3 Harnessing the untapped potential of terrestrial ecosystems

> Terrestrial ecosystems store significantly less carbon than the oceans. Nevertheless, they can make a valuable contribution to the fight against climate change. We must protect existing forests, grasslands and wetlands to this end, engage in large-scale ecosystem restoration and return to sustainable methods of farming and forestry. We've known how to do this for a long time. The only thing that's missing is the will to actually do it.

Forests, grasslands and soils as carbon stores

> Whenever people ask how nature could help us humans in combatting the climate crisis, the answer is often to "plant trees". While that answer is quite valid, it is far from the only option. There are dozens of known methods we can use to help terrestrial vegetation and its soils absorb more carbon dioxide from the atmosphere. But we must employ these methods in the right places, leave enough room for nature and treat the soils with care. To date, none of this is happening to the extent necessary.

Natural climate solutions

Although the concentration of carbon dioxide in the Earth's atmosphere has been rising steadily for decades, carbon dioxide itself makes up only a tiny fraction of the air itself. The concentration of CO_2 in the atmosphere is 0.04 per cent by volume. If one wanted to extract one cubic metre of carbon dioxide from the atmosphere, one would have to filter at least 2500 cubic metres of air to do so. For one tonne of carbon dioxide, this would be around 1.27 million cubic metres of air, even at 100 per cent filtering efficiency.

Soil carbon
The term "soil carbon" refers to the quantifiable carbon content of organic matter in the soil. It includes both living and dead biomass and makes up between two and ten per cent of the soil mass. The soil carbon stock is the basis for vital services provided by the soil, such as the storage and provision of water and nutrients as well as the breakdown of pollutants.

Technical systems that can remove carbon dioxide from the air are expensive and consume a lot of energy. Many experts therefore advocate so-called Natural Climate Solutions (NCS), i.e. measures that increase natural carbon dioxide uptake and carbon sequestration by oceans, terrestrial areas and their respective vegetation, or measures that prevent future greenhouse gas emissions.

However, the term "natural" does not automatically imply that all such measures are sustainable or environmentally friendly in the long term. Large-scale tree plantations (monocultures) for example can certainly be counted among the natural climate solutions, but they come at the expense of species diversity. Moreover, plantation-type forests store significantly less carbon in the long term than a species-rich, naturally grown mixed forest. It is for this reason that experts now vehemently call for all greenhouse gas emissions avoidance and atmospheric carbon dioxide removal measures to also be assessed in terms of their impact on nature and human communities, and to weigh up their potential risks against and benefits. A best-case situation is for all three – climate, nature and humankind – to benefit.

The discussion on natural climate solutions has so far focused primarily on the Earth's forests, wetlands, savannas and grasslands, as the way we have been utilizing these ecosystems has significantly impacted the Earth's carbon cycle and thus also the climate.

Land-use change impacts the climate globally as well as locally

The effects of land-use change on the climate are now well understood. At a global scale, they mainly throw off the balance of important greenhouse gases such as carbon dioxide, nitrous oxide and methane. Carbon dioxide, for example, is released in large quantities when we clear (burn) forests, convert natural grasslands and wetlands into cropland, drain peatlands or overuse pastures and fields to such an extent that their capacity to store carbon and grow vegetation is increasingly diminished. In contrast, the uptake of carbon dioxide by terrestrial vegetation is enhanced when forests are (re)planted, grow back naturally or when livestock grazing ceases on natural grasslands and the native animal and plant community can recover.

Methane and nitrous oxide emissions arise primarily in farming. Nitrous oxide is released when nitrogenous fertilizers are used and when farmers collect and spread slurry on agricultural land or burn biomass. Methane emissions mainly come from intensive livestock farming, rice cultivation and incomplete biomass combustion.

When humans change the way they use terrestrial vegetation, the physical surface properties also change. This in turn can alter the local climate in different ways, depending on the location and type of vegetation in

3.1 > The carbon stored in a forest's leaves, branches and twigs is highly susceptible to disturbance. Often a forest fire is enough to destroy this carbon store and release it back into the atmosphere in the form of carbon dioxide and ash particles.

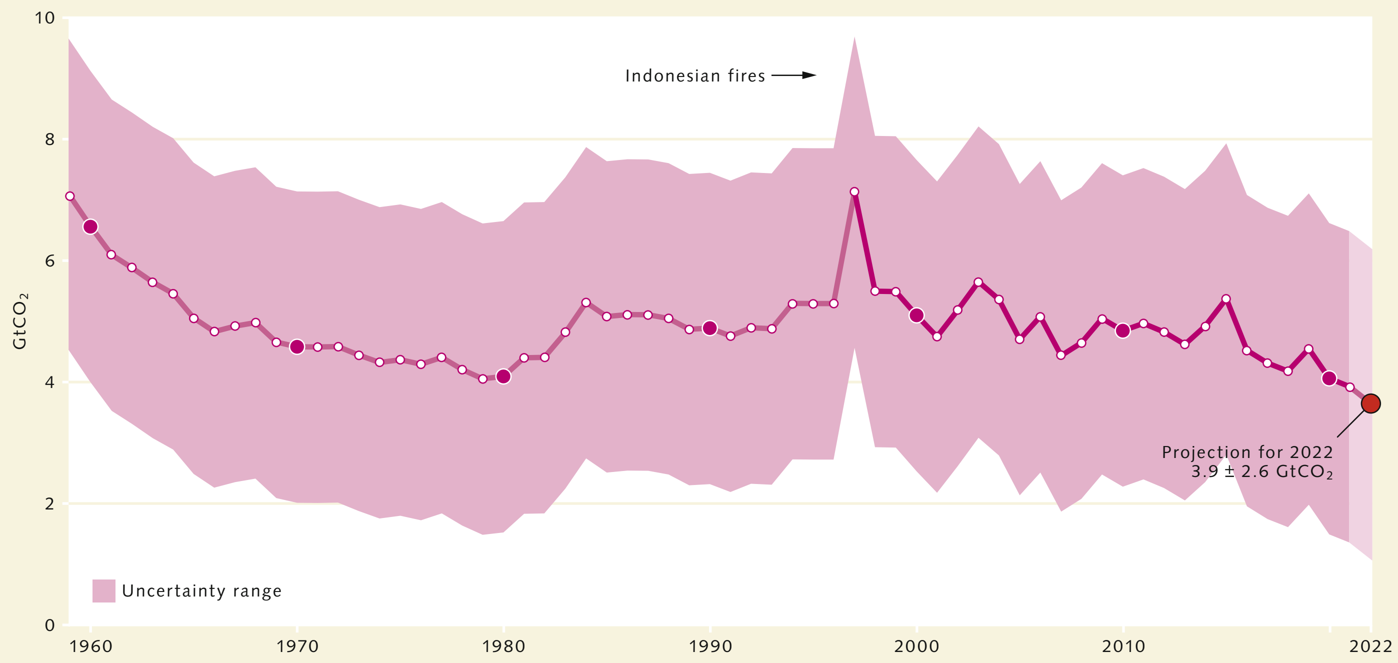
question. If, for example, the forest is cleared in a region, the reflectivity (albedo) of the earth's surface changes, as does the surface roughness. Moreover, the region's "leaf area" is reduced, through which forests contribute to evaporation and cooling. As a result, the region's radiant balance changes and along with it important climate parameters such as surface temperature, evaporation rate, soil moisture, air circulation, heat fluxes and many more.

The extent to which changes in the local climate can result from land-use change is evidenced by deforestation in the Amazon rainforest. Due to the vast area it covers and its high levels of evapotranspiration, this forest was previously able to form its own high-precipitation climate. However, as a result of large-scale deforestation and slash-and-burn farming, the original forest area has shrunk to such an extent since the 1980s that the forest's own evaporation is no longer sufficient to generate enough precipitation. Dry conditions, droughts and the risk of forest fires are increasing, so that the remaining rainforest is now at risk of turning into a dry forest. A dry forest not only sequesters significantly less carbon than the original rainforest, it is also more susceptible to fire.

Terrestrial vegetation and its soils as carbon dioxide source and sink

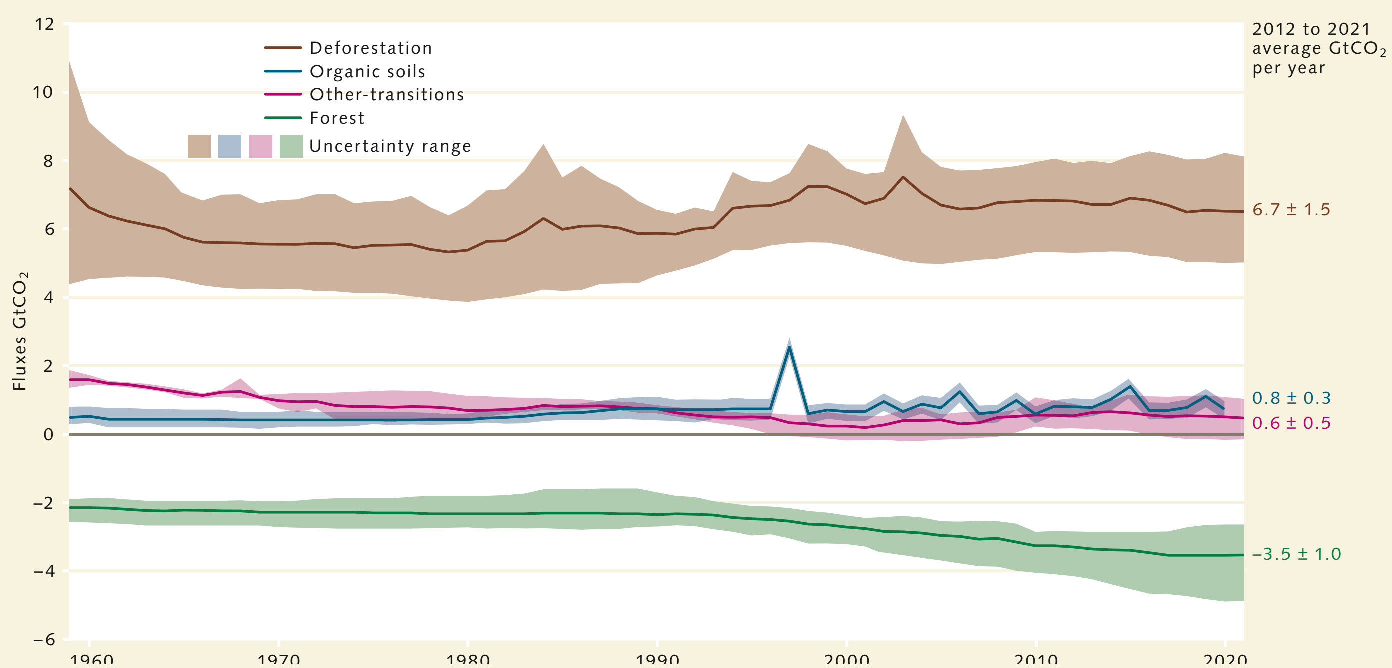
Scientists use a range of different methods to study the effects of land-use change on the Earth's greenhouse gas balance. Their most important tools include vegetation and climate models as well as vegetation data from satellite observations. However, their work is made more difficult by the fact that so far it has not been possible to

Annual CO_2 emissions from land-use change



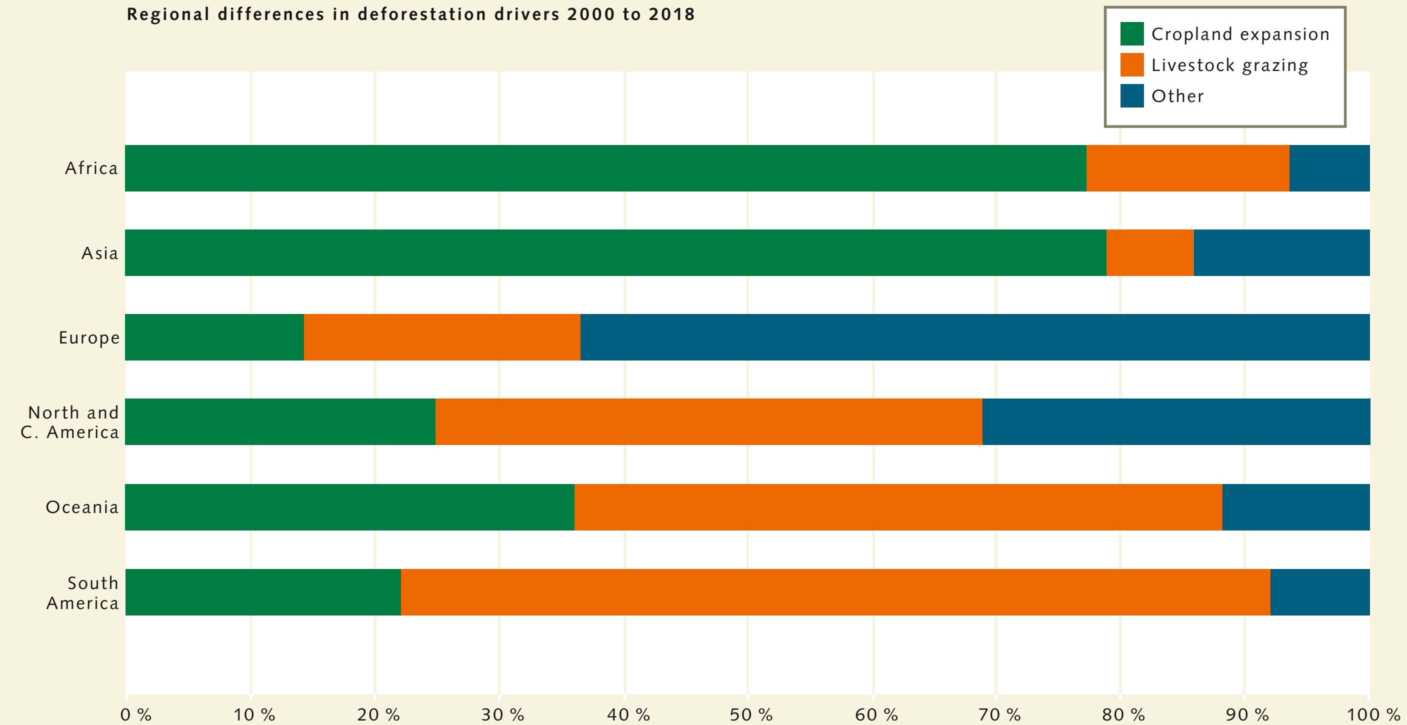
3.2 > Total carbon dioxide emissions due to land-use change have decreased slightly in recent years. The record emissions in 1997 were due to forest fires in Indonesia, triggered by drought and overexploitation of forests and wetlands.

Components of land-use change emissions



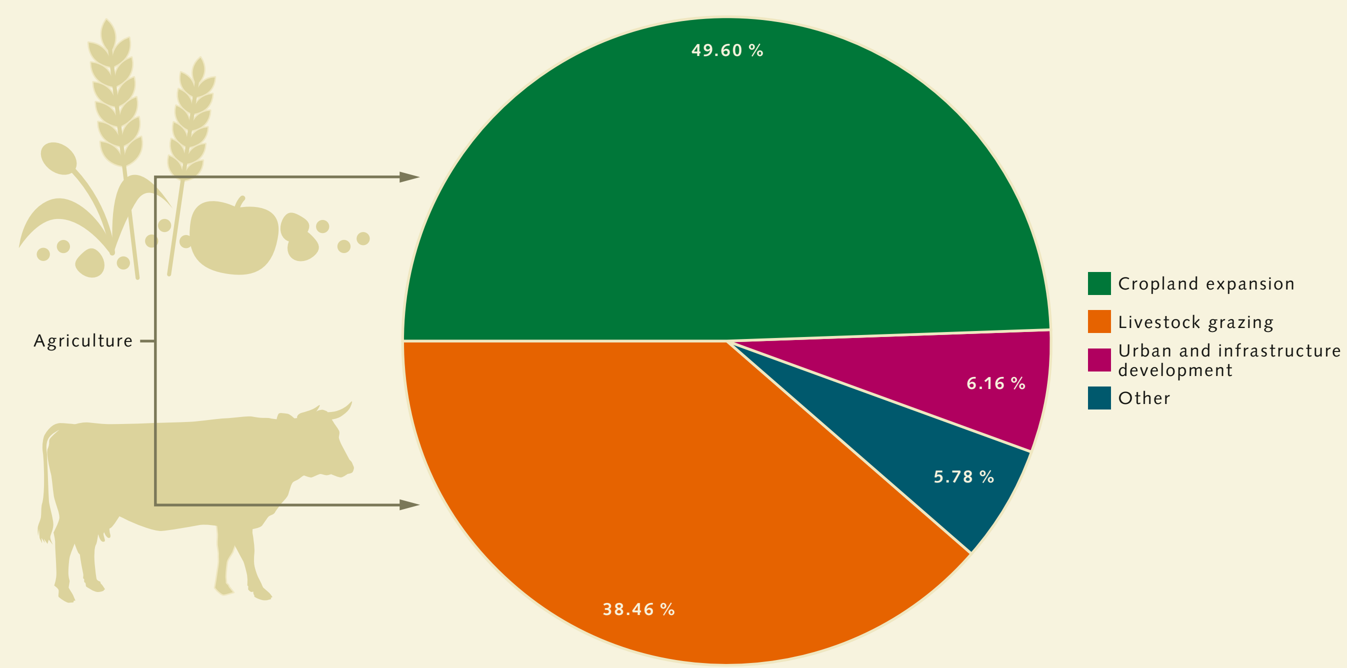
3.3 > Carbon dioxide emissions resulting from deforestation and slash-and-burn agriculture continued to account for the bulk of emissions from land-use change in 2021. (Re)afforestation measures and sustainable forest management were able to compensate for only about half of these emissions.

Regional differences in deforestation drivers 2000 to 2018

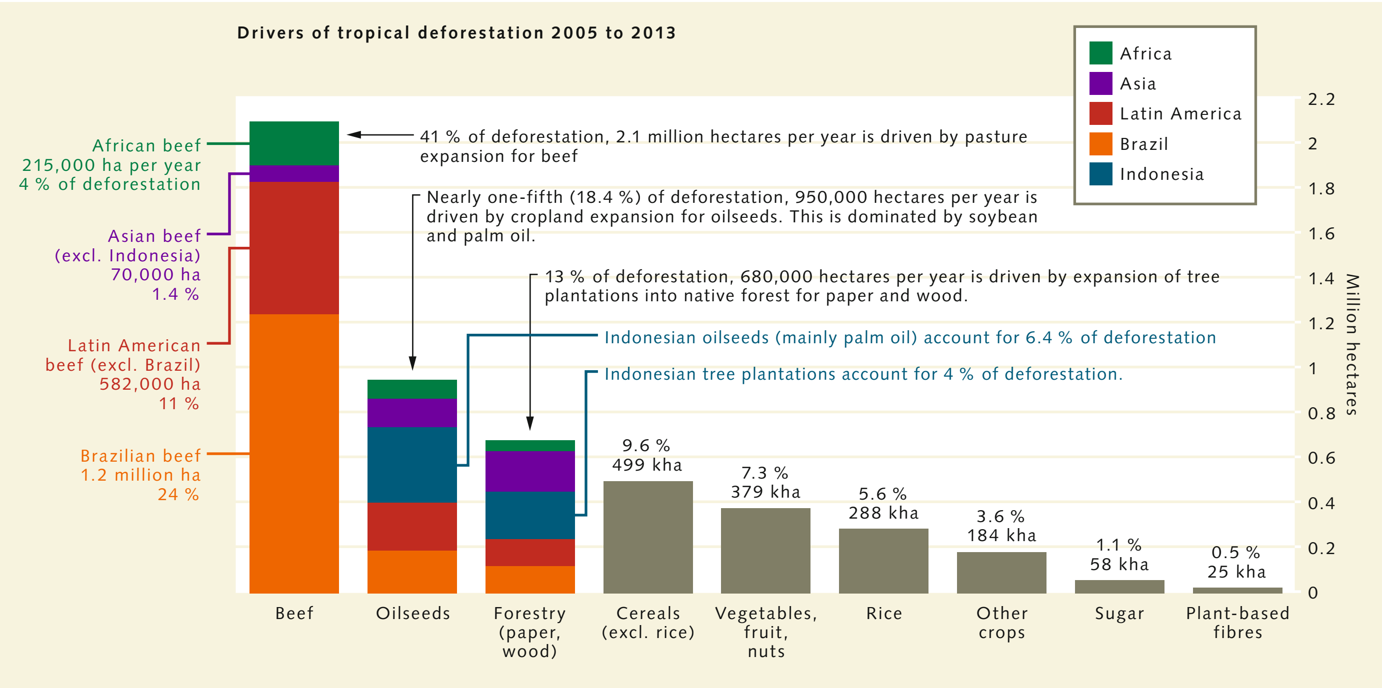


3.4 > In the period from 2000 to 2018, forests were cleared primarily to gain arable or grazing land in all regions of the world, apart from Europe. In contrast, other drivers of deforestation, such as the construction of residential areas and roads, predominated in Europe.

Global causes of deforestation 2000 to 2018



3.5 > Almost 90 per cent of the forest areas cleared worldwide in the period from 2000 to 2018 are now used as cropland or for grazing livestock. The remaining areas were converted into building land or lost, for example to dam construction or open-cast mining.



3.6 > Since the turn of the millennium, the world has lost around five million hectares of forest area per year, most of it in the tropics. Nearly 60 per cent of the deforestation in tropical rainforests is driven by the production of beef, palm oil and soybeans. As these commodities are largely exported, people in industrialized countries are indirectly responsible for a not insignificant part of the deforestation in the tropics.

clearly distinguish between natural and anthropogenic processes of change when recording global observation data, because these often occur simultaneously. If, for example, satellite observations show a decline in forest cover in a particular region, this may have been caused by deforestation. But it is equally possible that the trees have died as a result of pest infestations or climatic changes. Information on the global carbon balance of terrestrial vegetation and possible changes therein is therefore still fraught with uncertainty.

Nonetheless, researchers now have a clear idea of how crucial terrestrial vegetation and its associated soils are for the Earth's natural carbon cycle and what role, at best, they can play in the fight against climate change. Experts engaged in the international *Global Carbon Project (GCP)* have been keeping an annual record of how much carbon dioxide has been released so far as a result of the burning of fossil resources and land-use change, and what proportion of this has been naturally absorbed by terrestrial vegetation and the oceans.

According to the *GCP*, global land-use change emissions in 2022 amounted to 3.9 gigatonnes of carbon dioxide or one tenth of the total anthropogenic carbon dioxide emissions. Experts cite the continuing high levels of deforestation and forest fires as the main cause. Only half of the carbon dioxide release due to these causes (6.59 gigatonnes) was compensated by the additional carbon dioxide uptake of new, reforested or now sustainably managed forests (3.3 gigatonnes). Carbon dioxide emissions resulting from peatland fires, soil overuse or wetland drainage played only a minor role in the overall balance.

Regardless of land-use change, forests, wetlands, grasslands and agricultural fields still act as natural carbon sinks and thus slow down climate change, i.e. overall they absorb more carbon from the atmosphere than they release. According to the *Global Carbon Project*, the global terrestrial vegetation has absorbed approximately 31 per cent of anthropogenic carbon dioxide emissions since 1850 and sequestered the carbon below ground or in its biomass. Forest ecosystems, including their soils, have accounted for the largest share of this carbon sequestration. In the period from 2012 to 2021, carbon dioxide uptake by terrestrial vegetation totalled 11.4

3.7 > This coastal forest in Norway is among the roughly 28 per cent of the world's forests categorized as boreal coniferous forests – ecosystems consisting primarily of coniferous species such as pine, spruce and fir and occurring across eight countries: Canada, China, Finland, Japan, Norway, Russia, Sweden and the USA.

gigatonnes per year – 1.4 gigatonnes more than in the 2000s. For the year 2022, preliminary analyses indicate an increase to 12.4 billion tonnes of sequestered carbon dioxide.

The fertilization effect of an increasing atmospheric carbon dioxide concentration

Scientists are not surprised by the increasing carbon dioxide uptake. Quite the opposite – it confirms a long-term trend. Over the past 60 years, terrestrial plant communities have steadily absorbed more carbon dioxide from the atmosphere and incorporated the carbon it contains into their biomass, or to put it simply: plants have grown better.

This is due to the so-called carbon fertilization effect of rising atmospheric carbon dioxide concentrations on terrestrial vegetation, which, the Intergovernmental Panel on Climate Change notes, has been evident in the global carbon cycle since the 1980s. Simply put, the higher carbon dioxide concentration in the Earth's atmosphere makes it easier for plants to photosynthesize. Their photosynthetic rate increases, and the plants therefore grow better. At the same time, the more efficient photosynthesis means that the amount of water needed to produce a certain amount of biomass is reduced. This more efficient water use is due to the fact that plants can achieve sufficient carbon dioxide uptake with smaller stomatal apertures. As less water evaporates (transpires) from small stomata openings compared to wide open ones, plants can use their water reserves more efficiently. Moreover, due to global warming the growing season has also lengthened, especially in the northern hemisphere. This factor also contributes to increased atmospheric carbon dioxide uptake by terrestrial vegetation.

However, it is questionable whether this trend will continue, because plant growth does not depend solely on photosynthesis but is also determined by available amounts of water and nutrients, temperature and a number of other environmental factors. New research also shows that an increase in photosynthesis does not automatically mean that trees, for example, actually extensively incorporate the carbon from carbon dioxide into their biomass (leaves, twigs, trunks, root systems) and thus remove it from the atmosphere for long periods. The processes and interactions appear to be much more complicated than previously thought.

Reducing greenhouse gas emissions or removing carbon dioxide – two very different things

Three quarters of our planet's ice-free land areas are now used and shaped by humans, meaning that we have altered their original vegetation by clearing old-growth forests, draining peatlands and converting grasslands to cropland or using the land as building land or as pastureland for cattle, goats and sheep. Today, 85 per cent of all former wetlands are considered destroyed. As a result of this wide-scale change of the land surface and its vegetation, we have more than halved the natural carbon stocks of terrestrial ecosystems in the course of our human history, reducing them from the original 916 gigatonnes to a current level of 450 gigatonnes.

To achieve greenhouse gas neutrality by 2050, the natural carbon stores of terrestrial vegetation need to be vastly increased again. Land use thus needs to prevent future emissions from agriculture and forestry while ensuring that terrestrial vegetation can uptake additional carbon dioxide from the atmosphere. In the public discourse, a clear distinction is often lacking between measures to reduce greenhouse gas emissions and carbon dioxide removal processes respectively. Even experts often do not separate the two, usually using the all-encompassing term "mitigation options".

As a reminder, carbon dioxide removal (CDR) measures by definition only include actions taken by humans that lead to increased carbon dioxide uptake from the atmosphere. The avoidance of future emissions, however, is of much higher priority for climate change mitigation, as the more emissions we avoid, the less carbon dioxide we will ultimately have to remove from the atmosphere.

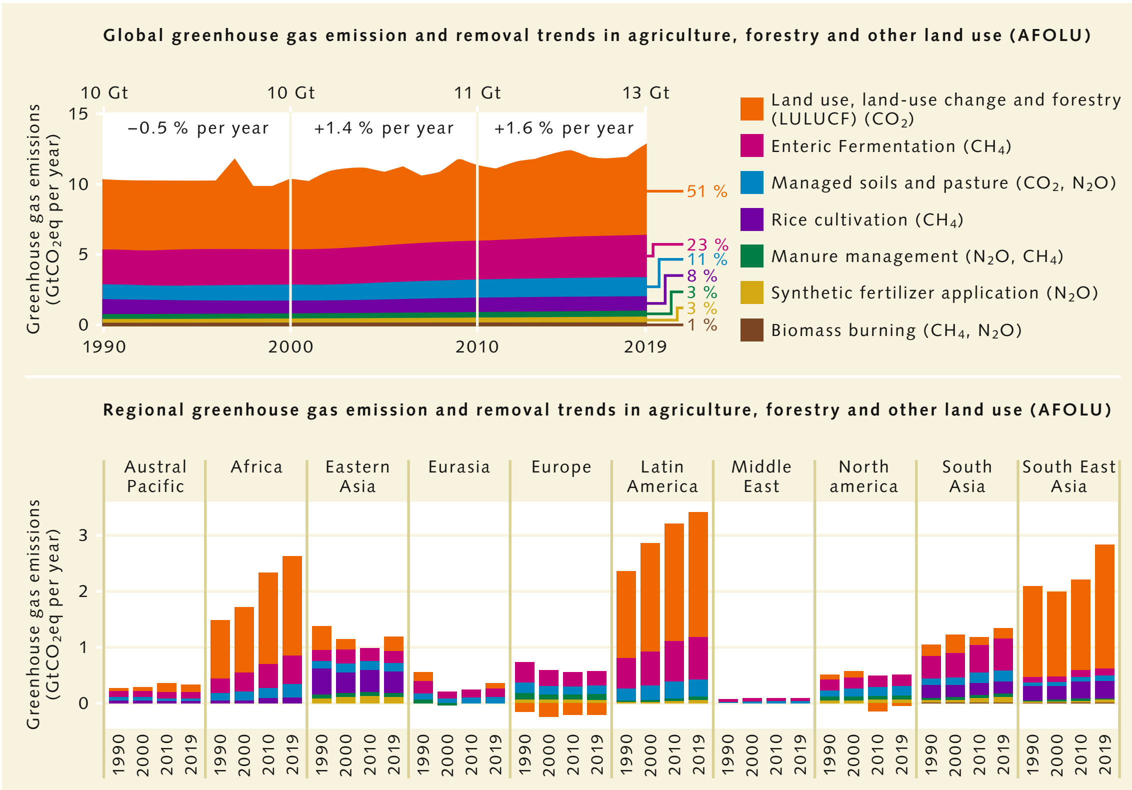
The most effective and cost-efficient way to avoid emissions from land-use change is to protect existing forests, grassland landscapes, wetlands and carbon-rich soils from destruction, overuse and fires. To simultaneously achieve increased carbon uptake and sequestration, we must also restore destroyed, degraded and overused terrestrial ecosystems and utilize them with a focus on long-term sustainability. The Intergovernmental Panel on Climate Change notes that, if properly implemented, sustainable agriculture and forestry, soil carbon enrichment measures and changes in consumer behaviour could achieve about 20 to 30 per cent of the greenhouse gas emission reductions and carbon dioxide removal needed by 2050 to limit global warming to below two degrees Celsius.

Sustainable land use and the proper use of land-based CDR practices would in many cases yield additional benefits for nature and humans: by protecting and restoring natural ecosystems, we strengthen global species diversity and the health of forests, grasslands and wetlands. There would be more clean water and food, and soil and air quality would improve. The bottom line is that we humans would live in a healthier environment and would also be better able to adapt to the impacts of climate change.

The use of land-based CDR methods is moreover supported by the fact that:

- some of the methods are already well researched and have been in use for centuries for other purposes in agriculture and forestry (e.g. reforestation, measures to increase soil carbon content, etc.);
- the climate change mitigation potential of the global terrestrial vegetation and its soils is high. Scientific studies show that sustainable land use and the proper

3.8 > Roughly 120,000 cattle live in the world's largest cattle feedlot, operated by the US company Monfort Beef in the US state of Colorado.



3.9 > With increasing livestock production, methane emissions in farming (enteric fermentation) have been rising for decades. In 2019, they accounted for about 23 per cent of total emissions from agriculture. The figures show that emissions from agriculture and forestry are particularly high in Africa, South America and Southeast Asia.

use of land-based CDR methods can achieve annual greenhouse gas emissions savings and carbon dioxide removal in the order of eight to 14 gigatonnes of carbon dioxide equivalents by 2050;

- many of the methods are cost-effective in their implementation;
- the public tends to perceive carbon storage in vegetation and soils as semi-natural and thus less risky than technical solutions.

Risks of land-based CDR methods

The use of land-based carbon dioxide removal (CDR) methods does however pose a number of risks to humans and nature. If not properly planned and implemented, certain methods lead to a decline in species diversity and jeopardize the functioning of natural ecosystems. Important services delivered by terrestrial vegetation may be lost, affecting primarily those who depend directly on nature for their food and livelihoods. Often these are the local communities.

Three striking examples of misguided measures to enhance natural carbon sinks on land are:

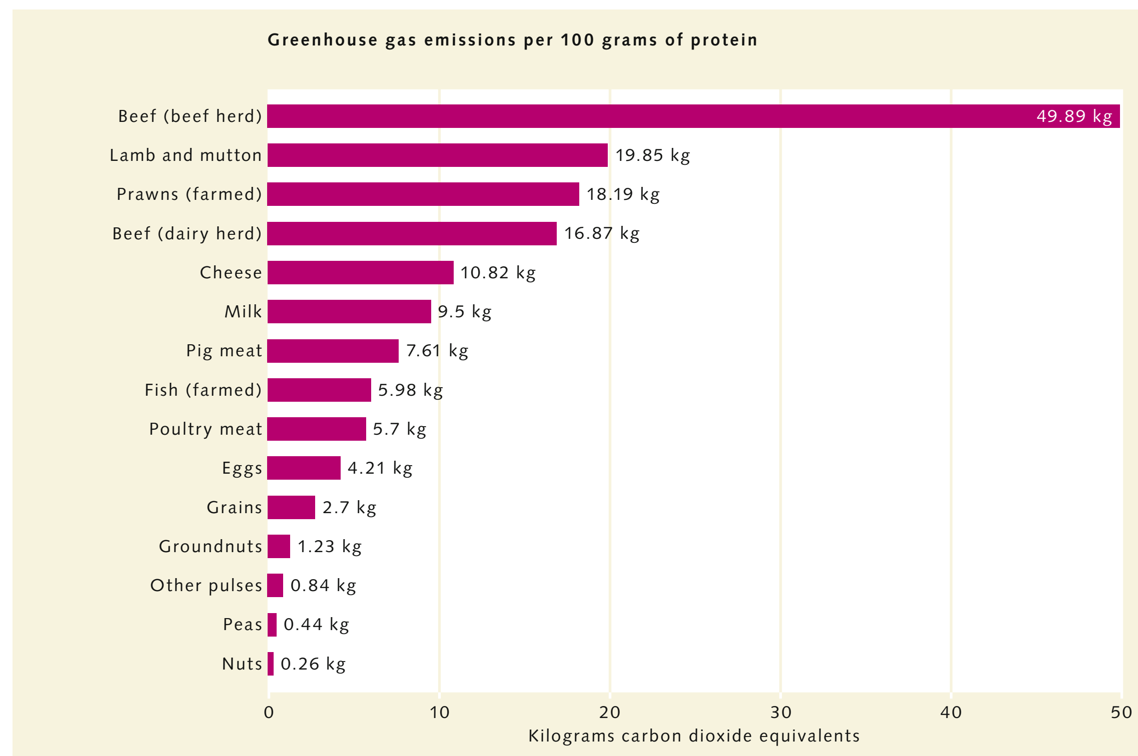
- *reforestation with monocultures* (This usually leads to acutely species-poor systems and renders the new forests susceptible to pests and diseases. Moreover, plantings of non-native species, e.g. eucalyptus in southern Europe, can increase the vegetation's water needs beyond the usual levels, thus putting at risk groundwater resources);
- *afforestation of natural grassland landscapes and savannas* (Interventions of this kind destroy the habitat of species of flora and fauna that are specifically adapted to these ecosystems; they alter local water cycles and can accelerate the decomposition of the large soil carbon stores);

- *the wide-scale cultivation of bioenergy crops, such as maize, in monocultures and aided by significant quantities of crop pesticides* (They result in species diversity declining to a minimum, soil quality deteriorating, and global competition for productive arable land intensifying).

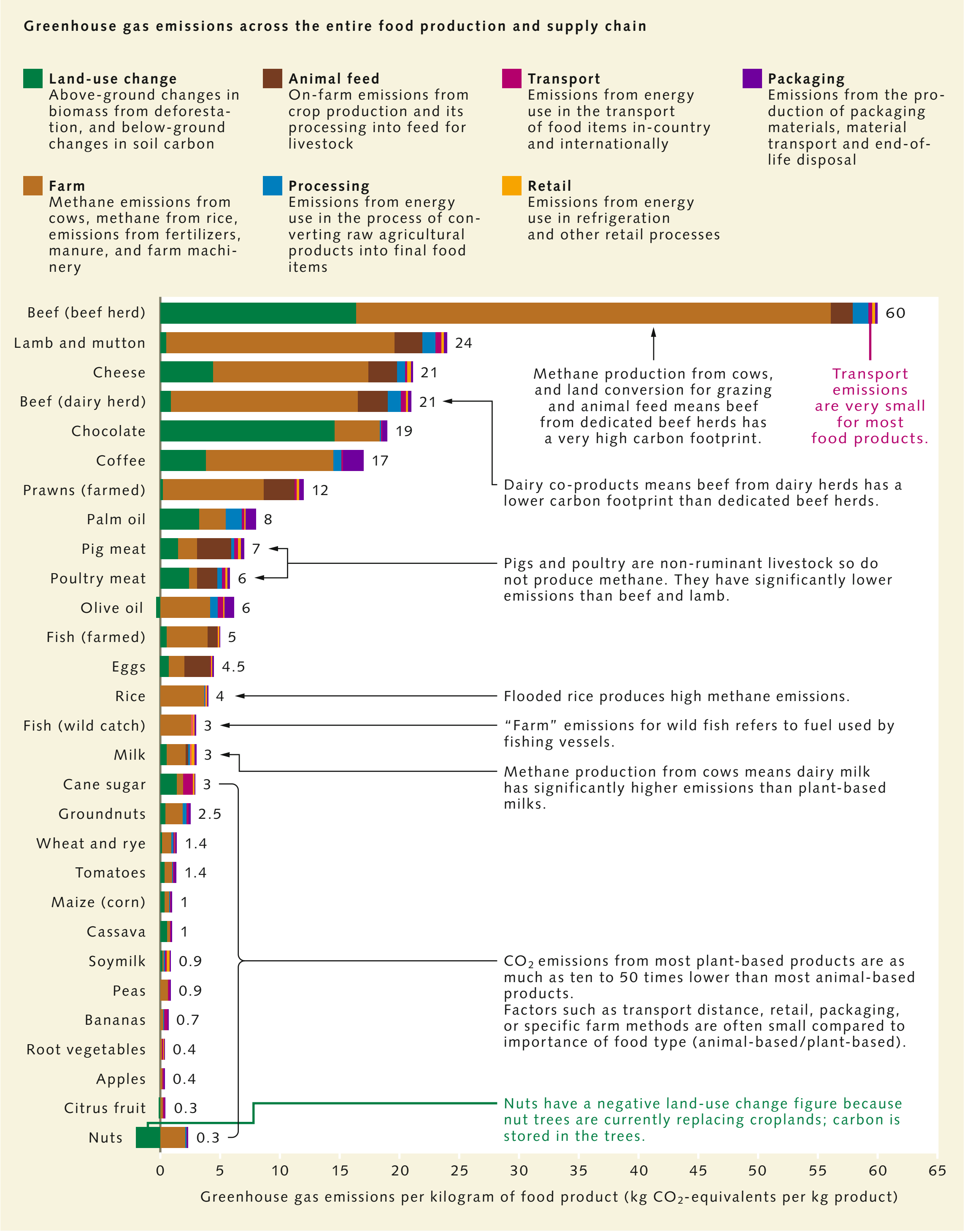
Mistakes of this kind can be avoided by favouring sustainable, biodiversity-enhancing CDR measures and with science-based planning, taking into account all local conditions and potential changes therein (e.g. due to climate change). Moreover, environmental protection, species and water protection, as well as all other UN Sustainable Development Goals, should be given high priority. Stakeholders and local experts should be consulted from the outset and involved in all decision-making processes. It has long been known that there is no one solution that fits all regions – CDR processes that worked well in one place and produce the desired results may harm people and the environment elsewhere. This is why transparent and evidence-based planning and decision-making are so important.

Are CDR measures a threat to our food security?

As part of the public discourse on the use of methods to increase carbon uptake by terrestrial vegetation, experts have repeatedly pointed out that the large acreage needed for reforestation and the cultivation of energy crops could jeopardize agricultural food production. In Germany, for example, it is estimated that roughly a quarter of the agricultural land would have to be afforested to offset the country's difficult-to-avoid emissions. Taking a global perspective, a land area the size of India would be needed to afforest a sufficient acreage by 2050 to remove enough atmospheric carbon dioxide to limit global warming to 1.5 degrees Celsius. And we would need additional land to produce bioenergy crops – an area equating to the area of Mexico by 2100. At least these are the assumptions under-



3.10 > The production of livestock-based foods such as beef, cheese and milk results in particularly high greenhouse gas emissions. A low-meat diet is therefore one of the simplest and most effective ways to reduce one's carbon footprint.



3.11 > Research conducted in 2018 showed that for most foods, the greatest share of the greenhouse gas emissions associated with their production was due to land-use change and farm management.

lying numerous scientific climate scenarios that ultimately reach the 1.5-degree target.

Widespread ecosystem restoration would have to be undertaken, particularly in the world's tropical and subtropical regions, as their rainforests and wetlands take up and store particularly large amounts of carbon. If the necessary measures were to be implemented, calculations suggest that roughly half of all utilized agricultural land in Southeast Asia, Central Africa, the Caribbean and Central America would be lost. As a result, competition for land would increase and, in the long term, food prices would rise in the affected regions. Both would primarily impact food security in these regions' poorer population segments.

If we consider the question of land use from a global perspective, the answers are not quite as clear. A large meta-study undertaken in 2018 concluded that the production of meat, eggs, milk and fish from aquaculture used roughly 83 per cent of the world's farmland (for livestock husbandry and, in particular, the production of animal feed). If global meat and dairy consumption were to sharply decline, large areas of farmland would be freed up and become available for reforestation and ecosystem restoration projects as well as for the sustainable cultivation of bioenergy crops – even if crop production had to be scaled up to meet the increasing demand for plant-based food. Other studies suggest that, if meat-rich diets and land management remain unchanged, the widespread cultivation of energy crops in particular could jeopardize the long-term and adequate supply of food for the world's growing population.

The 20 most important land-based measures to mitigate climate change

The Intergovernmental Panel on Climate Change breaks down processes for greenhouse gas emissions avoidance and increased carbon dioxide uptake by terrestrial ecosystems into four categories: (1) forests and other ecosystems, (2) farming, (3) biomass production for goods and energy generation from biomass, and (4) changes in consumer behaviour (demand-side measures).

Measures pertaining to *forests and other ecosystems* include:

- *the protection of existing forests, (coastal) wetlands, peatlands, grassland landscapes and savannas* from overexploitation, deforestation or destruction due to land reclamation, urban growth, resource extraction, fires, or pests and diseases. A particular focus in this category is on tropical rainforests and savannas;
- *reforestation of degraded forests and improved sustainable forest management* with a focus on species diversity and increased resilience to diseases and impacts of climate change;
- *restoration of degraded (coastal) wetlands, peatlands, grassland landscapes and savannas,* for example through rewetting and restoration of formerly drained areas, or by means of planting new mangrove forests and salt marshes;
- *improved fire management* in forests, grassland landscapes and savannas, for example through controlled burning of undergrowth.

Measures pertaining to *farming* include:

- *improved soil management on arable land to safeguard and increase soil carbon contents.* This necessitates, for example, improved species-rich crop rotations that include the cultivation of catch crops, dispensing with soil cultivation such as ploughing and harrowing, and using organic fertilizers such as manure;
- *improved grassland management* to safeguard or increase soil carbon content, especially immediately below the sward. Possible solutions include low-input grazing systems and the sowing of deep-rooted grasses;
- increasing use of *agroforestry land uses.* This involves farmers cultivating trees, shrubs and crops together on the same piece of land, ideally generating a range of different synergies. The benefits in a nutshell: trees and shrubs accumulate carbon in their biomass as well as in the soil, prevent soil erosion and improve water

3.12 > Intelligent irrigation methods and the targeted use of fertilizers can significantly reduce methane and nitrous oxide emissions from rice cultivation.

quality. They also provide shade that protects both crops and livestock from extremely high temperatures;

- *applications of plant-based biochar*. Biochar is produced from waste such as wood residues, sawdust, straw and other plant biomass in the absence of oxygen and at temperatures of 450 to 550 degrees Celsius. The carbon-rich biochar is considered a soil improver. It increases the soil's water and nutrient retention capacity and slows down the decomposition of carbon stored in the soil. Rice paddies treated with biochar emit less nitrous oxide, for example. Once applied to a field, biochar fulfils these important functions for decades, or even millennia. However, how successfully it can be used strongly depends on soil conditions and the feedstock used to produce the biochar;
- *a reduction in enteric fermentation*. This refers to measures that influence the digestion process of ruminant livestock in such a way that they generate less methane. These include, for example, feed additives or the targeted breeding of animals that produce less methane;
- *improved slurry management*, aimed at minimizing methane and nitrous oxide emissions. This includes, for example, the use of special feedstuffs, improved grazing management, treatment of slurry with fermentation inhibitors and optimized storage;
- *improved crop nutrient supply*. This can reduce nitrous oxide emissions from arable agriculture. The catalogue of measures includes a number of sustainable fertilizer application techniques and the use of various fertilizers, including organic fertilizers such as compost or manure.
- *optimized rice cultivation*, resulting in less methane and nitrous oxide escaping into the atmosphere. Improved irrigation methods and more targeted fertilizer use are among the options.

Category 3 contains solely processes that are summarized under the acronym BECCS (Bioenergy with Carbon Capture & Storage), referring to methods for *energy generation from plant biomass*, including wood and crop residues, organic waste and biomass from conventional food and feedstuffs such as maize. These can help reduce emissions if, firstly, the energy produced is used to power engines (biofuels) or for heat and electricity generation, replacing energy from fossil fuels. Secondly, the carbon dioxide emissions produced during combustion must be captured and then stored safely and permanently. Thirdly, the biomass should be grown or produced in a way that does not cause additional greenhouse gas emissions and does not have other adverse impacts on people and nature.

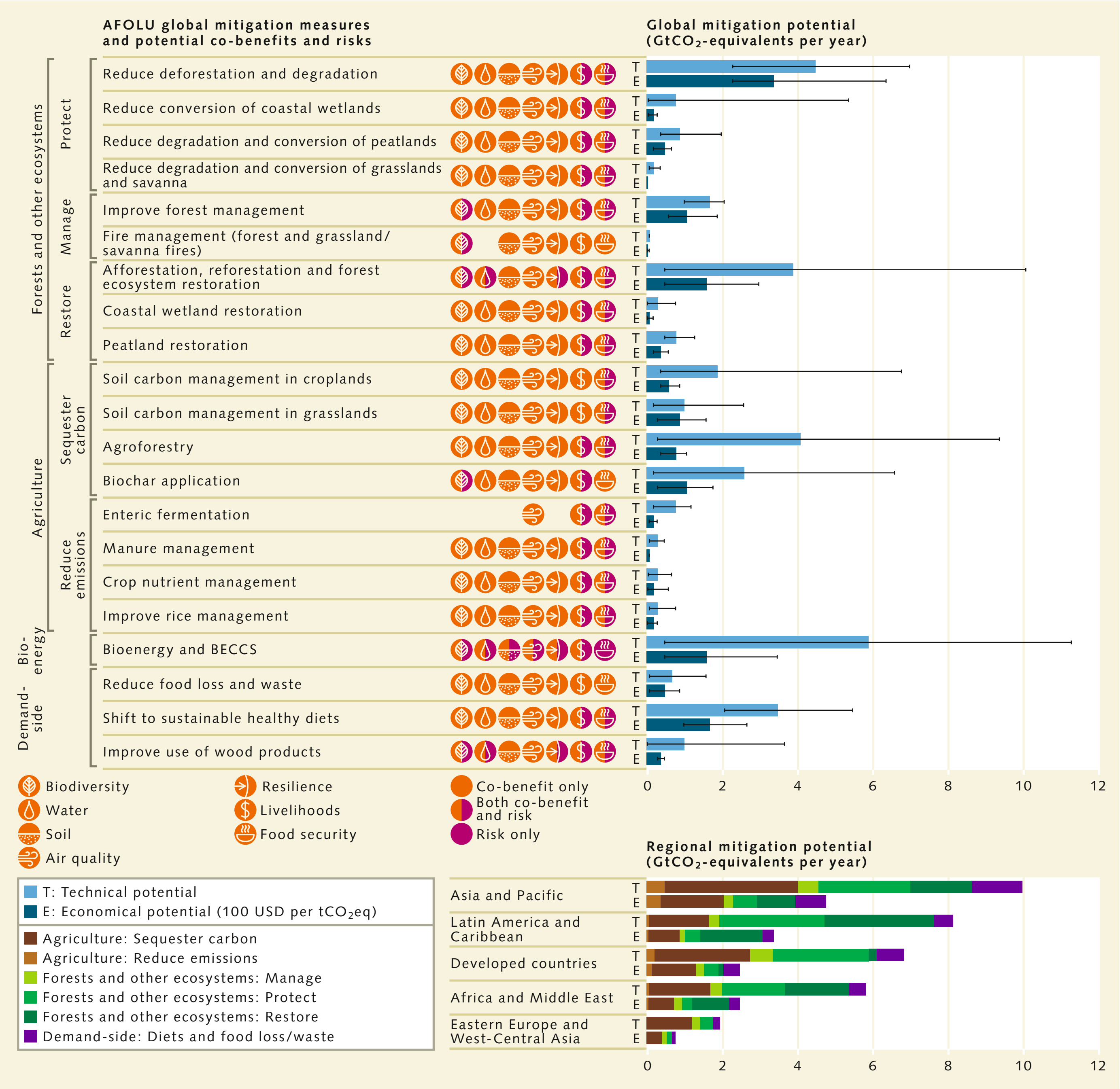
Measures to achieve *changes in consumer behaviour*:

- a *drastic reduction in food losses and food waste.* About one third of all food produced worldwide spoils on its way from the farm to the consumer or is discarded unused by consumers post-purchase;
- a *fundamental dietary shift for many people* towards a sustainably produced, largely plant-based diet. This is possible in many, but not all regions of the world;
- *increased and improved use of timber products.* When timber is used as a building material or manufactured into durable products, the carbon it contains remains sequestered for a long time. Timber use is emissions-reducing, for example, if it comes from sustainable forestry systems and substitutes for high-emissions construction materials.

Barriers and lacking frameworks

Despite their great potential, measures to save greenhouse gas emissions or to increase carbon sequestration in terrestrial vegetation have as yet contributed little to climate change mitigation. This is because so far they have been implemented on far too small a scale. The IPCC attributes this failure primarily to a lack of investment and insufficient political, institutional and societal support.

For example, policy-makers in many areas have failed to abolish subsidies for intensive farming enterprises and



3.13 > Sustainable land use and the proper use of land-based carbon removal techniques would yield benefits for climate, people and nature. This overview shows the extent to which greenhouse gas emissions could be prevented or compensated for by means of 21 selected land-based methods. It also shows the estimated annual mitigation potential at a carbon price of 100 US dollars per tonne of carbon dioxide equivalents. Potential co-benefits and trade-offs arising from the implementation of the mitigation measures are summarized in the round icons for each of the 21 measures. What is striking is that the mitigation potential is greatest in Asia and the developing Pacific region.

3.14 > Three quarters of our planet's ice-free land area is now used and shaped by humans. This also includes food production, as seen in this example, showing wheat cultivation in Tibet. It further means that these land areas are no longer in their original, natural state.

to invest the freed-up funds in sustainable arable and livestock farming instead. In addition, people in poverty-stricken rural areas whose livelihoods are based on arable farming or the timber trade (often illegal logging) often still lack alternative sources of income. Until 2020, the international community spent just 700 million US dollars per annum on measures to reduce emissions from land use. By 2030, however, investments of 178,000 million US dollars per year will be needed in the global forestry sector alone if carbon dioxide emissions of five gigatonnes per year are to be avoided or additionally sequestered – 254 times as much. To put this into perspective: five gigatonnes of carbon dioxide equate to just under half the amount of carbon dioxide that terrestrial vegetation naturally absorbs per year.

International programmes for the protection of tropical rainforests and wetlands report both successes and failures, depending on which nation one looks at. In countries where livestock farming controls large tracts of forested and non-forested land (such as Brazil), incentives to reduce the national herd in favour of reforestation are low. In Germany and other countries, complex responsibilities and ownership structures are barriers to reforestation and large-scale sustainable forest management. Yet both are urgently needed, especially on foot of the forest dieback in Central Europe due to the drought summers of 2018 to 2022.

Last but not least, the shift from conventional to sustainable farming and forestry requires investments in new or different technologies. The associated financial risks are too great for many farmers and foresters – in part also because they rarely receive remuneration for the increased carbon uptake on their land. What is needed here are new procedures in national and international emissions certificate trading and more research, the results of which will educate local communities and decision-makers as to the costs and benefits of sustainable land use.

Two additional options for increased land-based carbon dioxide removal

Accelerated rock weathering

Accelerated rock weathering, known as "enhanced weathering (EW)", is a chemical approach that makes use of the fact that rock naturally chemically weathers. This requires rainwater, for example, which always absorbs a certain amount of atmospheric carbon dioxide as it falls to the ground. When carbon dioxide reacts with water, carbonic acid is formed. When rain falls on the surfaces of stones or rocks, this carbonic acid attacks and dissolves the minerals of which they are formed. The dissolved material is washed away with groundwater and surface water. In a further step, acid-binding minerals such as calcium and magnesium react with the carbon dioxide dissolved in the rainwater. Carbonate minerals are formed in the course of this reaction, or, to put it simply, new rock is formed in which parts of the former atmospheric carbon dioxide is firmly bound. In nature, rock weathering is a very slow process. However, accelerated weathering can be achieved by mining, crushing and then field-spreading suitable rocks over large areas to increase the reactive rock surface. Certain types of construction waste and residues from cement production or mining could also be used as source materials. Enhanced weathering processes have as yet only been tested and researched in lab and small-scale field experiments. Knowledge as to potential environmental risks or co-benefits of large-scale applications is therefore still lacking. It is also still unclear where the required quantities of rock could be mined. According to the German National Academy of Sciences Leopoldina, in order to compensate for the unavoidable emissions in Germany, about 200 million tonnes of rock would have to be mined, ground and landspread annually. This would equate to roughly three quarters of the sand and gravel extraction for construction purposes in Germany in 2019. Experts note that the required logistic effort would likely be very high.

Direct carbon dioxide extraction from the ambient air

According to the Intergovernmental Panel on Climate Change, Direct Air Capture (DAC) methods of carbon dioxide fall into the category of "geochemical CDR methods". DAC requires technical systems that draw in the ambient air and filter out the carbon dioxide it contains, using a chemical binder medium (liquid or solid). These chemical media are subsequently stripped from the carbon dioxide through the application of heat (up to 900 degrees Celsius) and moisture or under pressure – a generally highly energy-intensive process. This regenerates the chemical media for reuse and the removed carbon dioxide is either stored deep underground (Direct Air Carbon Capture and Storage, DACCS) or used for the production of carbon-containing products (Direct Air Carbon Capture and Utilization, DACCU).

The advantage of the DAC method is that it has a much smaller land footprint than other methods. Moreover, it also lends itself to locations that are not suitable for farming or forestry, such as deserts or inner city areas. However, since air contains very little carbon dioxide, such systems need to filter vast quantities of air, driving up their energy consumption and causing much higher costs than if the carbon dioxide were captured in a power plant or a steel mill.

A sample calculation: according to the German Environment Agency, even with a highly ambitious climate policy, at least five per cent of Germany's greenhouse gas emissions would still be unavoidable in 2050 and would have to be offset by means of carbon dioxide removal. If one were to attempt to offset these unavoidable emissions through DAC methods, the energy required might amount to more than 100 terawatt hours per year. This would correspond to about one fifth of Germany's electricity generation in 2021 (518 terawatt hours). However, since DAC processes mainly require heat, waste heat from industrial processes or geothermal energy could also be considered as energy sources.

According to the International Energy Agency, 18 DAC demonstration plants were already in operation in Europe, the USA and Canada in September 2022. Taken together, they were removing about 10,000 tonnes of carbon dioxide from the atmosphere per year. The captured gas was subsequently used mainly in beverage production (carbonic acid) and only a small proportion was injected underground for permanent storage. At that time, a DAC facility capable of capturing one million tonnes of carbon dioxide per annum was under construction in the USA.

Industrial-scale usage of DAC will depend on whether future facilities can be operated with renewable energy and whether sufficient water will be available wherever moisture is needed for the separation of carbon dioxide and binder media. In countries like Germany, the situation is further complicated by the fact that geological storage of captured carbon dioxide is controversial at the societal level and the process currently lacks public support.

Conclusion

Solutions implemented far too rarely

The terrestrial carbon stores are much smaller than the oceanic carbon stores. Oceans store ten times as much carbon than is contained in terrestrial organisms and soils. Nonetheless, there are several reasons why the land carbon balance (soils and terrestrial vegetation) plays a key role in the current climate crisis.

Human societies have always contributed to the depletion of land carbon stocks through land-use change. This kind of depletion occurs wherever forests are cleared, be it by fire or otherwise. It also happens when wetlands are drained, natural grasslands are converted to arable land or soils are depleted by intensive agriculture. Each of these activities burns or results in the decomposition of organic matter, thus creating and releasing greenhouse gases. Carbon dioxide emissions from land-use change currently account for about one-tenth of all carbon dioxide emissions attributable to human activities. In addition, methane and nitrous oxide emissions from livestock farming and from the intensive use of fertilizers are on the increase.

Globally, humankind has so far converted 75 per cent of all original land areas and has destroyed 85 per cent of the wetlands that once existed. This has not only altered local climatic processes. It has also had the further effect of reducing the capacity of the remaining ecosystems to absorb and store carbon. The world's terrestrial vegetation and soils do however still function as a carbon sink, i.e. they absorb more atmospheric carbon dioxide and store the carbon it contains than they release through counteracting processes.

This characteristic means that terrestrial vegetation, and especially forests, has absorbed roughly 31 per cent of our carbon dioxide emissions since 1850 and stored them below ground and in its biomass. Scientists have also been observing a fertilization effect of the rising atmospheric carbon dioxide concentration, which leads to terrestrial plants showing improved growth and steadily taking up and storing more carbon overall.

Based on this knowledge, a number of solutions have been developed that can largely prevent further greenhouse gas emissions from land-use change, increase the size of the land carbon sink and compensate for anthropogenic emissions remaining after all emissions reduction options have been exhausted.

In essence, it is about protecting existing forests, wetlands and grasslands, restoring destroyed ecosystems and soils, practising agriculture and forestry in an environmentally friendly way, and producing enough biomass so that part of it can be devoted to bioenergy generation and the manufacture of goods.

Not all measures are without risk, and competition for land is fierce in some places. Properly implemented, however, known methods could achieve roughly 20 to 30 per cent of the greenhouse gas emissions reductions and carbon dioxide removal needed by 2050 to keep global warming to below two degrees Celsius.

But thus far these have been implemented on far too small a scale. The Intergovernmental Panel on Climate Change attributes this failure to a lack of investment and political, institutional and societal support. There is thus a clear disconnect between our lived reality and the scientific insight and recognition that humankind can only overcome the climate and biodiversity crises with the help of healthy and functional ecosystems.