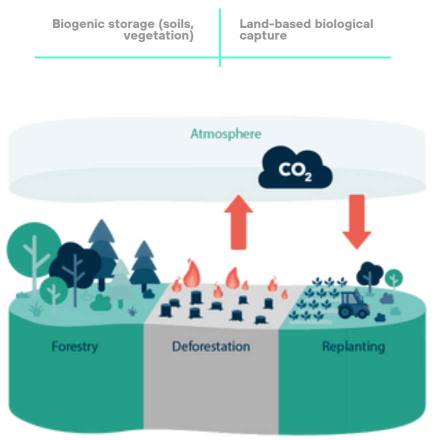
The future availability of non-plantation based feedstock is uncertain, and the limited amount will need to be shared amongst other potential feedstock uses (e.g. construction materials, biochar or alternative fuel production). Climate change may impact biomass growth rates and constrain future feedstock quantity.

There is uncertainty in the CDR potential and BioCCS cost due to the lack of a standardised methodology. Clarity is needed on feedstock value chain carbon accounting as uncertainty exists as to whether many BioCCS projects actually create net-negative emissions.

Carbon storage availability is currently low and the benefits/risks of on/offshore storage are still being studied.

RECOMMENDATIONS

- Ensure that certification schemes provide appropriate incentives to securely capture of all concentrated CO_2 streams regardless of carbon emission type (fossil, biogenic); account for the carbon throughout the entire value chain to enable a systemic assessment of each BioCCS project and determine the net removal of carbon.
- Conduct system-level BioCCS project life-cycle impact assessments to determine impacts on land-use change, natural resources, ecosystem health, biodiversity, nutrient flows and soil carbon stocks, measured against potential trade-offs with planetary boundaries and the achievement of Sustainable Development Goals.
- Develop policies that support a transition towards plant-based diets e.g. EAT-Lancet planetary health diet that repurposes pastureland and alleviates land resource demand.
- Prioritise sustainable feedstock sources such as municipal waste, forestry and agricultural residues, and pulp and paper mills to avoid further transgression of planetary boundaries. Prohibit high quality and high value biomass as a feedstock in bioenergy.
- Source feedstock biomass sustainably, in full compliance with EU and international regulations; ensure that biodiverse ecosystems are not converted into biomass plantations. Use limited biomass sources in hard-to-abate sectors where no other appropriate feedstocks are available.
- Foster international trade and cooperation to address uneven distribution of domestic capacities such as biomass resources and storage sites.



Afforestation and Reforestation

A practice which enhances natural carbon stores and can reduce emissions

Expected permanence	decades-centuries
Reversal risk	high
Uncertainty in amount of initially captured carbon	medium
Uncertainty in amount of carbon stored over time	high
Ease of MRV	low
Key co-benefits	Can enhance biodiversity, ecosystem function

Advantages

MULTIPLE CO-BENEFITS

Reforestation has extensive co-benefits. It contributes to nature restoration, soil health, biodiversity, biosphere integrity and climate stabilisation.

LOW COST

A/R already occurs and is cheaper to implement than other NETPs. Little additional infrastructure is required.

POSITIVE PUBLIC PERCEPTION

Generally A/R is well-perceived by the public.

ECONOMIC BENEFITS

Projects can empower and provide economic benefits to local communities.

What are afforestation and reforestation and how do they store carbon?

Afforestation (A) involves planting new trees and increasing forest cover in previously non- forested lands, whereas reforestation (R) refers to replanting trees on recently deforested or degraded land. Forests act as carbon sinks as they remove CO_2 from the atmosphere via photosynthesis and store it in living biomass, dead organic matter, and forest soils. Carbon can accumulate in the stem and branches (above-ground biomass) but also in the roots (below-ground biomass) and soil. Continuous management of forest biomass is necessary to retain carbon in the vegetation and soils, hence this storage type is vulnerable to leakage and therefore likely to be temporary. Afforestation and reforestation practices that prioritise native mixed species, instead of non-native monoculture plantations, provide extra ecosystem functions and boost biodiversity.

Current annual rates of carbon storage from land-based sequestration (includes afforestation, reforestation and existing forest management) are estimated at 2 Gt CO_2 according to the State of CDR report from 2023.

Relevant regulatory frameworks: Land Use, Land-Use Change and Forestry regulation, Nature Restoration Law, proposal for a Monitoring Framework for Resilient European Forests. Society has agreed to several biodiversity and ecosystem restoration targets as set out in the Kunming-Montreal Global Biodiversity Framework and the Bonn Challenge.

Challenges

HIGH LEAKAGE RISK

Carbon stored in forest vegetation is vulnerable to disturbances such as wildfires, pests and disease, as well as land ownership change, where forests may be lost.

HARD TO QUANTIFY STORED CARBON

Carbon stored below ground carbon is hard to measure. Geographical location affects forest capacity to sequester carbon and bears associated climate feedbacks (e.g. albedo, evapotranspiration).

LIMITS ON STORAGE CAPACITY

Sequestration rate and forest growth is slow. Eventually, forests saturate, and therefore release as much CO_2 (e.g. from trees dying) as they absorb.

LOCAL COMMUNITY RIGHTS

Projects may not always prioritise the rights of local and marginalised communities, which are often excluded from decision-making processes.

ADDITIONAL LAND REQUIRED

Afforestation on previously non-forested land can lead to extensive land-use change, exacerbating food insecurity, land conflict, and adding pressure onto planetary boundaries.

ADVERSE ENVIRONMENTAL IMPACTS

Afforestation projects on previously non-forested land can demand significant fertilisation and irrigation inputs. Projects can also involve the introduction of non-native species.

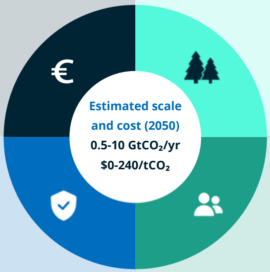
What is the sustainable potential of afforestation and reforestation to sequester carbon?

Economic performance

CapEx
Costs for roads and irrigation systems vary depending on the scale and location of the project. Potential increases in land prices will drive up costs.
OpEx
Sustained but low costs for continuous forest and land management.

Environmental performance

Depends on vegetation type and species diversity, fertiliser use and irrigation needs. Potential for beneficial land-use change, improved biosphere integrity, freshwater impacts and nutrient flows under reforestation using diverse and native species. Afforestation with plantations may lead to loss of biodiversity.



Resource security

Substantial additional land area will be required for afforestation projects.

Reforestation will also require land conversion, given that the majority of agricultural areas were established on previously forested land.

Social and governance performance

A/R carries popular public support due to expected positive consequences for nature and future generations.

Risk of reversal is strongly linked to land use and management policies.

Current unknowns and future research perspectives

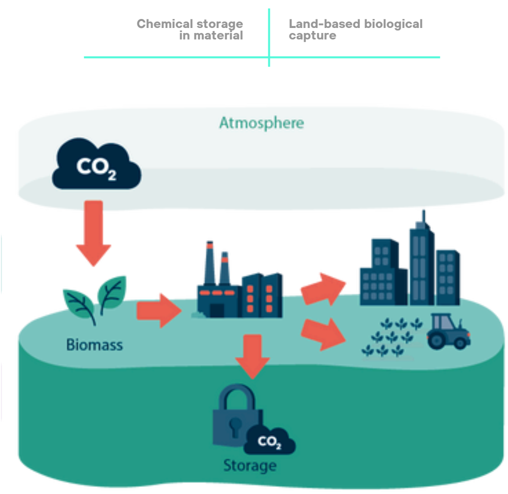
It is not clear to what extent A/R is compatible with other land-based NETPs, considering economic, political, and social pressures on land area for food and urban development.

Climate feedbacks from the emissions of non-CO_2 greenhouse gases, volatile organic compounds, evapotranspiration and albedo changes can counterbalance the climate mitigation from the reduction in atmospheric CO_2 concentrations. These impacts need more accurate quantification to clarify the net climate benefit.

It is unclear what the continued impact of climate change will have on the ability for forests to grow, survive and store carbon, further complicating accounting, MRV and overall CDR efficiency.

RECOMMENDATIONS

- Align climate and nature restoration regulation to achieve better, more coherent environment policy.
- End deforestation, protect old forests, ban illegal and intensive logging, reduce commercial plantations, and avoid harvests for short-term uses (such as for bioenergy, pulp and paper); ensure that the amount of harvested biomass does not exceed the capacity for forests to grow biomass to replace the losses.
- Adopt close-to-nature forestry management and other sustainable practices including planting mixed, native species and promoting old-forest growth; continue forest management after saturation to prevent disturbances from releasing sequestered carbon.
- Implement a large-scale food system transformation, in line with the EAT-Lancet planetary health diet to free up land, contribute to forest restoration, and to avoid conflicts with food production and security; prioritise reforesting and restoring degraded and desertified lands in primary and secondary forests.
- Take into account trade-offs (biosphere integrity, land use change, ecosystems, water cycle), local conditions, climate conditions, and climate feedbacks (surface albedo or evapotranspiration processes) in A/R projects.
- Adopt a rights-based approach that respects land rights of local and indigenous communities



Biochar

A material that stores carbon and can reduce CO_2 emissions

Expected permanence	decades to millennia
Reversal risk	medium
Uncertainty in amount of initially captured carbon	low
Uncertainty in amount of carbon stored over time	high
Ease of MRV	medium
Key co-benefits	increased crop yields, reduced soil N2O emissions, soil pH, reduce use of synthetic fertiliser

What is biochar and how does it store carbon?

Biochar is produced through the thermal decomposition of biomass in the absence of oxygen, in a process called pyrolysis, at a feasible temperature range between 450°-600°C. Heating levels above this range can create liquid form 'bio-oil' and 'pyrogas'.

Biomass can be obtained from a variety of sources, such as urban and municipal waste or agricultural, plant and forestry residues as well as dedicated biomass crops, and its quality determined by its feedstock source and the temperature at which it was produced. For example, a woody feedstock that was heated beyond 450°C has greater stability and a lower decay rate than manure-derived feedstock, heated at a lower temperature.

Permanence and reversibility are dependent on labile and recalcitrant carbon fractions, storage, and storage medium. Biochar can be added to construction material, such as cements and tar, or can be added to soils as it enriches the natural soil carbon sink. Research has shown that the recalcitrant portion of biochar is highly stable, however, due to a lack of long-term field studies, the potential release of stored carbon in biochar over time periods relevant for CDR is unclear.

According to the latest European Biochar Industry report, by the end of 2023, biochar production reached around 49 000 t (equivalent to over 130 000 t CO_2e).

Relevant regulatory frameworks: Renewable Energy Directive; Land Use, Land-Use Change and Forestry Regulation; Regulation for the purpose of adding pyrolysis and gasification materials as a component material category in EU fertilising products as a fertiliser.

Advantages

MULTIPLE CO-BENEFITS

Physical properties of biochar (e.g. high porosity) provide a range of co-benefits for agriculture, such as increased soil nutrient and moisture retention.

MIXED FEEDSTOCK

No separation of feedstock types is required throughout the pyrolysis process.

SMALL-SCALE DEPLOYMENT

Can be widely and rapidly deployed through multiple small-scale plants, utilising locally sourced and sustainable biomass side- streams.

COST-EFFICIENT

Economic viability is high; co-produced syngas and bio-oil can be sold for profit, generating revenue to the plant operators.

Challenges

STANDARDISED CERTIFICATION CHALLENGING

The numerous storage options for biochar makes a standardised approach to certification of permanently stored carbon with certainty challenging.

LESS CDR EFFICIENT

Lower CDR efficiency than other negative emission technologies and practices due to carbon lost during pyrolysis process and decay.

LIMITS ON STORAGE CAPACITY

Overall biomass demand will increase, leading to competition with other biomass-based NETS such as BioCCS.

HARD TO MONITOR

Permanence of carbon storage biochar and reactivity in open field applications is still unproven. When applied over a large area, monitoring the dispersed storage of extracted CO_2 and adhering to MRV requirements with certainty is challenging.

ECOSYSTEM DEPENDENT CO-BENEFITS

Agricultural benefits are dependent on the soil, biochar properties, climate conditions and the interaction between these.

POTENTIAL CLIMATE FEEDBACKS

Albedo changes may result, depending on the application method and the land on which biochar is applied.

What is the sustainable potential of biochar to sequester carbon?

Economic performance

Cheaper than other NETPs.

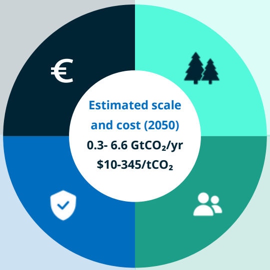
CapEx
Cost of leasing land, materials, machinery and trucks, feedstock and energy.

OpEx
Labour (farmer or pyrolysis operator), maintenance, and utilities.

Environmental performance

Biosphere integrity and land-use change where wood or purpose grown crops are used as feedstocks.

Intensive freshwater use when biomass pyrolysis is based on feedstock from irrigated plantations.



Resource security

Dedicated crops and large-scale biomass plantations place pressure on land, and own crops and large-scale biomass consequently, on food security.

Risk of water scarcity for other uses e.g. food production.

May produce energy and useful products (pyrogas, bio-oil).

Social and governance performance

More resilient soils will secure livelihoods.

Allows for local, bottom-up infrastructure, and is therefore less dependent on biomass prices.

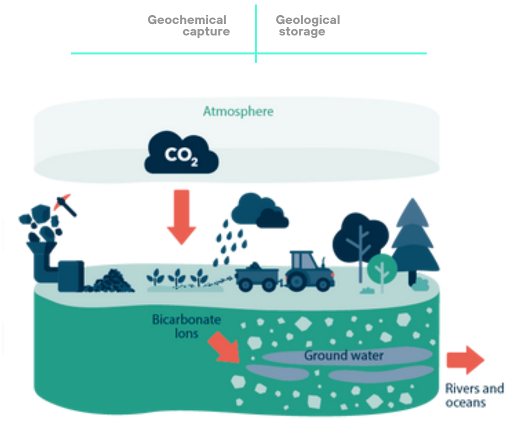
Current unknowns and future research perspectives

Reactivity of biochar in different storage mediums (e.g. soils, buildings materials, concrete, asphalt, tar) and the proportion of labile (chemically unstable) and recalcitrant (stable) biochar carbon retained in storage medium e.g. soils over long time periods.

Interaction between biochar and soil properties at the application site and the influence on total carbon loss (i.e. from soil organic carbon stocks and biochar degradation) and on ecosystem co-benefits of biochar application in different soil types e.g. water-holding capacity, crops, yield, climate conditions, non-CO_2 GHG emissions, and binding of heavy-metal pollutants.

RECOMMENDATIONS

- Design long-term duration field experiments to provide an increased understanding on biochar properties, functions, and to help develop a comprehensive biochar application policy.
- Ensure that the addition of biochar to soil suits the application context by, amongst others, considering climate and soil conditions. Create a regulation with a robust methodology that monitors dispersed storage, potential albedo change, accounts for decay rates and emissions, and assigns liability for reversal.
- Ensure that biomass is sourced from side streams such as agricultural and forestry residues, or food waste to avoid accumulating a carbon debt, taking land away from nature, competition with other NETPs, or food insecurity.
- Avoid growing dedicated crops. Prioritise growth in abandoned cropland or apply a land- and calorie-neutral pyrolysis system that requires fewer fertilisers, pesticides and irrigation, while providing co-benefits.



Terrestrial enhanced weathering

A practice that enhances a natural process to remove CO_2

Expected permanence	millennia
Reversal risk	low
Uncertainty in amount of initially captured carbon	high
Uncertainty in amount of carbon stored over time	high
Ease of MRV	low
Key co-benefits	potential increased crop yields, reduced fertiliser use

What is terrestrial enhanced weathering and how does it store carbon?

Terrestrial enhanced weathering (TEW) is the application of silicate or carbonate mineral particles with high reactive surface area to soils. These minerals dissolve in water and react with CO_2 to produce bicarbonate ions that flow via groundwater to rivers and to the ocean, or mineralise on land, becoming stable carbonates. This does mean that the time of carbon removal is not identical to the time of application. Both the dissolved ions and the formed minerals are highly stable storage mediums that lock carbon securely for long periods of time (>10 000 years), with a low risk of leakage.

Different minerals can be used in enhanced weathering which have different chemical composition, dissolution reactions, CO_2 sequestration capacity, and contain different toxic heavy metals or compounds that could be health or environmental risks. Two commonly applied minerals are basalt and dunite. Basalt requires substantial mining operations and material transport, which if using fossil resources, will offset the climate benefits of the carbon removal itself. Dunite-based TEW requires less material than basalt but does have higher toxicity due to substantial nickel content in the mineral. Hence each project requires assessment of its unique impacts, based on, for instance, application location and mineral applied.

Lime is commonly applied in agricultural practice to control the pH level in soil, pH but its use in carbon removal and storage is novel and research is on-going. Its usage as a NETP is not commonly considered in country portfolios within the EU. According to the IPCC, economic, environmental and technological feasibility is first expected after 2030 or even 2050.

Relevant regulatory framework: There is currently no specific EU legislation that regulates enhanced weathering.

Advantages

PERMANENT STORAGE

Sequested carbon is stored permanently with low risk of stored carbon being re-emitted.

NO ADDITIONAL LAND REQUIRED

Existing agricultural land can be used for TEW and its application may enhance crop yields and reduce fertiliser use.

SIMILAR TO SOIL PH MANAGEMENT

Enhanced weathering is a similar process to lime application to soils and standard tests exist that can be used to measure reaction rates in soils for relevant projects.

COST-EFFICIENT

Comparatively cost-effective application, with large theoretical and indefinitely sustained capacity.

Challenges

HIGH VALUE CHAIN GHG EMISSIONS

Both the rock crushing process and associated mining of minerals have high upfront GHG emissions.

DIFFICULT TO QUANTIFY IN FIELD

CO_2 sequestration is not immediate after application. The slow reaction rates are difficult to quantify accurately in the field.

HARD TO MONITOR

Applied over a large area, monitoring the dispersed storage of extracted CO_2 and adhering to MRV requirements with certainty is difficult.

SEQUESTRATION RATES VARY WITH LOCATION

Rate of CO_2 sequestration is variable due to different soil chemistry. In certain locations CO_2 may be released and lower the CDR efficiency.

What is the sustainable potential of terrestrial enhanced weathering to sequester carbon?

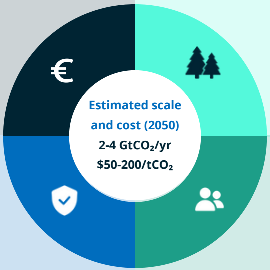
Economic performance

CapEx
High initial investment in mining/grinding/ transport infrastructure.
OpEx
Sustained monitoring, maintenance costs. High costs to power rock crushing, transport of minerals to deployment site. Application costs comparatively low.

Environmental performance

Large amounts of minerals required and sustainable sourcing is unlikely. Environmental impacts of mining depend on the source mineral. Mining can also cause freshwater pollution and GHG emissions.

Mineral application can leach metals into soils/groundwater.



Resource security

No extra land area is required for application, but maximum mineral application thresholds will exist.

Crushing, grinding and transportation of rock material could strain available renewable energy sources and transport networks.

Social and governance performance

Environmental impacts of mining, risk of human rights abuse in mining operations, international material transport. Mining impacts on human health (e.g. carcinogen production, fine particle pollution), but these may be outweighed by climate mitigation health benefits.

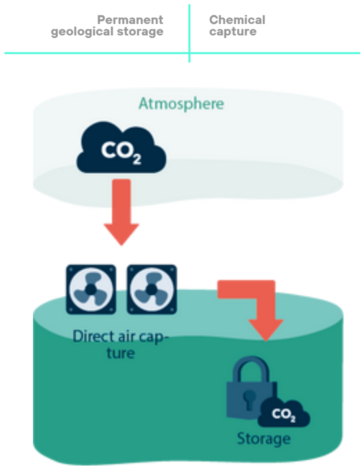
Current unknowns and future research perspectives

Field studies have not yet been able to replicate theoretically possible dissolution rates. Mineral reactivity is strongly influenced by environmental conditions, working more favourably in warm and humid locations (e.g. Brazil, SE Asia, China, India). More accurate modelling alongside field measurements is therefore necessary to boost understanding of chemical reactions, the dispersion of the mineral, reaction rates and any potential loss that may occur from secondary mineral precipitation.

The rate of grain dissolution is a key factor for the carbon sequestration rate within the weathering process. However, more research is needed to measure how fast rock grains dissolve under different soil conditions in the field, and to optimise its application. New methods for enhanced rock weathering are being developed, including the use of catalysts or organisms such as lichen or mosses, which, when applied to rocks, can dissolve them by modifying rock surface chemistry.

RECOMMENDATIONS

- Develop appropriate and comprehensive MRV for the carbon sequestered and stored, as well as standardised environmental impact assessments to support TEW applications as permanent CDR. This may include standardised modelling methodologies that enable accurate MRV of dispersed carbon stores and are validated by measurements of mineral dissolution rates in the field weathering rates for different minerals.
- Consider interim incentives based on the co-benefits of enhanced weathering, and vehicle comprehensive MRV as CDR is being developed.
- Align the scale of enhanced weathering deployment with the scale of sustainable mineral powder availability, as opposed to the potentially inexhaustible application to agricultural fields.
- Apply sustainability assessments and standards to mineral sources both inside and outside the EU and ensure all potential GHG emissions and environmental impacts are accounted for. Adapt existing EU environmental protection legislation, where needed.
- Ensure project permits consider suitable locations for mineral extraction and grinding that have ample renewable energy available and are close to application sites so as to minimise value chain GHG emission.



DACCS

A process that removes CO_2 directly from the atmosphere

Expected permanence	millennia
Reversal risk	low
Uncertainty in amount of initially captured carbon	low
Uncertainty in amount of carbon stored over time	low
Ease of MRV	high
Key co-benefits	non

Advantages

PERMANENT STORAGE

Sequested carbon is stored permanently with low risk of reversal.

Technology Readiness Level

DACCS is one of the more developed technologies (TRL 6). It is already being piloted.

MRV

Easy to quantify how much carbon is removed and stored. Baseline definition is straightforward and DACCS is, by default, considered additional.

ENVIRONMENTAL BENEFITS

Low impacts on terrestrial biosphere, generally not constrained by biophysical limitations and may provide valuable freshwater source in arid regions.

What is DACCS and how does it store carbon?

Direct air capture with carbon storage (DACCS) refers to the chemical extraction of CO_2 from the atmosphere by chemical adsorption, followed by the recovery and compression of CO_2 into a concentrated liquid, and storage in geological reservoirs. It is an example of removals with easy MRV because the capture and storage processes are relatively easy to quantify and measure. The process to separate CO_2 from the other components of ambient air is either done through absorption or adsorption. Once extracted, the carbon is then stored in geological reservoirs such as saline aquifers, or in other mineral forms in the Earth's crust.

Solid sorbent and liquid solvent DACCS are two common approaches used to capture CO_2 directly from the air. In the liquid solvent DACCS process, high-grade heat (900°C) is supplied by natural gas or hydrogen, with electricity sourced from the power grid. CO_2 emissions resulting from natural gas combustion are assumed to be captured within the plant limits. In the solid sorbent DACCS process, heat and electricity are both obtained from the power grid, using an industrial heat pump which converts electricity to low-grade heat (100°C). Newer capture technologies use more economical, reversible carbonate-based chemical reactions (carbonation and calcination), which are cheaper.

As of February 2024, there are over 20 DAC/DACCS initiatives in Europe. Current capacity at one of the largest plants in operation, Mammoth, is on the scale of 36,000 tons of CO_2 each year.

Relevant regulatory framework: Geological storage is currently regulated under the EU CCS Directive. According to the IEA, potential cross-boundary CO_2 transport may be regulated under the London Protocol, once ratified.

Challenges

ENERGY INTENSIVE

Dependent on plentiful (and renewable) energy and heat source. Approximately 200mk₂ of non-arable land is needed for renewable energy generation to remove 1 Gt of CO_2.

PLANT LOCATION

Limitations on plant location due to necessary proximity to renewable energy supply. Storage capacity limited due to low current capacity of stable and permanent storage reservoirs.

FEW CO-BENEFITS

DACCS has fewer associated co-benefits compared to land-based sequestration or BioCCS.

COST

Costs are high and infrastructure is expensive to build.

What is the sustainable potential of DACCS to sequester carbon?

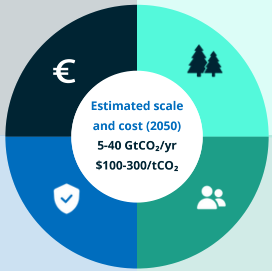
Economic performance

CapEx
Relies on costly grid and electricity transmission expansion, CO_2 pipelines and storage facilities.

OpEx
High energy costs (heat, power) and high cost of CO_2 transport and storage.

Environmental performance

Large amounts of minerals and metals are required for renewable energy infrastructure, which can impact water/air quality.



Resource security

Requires substantial additional clean and renewable energy source.

Sustainability of sorbent materials depends on the material lifetime and CO_2 uptake efficiency.

Social and governance performance

The type of energy source can incur human health impacts (water consumption, fine particle pollution).

Social barriers to large-scale DACCS include plant locations, risks to local energy security, as well as associated impacts of rare earth metal mining.

Current unknowns and future research perspectives

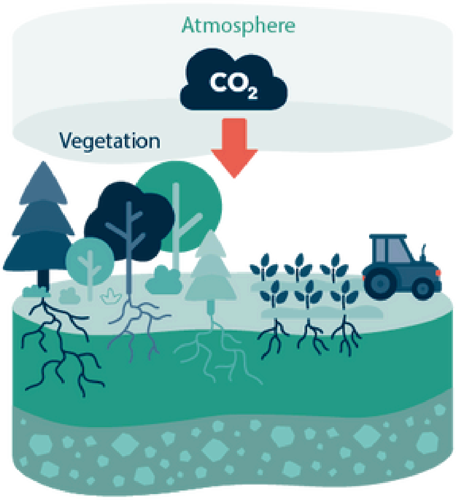
DACCS is currently expensive and its future cost is hard to predict. Experts believe that economies of scale, process optimisation, including the development of more efficient and less costly sorbents, will eventually decrease sorbent fabrication costs. Greater availability and subsequent lower cost of renewable energy could significantly reduce the energy costs of the technology. Options include novel configurations or technologies that use carbonation cycles rather than sorbent materials.

Regulation is currently limited to CO_2 storage in geological storage sites under the EU CCS Directive (2009/31/EC), which also sets out clear liability and monitoring mechanisms. However, clear international or European regulatory framework for the cross-boundary transport of carbon has not yet been developed.

RECOMMENDATIONS

- Support renewable energy development to ensure DACCS-related energy requirements can be accommodated, as opposed to further straining energy demand on partially-renewable energy systems. This avoids harmful health impacts arising from non-renewable electricity generation.
- Acknowledge the uneven distribution of domestic capacity for renewable energy and permanent carbon storage for DACCS. Prioritise DACCS in regions where renewable energy is plentiful and ensure that the energy required for DACCS does not detract from grid decarbonisation. Ideally, locate DACCS plants in proximity to geological storage sites.
- Coordinate transboundary CO_2 transport and storage to achieve DACCS deployment at scale. Create legal instruments that include socio-political and ethical compensation or incentivisation mechanisms for Member States that are expected to host optimal DACCS. Respect sovereign rights to equity and development in transboundary initiatives with third countries.
- Ensure that policies coordinate key industries involved in capture, storage and transport of CO_2 and give certainty to stakeholders, incentivise financial investment and establish secure business models.

Land-based biological capture | Temporary biogenic storage



Soil carbon sequestration

A practice which enhances a natural process to store CO_2 and can reduce emissions

Expected permanence	decades
Reversal risk	high
Uncertainty in amount of initially captured carbon	medium
Uncertainty in amount of carbon stored over time	high
Ease of MRV	low
Key co-benefits	Enhances soil resilience, water retention and contri- bute to ecosystem integrity

What is soil carbon sequestration and how does it store carbon?

Soil organic carbon (SOC) sequestration occurs because plants capture atmospheric CO_2 via photosynthesis and convert it into organic carbon. Part of this organic carbon is then transported into soils, thereby increasing the soil organic carbon content. Sustainable management practices such as conservation tillage, cover cropping, plant/crop variety, organic amendments (compost or manure), and drastic reduction in synthetic fertilisers help to retain organic carbon in soils and maintain or restore soil health and stability.

Measures that enhance SOC are common practice within sustainable land management due to the resulting co-benefits that secure the livelihoods of farmers. Yet, as an activity-lead practice, stored carbon is not commonly quantified, and will likely vary depending on the particular ecosystem and geographical location conditions. Numerous habitats contain substantial amounts of organic carbon such as agricultural soils, forests, wetlands, and grasslands, but soil carbon content is unevenly distributed across Europe; northern countries tend to be carbon-rich whereas the Mediterranean region is carbon depleted. Despite a clear value to society, around two-thirds of EU soil ecosystems are in poor health, acting as an emissions source, as opposed to a sink. Continuous land management and consistent policy measures are necessary to support carbon retention in soils.

Relevant regulatory frameworks: Soil Monitoring Law (under negotiation), Common Agricultural Policy, Nature Restoration Law.

Advantages

IMPROVES SOIL HEALTH

Addressing SOC will improve soil quality and resilience and promote nutrient cycling in terrestrial ecosystems.

ADDRESSES A HIGH EMISSION SECTOR

Adequate implementation of sustainable land management practices in agriculture could cut emissions in a top polluting sector.

MULTIPLE CO-BENEFITS

Healthy soils fulfill societal needs such as food security, healthy ecosystems, and water storage.

Challenges

RISK OF STORAGE REVERSAL

SOC storage is vulnerable to disturbances that can re-emit stored carbon.

ACCURATE QUANTIFICATION OF CARBON

Land management practices, soil types and climate conditions have different impacts on the soil carbon cycle. This complicates MRV and the design of methodologies.

LIMITED STORAGE CAPACITY

Biophysical constraints such as rainfall impact on vegetation growth rates, can reduce soil carbon sequestration capacity.

CONTINOUS MANAGEMENT

Inadequate land management or transfer of land stewardship can transform soils into a carbon source, as opposed to a carbon sink.

What is the sustainable potential of soil carbon sequestration?

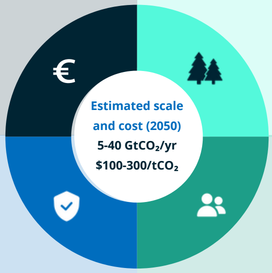
Economic performance

CapEx
May be low unless purchase of equipment necessary e.g. for conservation tillage
or composting/infrastructure changes, especially when no support system for land stewards exists.
OpEx
Sustained monitoring, maintenance costs as well as labour for land management practices.

Environmental performance

Limitations on SOC storage capacity.

Impacts of climate change may increase storage vulnerability.



Resource security

Not relevant, if implemented on existing agricultural or forestry land.

Social and governance performance

Healthier soils boost food security, human health, and farmer livelihoods

High risk of contractual reversal. Success is highly dependent on agricultural policies and practices.

Current unknowns and future research perspectives

SOC content impacts soil function and above a certain threshold ceases to additionally benefit the ecosystem. Further research is needed to establish these thresholds.

Influence of soil type, climate (e.g. change in rainfall patterns, rising sea levels, erosion) and management practices on SOC content. The realistic long-term capacity and potential of SOC sequestration long-term is not well understood.

RECOMMENDATIONS

- Establish legally binding targets and sustainable management practices across all habitats that focus on protection, restoration and soil health, including its role in regulating water, air quality, assuring food production and supporting biodiversity. Focus policy on enhancing ecosystem integrity, while designating associated carbon sequestration as the co-benefit.
- Reform the Common Agricultural Policy to set higher targets, combining both activity and results-based goals, regenerative practices, and prevention of further degradation of soils and carbon stocks; apply tighter conditionalities that favour small scale farms, provide training, technical support, and advice to farmers.
- Shift dietary preferences towards a plant-based diet and adopt policies that seek to reduce food waste.
- Develop a standardised accounting, MRV and liability system, tailored to the different climate conditions and soil type, if the practice is incentivised by carbon removal units.
- Create detailed databases, including land use data, to measure and monitor soil systems and their health, including their baselines. Develop remote sensing and other machine learning techniques.