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FLUXES

The European Greenhouse Gas Bulletin

Nature-based solutions for net zero

Forest carbon sinks under pressure

Coastal ecosystems – reservoirs of life

Carbon farming – a path to more sustainable agriculture

ICOS Integrated Carbon Observation System

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#2 / 2023 Nature-based solutions for net zero

Photo: Sander Karsen

FLUXES by ICOS

ICOS, the Integrated Carbon Observation System, is a European-wide greenhouse gas research infrastructure: ICOS produces standardised data on greenhouse gas concentrations in the atmosphere, as well as on carbon fluxes between the atmosphere, the ecosystems, and the oceans. This ICOS-based knowledge supports policy and decision-making to combat climate change and its impacts.

The high-quality ICOS data is based on the measurements from over 170 observation stations – run by top universities and research institutions across 16 European countries – and produced by the roughly 800 scientists in the community.

The ICOS Carbon Portal offers unlimited access to thousands of datasets and other advanced digital products and services. ICOS has the status of an ERIC, European Research Infrastructure Consortium, with a legal capacity recognised in all countries within the European Union.

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FLUXES VOL 2

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DR WERNER L. KUTSCH

Director General of the Integrated Carbon Observation System (ICOS)

Carbon sinks are the hype of the time. Some say they are at risk of being lost, others say they need to be increased. For some, nature-based carbon sinks will solve the entire climate change issue. For others, they are negligible or too uncertain to count on. The fact is, however, that if we want to establish credible strategies to mitigate climate change, we need to evaluate the status of the nature-based carbon sinks and storages. This represents a massive challenge if we want to do it right.

The European Union (EU) has included new targets to increase natural sinks into its portfolio of measures to fight climate change. Natural sinks refer to the removal of carbon dioxide (CO_2) from the atmosphere and storing it long-term in forests, wetlands, soils and oceans. The EU regulatory framework currently under development calls for a scientifically-robust assessment of carbon removals. This is where ICOS has a role to play.

This issue of FLUXES addresses the potential and limitations of nature-based solutions for carbon removals from a scientific perspective: What can be measured? What conclusions can be drawn? What solutions seem adequate? The observational data produced by ICOS can support policy-makers in various ways. Robust data can help to identify whether and how strong a carbon sink is. Long-term and consistent data can produce reliable estimates of the sizes of the carbon pools and inform how these pools respond to environmental and management changes as the world transitions towards carbon neutrality.

To avoid the worst consequences of climate change, we absolutely must reduce our fossil fuel emissions. But if carbon removals will be absolutely needed to compensate and offset overshoot and unavoidable emissions – as nature is already helping by compensating almost half of the human-derived emissions – we need to be able to evaluate the nature-based solutions we have at hand. This issue of FLUXES sheds light on two such solutions: carbon storage on land and in the ocean via blue carbon. We at ICOS hope this ‘scientific voice’ will bring new perspectives and support those working with climate policies. ■

> “The EU regulatory framework calls for a scientifically-robust assessment of carbon removals. This is where ICOS has a role to play.

Nature-based carbon sinks have a dual role in climate action

Nature takes up carbon dioxide in its sinks, such as forests, soils and the ocean. For a carbon-neutral future to be realised, total human and natural emissions cannot exceed what sinks can absorb. Fossil fuel emissions must go to zero. ICOS provides almost real-time data on how nature responds to these reductions, which can be a powerful tool for informing which climate actions might actually be counterproductive.

Katri Ahlgren, Werner Kutsch, Sindu Raj Parampil

Photo: Adobe Stock

Analysing nature-based carbon sinks and evaluating their potential and limitations requires understanding of the carbon cycle and clear definitions. The Intergovernmental Panel on Climate Change (IPCC) describes four major sources of greenhouse gases: fossil fuels (extraction and burning of coal, oil and gas), land use, land use change and forestry (deforestation, soil disturbances, etc). All of these sources release carbon dioxide (CO_2). Other emissions, such as nitrous oxide and methane emissions from agriculture, are more potent greenhouse gases, but do not linger in the atmosphere as long as carbon dioxide. Of these three gases, CO_2 is the greatest contributor to climate change.

As part of the natural carbon cycle on land, CO_2 is taken up by plants, stored in biomass, dead wood and soils, and eventually released back to the atmosphere through respiration. In addition, CO_2 is taken up and released by the ocean through a combination of biological and abiotic processes. These exchanges of gases between plants and the atmosphere, and the ocean and the atmosphere, are often called fluxes.

Currently, the uptake and release of carbon dioxide by land ecosystems and oceans is almost in balance, with uptake being slightly higher than release. This net uptake of natural CO_2 compensates for a part of fossil fuel CO_2 emissions. However, the majority of fossil fuel emissions linger in the atmosphere for hundreds of years, increasing the CO_2 concentration.

Human disruption of the global carbon cycle

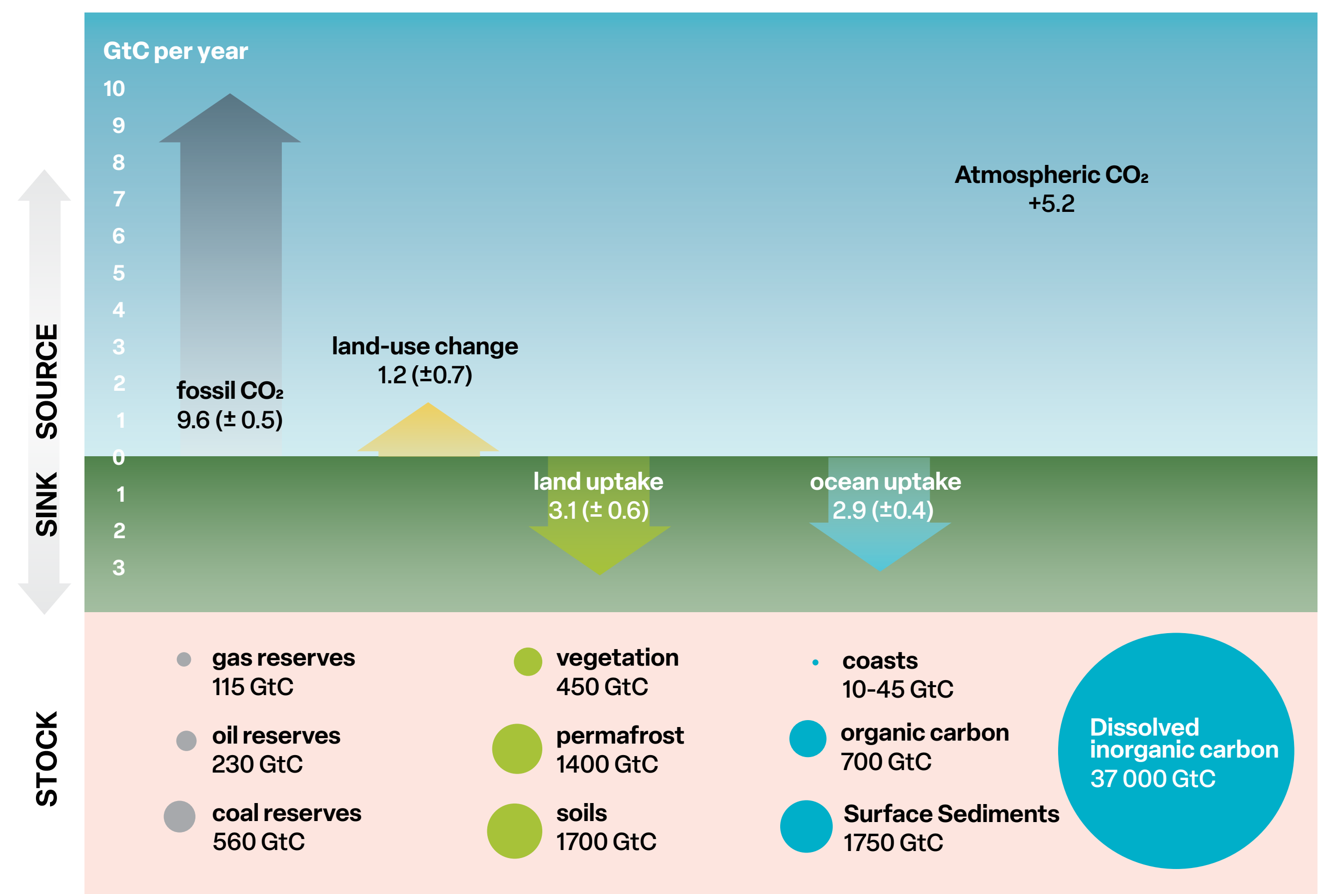


Figure 1. Average human influence in the global carbon cyclein GtC per year, gigatonnes of carbon, for the decade 2012-2021. adapted from Global Carbon Project 2022[1].

Strategies and regulations related to the European Green Deal

- **The EU Climate Law (2021)** establishes a framework for the irreversible and gradual reduction of anthropogenic greenhouse gas emissions by sources and enhancement of removals by sinks regulated in Union law.
- **The LULUCF Regulation (2023)** sets out rules concerning commitments of Member States for the land use, land use change and forestry ('LULUCF') sector that contributes to achieving the objectives of the Paris Agreement and meeting the greenhouse gas emission reduction target of the Union for the period from 2021 to 2030 and accounting for greenhouse gas emissions and removals from the LULUCF sector and checking the compliance of Member States with these commitments.
- **EU Forest Strategy 2030 (2021)** sets out to improve the quality and quantity of Europe's forests and strengthen their protection, restoration and resilience. The strategy also includes re- and afforestation, and focuses on monitoring, reporting and data collection, as well as improving our knowledge of forests through research and innovation. The Forest Strategy is part of the actions listed in the Biodiversity Strategy.
- **EU Biodiversity Strategy 2030 (2021)** and the related Nature Restoration Law currently under discussion, "aims to put biodiversity on the path to recovery by 2030." The actions relate to increasing the network of protected areas in the EU, restoring degraded ecosystems both on land and in the seas and unlocking new funding, as well as actions aimed at adopting the new global biodiversity framework. The law stresses the importance of protecting and restoring forests, as well as agricultural, marine and riverine ecosystems for the environmental benefits and services they provide and for their positive socio-economic impacts.
- **EU Soil Strategy (2021) and the related new Soil Health Law (2023-2024)** being prepared, target to improve the condition of European soils. The law will specify the conditions for healthy soil, determine options for monitoring, and lay out rules conducive to sustainable soil use and restoration.
- **EU Common Agriculture Policy 2023-2027 (CAP)** entered into force in January 2023. It aims to support farmers and improve agricultural productivity, ensuring a stable supply of affordable food and a living for farmers, while maintaining rural areas and landscapes across the EU. The new CAP also aims to make a significant contribution to the ambitions of the Green Deal, Farm to Fork Strategy, and Biodiversity Strategy.
- **EU Farm to Fork Strategy (2020)** aims at accelerating the transition to a sustainable food system that helps to mitigate climate change and adapt to its impacts, as well as reverse the loss of biodiversity. It also seeks to ensure food security and everyone's access to sufficient, safe, nutritious, sustainable food at an affordable price, while generating fairer economic returns.
- **Carbon Removal Certification Regulation (2023 or 2024)** is being discussed in the European Parliament and by the EU Council in 2023. According to the proposed criteria, the carbon removals need to be quantifiable, additional, long-term and sustainable, and they need to be verified by an external independent verification body. The regulation covers both industrial techniques and natural carbon removal solutions.

Photo: AdobeStock

Furthermore, the well-being and productivity of ecosystems are severely threatened by climate change. Temperature increases, changes in precipitation patterns and ocean acidification decrease sink capacity – alongside the pressures and strains human activity has on natural resources.

The carbon dioxide levels in the atmosphere will continue to rise dangerously until all sources and sinks, natural and human, are in balance. This balance is often called carbon neutrality, or net zero.

The most important climate action, therefore, is to reduce fossil fuel emissions as fast as possible. The second most important climate action is to reduce emissions from agricultural land use and land use change, e.g. by reducing deforestation, reducing the number of cattle, and improving fertilisation and other soil management methods.

These climate actions can be supported by measures that increase the carbon sink capacity – and here even more challenges start:

- What are the best ways to increase the number of long-lasting or even permanent carbon sinks?
- How do we predict the impacts of our actions?
- How are we going to monitor real success?
- How do we define additionality, e.g. whether our actions are increasing already existing carbon storage or uptake?

While legal rules and directives are under development, many of these questions remain unanswered.

The Green Deal requires scientific support

The EU has recently published several strategies and laws that seek to reach carbon neutrality, and is preparing additional measures. Many of these measures target reducing fossil fuel emissions. The newly-strengthened Emission Trading System, a mechanism through which companies must pay for their emissions, and tighter CO_2 emission standards for cars, are two examples of such measures.

The Green Deal aims to reduce the EU's greenhouse gas emissions by at least 55% by 2030 with climate neutrality achieved by 2050. The Deal aims at increasing and strengthening carbon sinks as a tool to mitigate and adapt to climate change, thereby preserving biodiversity.

The envisaged increase in carbon sinks is mainly related to the land use, land-use change and forestry (LULUCF) sector: reducing emissions from croplands or drained wetlands, and strengthening existing sinks such as forests and permanent grassland soils. The goal is to get overall LULUCF fluxes towards a sink of 310 Mt CO_2 equivalents by 2030.

The Green Deal in general and the related climate actions require strong scientific support and good dialogue between different actors. Scientists need to understand the needs of greenhouse gas emission inventory experts and policy-makers. In return, inventory experts will benefit from the latest scientific results. Long-term observational data plays a crucial role in both worlds and at their interface. This is exactly what research infrastructures and particularly ICOS can offer: ICOS measures greenhouse gases and the carbon cycle. With over 170 observation stations across Europe and the adjacent oceans, ICOS scientists deliver standardised, high-quality open data on land ecosystems, oceans, and the atmosphere, almost in real-time.

ICOS contributes to the Green Deal with long-term data and science-based knowledge

This FLUXES issue showcases ICOS contributions to Green Deal and other policies:

The carbon sink of European forests is rapidly decreasing, according to the latest greenhouse gas inventory report (2023). The reasons are manifold and need in-depth scientific analyses added to inventory calculations. ICOS observational data can be used together with modelling techniques to develop a validation and verification system for better estimating forest sinks and defining ways to increase them as envisaged in the LULUCF regulation. The Forest article discusses this, pages 14-25.

Over the last few decades, many agricultural soils in Europe have suffered a depletion of organic carbon, posing a risk of decreased yields, particularly during dry years. The new Common Agricultural Policy, CAP, and the new Soil Law aim at protecting and improving soil conditions by reducing soil carbon losses or even increasing the organic matter stocks in soils where possible. Since the carbon stock in soils takes years, even decades, to change, we need long-term measurements with standardised methodologies to track these changes. This is the core competence of ICOS RI, which runs long-term observations in croplands. Adding more agricultural sites into the ICOS network would improve our understanding and validation of changes in soil carbon stocks. This would in turn allow for estimating the success of chosen management strategies on a country or EU level. The Carbon Farming article discusses this in more detail (pages 40-51).

Another question is how actions with unknown success in the future can be monetised in the carbon offset market. Both LULUCF and the agricultural sectors are targeted by the new Carbon Removal Certification regulation, which is being discussed in the European Parliament and the Council during 2023-2024. According to the proposed criteria, carbon removals need to be quantifiable, additional, long-term and sustainable. ICOS data and science can give guidance and answers by defining certification rules and baseline information for measuring and verifying removals.

Photo: AdobeStock

> “Carbon dioxide levels will continue to rise dangerously until all sources and sinks, both natural and human, are in balance.

The ocean is an important natural carbon sink, and currently absorbs 25-30% of human emissions annually. The ocean absorbs CO_2 from the atmosphere, a process partly driven by physical properties like temperature, and partly by photosynthesis in marine vegetation such as algae, sea grasses, and salt marshes. This FLUXES issue takes a closer look at coastal marine ecosystems such as sea grasses that can sequester large amounts of carbon into sediments and vegetation. This is called blue carbon (pages 26-39). Protecting existing marine ecosystems such as sea grasses, salt marshes and mangroves in the marine environment can significantly contribute to carbon dioxide removal. While most of the ICOS ocean stations do not observe carbon pools in sediments or biomass, dissolved carbon in the surface seawater is being measured, along with alkalinity, nutrients, salinity and dissolved oxygen. These measurements play an important role in monitoring the ocean carbon cycle and, by extension, the health of marine vegetation, i.e. blue carbon. Quantitative estimates of the European carbon cycle require more comprehensive observations of the coastal ocean. This also highlights the importance of cooperation across organisations and the development of new technologies.

In addition to CO_2, other potent greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) increase the complexity of mitigating climate change. Methane has both natural and human-related sources, and it has a complex chemistry in the atmosphere, making its growth difficult to estimate. The methane article, pages 52-55, looks at the reasons driving increasing concentrations of methane in the atmosphere.

Finally, on pages 13-17 we show estimates of carbon dioxide fluxes between ecosystems and the atmosphere (Net Ecosystem Exchange, (NEE), ocean-atmosphere fluxes, and fossil fuel emissions illustrated using a map of Europe. These estimates are from a highly-integrated product of measurements and models. 'Net Ecosystem Exchange' indicates the net CO_2 exchange between plants and the atmosphere via photosynthesis and respiration. The map on fossil fuel emissions presents the distribution of CO_2 sources from human activity. ■

> "Long-term observational data can support policy-making with evidence on the efficiency of climate actions.

Photo: AdobeStock

Carbon emissions and sinks vary between the years

The maps in the following pages present the three major CO_2 fluxes for Europe and nearby ocean areas, and their variation from 2018 to 2022: biogenic fluxes of land ecosystems, ocean fluxes, and human emissions from fossil fuels.

By Alex Vermeulen, Werner Kutsch, Sindu Raj Parampil

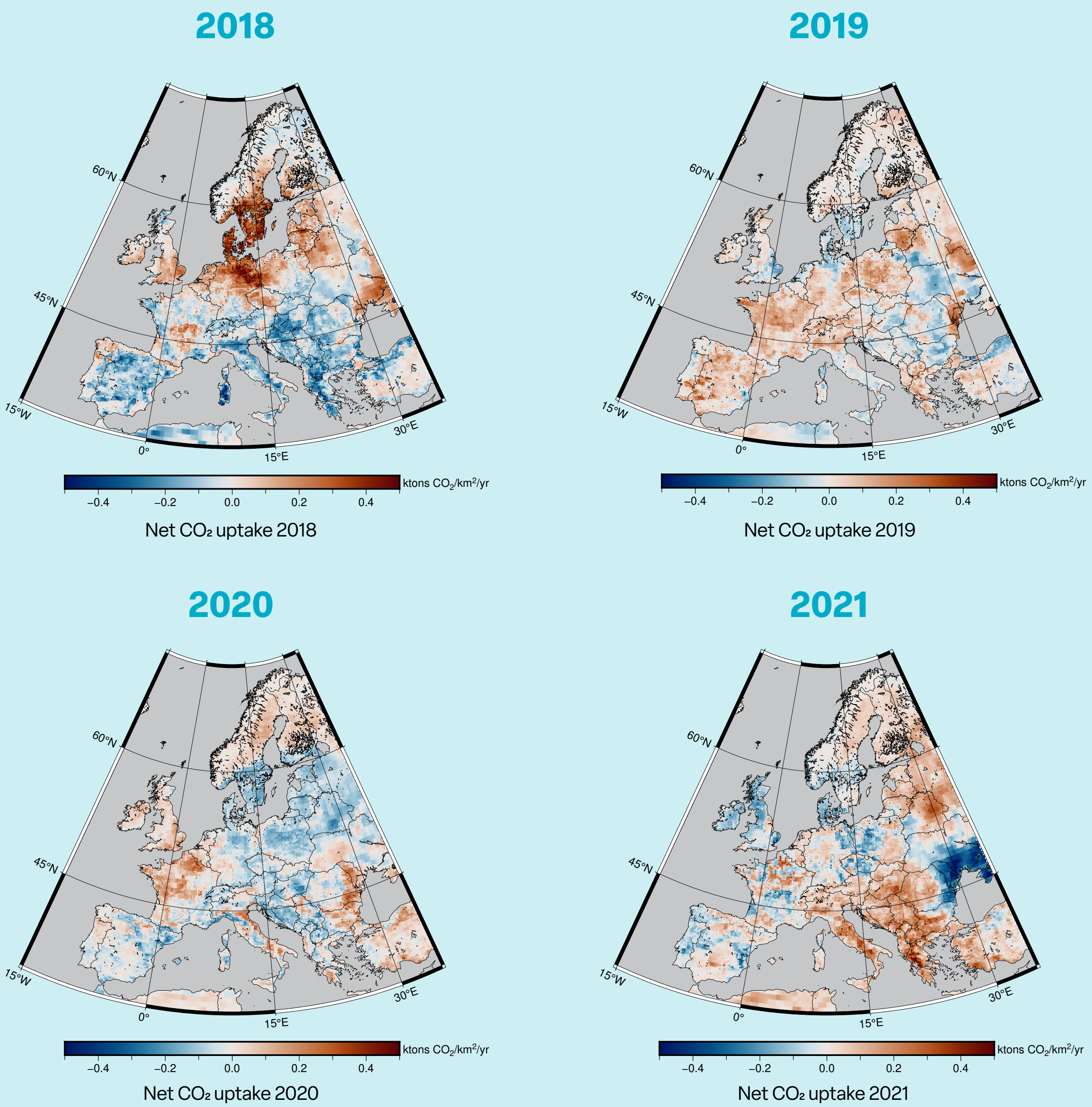
The concentration of CO_2 in the atmosphere is determined by the interplay between three major fluxes: biogenic land ecosystem fluxes, ocean fluxes, and human-induced emissions. Land and oceans often take up more CO_2 from the atmosphere than they release. In net terms, they are considered natural 'sinks'. Land and ocean sinks are also called 'nature-based carbon dioxide removal' and they balance parts of the emissions generated by human activity (fossil fuel burning, land use changes etc) which are 'sources' of CO_2.

Estimates of annual mean exchange fluxes means of these major fluxes over Europe for the year 2022 are shown in the following maps in the context of the previous years. It is important to note these are highly-integrated products of observations, inventory data, and models. Blue regions show net uptake of CO_2 from the atmosphere. In the red areas, more CO_2 is released than taken up, thus from these areas there is a net release of CO_2 to the atmosphere. Note that the maps show only the CO_2 exchanged between the atmosphere and ecosystems/ocean/emission sources - they do not account for carbon moved in or out of the region, for example crops or timber.

The fluxes presented here are annual means. The different fluxes also have widely ranging variability in time. Ocean fluxes show strong seasonal trends, but changes from year to year are rather small. Biospheric fluxes on land ecosystems have high variability and can even change direction from hour to hour, day to day, season to season and year to year. Anthropogenic fluxes vary strongly by the hour and by season, but not so much from year to year and only moderately from day to day. Although the annual average flux of biogenic sources is small compared to the annual average of areas with high fossil fuel emissions because of compensating biogenic sources and sinks, on hourly and daily time scales the fluxes per area are very comparable between biogenic and fossil fuel fluxes.

Net carbon dioxide uptake in the land ecosystems

Blue regions show net CO_2 uptake of land ecosystems, thus reducing the amount of CO_2 in the atmosphere. Red regions show net CO_2 loss, so CO_2 is released to the atmosphere. In 2022, Italy, parts of France and Germany, most of the Balkan countries, and the Iberian Peninsula showed pronounced carbon losses mainly related to dry weather conditions.



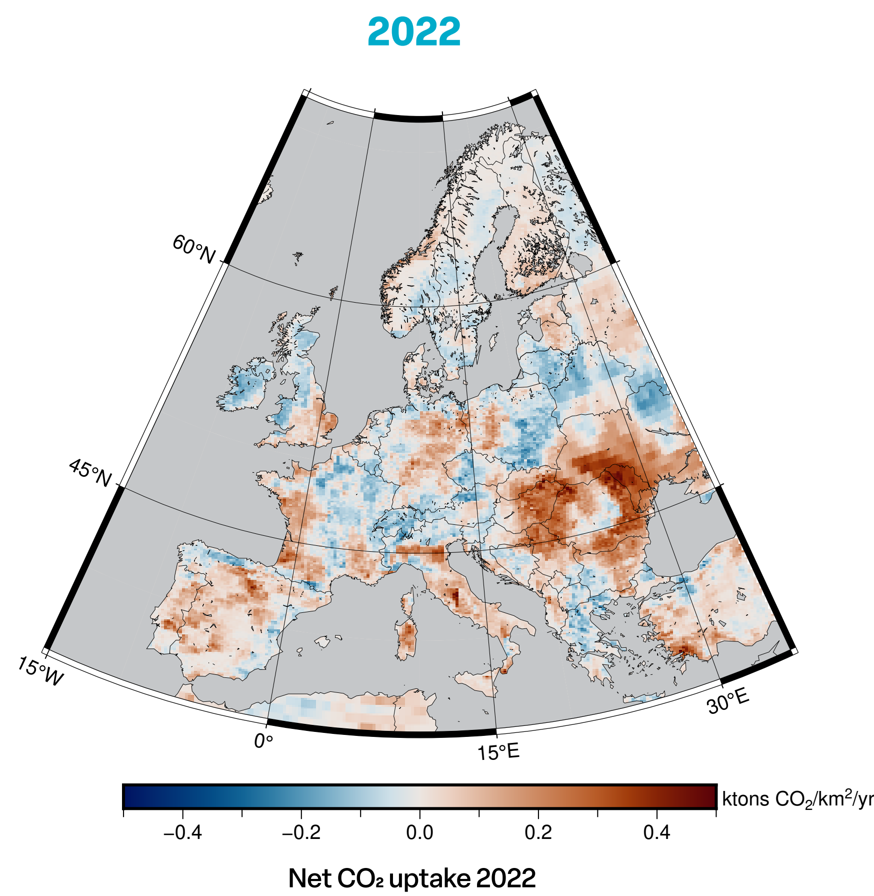


Figure 2. Annual mean net ecosystem exchange of central Europe from 2018 to 2022[1].

The maps use highly-integrated products based on observations, inventory data and models (hence are not the outcome of one kind of data alone). The colour scales in the maps are different to account for the different magnitude of the fluxes.

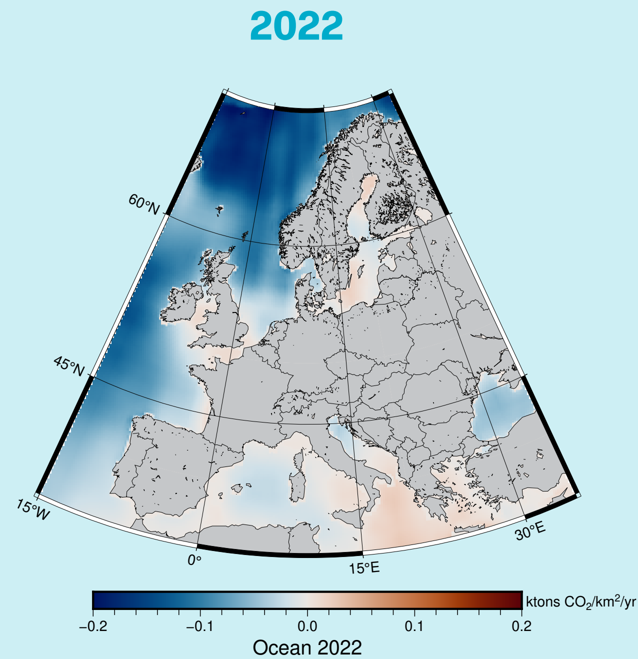
The biogenic land ecosystem fluxes (Figure 2) show the net ecosystem exchange (NEE), the balance between photosynthetic uptake of CO_2 (gross primary production, GPP) and release of CO_2 (total ecosystem respiration, TER). Land ecosystem fluxes over Europe show a complex pattern of regions with regards to net CO_2 uptake and release. This pattern changes from year to year with the weather being the main driver of the land fluxes and land management the second most important factor. In regions with net uptake (in blue), the weather has been favourable and no other major disturbances have occurred. Thus, photosynthesis in these ecosystems over the year was higher than the release by respiration. In red regions, unfavourable weather conditions (e.g. droughts) or major disturbances (e.g. excessive forest harvesting) resulted in a net release of CO_2. On average, land ecosystems take up about a quarter of the global human-induced CO_2 emissions, but the year to year variability is large. Europe reports a land sink through the LULUCF part of the inventories which is currently ~230 Mt CO_2e per year for the area of the European Union. However, this number cannot directly be compared to the maps shown here since the lateral fluxes are treated differently in both systems (see article on carbon farming). Nevertheless, these maps include an important message related to the ambition of the EU to increase the land sink: deep red areas symbolising severe droughts (e.g. 2018 in Germany, Denmark and the South of Sweden or 2022 in the Balkan region) have become more frequent and influence the land sink severely.

The maps are based on measurements from ICOS and other sources and models (see references for more information). Lateral fluxes of carbon (harvest, manure) are not considered.

Net carbon dioxide uptake in the ocean

These maps show strong CO_2 uptake in the open ocean. Fluxes in the coastal areas, the Baltic Sea, the English Channel, and the Mediterranean Sea show a more complex pattern of sources and sinks. The inter-annual variation is small.

Ocean is a significant sink as it takes up about another quarter of the global CO_2 emissions. Ocean fluxes per area are smaller than the land fluxes and vary significantly depending on the region while inter-annual variation is small (Figure 3). They are calculated based on surface ocean measurements of dissolved CO_2 which are conducted by ICOS and combined with other observations in the global data base SOCAT (Surface Ocean Carbon Atlas). The biggest differences are seen between the open ocean and coastal regions. Generally, the open ocean takes up CO_2 from the atmosphere (in blue), while many coastal regions release CO_2 – into the atmosphere (in red). However, proximity to land adds to this complexity and coastal regions can be both sources and sinks.



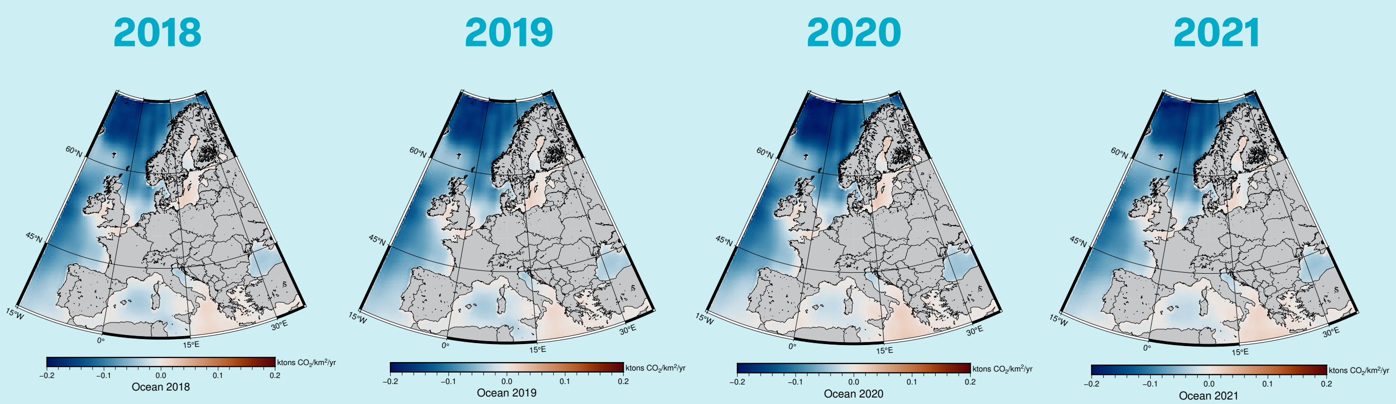


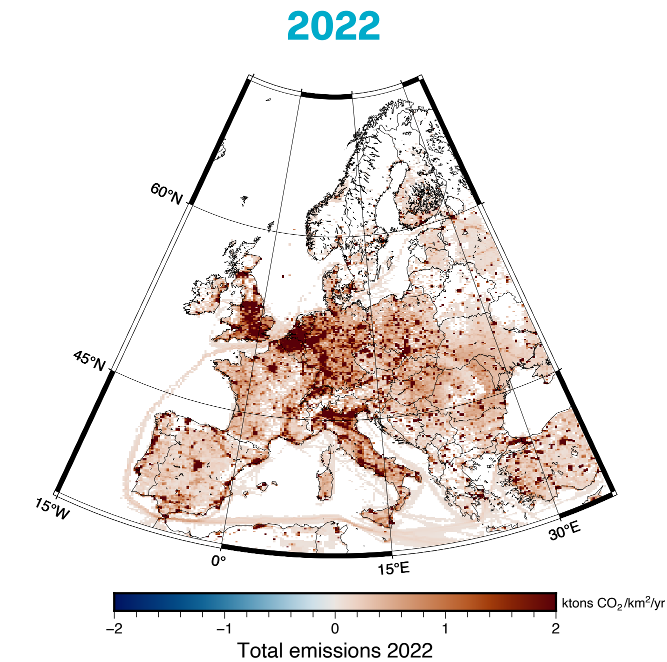
Figure 3. Annual mean net ecosystem exchange of oceans and coastal regions around Europe from 2018 to 2022[1].

Carbon dioxide emissions from human activity

CO_2 emissions from human activity include contributions from electricity production, industry, households, ground transport, aviation, shipping and cement production. Highest emissions are seen in industrial areas and densely populated cities.

The map of fossil fuel emissions shows only red regions and the scale of the emissions is larger than that of biogenic and ocean fluxes by a factor of 10 (Figure 4). Emissions from marine transport can be seen clearly along major shipping routes.

The figures illustrate that we continue to produce more emissions than terrestrial ecosystems and oceans take up, suggesting that European efforts towards carbon neutrality have not been very effective until 2022 (as reported in FLUXES Vol. 1, 2021). Natural sinks continue to become more vulnerable due to climate change. Thus, the key message in this second volume of FLUXES has not changed: the only way to mitigate climate change is to rapidly reduce fossil fuel emissions.



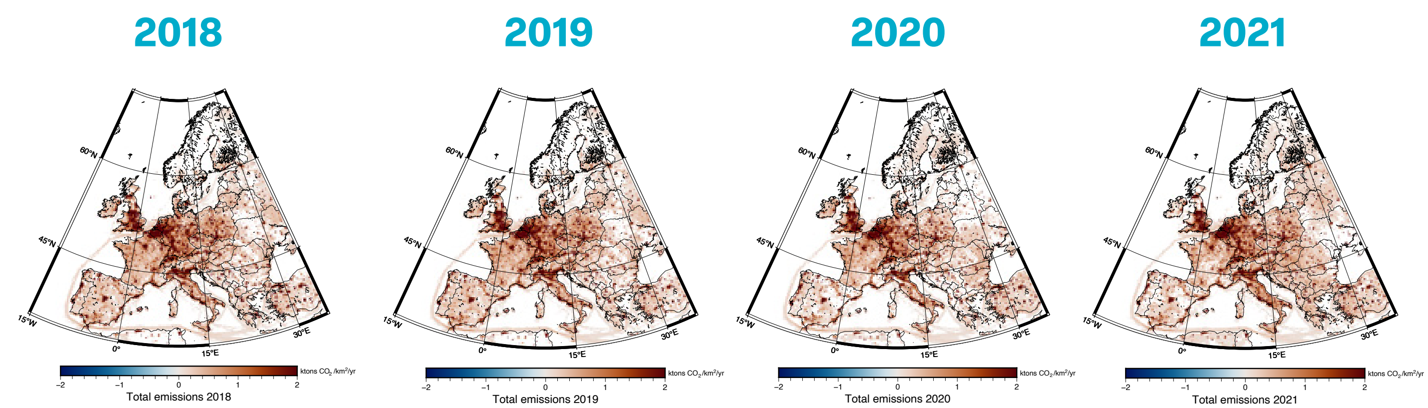
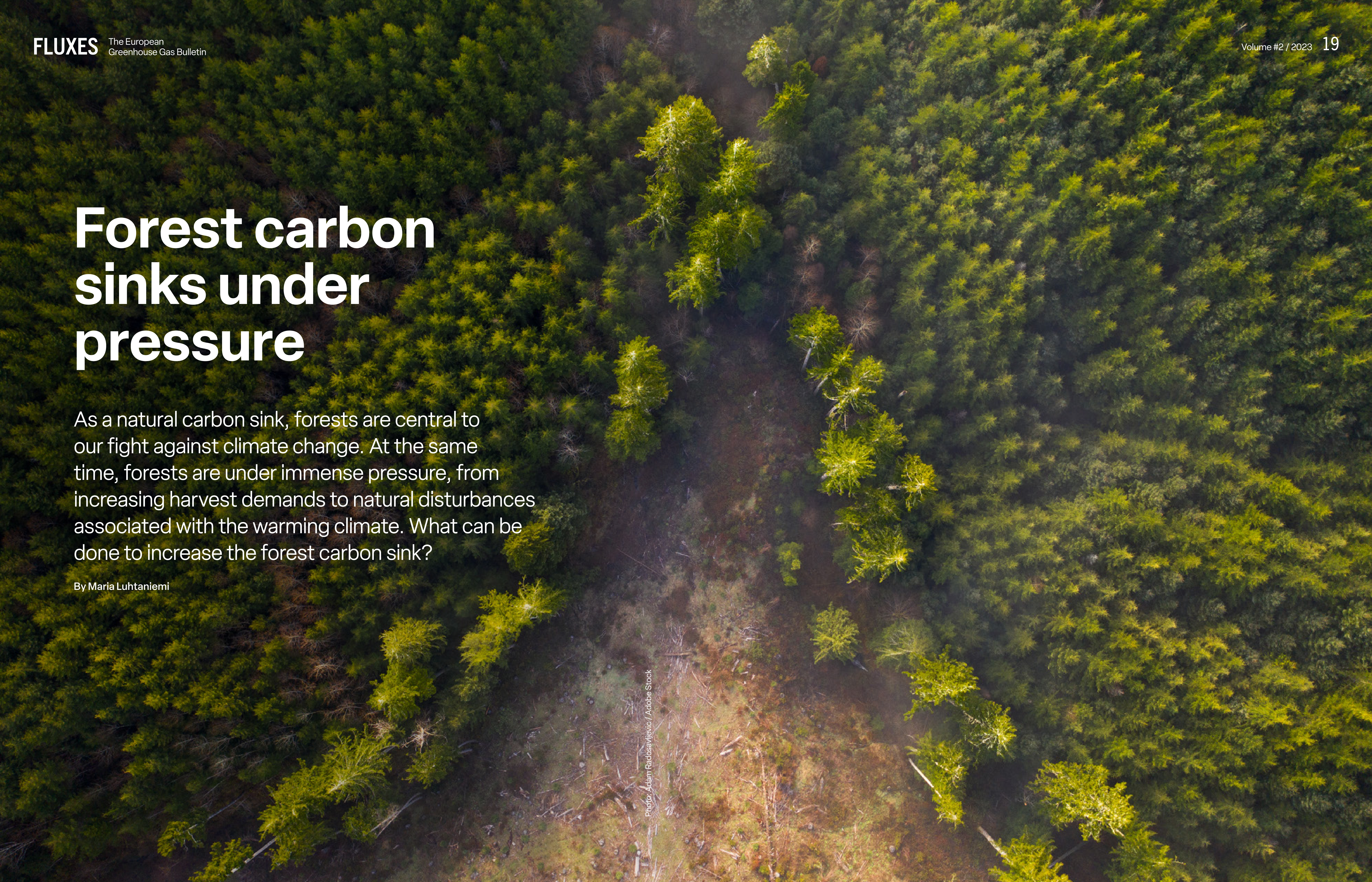


Figure 4. Annual mean human emissions of CO_2 from fossil fuels in and around Europe from 2018 to 2022. Highest emissions are in industrial areas and highly populated cities[1].



Forest carbon sinks under pressure

As a natural carbon sink, forests are central to our fight against climate change. At the same time, forests are under immense pressure, from increasing harvest demands to natural disturbances associated with the warming climate. What can be done to increase the forest carbon sink?

By Maria Luhtaniemi

Photo: Adam Radosavljevic / Adobe Stock

Key takeaways

- **The EU's total forest carbon sink decreased** by nearly a third between 2010 and 2020. This decrease is attributed to increased harvests and natural ageing of the forests.
- **Climate change** creates new threats for forests. Fires, droughts, insects and other disturbances diminish the forests' ability to take up and store carbon.
- **Clear-cutting** turns a forest into a carbon source. It can take up to 15 years until the forest becomes a sink again, and 20-40 years until initial emissions are compensated for.
- **Old forests** are vital for carbon storage and biodiversity. The last remaining old forests in the EU should be protected immediately.
- **Forest carbon sinks** should not be used as an excuse for watering down ambitions of emission reductions. Reducing the use of fossil fuels is still by far the most impactful climate mitigation measure.

Forests have an incredible ability to store carbon – both below ground in the soil and roots – and above ground in the tree's trunk and branches, making them an important ally in the fight against climate change. The forest sector is highlighted in the Paris Agreement as one of the key components in climate change mitigation. The European Union (EU) also relies on forests to stay on track with their climate targets.

One example is the EU Forest Strategy 2030, which seeks to increase the quantity and quality of natural carbon sinks in Europe, by planting new forests and halting deforestation. Similarly, the EU's new regulation for the land-use sector (LULUCF) aims to increase the forest carbon sink by 42 million tonnes of CO_2 equivalents by 2030, compared to 2016-2018, bringing the total net sink to 310 million tonnes of CO_2 equivalents. To help achieve this goal, LULUCF introduces targets and improved monitoring requirements for all EU member states.

Besides their ability to store carbon, forests perform a variety of positive functions for natural and human life. They provide livelihoods, recreation, and mental and physical wellbeing for people. Forests also provide habitats and host biodiversity, conserve soil and prevent land degradation. They help in adapting to climate change, and protect against natural disasters such as floods.

The forest carbon sink, however, is currently exhibiting concerning signs of diminishing capacity. Between 2010 and 2020, the EU's total carbon sink from forests and their soil decreased by nearly a third, from approximately 430 to 290 million tonnes of CO_2 equivalent per year.[1] The decrease in the forest carbon sink has been attributed to increasing harvests, stress factors, and to the natural ageing of the forests. Climate change is putting forests under growing pressure through climate extremes and increased natural disturbances such as wildfires, droughts, and insects. This article explores ways in which European forest carbon sink could be strengthened in the face of conflicting demands and new risks posed by climate change.

Clear-cutting increases greenhouse gas emissions

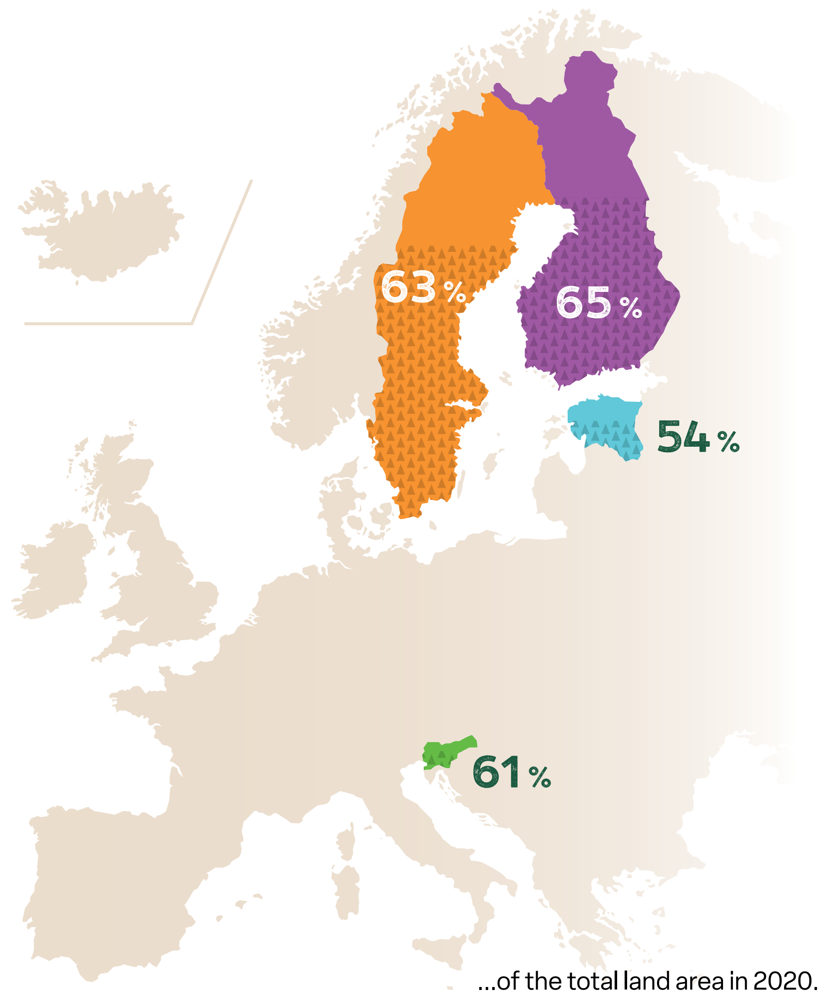
The EU's boreal region, consisting of most of Sweden and Finland, and all of Estonia, Latvia and Lithuania, is a major timber-producing region, with most of the land dedicated to commercial forestry. The dominant form of forest management in this region is rotation management, where forests are managed in cycles called rotation periods, with clear-cutting towards the end of the rotation. Rotation-managed forests are typically less biodiverse compared to natural forests, and they are generally less resilient to natural disturbances such as storms, insects and droughts.

Clear-cutting increases greenhouse gas emissions, transforming the forest from a carbon sink into a carbon source. After a clear-cut, it takes 10-15 years for forest in temperate and boreal regions to become a carbon sink again, and 20-40 years until initial emissions

forest facts

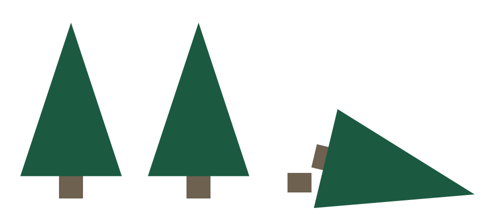
FORESTS COVER AROUND 40 % OF EUROPEAN LAND

THE MOST FORESTED COUNTRIES IN EUROPE ARE FINLAND SWEDEN SLOVENIA AND ESTONIA



...of the total land area in 2020.

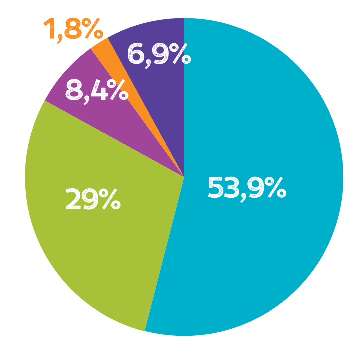
The EU total carbon sink from forests and their soil decreased by nearly a third in 2010–2020, from 430 to 290 million tonnes of CO_2 equivalent per year



NEARLY 10%

of total EU greenhouse gas emissions each year are absorbed by EU forests.

Proportions of forest carbon pools in Europe 2020



Soil 53,9%
Above-ground biomass 29%
Litter 8,4 %
Below-ground biomass 6,9%
Deadwood 1,8 %

Clear-cutting turns a forest into a carbon source. It can take

UP TO 15 YEARS*

until the forest becomes a sink again, and 20-40 years until initial emissions are compensated for.

* The speed of the recovery depends on the size of the clear-cut, climate and soil conditions as well as the tree species in question.

Sources: Eurostat 2020, Forest Europe 2020, Copernicus, EEA 2023 associated with the clear-cut are compensated for [2,3,4]. The speed of the recovery depends on the size of the clear-cut, local climate and soil conditions as well as the tree species in question.

Clear-cutting is heavily restricted by law in many parts of central and southern Europe largely due to the risk of increasing soil erosion, particularly in mountain areas. In the Nordic countries, however, it remains a widely used method.

“Some researchers and forestry experts say that clear-cutting is not harmful because you still have carbon uptake on the landscape level. For me, this is a weak argument, because by improving the carbon uptake in all forests [by avoiding clear-cuts], the total carbon uptake of this landscape would be higher,” says Dr Patrik Vestin, Research Engineer at Lund University in Sweden. “Harvesting operations can also increase the risk of storm damages in thinned stands and in stands surrounding clear-cuts.”

Selection harvesting is an alternative to rotation management. Harvest removals by this type of management are made by selectively harvesting individual trees or small groups of trees and retaining the rest of the trees in the forest. The method is considered less intrusive to the forest ecosystem, particularly regarding soil, which is one of the important components of the forest carbon sink.

“Forest soil stores three times more carbon than the trees above ground,” adds Dr Manuel Acosta, Senior Scientist from Global Change Research Institute CAS - CzechGlobe “The less you disturb the soil, the better.”

Around half of the forests in the EU are privately owned and, according to Patrik Vestin, the benefits of selection harvesting are usually the biggest for private forest owners. “The cost of harvesting is higher in the selection system, but the total cost is most likely lower. The slightly higher harvesting costs are probably compensated for by the avoided costs of soil scarification, planting, thinnings etc. associated with the rotation system.”

Clear-cutting has historically been favoured due to cost-efficiency and its ability to produce high yields and financial gains.

”A commonly-heard statement in the Swedish debate is that selection-managed forests grow 10-20% slower compared to rotation-managed forests,[5]” says Prof. Anders Lindroth, from Lund University in Sweden. “This has been challenged in several studies, including a Finnish modelling study which showed that carbon budget in selection-managed forests was on average 35% higher over a 100-year period compared to that of rotation-managed forests.”[6]

> “Forest soil stores three times more carbon than the trees above ground.

”There is no consensus that selection-managed forests would have a larger net carbon sink on the long-term, compared to rotation-managed forests, but there are some results that point in that direction,” Lindroth summarises. ”Most research is done on rotation-managed forests, so selection management needs to be studied more.”

Choosing a certain method permanently is not strictly necessary, some researchers argue. Instead, owners should select the method according to what is best for a forest at a certain point in time. National forestry recommendations in Finland, for example, have as many as 12 different types of forest management methods, and emphasise that choosing the harvesting methods should be a free choice.

Whether clear-cuts should be avoided or not divides experts. Some are in favour of multi-objective forest management, which allows for small clear-cuts as well, while others support dramatically reducing the clear-cuts.

“Sweden and Finland are in a fantastic position to meet the climate mitigation targets,” Anders Lindroth points out. “For me, reducing clear-cuts and having a financial system where landowners are compensated for storing carbon would be the best way to meet these targets.”

Forests do more than just store carbon

Climate change poses many risks to overall forest health. Degradation of forest health can lead to a phenomenon known as forest dieback, where forests start to die without a visible cause.

The effects of thinnings to annual carbon uptake and release in Hyytiälä, Finland 2018-2022.

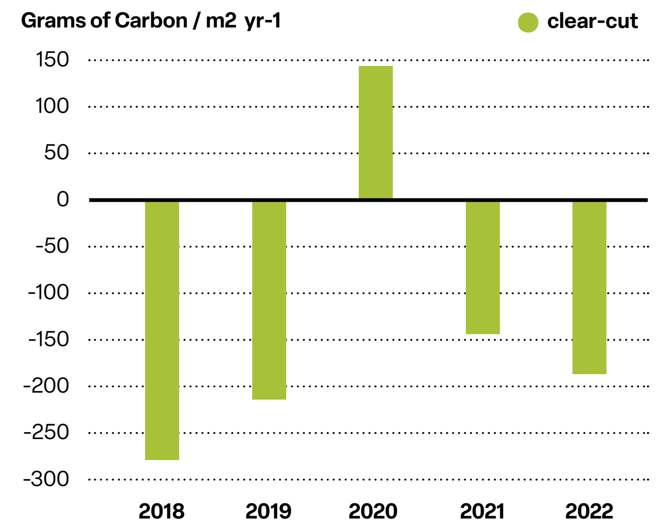


Figure 1. Graph showing the Net Ecosystem Exchange (NEE) on a forest site on mineral soil in Hyytiälä, Finland. The forest acted as a carbon sink until 2020, when thinnings took place, after which the forest turned temporarily into a source of carbon. Values below zero indicate a carbon uptake, i.e. the forest being a carbon sink, whereas values above zero mean the forest was a carbon source. The forest carbon sink recovered in the following years but to a lower level than before the thinnings.[12]

The effects of clear-cuts and partial cuts to annual carbon uptake and release in Lettosuo, Finland 2016-2021.

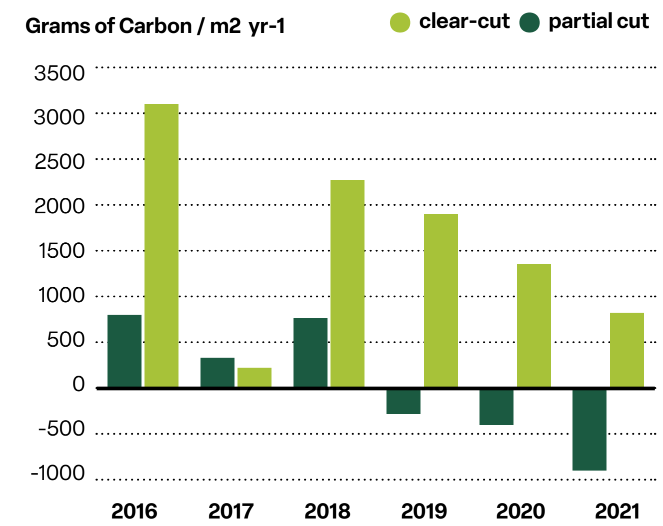


Figure 2. Graph showing the Net Ecosystem Exchange (NEE) on a forest site on organic soil (peatland) in Lettosuo, Finland. Values below zero indicate a carbon uptake, i.e. the forest being a carbon sink, whereas values above zero mean the forest was a carbon source. Clear-cuts and partial cuts in 2016 turned the site from a carbon sink to a carbon source. The recovery from a clear-cut was much slower than from the partial cuts because in the partial cuts, some trees were left in the area.[13]

Years before the forest has compensated the carbon dioxide losses caused by a clear cut and turned to a sink.

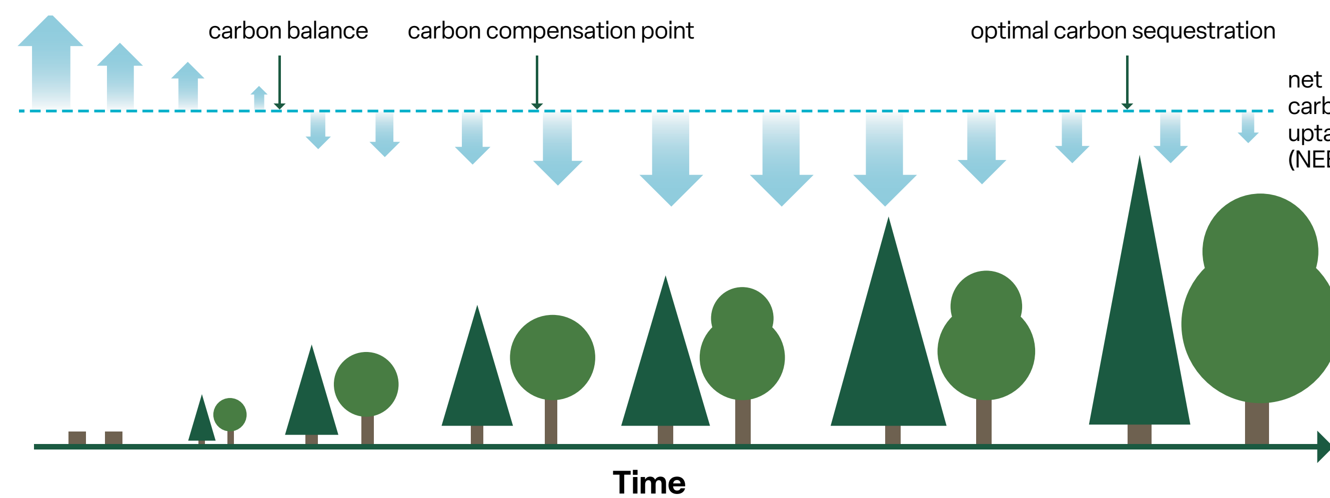


Figure 3. Clear-cutting of a forest causes large CO2 emissions immediately after the cut. It takes years before the forest can achieve carbon balance again, and even longer until the initial losses are compensated for. To determine the time for optimal carbon sequestration, it is important to know, how the carbon dioxide uptake (Net Ecosystem Exchange, NEE) of the forest varies over time.[14]

"Large-scale diebacks would not only disrupt biodiversity and carbon storage but the overall forest bioeconomy," says Dr Sebastian Luyssaert, Associate Professor from Vrije Universiteit Amsterdam. "We have seen this with storms before, such as the Gudrun storm in Sweden, that have suddenly destroyed so much wood that the market was disrupted for several years."

Luyssaert argues that merely increasing carbon sinks can be dangerously short-sighted and that by focusing only on one aspect, we risk repeating the mistakes of the past. Production-oriented forest management in Europe over the last 100 years has led to monoculture forests, which are now increasingly vulnerable to climate change. More recently, attempts to increase wood production and carbon stocks in southern Europe through planting eucalyptus forests have led to an increased risk of wildfires.

"From a pure carbon storage point of view, monoculture could be a way to go, but from all the other aspects, it's not working. Biodiversity in these types of forests is extremely low, risk of fire is higher, and erosion will likely happen because of the very short, 12-year rotation periods," he says. "These are the kinds of problems we run into when we only focus on one aspect of the forest ecosystem."

"The carbon sink is important, but should not be the only focus," agrees Dr Giacomo Grassi, Senior Scientist at the Joint Research Centre (JRC) of the European Commission. "We need to find win-win solutions between maximising the sink and adapting the forests to climate change. Resilient forests are a prerequisite for any mitigation strategy."

Biodiversity is key for resistant forests

One cautionary tale of neglecting biodiversity can be taken from the Czech Republic, which between 2017 and 2019 was the epicentre of an extreme spruce bark beetle epidemic. The outbreak, caused by droughts that had weakened the natural defence mechanisms of the trees, damaged 3-5% of the forests planted with Norway spruce-trees distributed in low to medium elevations. Some regions encountered total destruction of these forests. A decrease in timber price, an excessive workload, and other cascading effects caused large revenue losses, requiring state interventions amounting to around 260 million euros.[7]

"Losing that much forest in less than a year was a shock to society," explains Manuel Acosta. "Now that people could see the consequences of climate change, landowners started to listen and change the composition of the Czech forests. Preventing future bark beetle attacks is now a priority in the national forest policies."

> "When you have a high level of biodiversity, the whole ecosystem benefits.
>
> Dr Manuel Acosta, Senior Scientist, CzechGlobe

The Norway spruce forests in Czech Republic, which were impacted by the bark beetle, were particularly vulnerable because of the species' high sensitivity to droughts, which in turn diminished their resistance to the insects. Having large forests of just this one species helped the bark beetle to spread freely from one tree to the next. Acosta recommends always matching the tree species to the site conditions, specifically in regard to the water supply.

"When you keep the forest in good condition and have a high level of biodiversity, the whole ecosystem benefits. The research undertaken with data from the ICOS station Lanžhot – which we call the Amazon of Czech forests thanks to its incredible biodiversity – is a good example of the importance of a mixed forest."

Old forests important for carbon storage and biodiversity

Old forests can store carbon for centuries and thus play a significant role in climate mitigation.[8] Additionally, old forests are important for biodiversity. They are recognised as one of the species' richest ecosystems in the European Union, and are very rare. The EU Biodiversity Strategy aims to protect these forests completely.

"There's an absolute need to increase the preservation of our last pristine forest ecosystems," Patrik Vestin emphasises. "Both for carbon storage and biodiversity."

Forests are often harvested too young. In Finland and Sweden, for example, forests are harvested by clear-cutting usually between 45 and 100 years after initial

> "Losing that much forest in less than a year was a shock to society.

photo: Konsta Punkka © ICOS

Researcher Marian Pavelka controlling the automated chamber system for stem CO_2 efflux measurements at ICOS station Lanžhot in Czech Republic.

"We need to decarbonise society, not rely solely on forests."

Dr Clemens Blattert, Scientist, WSL

"We should not overestimate the contribution of forests and their timber resources in climate change mitigation", says Dr Clemens Blattert.

Photo: Carmen Sirboiu

planting, depending on site productivity and geography. In many cases trees are harvested quite close to the minimum age, although trees are able to sequester carbon for much longer. A recent study concluded that the optimum age for harvest in the boreal region was in fact between 138-155 years[9], and at that age, the trees were still resistant towards natural disturbances. Longer rotation periods would thus be very beneficial for carbon sequestration and climate change mitigation.[10]

Allowing forests to grow for longer in one location could, however, increase the pressures for harvest elsewhere. Intensive forestry in a limited area has been seen as a possible way to satisfy the need for timber but take the pressure off other types of forests. The sole purpose of this type of plantation forestry is to produce large amounts of wood. Plantation forestry has been practiced in southwestern Europe, but experts say their placement should be considered carefully.

"These types of forests should not be planted on the most fertile land so that they don't conflict with food production," says Dr Giorgio Matteucci, Research Director at the National Research Council of Italy. "Public opinion is often against this plantation forestry because of their artificial nature, but for the sake of reducing the burden of wood production from the natural forests, they could be considered."

In scientific debates, plantation forests have often been viewed rather negatively because of their low biodiversity. Proponents of this type of forestry argue, however, that problems can be avoided with proper management. Water and fertiliser use should be considered carefully, and the species should be selected for their ability to maintain or enhance the capacity of the forest to adapt to climate change.[10]

"In some countries, such as Brazil and China, plantation forests provide most of the wood needed for industrial use, including pulp and paper. This has reduced the exploitation of natural forests," Matteucci adds. "In Brazil, there is a serious problem of deforestation of the tropical forests, but this is caused mostly by agriculture and meat production, and not by plantation forestry."

Forest strategies produce diverse outcomes

Though the LULUCF regulation impacts legislation across the EU Member States, the EU has no common forest policy in place, as forests were not included in the

Modelling of the forest carbon sink under three different Finnish forest strategies

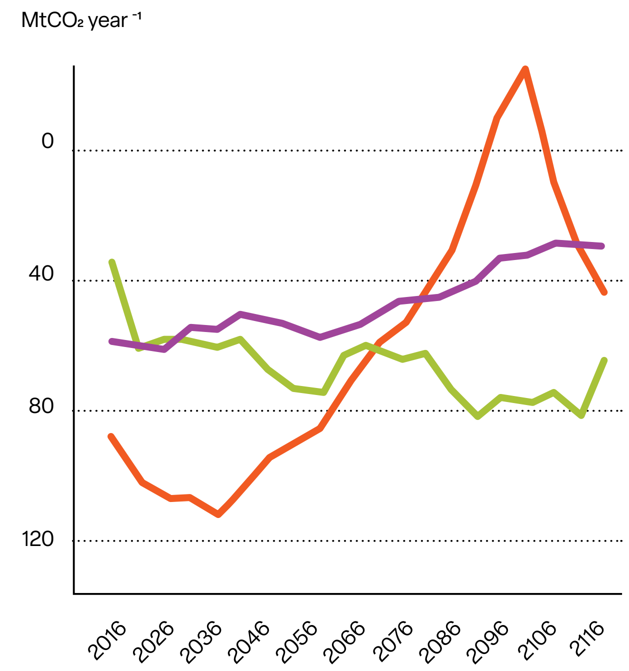


Figure 4. Graph showing the results of a modelling study done on the outcomes of three different Finnish forest strategies. The model did not include natural disturbances (i.e., insects, storms, or droughts).[11]

Rome Treaties. Agriculture, on the other hand, has been regulated with binding Common Agricultural Policy (CAP) in place since the 1960s. Forestry has been viewed under the competencies of each EU member state.

Finland, which is one of the EU's most forested countries, has three different forest policies: the National Forest Strategy, the Bioeconomy Strategy, and the Biodiversity Strategy, which all have rather different emphases. A recent modelling study explored the consequences of pursuing the multiple objectives stated in these three Finnish forest strategies over a 100-year period.[15] From the perspective of the carbon sink, the National Forest Strategy produced the best outcome.

"The scenario representing the National Forest Strategy was the only one that included carbon sinks in the optimisation, while the other two addressed it more indirectly. It also emphasised selection harvesting more than the other two scenarios," explains Dr Clemens Blattert, the lead author of the study. "The Biodiversity Strategy, additionally, allowed for some harvests after reaching conservation targets, which is why you see a big increase in the graph around the 2080s."

Tradeoffs are normal for forestry, says Giacomo Grassi. "The debate around forestry is often quite polarised in Europe," he says. "People want more nature and biodiversity, but at the same time, they want wood to be used to spur economic growth and the bioeconomy. The best strategy maximises all these factors in policy-determined timeframes."

The forest carbon sinks are under a lot of pressure

The EU climate neutrality target for 2050 includes the increase of EU carbon sinks by 42 Mt CO_2e by 2030. The reality is, though, that the forest carbon sink cannot be increased indefinitely nor replace emission reductions in other sectors.

"This is indeed a challenging target," says Lucia Perugini, Senior Scientific Manager at The Euro-Mediterranean Center on Climate Change. "The forests in Europe are ageing, and facing a lot of pressure from natural disturbances. If you look at the projections, the forest sink is either stable or decreasing."

Perugini points out that increasing the forest sink is needed to counterbalance emissions that are hard to abate, such as emissions from agriculture. To incentivise forest owners to increase their carbon sinks, the EU is developing a regulation for carbon removal certification (see pages 40–51 in this issue).

"We need a combination of locally-determined solutions to maintain and, whenever possible, increase the forest carbon sink, while taking into account resilience and adaptation needs," says Grassi. "Solutions might include increasing afforestation, stimulating forest growth, or extending rotation lengths. They could also include climate-smart uses of wood, such as a shift towards more long-lasting wood products and improvement of the cascading use of wood over direct energy use."

> "We need a combination of local solutions to maintain and, whenever possible, increase the forest carbon sink.
>
> Dr Giacomo Grassi, Senior Scientist, JRC

To fully assess the effectiveness of any actions, and to change course if necessary, we need up-to-date information on how our actions impact the forest carbon sink.

"You cannot determine where to go next if you do not know where you are now," Grassi says. "We need timely monitoring of our actions in different locations and over long periods of time."

This is where the ICOS research infrastructure can come into play. ICOS has almost 100 ecosystem stations all around Europe making continuous measurements of greenhouse gases in croplands, grasslands, forests and more. ICOS data can be used for modelling and verifying emissions.

"The greenhouse gas inventories used by the EU are tied to IPCC guidelines. The eddy covariance method, used by ICOS to measure the CO_2 uptake and release, is not fully recognised by IPCC, meaning ICOS cannot directly contribute to the inventory," Lucia Perugini says. "Regardless, ICOS can definitely provide data for the modelling of forest dynamics, which can then be used by the countries when reporting their emissions for the United Nations Framework Convention on Climate Change (UNFCCC)."

While forests have their part to play, climate scientists unanimously agree on one thing – we need to keep reducing our use of fossil fuels.

"We should not overestimate the contribution of forests and their timber resources in climate change mitigation," Clemens Blattert says. "We need to decarbonise society and reduce carbon output, not solely rely on forests." ■

Dr Natalia Kowalska, Principal Investigator at ICOS station Lanžhot and Dr Daniel Burgas, Senior Researcher from the University of Jyväskylä, were also interviewed for this article.

Photo: AdobeStock

ICOS station Norunda collects essential data on the impacts of clear-cut

Norunda is Sweden's oldest measuring station for greenhouse gases. The forest around the station has been managed at least for the last 200 years by different land owners. During late summer and autumn 2022, an area of 300 metres around the station (30.5 hectares) was clear-cut completely.

The carbon dioxide measurements showed a significant increase following the clear-cut. "Usually, the carbon dioxide concentration is around 410 ppm, but now it has risen to about 500 ppm for short periods, with a few peaks above that. It is a significant increase," points out Dr Natascha Kljun, Professor at Centre for Environmental and Climate Science at the Lund University and the leading scientist of the ICOS station Norunda.

During the following year, forest owners and managers will carry out soil scarification, and plant young pine seedlings. It will probably take 10-15 years before they have grown enough to turn the forest into a carbon sink.

"We now have an excellent opportunity to see how the carbon cycle changes with clear-cutting, replanting and tree growth. This will help us to calculate how much the forests can help to slow down climate change in the future," says Kljun.

Original article by Sara Håkansson, Lund University

Coastal ecosystems, reservoirs of life

Coastal ecosystems sequester carbon from the atmosphere, help maintain high biodiversity levels, enhance water quality, protect coasts from extreme tidal events, and are an important resource for coastal communities. Despite the benefits they provide, coastal ecosystems are still poorly understood and face life-threatening pressures from human activities. As European coastlines lose their natural habitats rapidly, time is running out for action.

By Laurent Chmiel

What is blue carbon?

The term blue carbon was coined to differentiate carbon sequestered by coastal ecosystems from carbon sequestered by land ecosystems. It refers to carbon sequestered from the atmosphere and stored in biomass, soil and sediments of vegetated coastal ecosystems such as mangroves, salt marshes, seagrass meadows, and seaweed beds.[1] In particular, "coastal blue carbon" has emerged as a potentially promising contribution to climate change mitigation.

Healthy Fucus vesiculosus in shallow waters.

Photo: Alf Norkko

Key takeaways

- Coastal ecosystems provide significant benefits such as contributing to biodiversity, improving water quality, providing resources for coastal communities, consolidating shorelines and sequestering carbon from the atmosphere.
- It is estimated that Europe has lost 50% of its coastal ecosystems since the 1950s, rising to 80% in some regions. Climate change is accelerating this loss.
- Coastal ecosystems degraded by eutrophication or other human activities, have been shown to emit more carbon dioxide (CO_2) and methane (CH_4) than healthier ones.
- Losing more coastal ecosystems would have an enormous financial cost: the cost of shoreline erosion in Europe was estimated in 2004 to be one billion euros per year. When accounting for biodiversity loss, decreased water quality and degraded coasts as well, the cost would increase by several billion annually.
- More measurements are needed to fully understand how coastal ecosystems sequester carbon, at what rate, and under which conditions. We also need to quantify how much greenhouse gases coastal ecosystems emit.
- Blue carbon studies need long-term monitoring and standardised measurements which are currently unavailable. Existing ICOS ocean data is valuable in supporting these studies, but new and dedicated blue carbon sites are needed. ICOS and two other ocean research infrastructures, JERICO and EMSO, need to work together to bring about this change.
- It is urgent to act now: we must save existing ecosystems by removing the pressures threatening them, efficiently conserving protected areas and restoring degraded ecosystems.
- Although coastal ecosystems sequester carbon dioxide from the atmosphere, they cannot offset the quantities of CO_2 we emit. Coastal ecosystems are not a magic solution to the climate crisis: we must reduce our emissions.

Coastal ecosystems, such as salt marshes, seagrass meadows, seaweed beds and mangroves can potentially sequester vast amounts of carbon dioxide from the atmosphere: some scientists estimate that seagrasses, which cover only 0.1% of the seafloor globally, could store up to 18% of the total carbon burial in the ocean. This stored carbon - often referred to as 'blue carbon' – can stay trapped for a long time. Seagrass meadows could keep carbon for several thousand years, for example[3]. But blue carbon is only one part – the key to adding coastal ecosystems to our climate mitigation repertoire is to look beyond the blue carbon they harbour.

"Carbon sequestration is just a fraction of the immense services delivered by coastal ecosystems, " explains Dr Claire Evans, Senior Research Scientist at the National Oceanography Centre in the United Kingdom. Like many other marine scientists, Dr Evans advocates for a holistic approach to considering coastal ecosystems. She explains that these habitats contribute to a healthier ocean by increasing biodiversity, improving water quality, stabilising the coastal floor, and protecting the coastline from extreme tidal events. All these are immensely valuable for the entire planet. "Coastal ecosystems are reservoirs of life," says Dr Evans.

"We should focus on these multiple long-term benefits that coastal ecosystems deliver because they are much more important and impactful than just carbon sequestration. We know that having more biodiverse, resilient coasts will pay in the long run". Restoring coastal ecosystems to a healthy state initiates a positive dynamic, with impacts reaching far and wide. "In the Isle of Man, where I am from, we have noticed that marine protected areas boost fishing through a spillover effect," notes Dr Evans. She underlines that it is possible to reach a healthy state in coastal activities through education, political will and the integration of

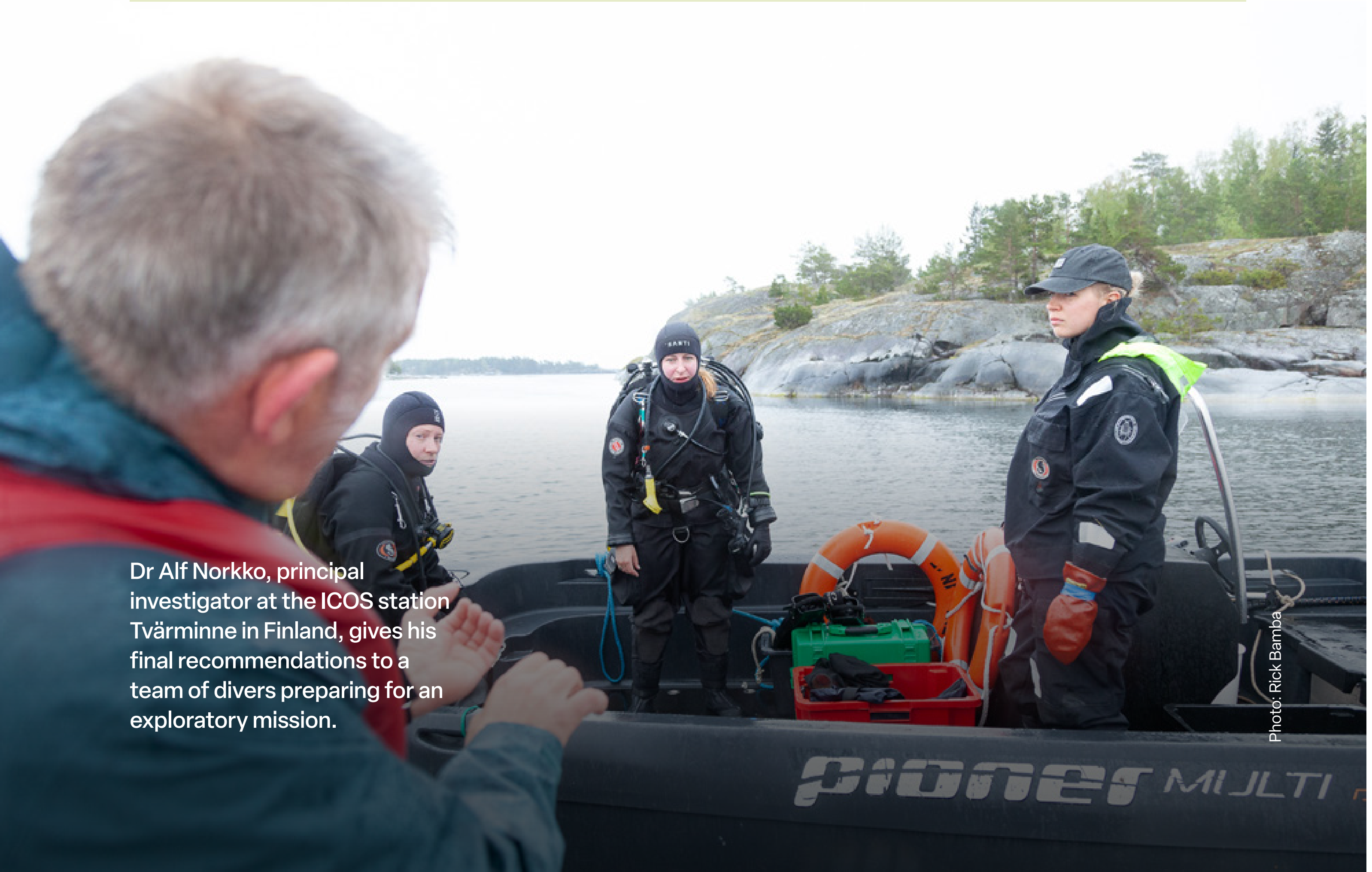
> **Coastal ecosystems are reservoirs of life.**
>
> Dr Claire Evans, Senior Research Scientist, the National Oceanography Centre, UK

Photo: Nigel Standerline

Dr Claire Evans at the National Oceanography Centre in Southampton, UK. The samples in front of her are used to measure the carbon content in sediments under coastal ecosystems.

Carbon removal, assimilation, storage and sequestration in coastal ecosystems

- **Carbon removal** refers to the uptake of carbon dioxide from the atmosphere and its storage as carbon either in the biomass of marine flora, in seawater, or in marine sediments.
- **Carbon assimilation** refers to carbon dioxide uptake by marine plants through photosynthesis and its transformation into organic carbon. Plants, such as mangroves, seagrasses and salt marshes can fix carbon dioxide directly from the atmosphere. Another way is that carbon dioxide is first absorbed from the atmosphere by the ocean, and then assimilated by underwater ecosystems, such as seagrasses or seaweeds.
- **Carbon storage** refers to the quantity of carbon stored by coastal ecosystems durably and stably: if left undisturbed, the carbon remains stored for several hundreds of years. The carbon is stored either in coastal sediments of ecosystems such as mangroves, salt marshes, and seagrasses that bury carbon through their root systems, or deeper in oceanic waters, e.g. when seaweeds sink to the ocean floor where they release their carbon content which remains trapped there.
- **Carbon sequestration** refers to the process of removing carbon dioxide from the atmosphere and storing it in reservoirs like sediments, plant biomass or seawater at greater depths. Carbon sequestration is quantified as a rate, such as kilograms per year per hectare for example.



Dr Alf Norkko, principal investigator at the ICOS station Tvärminne in Finland, gives his final recommendations to a team of divers preparing for an exploratory mission.

Photo: Rick Bamba

the local population into shoreline protection initiatives. "We will not be able to make change happen if we don't understand coastal communities," continues Dr Evans. "Viewing those ecosystems from their cultural dimension is as important as considering the ecological aspects. All these parts interact. We need to learn from the traditional usages of the shoreline and integrate these insights into our conservation policies." Coastal ecosystems are part of an ensemble, where people and how they manage the surrounding land are essential in keeping coastal habitats healthy and functional. "Changes onshore directly impact the coast," adds Dr Evans. "It's useless to create a marine protected area in an environment that is being degraded by harmful land-management practices up the river. We must consider all the interconnected elements and keep the big picture in mind." This holistic approach to coastal ecosystems should also include the complete cycle of greenhouse gas fluxes, not just carbon uptake. From a climate mitigation perspective, this is critical.

> Focusing only on carbon services brought by coastal habitats without considering their methane emissions would lead to a false, unrealistic and ultimately dangerous representation.
>
> Dr Florian Roth, ocean scientist specialised in carbon and nitrogen cycles in coastal seas.

The emissions of coastal ecosystems

Coastal ecosystems are not just carbon sinks. They naturally emit carbon dioxide through respiration, releasing carbon directly into the atmosphere or water[4]. "Carbon emissions in coastal ecosystems vary a lot," explains Dr Florian Roth, marine scientist, former researcher and currently climate protection manager at the city of Wuppertal in Germany. "The changes depend on the surrounding conditions. Warmer temperatures, for example, can lead to higher respiration rates and increase the quantity of carbon released. But the variations also depend on the state of the ecosystem itself. Coastal ecosystems that are degraded, due to eutrophication or a disturbed environment, will tend to emit more carbon dioxide than healthy habitats."

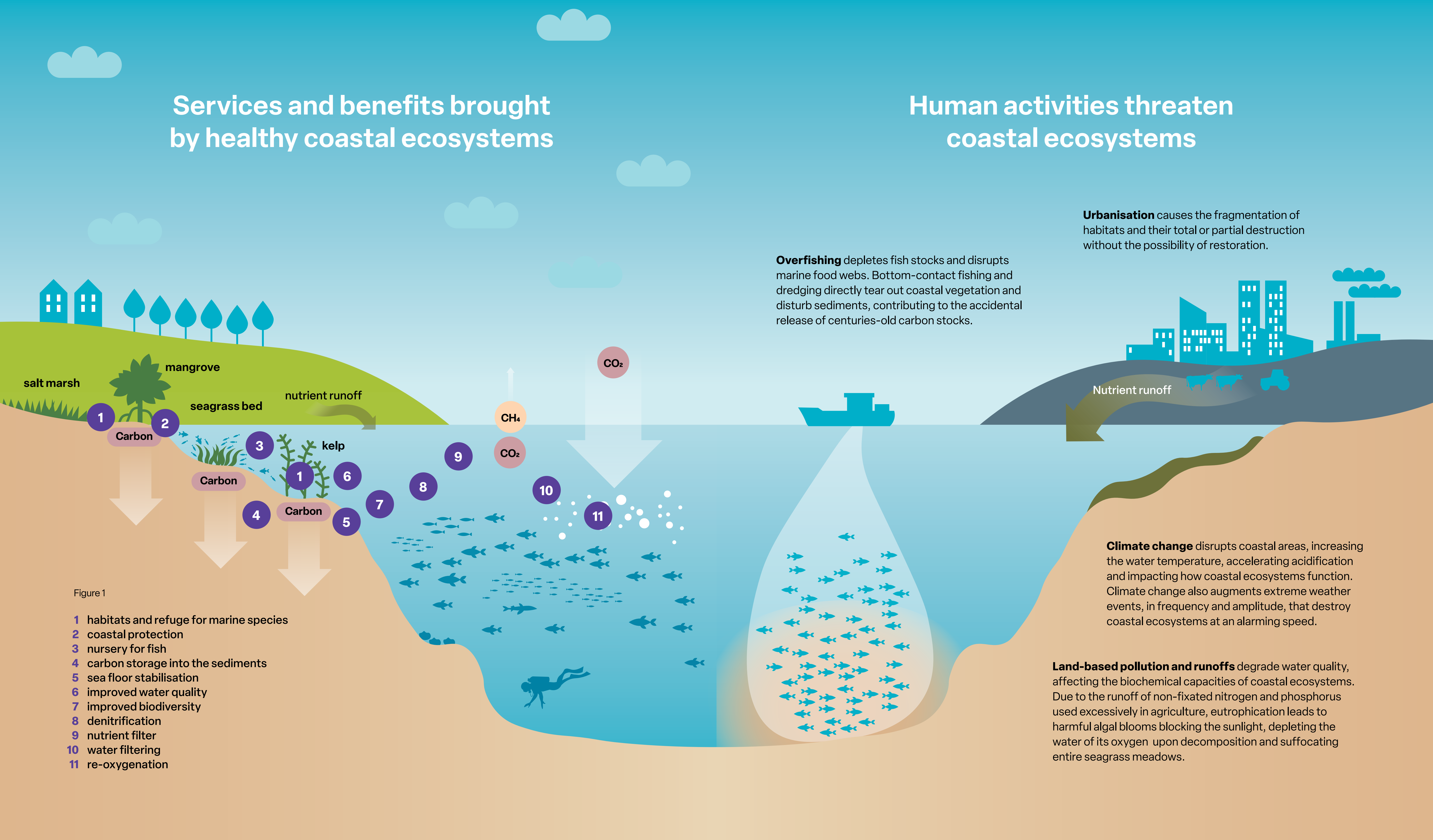
Coastal ecosystems also emit methane, a potent greenhouse gas with a much higher global warming potential than carbon dioxide. A recent study[5] reports that the methane emitted by coastal ecosystems attenuates the benefits of carbon dioxide uptake by 28% to 35%. "Focusing only on carbon services brought by coastal habitats without considering their methane emissions would lead to a false, unrealistic and ultimately dangerous representation," explains Florian Roth, the lead author. By offsetting the carbon dioxide uptake with the emitted methane, the study aims to paint a more truthful and balanced picture of the role of coastal ecosystems in greenhouse gas mitigation, realistically lowering their overall potential. "Confirming that some coastal ecosystems emit methane is a first step," explains Florian Roth. "Now we need to get in-depth understanding if all coastal ecosystems emit methane, at what rate, under which conditions, and how much these emissions, as we suspect, are accelerated by climate change. There is much more to research," he concludes.

Mounting pressures on European coastal ecosystems

For centuries coastal areas have been used as shelters, sources of food and income, but also as dumpsites, territories for urban expansion and recipients of land-based runoffs, resulting in a mass degradation of coastal ecosystems. "Some people see salt marshes as useless: you cannot walk in there, they are not picturesque, they are a bit scruffy and might be a reservoir for mosquitoes," explains Dr Amani Becker, a marine researcher at the National Oceanography Centre. "But salt marshes are an integral part of the European coastline and have a high ecological value. They belong there. We need them there," she adds.

Services and benefits brought by healthy coastal ecosystems

Human activities threaten coastal ecosystems



Urbanisation causes the fragmentation of habitats and their total or partial destruction without the possibility of restoration.

Overfishing depletes fish stocks and disrupts marine food webs. Bottom-contact fishing and dredging directly tear out coastal vegetation and disturb sediments, contributing to the accidental release of centuries-old carbon stocks.

Climate change disrupts coastal areas, increasing the water temperature, accelerating acidification and impacting how coastal ecosystems function. Climate change also augments extreme weather events, in frequency and amplitude, that destroy coastal ecosystems at an alarming speed.

Land-based pollution and runoffs degrade water quality, affecting the biochemical capacities of coastal ecosystems. Due to the runoff of non-fixated nitrogen and phosphorus used excessively in agriculture, eutrophication leads to harmful algal blooms blocking the sunlight, depleting the water of its oxygen upon decomposition and suffocating entire seagrass meadows.

Figure 1

1 habitats and refuge for marine species
2 coastal protection
3 nursery for fish
4 carbon storage into the sediments
5 sea floor stabilisation
6 improved water quality
7 improved biodiversity
8 denitrification
9 nutrient filter
10 water filtering
11 re-oxygenation

This negative perception of coastal habitats has contributed to their destruction. The European Environment Agency (EEA) estimated in 2019 that Europe had lost more than half of its coastal ecosystems over the past century, with some areas experiencing losses of up to 80%, with knock-on effects on the species that depend on them[6]. Most threats have an economic origin where financial gain leads to destroying coastal ecosystems.

A lack of ground-based observations for coastal blue carbon

At the moment, the core ocean observation in ICOS is the partial pressure of carbon dioxide (pCO_2), which determines whether the ocean is taking up or losing carbon dioxide. Some stations measure other carbon variables, and there are a variety of other ocean variables which could be considered.

Currently, almost all blue carbon observations around the world are project-based. There are almost no long-term studies, and there are few standardised measuring processes. "ICOS has a crucial role to play here," says Dr Richard Sanders, ICOS Ocean Thematic Center Director.

"The ICOS structure and philosophy are a perfect fit for developing new blue carbon observation stations. We should apply the long-term, collaborative, rigorous ICOS methodology to coastal ecosystem observations. We should have the same station labelling process for blue carbon as we have for the existing stations of the ICOS network." For Dr Sanders, blue carbon measurements and coastal ecosystem observations are decades-late compared to their terrestrial counterparts. "ICOS can get to grips with coastal blue carbon issues. The next step: get involved," he adds.

Measuring coastal blue carbon would require new and dedicated stations in strategic locations. "We should find new sites identified by geochemists and seafloor experts, and apply ICOS experience in standardising measurements to sediment core sampling, the primary method to measure blue carbon stocks," Sanders continues. He is convinced that collaboration between research infrastructures is key: "We must engage with the scientific community on the coastal blue carbon measurement issues. Currently, ICOS is missing this land-ocean interface. We can collaborate with other research infrastructures, like JERICO and

The case of kelp

Kelp, and other large brown seaweeds, grow in shallow coastal waters worldwide in dense formations that resemble forests. Kelps grow on hard substrates such as rocks. The carbon dioxide that kelp assimilates is entirely stored in its biomass. Kelp can grow up to several centimetres daily under optimal conditions. "There are still many uncertainties regarding kelp's actual carbon sequestration potential," says Lydia White, a postdoctoral researcher at the ICOS Tvärminne Zoological Station. "At the end of its life cycle or during disturbance events, kelp becomes detached from its support and sinks to the seafloor. Many kelp species also regularly shed fragments, providing a continuous supply of detritus to the surrounding environment. Some of these plants and fragments get washed ashore, some are consumed, whilst a proportion is transported deeper in the ocean. The plants decay, their carbon is mineralised and released into the surrounding environment. Beyond a certain depth, it doesn't really matter if it is buried or not: it is precluded from exchanging with the atmosphere over extended timescales even after being mineralised," explains Dr White. "What we don't know and need to research, is the journey and fate of this transient kelp detritus during the degradation process, and how much of it gets trapped in deep waters and sediments. We are currently investigating these issues at the ICOS station in Tvärminne," she concludes.

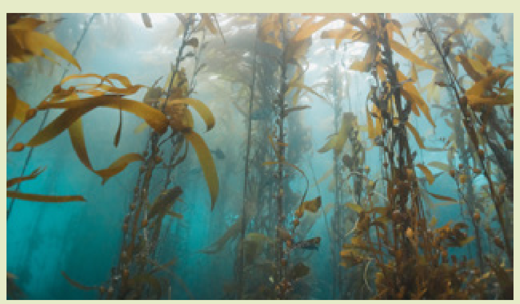


Photo: AdobeStock

Current ocean parameters measured at ICOS stations and parameters needed to measure blue carbon storage in coastal ecosystems.

What is measured?	Why is this measured?
Core observations made at ICOS stations on the sea surface to establish CO_2 uptake and release	
pCO_2	The partial pressure of CO_2 (pCO_2) is a core ICOS parameter. When compared to atmospheric data, it indicates whether the ocean emits or takes up CO_2 from the atmosphere. pCO_2 is controlled by the CO_2 concentration of seawater and its temperature and salinity.
Temperature	pCO_2 is strongly dependent on temperature. Long-term monitoring of the sea surface temperature allows for an accurate assessment of ocean warming and the precise tracking of temperature variations.
Sea surface salinity	Salinity is needed to calculate pCO_2 and to compute fluxes across the sea surface interface. Salinity can be used to track freshwater input in coastal areas and to monitor runoffs from the land.
Additional observations are often made to contextualise the primary surface observations described above.	
Total alkalinity	Alkalinity is the balance of proton acceptors over proton donors. Alkalinity controls how easily or quickly the pH of the seawater can change. Biological processes affect alkalinity, and it is linked to river inputs in coastal areas, since different rivers have different alkalinity levels.
pH	Measure of the amount of nitrates, phosphates and silicates. High values can be a sign of eutrophication
Dissolved inorganic carbon	Total amount of carbon dissolved in seawater in inorganic forms, such as carbon dioxide, bicarbonate, and carbonate. It is important for assessing how much CO_2 caused by human activity the ocean has absorbed.
Nutrients	Nutrients are needed for phytoplankton (small microscopic plant) growth and come to the surface ocean either from deeper water masses or, in coastal areas, also from land. In marine ecosystems, the lack of macronutrients, such as nitrate or phosphate, often controls phytoplankton growth.
Dissolved oxygen	Oxygen is produced in the sea surface by phytoplankton growth and consumed by organic matter decaying in the ocean. It can be used to track eutrophication and assess the health of a coastal area and the efficiency of restoration actions.
CO_2 flux across the sea surface	A station with a with a flux tower measuring the flux of CO_2 and heat across the sea surface.
Additional variables that could be considered for inclusion in a blue carbon monitoring system	
Dissolved organic carbon	Some carbon taken up by marine ecosystems is released as dissolved organic carbon: compounds such as sugars and amino acids. These compounds coexist alongside dissolved organic carbon coming from river flows. Researching the origin and fate of them is important for blue carbon accounting purposes.
Vegetation carbon concentrations	Vegetated marine ecosystems' cells contain carbon, determining their capacity to store carbon. Quantifying this storage and its change over time will be important for blue carbon accounting.
Sedimentary concentrations of organic carbon	Some marine ecosystems accumulate organic carbon in the underlying sediments. Understanding this carbon's age, profile, and origin will be important for blue carbon accounting.
Seagrass/ mangrove/ saltmarsh community structure	Mapping marine vegetation types is crucial to help determine carbon accumulation rates. This mapping is important for remote-sensing-based methods to measure blue carbon.

Photo: Alf Norkko

Seagrass restoration in coastal areas?

Seagrass restoration is a difficult process with a relatively high failure rate, depending on the location of the restored area. There are currently five key approaches to restore a seagrass meadow:

- **Seeding:** Seeds are manually collected from healthy meadows, transported and planted individually into the sediment.
- **Vegetative propagation:** Fragments of healthy seagrass plants are transplanted to the restoration site.
- **Turf transplantation:** Entire sections of seagrass from healthy areas are transplanted to degraded zones. This technique is suitable for restoring large degraded areas.
- **Biodegradable benthic grids:** These grids are installed on the sediment to stabilise it, prevent erosion and provide a surface allowing seagrass seeds to germinate.
- **Hydroseeding:** A mixture of seagrass seeds, fertiliser and nutrients is sprayed onto the sediment. This technique is particularly suitable for restoring large areas quickly.

EMSO to build common goals focusing on long-term observations of blue carbon. We can use our knowledge to increase our capacity to address societal questions related to blue carbon, such as source attribution."

Acting now for European coastal ecosystems

Local, regional, and national governing bodies and the European Union can act on five fronts to increase the healthiness of coastal ecosystems and the ocean.

1 Save and protect existing coastal ecosystems before restoring the degraded ones

"It is very challenging to restore coastal ecosystems because these habitats are often intertwined with their surrounding landscape and seascape," Dr Richard Lilley from Project Seagrass says. He explains that the physical environment changes when a coastal habitat, such as a seagrass meadow, disappears from a given location. "An entire area is disrupted, from the intergrity of the sea floor right through to the water quality at the surface. It takes time, and it is very complicated to re-create the favourable conditions for a new meadow to thrive. Older, preserved seagrass meadows tend to have higher biodiversity and other associated ecosystem benefits than newer, restored meadows. So the urgency is to save and protect what we have and then look to restore where appropriate," he continues. The deterioration of existing, older seagrass meadows could lead to the release of enormous quantities of carbon trapped in the sediments below.

For Dr Richard Lilley, an efficient action plan could follow three phases. Save existing ecosystems by assessing them and then removing as many of the pressures as possible that are threatening them. Once the pressures are removed, then protect the area, enforce protection, and monitor progress. Finally restore degraded habitats, starting from protected areas and privileging large-scale projects and long-term planning for an increased success rate.

2 Fund scientific research to tackle uncertainties on coastal ecosystems

If parties to the Paris Agreement want to incorporate coastal ecosystems into their budgets and inventories, researchers need to better understand how these habitats work. "To start, we don't know how much carbon exactly is stored in coastal ecosystems all around the globe," says Dr David Ho, climate scientist, blue carbon expert and a Professor at the University of Hawaii at Manoa, Columbia University and l'École Normale Supérieure. More research is needed, especially at a time when private companies want to sell blue carbon credits to offset private emissions. "We have some ideas but don't know precisely where the blue carbon stored in sediments comes from and how much stays there or travels elsewhere," Dr Ho explains. "We need to understand better how seaweeds, like kelp, contribute to storing carbon in the deep ocean. We also need to understand better the cycle of other greenhouse gases in coastal ecosystems, which is crucial for climate mitigation."

> **"Currently, blue carbon observations around the world are almost all project-based. There are no long-term studies, and there are no standardised measuring processes.**
>
> Dr Richard Sanders,
> Director of the ICOS Ocean Thematic Centre

3 Fund the development of ground-based greenhouse gas monitoring for coastal areas

"Two similar ecosystems will behave differently depending on a bundle of factors: we cannot just extrapolate measurements taken in one location to another," explains Dr Alf Norkko, the lead scientist at the ICOS Tvärminne station in Finland. "We need more long-term observation stations to track change over time in coastal ecosystems for all the greenhouse gases, not just for carbon. Just like we have been doing in forests for decades," he says. Denser ground-based measurements from coastal ecosystems would improve our understanding of these habitats. It would also contribute to calibrating satellites and verifying model-based predictions. Countries could verify their inventories and adapt their mitigation strategies accordingly. "We already have several ICOS Ocean stations measuring essential surface variables, like carbon and nutrients," adds Dr Norkko. “It is crucial that we establish how carbon turnover and greenhouse gas emissions relate to the biodiversity and health of coastal communities. We also need to keep a holistic view and increase our current capacity to do long-term, continous greenhouse gas measurements of coastal areas at the surface but also below, including in the sediments."

4 Require that claims from offsetting initiatives based on coastal blue carbon be monitored, reported and verified to avoid greenwashing

"In the current state of science," says Dr Norkko, "the carbon offsetting capacity of coastal ecosystems is based on extrapolations that don't consider methane emissions, generating false and potentially counterproductive values." Without an obligation to substantiate their claims through a scientific monitoring, reporting and verification system, companies could artificially increase their offsetting capacities for a profit, negating the actual objectives of emission offsetting. "Measuring carbon stocks once in an ecosystem barely gives a snapshot that will be rapidly outdated," continues Alf Norkko. "Monitoring over long periods allows for a more accurate picture while reporting and verification set accountability. Such a system would help to deter and avoid fraudulent claims."

5 Reduce our emissions

"Blue carbon cannot contribute to offset our emissions," asserts Dr Ho. "No system, natural or industrial, will be able to remove the 40 gigatons of carbon dioxide that humans emit yearly. Blue carbon is not for today but for tomorrow, when we are close to net zero and need to offset a small portion of our residual emissions. Today, we must focus on saving and protecting our coastal ecosystems for their intrinsic value and the socio-ecological benefits they provide. And we need to reduce our emissions. There is no alternative." ■

Dr Eugenia Apostolaki (Researcher at the Institute of Oceanography of HCMR), Hannah Muir MSc (PhD student at Swansea University and Student Fellow at National Oceanography Centre, Southampton), and Prof. Martin Zimmer (ZMT Bremen: Dept. Ecology - Mangrove Ecology) were also interviewed for this article. Dr Meike Becker (Researcher at the University of Bergen) and Richard Sanders have contributed to the table on ICOS measurements.

Dr Lydia White, postdoctoral researcher at the ICOS station Tvärminne, getting ready for a dive in the cold waters of the Baltic Sea.

Photo: Rick Bamba

“No system, natural or industrial, will be able to remove the 40 gigatons of carbon dioxide that humans emit yearly.

Dr David Ho, Professor of Oceanography, University of Hawaiʻi at Mānoa

Photo: Jean-Pierre Delorme

Carbon farming - a path to more sustainable agriculture

Agriculture causes about 11% of the European Union's greenhouse gas emissions[1]. The share is noteworthy because the two major emissions – nitrous oxide and methane – are very powerful greenhouse gases. Farming methods which tackle agricultural emissions are often referred to as carbon farming. This article discusses the role of agricultural soils in carbon farming, since only soils can be part of nature-based climate solutions.

by Katri Ahlgren

Photo: Sander Karsen

Key takeaways

- Major agricultural emissions are methane from livestock and manure management, and nitrous oxide and carbon dioxide from the soils and their fertilisation. These are considered hard-to-abate-emissions when agricultural management and consumer needs remain static. The emissions need to be compensated by sinks in the path to net zero.
- Currently, croplands and grasslands release more carbon dioxide than they take up, according to the European Environmental Agency (2021)[2].
- Carbon farming on croplands or grasslands offers only a very limited capacity for carbon sequestration within soils. It can compensate only a fraction of the agricultural emissions. The results also might not be permanent given the many factors affecting land management decisions.
- Reliably measuring changes in the soil carbon stocks in a given field is difficult, and possible only over long time periods.
- Carbon farming must be considered from a more general, sustainable farming perspective. Besides storing carbon in the ground, benefits include better soil health, improving yields and thus better livelihood for the farmers. More importantly, it improves food security in a changing climate and protects human health, biodiversity, and the environment.
- ICOS uses standardised, high-quality methods to measure carbon exchanges between the vegetation and the atmosphere, and the carbon stocks of the soil. ICOS also has a state-of-the-art laboratory for analysing the soil and plant samples.
- The ICOS data and the knowledge of ICOS scientists offer great potential to be utilised when creating a monitoring system for EU Carbon Removal Certification.

The new EU regulation on Carbon Removal Certification defines carbon farming as storing carbon in the soil and vegetation, such as bushes or trees, in order to mitigate climate change. However, ICOS scientists, most environmental organisations, and even some EU bodies argue that other benefits that an increased soil carbon stock will bring are equally important. These benefits consist, for example, of improved biodiversity improved biodiversity and soil health, resistance to droughts through improved water holding capacity, improved food security through better yields and thus better profitability of the farm. This wider approach could also be called regenerative agriculture or sustainable farming.

"Carbon farming transforms our agroecosystems to more efficient and resilient ecological platforms, able to face the new challenges brought by climate change," explains Dr Claire Chenu, Director of Research at the INRAE and Professor of Soil Science at AgroParisTech.

"In essence, carbon farming aims to increase the yields by improving the condition of soils. Possible carbon sequestration is a by-product of that," she continues.

Soils are the only farming emission sources that could become sinks

All industries and sectors need to reduce emissions to reach the European Union's 55% reduction target. In the emission inventories that countries provide to the United Nations Climate Change Convention (UNFCCC), the food production emissions are divided between several sectors. In the agricultural sector, over half of the emissions are caused by the livestock farming: rumination of cattle and sheep as well as the management of their manure cause methane (CH_4) emissions, while nitrogen fertilisation in crop production causes nitrous oxide (N_2O) emissions which are the second big part of agricultural emissions. The total emissions from the EU agricultural sector amount

The EU greenhouse gas emissions from the agriculture and LULUCF sectors in 2022

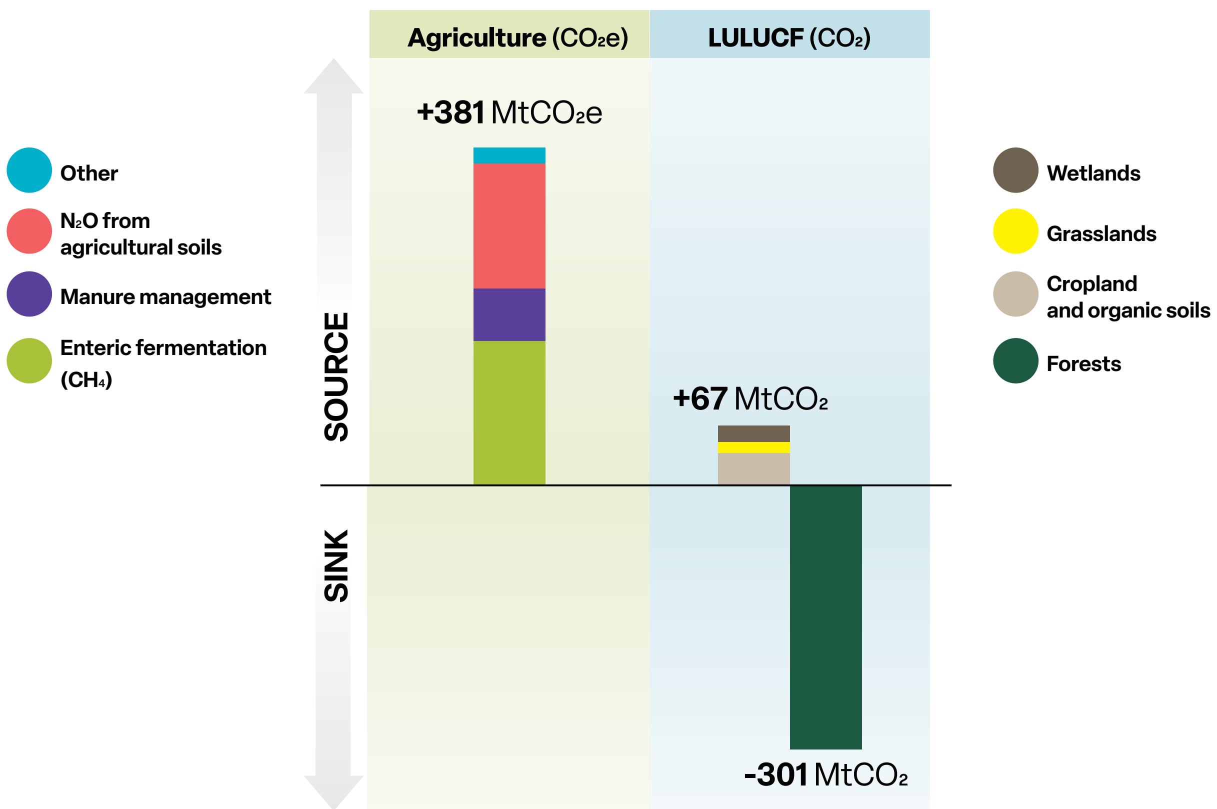


Figure 1. The emissions caused by agricultural land in the Land Use, Land Use Change and Forestry (LULUCF) sector are only 67 million tonnes of CO2e while the other greenhouse gas emissions by agriculture are around 400 million tonnes of CO2e. Note that many of the emissions caused by agriculture are attributed to other IPCC sectors, such as transportation. [1]

to 400 million tonnes of carbon dioxide equivalents (CO_2e), as seen in the figure 1.[1]

Carbon dioxide emissions from agricultural lands, on the other hand, are included in the so called LULUCF (emissions from land use, land-use change and forestry) sector. Croplands and grasslands lose about 40 million tonnes of CO_2 every year, mainly from soils containing organic matter e.g. derived from plants, animals and micro-organisms. The soils naturally respire CO_2, but due to removing the plants after harvests, this carbon is not replaced back to the soils. Ploughing and other tillage actions increase soil respiration as discussed later in this article.

Due to the high rate of emissions from the animals, it is practically impossible for livestock farming to become carbon neutral, although a possible reduction in livestock animals will decrease the emissions. While agricultural lands are also currently net CO_2 sources, soils could in theory be carbon sinks and thus be a part of the nature-based climate solutions.

Organic matter keeps soils healthy

Plants take up CO_2 from the atmosphere to grow, but they also need sunlight, nutrients and water for growth. The nutrients are in the soil, many of them tightly linked in the soil organic matter. Put simply, the more organic matter in the soil, the greater the nutrient availability for the plants. "Soil contains microbes that use organic carbon and nitrogen as their energy source, and change the organic matter to a suitable form for plants to use. This microbial process is called mineralisation, and it also releases carbon dioxide and nitrogen oxide into the atmosphere," explains Dr Ivan Janssens, Plants and Ecosystems professor at the University of Antwerp.

Since microbes mineralise the organic matter and with that unlock nutrients for plants, the soil loses carbon. In natural ecosystems, the lost soil organic matter is replaced by litter, but in agricultural ecosystems the plants are harvested and the carbon is taken away. This leads to a depletion of organic matter in those soils.

Additionally, tillage and other land management actions in croplands disturb the soil structure, which benefits some microbes, while disturbing others. "We see an increase of carbon dioxide released from the soil to the atmosphere for weeks after a management action, particularly after full harvest when all vegetation is removed," explains Dr Christian Brümmer, the Focal Point of ICOS Germany and researcher at the Thünen Institute of Climate-Smart Agriculture. Soil and nutrients are also removed from the fields by wind and rainfall, through erosion.

Because the microbial processes are not fast or plentiful enough to provide sufficient nutrients for plants, agricultural soils are usually fertilised regularly to keep the yields at sufficient levels. Fertiliser can contain organic matter such as manure, compost or non-edible plant materials left to the ground after harvest. However, quite often mineral fertilisers applied mainly consist of inorganic nitrogen, phosphorus and potassium. Using the mineral fertilisers will result in environmental problems such as lower carbon stocks in the soil, and more nitrous oxide (N_2O) released from soil into the atmosphere. N_2O is estimated to be about 300 times more potent a greenhouse gas than CO_2. Moreover, excess nitrogen amounts often leach into aquatic ecosystems, causing e.g. toxic algal blooms and threatening aquatic life and polluting drinking waters.

Agricultural soils in Europe are losing carbon

Currently, croplands and grasslands release more carbon dioxide than they take up, as stated by the EU inventories.[1] Furthermore, the EU's Joint Research Centre estimates that at least 60% of the soils in the Union are generally in poor condition: they are low in carbon, contain too many nitrates, or suffer from erosion or compaction. All these problems relate to low organic matter content in the soil.[3]

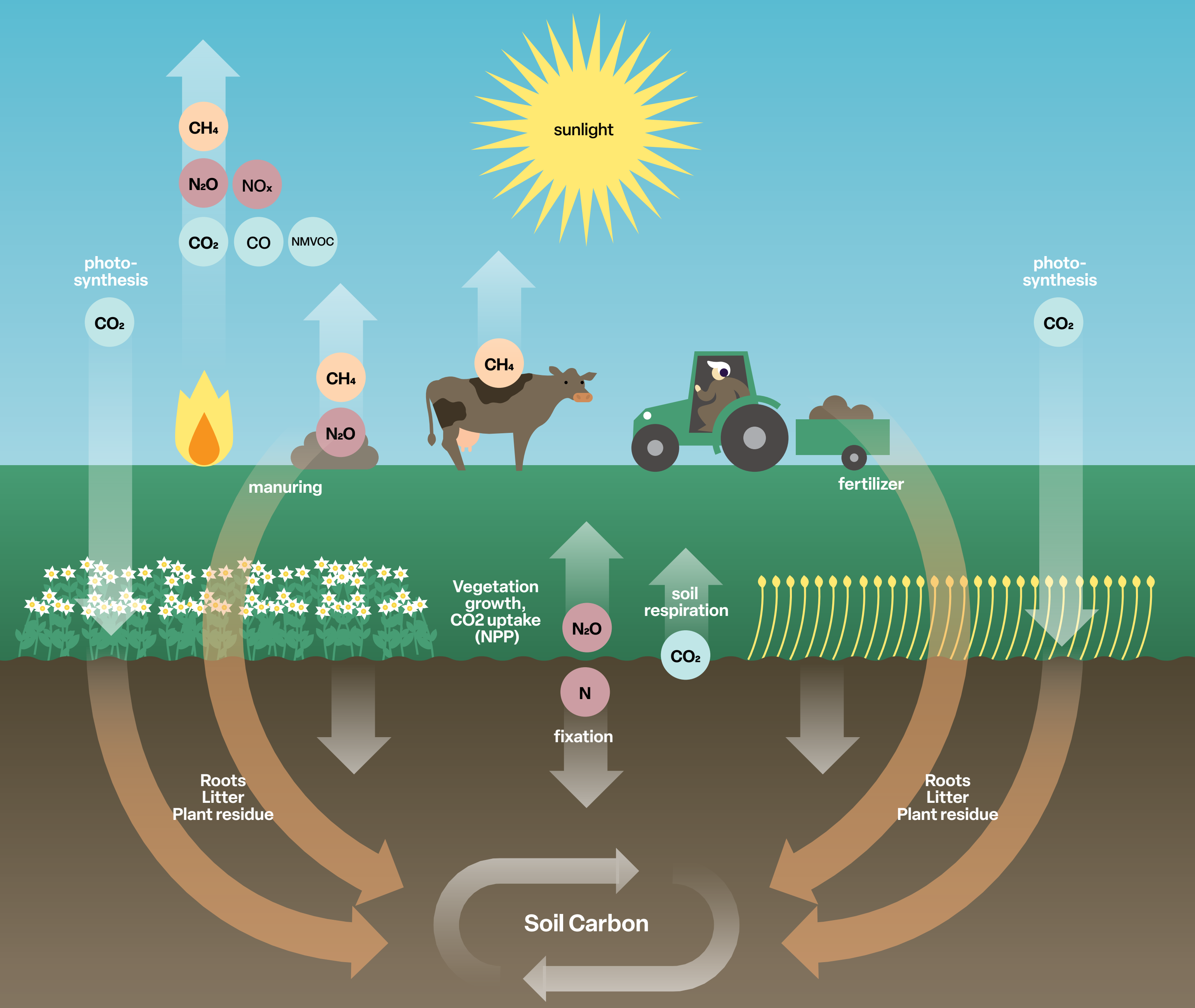
> "The LULUCF regulation aims to increase the land carbon sinks, so the Commission proposes the Carbon Removal Certification as an incentive system for the land managers.
>
> Dr Lucia Perugini, member of the ENVI committee of the European Parliament.

A recent joint study by the ICOS community in Germany presented long-term data of carbon fluxes in agricultural ecosystems. The group measured the net uptake of the ecosystems by a method called eddy covariance, and also monitored the import and export of carbon by harvest and manure. The result is called net biome production (NBP). The group showed that both cropland and grassland soils lose carbon year after year, despite regular organic fertilisation. The figure 3 illustrates the severity of the situation.[4]

"We are really alarmed and surprised by these results because our findings differ from the commonly used methods of repeated stocktake which often show that the soil organic carbon pool is stable," says Christian Brümmer, coordinator of the study as the the ICOS Germany Focal Point. The group is currently analysing the data in depth. Colleagues in other ICOS countries have found similar results and the carbon losses were supported by repeated stocktake. The standardised measurement techniques of ICOS make the comparison of the results easy and reliable. The reasons for the carbon losses may be explained by recent changes in management or by global warming that enhances the mineralisation.

Measures that reduce carbon losses or even increase the carbon in the soils include improved manure man-

Carbon cycle in agriculture



CH_4 = methane **N_2O** = nitrous oxide **NO_x** = nitrogen oxide **CO** = carbon monoxide
NMVOC = Non-methane volatile organic compounds **N** = Nitrate **NPP** = Net Primary Production

Figure 2. The carbon cycle between soil and atmosphere. Plants take up CO_2 from the atmosphere, but they also need sunlight, water and nutrients to grow. Since current cropland soils do not provide enough nutrients in a suitable format for the plants to use, nutrients are added to the soil to ensure profitable yields. (Source: IPCC, adapted)[7]

Accumulated soil carbon losses at ICOS cropland station Gebesee in Germany 2001-2023

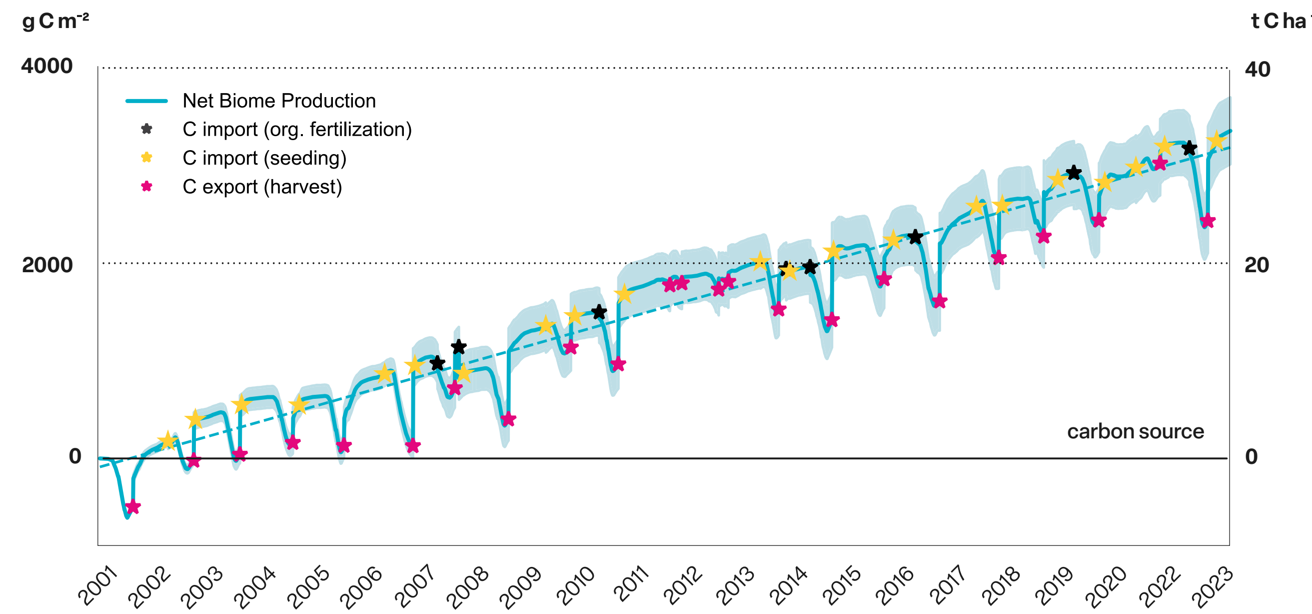


Figure 3. The blue line describes the net biome production (NBP) of the cropland at ICOS station Gebesee in Germany. NBP is the sum of CO_2 uptake by photosynthesis, respiratory losses, and carbon import to and carbon export by management, e.g. manure and harvest. The trend in the graph shows an average carbon loss of 157 grams of carbon per square meter and year suggesting a constant loss of soil organic matter. The values are calculated using the data from ICOS long-term measurements and information about fertilisation, sowing and harvest events received from the land managers.[4]

agement, more precise nitrogen inputs, and improved soil management, with inter-cropping and cover crops as well as protecting soils rich with organic matter, by rewetting peatlands not currently in use.[5] However, any increased carbon sequestration from these actions can compensate only a few percents of agricultural emissions, according to the ICOS scientists. They are not a long-term solution for the climate crisis.

But they bring other significant benefits. More organic matter in the soil gives a better water-holding capacity, which in turn makes croplands and grasslands more resistant to droughts. It reduces the need for mineral fertilisers, decreasing groundwater pollution and greenhouse gas emissions caused by excess nitrogen. More efficient manure management can solve several issues: waste management, nutrients to the soil, and energy supply in the form of biogas. All this needs to be organised in a way that overcomes existing or perceived conflicts between environmental measures, food security and the economic sustainability of farmers.

Dr Chenu points out that farmers are the key: "Farmers should be financially rewarded for the multiple benefits they provide. Potential carbon sequestration is only one benefit of healthier soils. They also contribute to better climate resilience, increased biodiversity, improved water quality, and food security".

Carbon removal certification is no silver bullet solving climate crisis

One way of rewarding the farmers could be the new Carbon Removal Certification system currently being prepared by the EU. Besides technological solutions, it also includes forestry and agriculture.

"The new LULUCF regulation puts pressure to increase the land-based carbon sinks, so the EU Commission proposes the certification as an incentive system for the land managers," explains Dr Lucia Perugini, Senior Scientific Manager at the CMCC in Italy.

This voluntary system would include criteria for additional, long-term removal of carbon, the quantification of the amounts, and the sustainability of removal practices. The Commission proposes to establish a common monitoring standard. The certificates would be part of the already existing voluntary carbon market, as a trading element and worth money for the farmer. The proposal currently presents mainly principles, and leaves many essential parts open, to be developed after the general regulation has been accepted by the European Parliament.

There is currently no European-wide standard for measuring or accurately estimating soil organic carbon. It also is difficult to measure small changes reliably, and to see any increase takes many years. "If I take a soil sample and send it to ten laboratories in Europe, I will get ten different answers," says Ivan Janssens. "The laboratories use different methodologies and instruments that are calibrated differently, which brings highly variable results."

Indeed, a transparent and standardised system must be put in place for the Carbon Removal Certification regulation to work. "The regulation says that carbon removals need to be based on measurements and quantified, but the methodologies are still under development," explains Perugini, who is a member of the Expert Group established by the Commission for that development.

ICOS has great potential for this work, Perugini says: "ICOS can help us to understand what are the effects of different management systems and practises in different conditions. For instance, how much cover crops affect the carbon sink, or what is the magnitude of possible side-effects. ICOS could also develop a baseline for certain type of soil or forest sinks. When the sinks are certified, they undergo a verification process to check whether the results are within the acceptable ranges. ICOS could provide external verification information."

Dr Perugini ponders that ICOS could participate in building an emission factor repository on the changes in agricultural practices, to provide data for the farmers for their decision-making. "And certainly, ICOS can help greatly to understand the year-to-year and seasonal variations caused by weather to the soil carbon dynamics. Even though the farmer would do everything by the book for five years, but then comes a very dry year destroying yields and carbon values. Then what happens?"

> "The permanence of increased soil carbon stock is highly uncertain.

The permanence of the increased soil carbon stock is one of the key issues, as it is highly uncertain. It depends very much on weather variability, and on the future actions of the land managers.

Proper monitoring and verification needs a combination of ground-based and satellite data, modelling and inventories

For Ivan Janssens,The ICOS focal point for Belgium, a robust and dense ground-based observation network is an essential part of a new data value chain for carbon farming: "ICOS is the leading European research infrastructure with standardised measurement and data processing protocols." The ground-based data from ICOS enables modellers to verify and better calibrate the satellite data, and thus make more accurate climate predictions. Models are important because neither ground-based nor satellite observations can cover all possible soil types and geographical variations all the time, the scientists say. If we want a reliable monitoring, reporting and verification system, we need all components working together: ground-based data, remote sensing, modelling and inventory analyses. ■

Dr Elisa Vainio from Baltic Sea Action Group foundation was also interviewed for this article, and Prof. Nina Buchmann and Dr Werner Kutsch have contributed to it.

Photo: Sara Angelucci

Dr Lucia Perugini (right) says the ICOS station network and the standardised data could be very useful for the development of carbon removal policies and practises.

Photo: Jean-Pierre Delorme and Christian Brümmer / ICOS Germany

> **“If we want a reliable monitoring, reporting and verification system, we need all components: ground-based data, remote sensing, modelling and inventory analyses.**
>
> Dr Ivan Janssens, ICOS Belgium, Professor at the University of Antwerp

Some carbon farming practices

The UN Food and Agriculture Organisation, FAO, has researched 49 re-carbonising practices.[5] Here are a few examples used in Europe.

- **Cover-crops, intercropping**: Cover-crops are a close-growing crop that provides soil protection, and improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. Intercropping is the cultivation of multiple crop species on a single piece of land with biologically significant interaction between individual plants belonging to different species. Both cropping-types increase the amount of organic carbon in the soil, improve soil health and decrease erosion because there is less bare soil.
- **Organic fertilisation**: Application of manure, slurry and compost. Manure and slurry, when applied and managed correctly, can be an effective way of improving soil quality and crop nutrition. Still, there are important aspects of soil health and food security to consider when manure and slurry are used as organic fertilisers.
- **Chemical methods**: Optimising the soil alkalinity is crucial in agricultural lands, because it increases nutrient use efficiency of crops and helps to reach the best possible crop yields. The most common practise to counteract soil acidification is liming, and for sodic soils gypsum can be applied. Liming increases soil organic carbon sequestration mainly by increasing biomass production and hence increases soil carbon stocks. On the other hand, liming can be a source or sink for CO_2 depending on other farming practises used, and overliming can cause nutrient deficiencies leading to decreased biomass production and yield. Gypsum application often also increases yields and improves the soil properties of sodic soils, particularly by preventing soil erosion and waterlogging. However, the effects of gypsum application to soil organic carbon levels are not yet extensively studied and hence uncertain.
- **Rewetting peatlands**: Particularly in Northern European countries, agricultural fields were often established on drained peatlands. Due to their organic soils, they release significant amounts of CO_2 into the atmosphere, particularly when winters are warming up, and the peat soils are not covered by plants or snow for long periods of time. Rewetting peat soil so that the water level is increased until it covers the soil surface prevents carbon from respiring to the atmosphere. This measure could be used particularly for those agricultural lands not in use anymore, because fully rewetted land cannot be cultivated.
- **Biochar**: Charred organic material applied to improve the soil properties and the carbon sequestration. Due to its non-molecular composition, biochar is highly resistant to decomposition, and can stay in the ground for 100s, even 1000s, of years. Biochar is commonly made by pyrolysis, and it can and should be made from biomass waste materials such as crop residues, food and forestry waste. The materials should not contain toxins such as heavy metals. Although in many cases improving yields, the use of biochar does not replace nutrition additions through fertilisers. The long-term impacts of applying different biochar types in a variety of soil types and environments are not yet known, and need more research. The biochar market size is still rather small, but growing rapidly.

Photo: Dennis Manda, Tom Oudijk

The complex chemistry behind the alarming growth in methane

The natural carbon sinks might support us in our last stretch towards carbon neutrality. However, the atmosphere is very complex. Methane concentrations have been on the rise since 2007, with a record growth rate in Europe in 2020-2021. Reasons for the growth are human-induced emissions, the chemical interplay of gases, and increased natural emissions caused by climate change.

By Michel Ramonet, Xin Lin, Philippe Ciais

Key takeaways

- The methane cycle in the atmosphere is complex, since it has both natural and human-related sources, and their processes are interlinked.
- The amount of methane in the atmosphere is affected by the amount of other gases like nitrogen oxides (NO_x), which break down methane.
- During the COVID-19 pandemic, less nitrogen oxide was released to the atmosphere from traffic and industries. As there was less nitrogen oxide to break down methane, more methane remained in the atmosphere.
- Heavy rains in tropical wetlands, due to climate change, increased natural methane emissions during 2021 and 2022.
- Thus two phenomena – less removal and more natural emissions – together caused peaking of growth rate of methane in the two years.

Monthly and annual mean methane concentrations 2011-2022

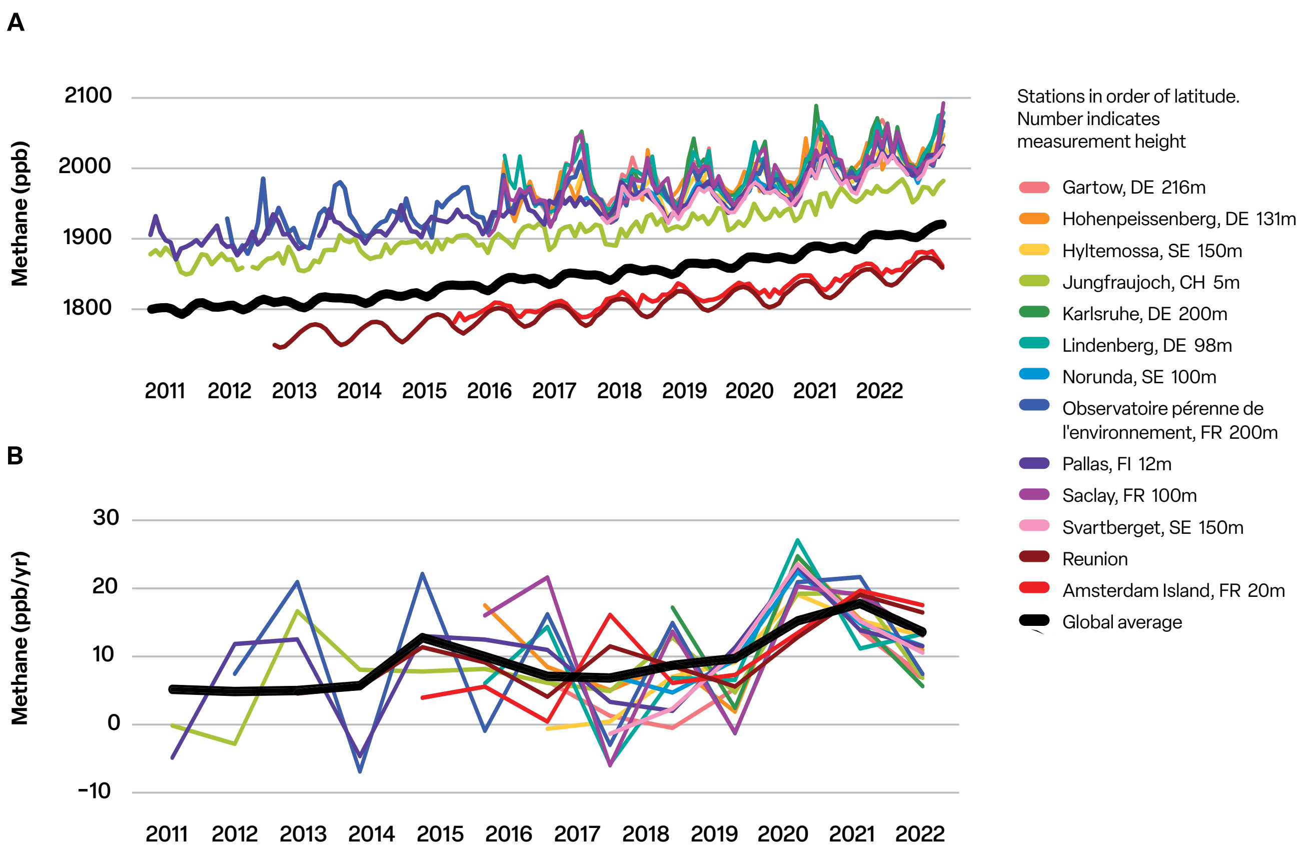


Figure 1: A. Monthly mean methane concentrations observed at ICOS sites and the global average estimated by NOAA/ESRL (in black). The two red curves with lower concentrations correspond to southern hemisphere sites in La Reunion and Amsterdam Island.[12,13,14]
B. Annual growth rates of methane.[12,13,14]

> **"The methane growth rates illustrate the complexity of the methane concentrations in the atmosphere, where natural and anthropogenic processes are interlinked.**

By the beginning of the 21st century, it seemed that the rise in methane concentrations had stabilised. The growth rate of 15 ppb per year (i.e., parts per billion per year), observed in the 1980s, had gradually slowed to 5 ppb per year by the 1990s, and to nearly zero by the early 2000s.

However, around 2007, methane concentrations (CH_4) began to rise again at a rate of 5 to 10 ppb per year[1]. There is more than one reason for this: a major contribution comes from microbial emissions such as wetlands, waste sector and agriculture, but other sources such as fossil fuel emissions, also play a role[2,3]. This has been studied using worldwide monitoring networks, including isotopic measurements, which are used to differentiate between fossil fuel and other methane sources.

In addition to the slow varying trend, there are year-to-year variations such as the 2014-2016 El Niño, which increased methane emissions from tropical wetlands[4].

Measurements from the ICOS network indicate a record growth of methane across Europe in 2020/2021, with growth rates exceeding 10 ppb per year, or even 20 ppb per year at some ICOS stations, before returning to below 10 ppb per year growth in 2022, as seen in Figure 1. The acceleration of methane growth in 2020, by about 50%, is surprising since it occurred during the COVID-19 lockdowns, a period in which there were marked reductions in many human-related emissions. Reductions in CO_2 emissions were about 9% in the first half of 2020[5], with decreases of nearly 20% on daily emissions in early April 2020[6]. The drastic reduction of surface and air traffic also led to a sharp decrease in nitrogen oxides (NO_2) emissions, to the order of 20-30% in spring 2020 in Eastern China, Europe and North America, and even larger decreases (3%-50%) in South America[7].

COVID-19 related reductions of methane emissions were more difficult to observe than those of CO_2. Methane is emitted from many sources, and lockdowns did not affect natural sources[8]. In addition, the concentration of methane in the atmosphere does not only depend on emissions, but also on how methane reacts with other gases in the atmosphere, such as nitrogen oxides, carbon monoxide (CO) and the hydroxyl radical (OH). OH is known as the "detergent of the atmosphere" as it oxidises methane to water vapour and formaldehyde. During the lockdowns, there were lower NO_x emissions, and therefore fewer OH radicals available, which meant methane stayed in the atmosphere for longer. It is estimated that the decrease of the methane photochemical sink associated with the reduction of nitrogen oxide emissions accounts for about half of the 2020 growth rate difference to normal[10].

The other possible reason to the exceptionally high growth rate in 2020 is the increased natural emissions from wetlands, which was caused by large rainfalls in the tropics and high up in the Northern Hemisphere[4,9]. Preliminary analyses for 2021 indicate that natural emissions from the wetlands in the northern tropics account for an even larger share in the methane growth rate. Interestingly, measurements from the European ICOS stations from 2022 indicate growth rates returning to levels prior to 2020-2021 as seen in the lower figure, 1B. However, stations located in the southern hemisphere, such as La Reunion and Amsterdam Island still show high growth rates in 2022. The mean global growth rate estimated by the National Oceanic and Atmospheric Administration Earth System Research Laboratories lies between that of the European and Southern Hemisphere stations.

This change in methane growth rate illustrates the complexity of the methane concentrations in the atmosphere, where natural and anthropogenic processes are interlinked, and where the cycles of many atmospheric compounds play a role. ■

Glossary

Abiotic non-living part of an ecosystem that shapes its environment

Alkalinity capacity of water to resist acidification

Anthropogenic [environmental change] caused or influenced by people, either directly or indirectly

Biodegradable benthic grids nets made of biodegrable materials such as jute used to plant aquatic weeds at the bottom of the ocean

Biomass the quantity or weight of organisms in a given area or volume at a given time

Blue carbon stocks amount of carbon captured by the world's ocean and coastal ecosystems

Carbon assimilation incorporation of carbon from atmospheric carbon dioxide into organic molecules, either by photosynthesis or technical processes

Carbon budget (1) numerical values for all components of carbon cycle (2) Policy concept of determining maximum acceptable amount of emissions per nation, per sector of society or entire mankind

Carbon dioxide removal removing carbon dioxide from the atmosphere

Carbon sequestration removing and long-term storage of carbon from the atmosphere through biological, chemical or physical processes

Carbon turnover the average time that carbon atoms spend inside of terrestrial ecosystems from photosynthetic assimilation until respiratory or non-respiratory loss

CH_4 photochemical sink solar energy and certain chemicals (OH, Chlorine) cause reactions removing methane from the atmosphere

CO_2 equivalent measure converting amounts of other greenhouse gases to the equivalent amount of carbon dioxide with the same global warming potential.

Coastal sediments material accumulating in sea bed in shallow areas, brought by rivers or sea waves.

Dissolved oxygen a measure of how much oxygen is dissolved in the water - the amount of oxygen available to living aquatic organisms.

Eddy covariance a method to measure vertical turbulent fluxes in the atmosphere

El Niño warm phase of the cycle of sea surface temperature in the tropical Central and Eastern Pacific Ocean, typically happening every 2-7 years.

EMSO European Multidisciplinary Seafloor and water column Observatory

Eutrophication process by which water becomes progressively enriched with minerals and nutrients, particularly nitrogen and phosphorus. Leads often to faster growth of algae and altered species composition

Flux amount of material moving (Here: exchange of gases between plants or ocean and the atmosphere)

Formaldehyde a molecyl containing carbon, hydrogen and oxygen, which is participating in many processes in the atmosphere

Ground-based data measurements where the sensor is standing on Earth surface (e.g. not satellites)

Hydroseeding planting seeds mixed with water and mulch

Hydroxyl radical (OH) a molecule consisting of one oxygen and one hydrogen atom. CH_4 reacts with OH and is thus removed from the atmosphere.

Inventory analyses a list of emission sources and the associated emissions quantified using standardized methods.

Isotopic measurements measuring the ratio of different isotopes (nuclear species) of same element. Used e.g. to distinguish whether carbon is from burning fossil fuel or biological matter.

JERICO integrated pan-European multidisciplinary and multiplatform research infrastructure dedicated to a holistic appraisal of coastal marine system changes.

Livestock domestic animals raised in an agricultural setting to produce food or products like fur, leather, and wool.

LULUCF sector of greenhouse gas emissions resulting from direct human-induced land use, land-use change, and forestry activities

Modelling techniques different ways of using computers to calculate the state of a system, e.g. the atmosphere, in places and times where no observations are available

Net carbon sink anything that absorbs more carbon from the atmosphere than it releases

Nitrogen inputs acquisition and transformation of non-reactive nitrogen into a biologically available form

Nitrous oxide, N_2O "laughing gas", a powerful greenhouse gas which also harms ozone layer

Non-fixated nitrogen inorganic nitrogen (e.g. from overuse of fertilizers) which is not converted to organic compounds by living organisms

NMVOC non-methane volatile organic compounds. They are emitted by a number of activities including combustion, solvent use and production processes. They contribute to the formation of ground-level ozone, which can harm human health.

Offsetting carbon dioxide uptake increasing sinks or reduction of emissions to make up for emissions that occur elsewhere.

Organic carbon carbon found in nature from plants and living things (whereas inorganic carbon is extracted from ores and minerals)

Phosphorus a chemical element P, essential for sustaining life

Photosyntesis a process, in which plants use energy of light to build carbohydrates from water and CO_2

PPB (parts per billion) 1/1000 000 000

Pyrolysis thermal decomposition of materials at high temperature but lack of oxygen. Used e.g. in tar and charcoal production.

Remote sensing measurements where the sensor does not touch the measured object, e.g. from satellites

Rumination animals (like cows) rechew cud to breakdown plant matter further and to stimulate digestion

Salinity dissolved salt content in water

Sediment core sampling drilling cylinders of lake or sea bottom material

Soil scarification plowing and rotating land prior to planting saplings

Thinning (WRT forests) removing some trees to make room for the growth of others and to harvest timber

Tillage preparing soil for growing crops

Total ecosystem respiration, TER Sum of all respiratory processes in an ecosystem

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