CHAPTER 10

Impact of planted forests on climate change mitigation

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Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), mitigation of climate change refers to actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere, reduce their levels in the atmosphere, or both. Restoring forests has large climate change mitigation potential, as has been emphasized by both the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) because forests are able to sequester atmospheric carbon dioxide (CO_2) and store carbon in woody plants and soil (IPBES, 2018; IPCC, 2022). In addition, producing and using wood can limit GHG emissions in comparison to other land uses and materials. In parallel, forests are natural systems dependent upon environmental conditions, and as a consequence, climate changes condition their structure and function. The process of adjustment to actual or expected climate and its effects is called adaptation. This process may be facilitated by human intervention through forest management. Thus, mitigation and adaptation of forests are intertwined in practice, since forest ecosystems adapted to climate change and modified disturbance regimes will perform better, ultimately having a greater potential for mitigating climate change.

Planted forests can contribute to climate change mitigation by increasing and maintaining forest area, increasing the CO_2 sequestered and carbon stored in above- and belowground biomass, and reducing GHG emissions in comparison to other land uses. Forest area increases through afforestation (e.g., planting agricultural land) are being pursued in multiple countries through large-scale planting programs (e.g., Plant a Billion Trees, 3 Billion Trees Initiative). There are several strategies for increasing the carbon stored in forest ecosystems that depend on context, but generally the strategies involve

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selecting appropriate species, managing forest structure, and increasing harvest cycles to keep carbon stored as long as possible (e.g., long rotation length). An example of these strategies would be to convert a monospecific plantation to a mixed-species forest managed on long rotation. Related strategies are using wood in products with long lives (e.g., furniture and houses), replacing industrial materials that require high energy inputs to manufacture (e.g., steel and concrete) with wood-based materials, or using bioenergy from wood-based fuels instead of fossil fuels. The entire planted forest/wood utilization chain, from the nursery to end uses, offers additional opportunities to increase carbon storage and reduce GHG emissions. The objective of this chapter is to elaborate on the role that planted forests could play in climate change mitigation.

Forests and the carbon cycle

Carbon is the main component in the structure of living organisms on Earth and flows between different reservoirs in the carbon cycle. The main carbon reservoirs in the cycle are the atmosphere, oceans, rocks and fossil fuels, sediments and soils, and biomass. Plants, a major part of biomass, incorporate atmospheric CO_2 through photosynthesis in chloroplasts that are mostly in their leaves. The carbohydrates produced by chloroplasts are the building bricks for living biomass. This process is energized by solar radiation and needs water.

Woody plants, and especially trees, can store the sequestered carbon from CO_2 for many years in the dead cells that constitute wood. Forest ecosystems, dominated by trees, play a key role in the carbon cycle, acting as persistent carbon sinks and reservoirs (Pan et al., 2024). If wood is harvested and used as a material, carbon can be stored for longer periods. Thus the potential of forest ecosystems to store carbon and contribute to climate change mitigation is characterized by a biological component (forest ecosystem) and an industrial component (forest products) (Ameray et al., 2021) (Fig. 10.1).

The amount of organic carbon stabilized in forest soil is a key, but often overlooked, factor for effective long-term carbon storage in forests. The forest soil compartment stores up to two-thirds of the carbon stock in forest ecosystems (Jackson et al., 2017; Pan et al., 2024; Ruiz-Peinado et al., 2017; Whitehead, 2011). Carbon stored in the soil is more stable than carbon stored in the aboveground compartment, which is more vulnerable to disturbances (Jackson et al., 2017). Extreme events such as wildfires, pest outbreaks, intense droughts, windstorms, and heat or cold waves have an extraordinary impact on the structure or function of the forest (Puettmann, 2021), increasing tree mortality and, as wood decomposes, liberating CO_2 into the atmosphere. During these events, a large part of the forest carbon stock (sequestered over decades or centuries) can return to the atmosphere in a short time.

Forests also release CO_2 into the atmosphere through respiration and decomposition. Respiration is an essential process for living organisms to produce energy for growth and

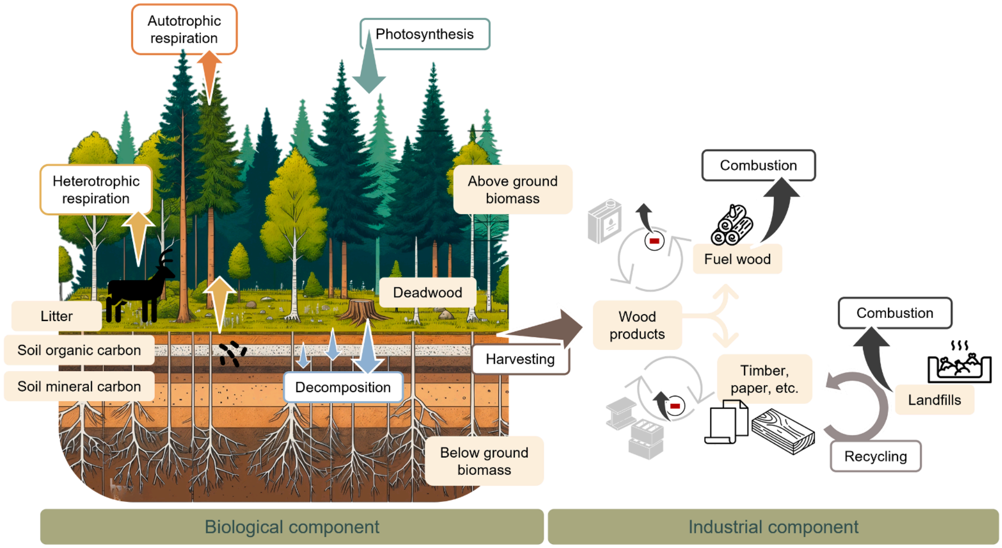

Figure 10.1 Main reservoirs (shaded boxes) and processes (non-shaded boxes) in the biological and industrial components of the carbon cycle associated with forests. Substitution effects by the use of wood products (light gray) and related reduced combustion are also represented. *(Credit: Icons by Gilang Abiogi Umri, Eugen Hunecker, Michael Appleford, Suhatidja, Brickclay, Maps, and Arfan Haq (The Noun Project).)*

reproduction. In forests, plant respiration occurs mainly at night, but respiration by heterotrophic organisms above and belowground contributes to CO_2 release during daylight. Decomposition occurs when some parts (e.g., leaves, roots) or the entire organism dies. When detritivores (invertebrates, soil fungi, and bacteria) decompose plants, their respiration releases CO_2, and a small part of their biomass ends up in the soil carbon stock. In forests, the carbon cycle is rapid for the carbon passing through metabolism and decomposition of leaves, twigs, and small roots. The cycle is slow for large dimensional wood decomposing into coarse woody debris. The speed of decomposition depends on factors such as wood structure and size, chemical composition, microclimate, soil conditions, and contact with soil (Přívětivý et al., 2016; Shorohova and Kapitsa, 2016). Increasing temperature and moisture favor decomposition until reaching a waterlogged state, where lack of oxygen slows down decomposition or causes it to completely cease.

Within the industrial component of the forest carbon cycle (Fig. 10.1), carbon stored in wood products can return to the atmosphere in short or long time, depending on their use (Ameray et al., 2021). When used for fuels, the cycle is short, whereas wood products can persist and store the sequestered CO_2 for a long time if protected against moisture and decomposition. Recycling is another option for extending the lifetime of wood products until they are no longer usable, at which point they can be repurposed as fuel or simply left to decompose. Use of wood material and biomass to substitute for nonrenewable fossil fuels and materials produced by use of fossil energy (Fig. 10.1) reduces combustion and atmospheric CO_2 since carbon in wood has a circular life.

The role of planted forests in the carbon cycle

Forests cover 30.8% of the Earth's land area (34.8% in Europe); 93% are naturally regenerated forests and 7% are planted forests. Approximately 45% of the planted forests globally are plantation forests, mainly established for production purposes, and the other 55% are forests established for multiple uses, including ecosystem restoration, protection of soil and water supply, as well as wood production. In Europe, about one-third of the forests are planted, and only 6% of planted forests are plantation forests (FAO, 2020; Chapter 1). Despite representing a small extent of total forest cover, planted forests experience alterations in carbon fluxes and stocks that can affect carbon cycling when compared with natural forests (Cruz-Alonso et al., 2019). For example, planted forests are usually designed in terms of structure or species selection to quickly accumulate biomass to produce renewables such as timber, paper fiber, wood biomass for energy, as well as ecosystem services (e.g., prevent soil erosion) (Vande Walle et al., 2007). Fast biomass accumulation in planted forests is also related to a higher transfer and accumulation of organic carbon into the soil. However, the structural features of planted forests, and particularly plantation forests (i.e., few species, equal age, regular spacing, and high stand density), can aggravate forest disturbances that affect major areas of forest promoting fast CO_2 emission.

Despite the trade-offs (i.e., quick biomass accumulation vs. higher vulnerability to disturbances), planted forests have been widely recognized for their crucial role in climate change mitigation (IPBES, 2018; IPCC, 2022; Canadell and Raupach, 2008; Pawson et al., 2013). Renewable forest products are expected to play an increasing role in substituting for fossil fuel-based products and energy. Innovative solutions in forestry and forest restoration need to address and solve the challenges and reduce the known risks of highly productive plantations, while at the same time, forest production expands to meet the demand for bioenergy to reduce consumption and dependency on fossil energy.

Planted forests as providers of multiple ecosystem services under global change

The multifunctionality of an ecosystem is related to its ability to provide various functions and services (Manning et al., 2018). Recognizing the significance of multifunctionality in forest management is gaining momentum, not solely for the provision of multiple ecosystem services, but also for enhancing resilience to future environmental changes (Gamfeldt et al., 2013; Nocentini et al., 2017; Van Der Plas et al., 2018). Planted forests not only contribute to climate change mitigation by sequestering CO_2, but also by cooling the local climate due to increasing evaporation and inducing cloud formation (Syktus and McAlpine, 2016; Yosef et al., 2018). In addition, planted forests provide numerous other ecosystem services that enhance human well-being. These include timber and other non-timber forest goods, water purification, prevention of soil erosion, biodiversity conservation, and recreational opportunities (Bauhus et al., 2010).

Planted forests are instrumental in achieving the UN Sustainable Development Goals of the 2030 agenda, not only addressing environmental objectives but also promoting social justice and alleviating poverty and inequality by mitigating land degradation and fostering economic development in rural areas (IPBES, 2018). Therefore, the establishment of planted forests is prominently featured in key areas of international policy, such as the European Nature Restoration Law that includes the EU's goal to plant at least three billion trees by 2030.

Implementing forest management strategies aimed at enhancing the multifunctionality of planted forests faces important challenges; however, these often stem from idiosyncrasies of the forestry sector, land use legacies, and the unique characteristics of the landscape (Messier et al., 2022). On the one hand, about half of planted forests continue to be managed largely for production (FAO, 2020). Ecosystem management focused on providing a specific service involves trade-offs with other services. A singular focus can lead to a less resilient and more vulnerable ecosystem under projected environmental change, not only from an ecological standpoint but also from a socioeconomic perspective (Rist and Moen, 2013). For example, plantations intensively managed for productive purposes often exhibit lower associated biological diversity and can be more vulnerable to climate change, pests, and diseases (Bauhus et al., 2010).

On the other hand, the limited economic returns from timber and other forest products in less productive planted forests of Europe have resulted in a gradual abandonment of forestry activities, particularly in the Mediterranean basin (Villar-Salvador, 2016). Consequently, many of these planted forests now exhibit overly dense structures, low diversity, and structural homogeneity, along with a lack of regeneration and widespread tree decline (Pausas et al., 2004; Sánchez-Salguero et al., 2013). This vulnerability is compounded by the fact that the Mediterranean basin is considered one of the primary climate change hotspots globally (Diffenbaugh and Giorgi, 2012), rendering these forests highly vulnerable to wildfires, pest infestations, and drought-induced dieback (FAO and Plan Bleu, 2018). The legacy of past management practices, abandonment of active management, and the emerging disturbance regime resulting from climate change (Seidl et al., 2011) present new challenges for the functioning of these ecosystems and the maintenance of the services they provide (Nelson et al., 2013).

Whatever the environmental and socioeconomic context, it seems necessary to ensure the multifunctionality of planted forests, including climate change mitigation, and to strengthen their stability in response to disturbances derived from climate change as much as possible. Alleviating concerns for potential negative effects on planted forests is crucial. Often referred to as ecosystem disservices (Dunn, 2010), these concerns include adverse hydrological impacts (Farley et al., 2005), heightened wildfire risks (Leverkus et al., 2022), or increased warming due to changes in albedo in boreal ecosystems and drylands (Bonan, 2008; Rohatyn et al., 2022).

Factors affecting CO_2 sequestration and carbon storage in forest ecosystems

Environmental factors

The availability of water and soil nutrients, along with sunlight, CO_2, and temperature (which regulates the activity of enzymes), are the primary controls of photosynthesis, and thus of forest growth and CO_2 sequestration (Lambers and Oliveira, 2019). Climatic and edaphic conditions determine the availability of resources used for tree growth and the conditions for physiological processes. These drivers strongly interact with each other in their effects on forest growth (Lázaro-Lobo et al., 2023; Lévesque et al., 2016), and their effects vary with scale. At the global scale, water availability and irradiance are the main limiting factors of terrestrial plant production (Lambers and Oliveira, 2019). However, at the regional or local scale, edaphic conditions, disturbances, or biotic interactions become more important (Elser et al., 2007; Tamale et al., 2021). Moreover, the effects of drivers vary across species and landscape contexts.

Water plays a preponderant role in plant growth. As the medium for transporting metabolites, water is necessary for cell expansion and protein synthesis. To allow CO_2 to enter the leaves for photosynthesis, stomata should be open, which allows water loss. Water availability positively affects forest growth in temperate and Mediterranean forests, and CO_2 sequestration could decrease with low water availability due to higher tree mortality (Lázaro-Lobo et al., 2023; Lévesque et al., 2016). Contrastingly, extreme rainfall episodes in already moist forests (e.g., boreal, hemiboreal) may decrease tree growth due to the negative effects of waterlogging (Edvardsson et al., 2024; O'Brien et al., 2024; Potapov et al., 2019).

In temperate and boreal forests, warmer conditions in spring may promote more forest growth and carbon sequestration due to enhanced fine root production, earlier bud and foliage development, and extension of the growth period (Bréda et al., 2006; Swidrak et al., 2014). These positive effects may be offset, however, if warming during spring overlaps with other weather conditions. For example, negative temperatures or late frosts occurring during the premature onset of spring can damage the vegetative and generative organs of species considered well adapted, such as *Quercus robur* (Klisz et al., 2023; Puchałka et al., 2016). On the contrary, in Mediterranean forests—characterized by summer water shortage—warming tends to decrease carbon accumulation because it exacerbates water stress and extends the dry period (Díaz-Martínez et al., 2023; Vayreda et al., 2012).

Forest species have different sensitivities to warming depending on differences in strategies to cope with enhanced evapotranspiration and water shortage (Dyderski et al., 2018). Vapor pressure deficit, a measure of the dryness of air, can cause plants to lose water more quickly. This can lead to water deficits and stress, causing trees to close their stomata to reduce water loss and take up less carbon. This can cause growth reductions and even death. A study in central Europe revealed that a warmer vegetative period promoted the growth of beech (*Fagus sylvatica*), oak (*Quercus* spp.), and ash (*Fraxinus excelsior*) but had neutral or negative effects on spruce (*Picea abies*), fir (*Abies alba*), and Scots pine (*Pinus sylvestris*) (Lévesque et al., 2016). Warmer temperatures during the vegetative period, accompanied by low precipitation, including during the previous winter, however, can reduce growth of *Fagus sylvatica* and *Quercus petraea* as well (Puchałka et al., 2024).

Assessing the effects of soil nutrients on forest growth across regions is challenging because fertility depends on multiple site factors (e.g., soil texture, organic matter, pH, and moisture). For example, productivity across boreal forests in Sweden decreased with a higher soil C:N ratio (less available N in the soil; Van Sundert et al., 2018). In central Europe, the growth of several common tree species negatively responded to higher soil C:N under dry soil conditions (Lévesque et al., 2016).

Anthropogenic emissions from fossil fuel burning and agricultural activity have increased atmospheric CO_2 worldwide and promoted N-deposition in forests of the industrialized world (Galloway et al., 2008; IPCC, 2023). Initially, the increase of these resources was expected to promote forest growth and CO_2 accumulation (a fertilization effect), somehow compensating for CO_2 emissions. Global and local studies indicated that ecosystem productivity and forest carbon stocks increased over several decades (Bellassen et al., 2011; Le Quéré et al., 2016), with CO_2 being identified as the main driving factor (Fernández-Martínez et al., 2017). However, responses are not linear and largely depend on the context (Astigarraga et al., 2020), and evidence is pointing to a slowing down of this CO_2 fertilization effect (Peñuelas et al., 2017). Among the reasons for explaining this saturation effect, we can mention tree acclimation to increased atmospheric CO_2, growth limitation by other factors (P, K, water), or increased respiration rates (De Vries et al., 2017; Peñuelas et al., 2017).

Moderate levels of N-deposition have released forest growth from N-limitation and promoted growth and CO_2 sequestration in many temperate and boreal forests (De Vries et al., 2017; Tian et al., 2018). However, above a certain level of N-deposition, the negative effects of soil acidification and the increased vulnerability of forests to pests, pathogens, or other disturbances offset the initial improvement of forest growth (De Vries et al., 2017). Moreover, when forest growth becomes N-saturated, it turns out to be limited by climatic factors or soil P (Braun et al., 2010; McNulty et al., 2005). All these processes explain why the positive effect of nitrogen fertilization may not be sustainable over time.

Disturbances

Forests can withstand extreme disturbances (resistance) and then conserve stored carbon to some extent. Forests could also recover from disturbances (resilience) and promote fast CO_2 sequestration later on. For example, cork oaks (*Quercus suber*) can withstand fires with little damage to the main stems—thanks to the insulation by cork—and recover the crown in a short time (Pausas et al., 2004). By contrast, most pine species are more likely to die in forest fires, and the forest can recover from the seed bank after decades (Farjon and Filer, 2013). Forest resistance and resilience depend on the type and intensity of the disturbance, forest structure and species composition, tree age, individual predisposition (genotype), or previous disturbances (recurrence interval and legacies).

Although extreme events are natural drivers of forest dynamics, their frequency and severity are increasing worldwide due to climate change, diminishing the potential of forests as carbon sinks and as tools for mitigating climate change (Seidl et al., 2014). Extreme droughts decrease forest growth, and this effect may extend for several years (Fig. 10.2A). A global study of 1338 forest sites across the world detected that after severe droughts, the reduced growth persisted for 1–4 years, with longer effects in dry ecosystems and in the Pinaceae family (Anderegg et al., 2015).

The resistance of trees to windstorm damage decreases with tree height and increases with tree diameter; tree spacing may reduce the damage propagation, but gap opening or the creation of edges increases the vulnerability of the remaining trees to wind damage (Gardiner, 2021). Wind damage is causing CO_2 sequestration reduction in lowland and mountain coniferous forests in central Europe, and it is projected to increase in mid-latitudes of Europe in the next decades (Seidl et al., 2014).

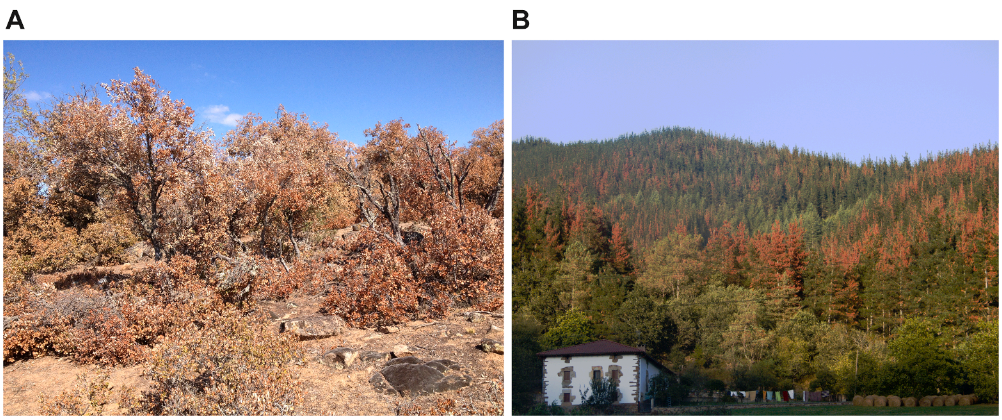

Figure 10.2 Left—declining stand of *Quercus ilex* in central Spain after the extremely drought-ridden summer of 2019. Right—stands of *Pinus radiata* in northern Spain affected by the fungi *Lecanosticta acicola* and *Dothistroma septosporum*. *(Credit Author: Jorge Mongil-Manso (left), Verónica Cruz-Alonso (right).)*

In Europe, large wildfires are becoming more frequent, particularly in the Mediterranean region, due to warmer temperatures and the forest decline induced by climate change, but also because of the densification of forests after rural abandonment (Seidl et al., 2014; Vayreda et al., 2012). Also, stressed forests are more vulnerable to pests (Kurz et al., 2008) (Fig. 10.2B), and bark beetles are expected to colonize previously unsuitable habitats at high elevations and latitudes due to warming (Seidl et al., 2009). Altogether, these extreme events are expected to have a major impact on the forest carbon stock. Projections on the effects of droughts, windstorms, fires, and pests on carbon stock in Europe bring into question the efficiency of forest-based solutions to compensate for anthropogenic CO_2 emissions (Seidl et al., 2014).

Forest management

Species choice for planting forests

Tree species inherently differ in their resource use strategy, which ultimately affects forest carbon storage and carbon sequestration (Lázaro-Lobo et al., 2023). Resource use strategies span from acquisitive (i.e., rapid resource capture and growth) to conservative (i.e., slow growth, long life, and high investment in storage and defense; Díaz et al., 2016; Wright et al., 2004). Many tree species used in tree plantations follow the acquisitive strategy (e.g., some species of *Pinus* and *Eucalyptus*) and have been selected and genetically improved to produce timber (Brundu and Richardson, 2016; Lázaro-Lobo et al., 2023; Serrada et al., 2008). These fast-growing tree species may sequester and store carbon at a faster rate than slower-growing trees.

Carbon storage in the forest depends on the stability of the tree biomass, which is influenced by the resistance and resilience of tree species against disturbances (Nuñez et al., 2021; Suryaningrum et al., 2022). Thus, tree species used in plantations should be adapted to local disturbances and resilient toward the expected disturbances, or species mixtures may provide an improved portfolio of response traits to unpredictable future conditions. In Europe, plantation forests are dominated by conifers such as *Picea abies*, *Pinus sylvestris*, and *Pinus pinaster*, in areas out of their climatic optima (e.g., see Box 1 in Vilà-Cabrera et al., 2023) or where these species had their climatic optima during colder periods of the Holocene (Feurdean et al., 2011), making these stands potentially less resistant and resilient.

Furthermore, some species increase disturbance effects, which increases carbon lability. For example, *Eucalyptus* spp., *Pinus* spp., and *Acacia* spp. are considered fire-promoters because they accumulate flammable fuels in the environment (Brooks et al., 2004; Lázaro-Lobo et al., 2023). In turn, the dense plantations that these species usually form can limit understory vegetation, which may contribute to the easier spread of fire along the ground, with low litter moisture and flammable compounds.

The species chosen for tree plantations greatly affects opportunities for long-term carbon storage in the soil compartment. CO_2 sequestration in the soil may be enhanced by planting tree species with a high ratio of root biomass to aboveground biomass, such as *Quercus* spp. (Lorenz and Lal, 2014). Tree species also affect the stability of soil organic carbon via the composition of their tissues, especially roots (Angst et al., 2019). Moreover, labile, high-quality' plant litter (i.e., containing high N and low phenol and lignin concentrations) promotes soil organic carbon stabilization (Castellano et al., 2015), and these relationships are modified by forest management (Mayer et al., 2020).

There is considerable evidence that greater plant species diversity leads to greater potential for supporting larger carbon storage in forest stands and, in some cases, also larger CO_2 sequestration per year, in both natural and plantation systems (Depauw et al., 2024; Ruiz-Benito et al., 2014). Mixed tree plantations, where multiple tree species are growing together, can be more efficient in carbon storage and CO_2 sequestration compared to monocultures, as well as in coping with climate change-related stress and other disturbances (Depauw et al., 2024). Two main, not mutually exclusive, mechanisms have been proposed to explain these positive effects of diversity on carbon storage and CO_2 sequestration: (1) the complementarity effect through facilitation and niche partitioning, which enhance resource use efficiency, and (2) the selection effect through the increased probability of inclusion of productive species (Grime, 1998; Loreau and Hector, 2001). Thus, promoting plantations with a variety of tree species may increase carbon storage and CO_2 sequestration, as well as resilience to climate change, if none of the species is fully outcompeted and suppressed.

Many plantation forests are dominated by nonnative tree species, which can greatly affect carbon storage and CO_2 sequestration (Castro-Díez et al., 2019). Nonnative tree species have generally been introduced for their fast growth rates, high productivity, adaptation to degraded lands (e.g., eroded soils), and better suitability for wood industries. Fast growth allows them to store more carbon in the aboveground biomass than co-occurring native species (Brundu and Richardson, 2016; Dimitrova et al., 2022; Medina-Villar et al., 2024; Nicolescu et al., 2020; Pötzelsberger et al., 2020). However, several studies suggest that stands dominated by nonnative trees have more labile carbon stocks than native forests (Suryaningrum et al., 2022) and store less carbon in the soil (Wu et al., 2020; Zarafshar et al., 2020). A global meta-analysis conducted by Lázaro-Lobo et al. (2024) supports these findings, which underpin the need to engage in planting nonnative species with a long-term strategy of management.

Silviculture

The strategies for increasing atmospheric CO_2 sequestration and climate change mitigation in planted forest stands include increasing forest area and forest management focused on (1) increasing biomass stocks (both above- and belowground), (2) improving assimilation of organic carbon into the soil, (3) increasing wood quality, (4) diversifying species composition, and (5) protecting carbon pools against disturbances or land use changes. The achievement of all these objectives can be simultaneous, although some trade-offs also arise that need to be considered.

Both intensive forest management and mechanical site preparation show trade-offs regarding CO_2 sequestration and storage (Dalmonech et al., 2022; Mayer et al., 2020). Mechanical soil preparation methods (scarification, mounding, subsoiling) are used in afforestation and reforestation for improving seedling survival and growth (Chapter 6). However, they cause soil disturbance that changes the microclimate and stimulates the decomposition of soil organic matter (Löf et al., 2012). In general, there is a loss of carbon from soil following site preparation because soil organic matter is exposed to different conditions of decomposition and mineralization. Nevertheless, both the performance of seedlings and the mineralization of soil carbon are also favored by soil mechanical preparation, and this may balance the carbon losses from soils in the overall ecosystem response (Ruiz-Peinado et al., 2017).

In general, intensive forest management in planted and, particularly, plantation forests enhances CO_2 sequestration capacity. However, a balance is needed between maximizing carbon uptake and wood products quality (Ameray et al., 2021) as well as with the other ecosystem services provided, including biodiversity conservation (Díaz et al., 2009; Pawson et al., 2013). Extending the rotation period and increasing cutting diameter limits increase the time trees sequester CO_2, and thus the stored carbon in biomass in planted forests (Zavala et al., 2024). As the quality of wood increases, its average lifespan also increases, since it is more typically used for the production of long-lasting products: construction, furniture, etc. (Ruiz-Peinado et al., 2017). Thinning stands reduces competition among trees and makes remaining trees grow faster (Ameray et al., 2021). However, low-quality products, wood with small dimensions, firewood, or other products from thinning, shorter rotations, and from forests where silvicultural interventions have been less intensive have shorter average lifespans of use (Montero et al., 2005). Consequently, the carbon they contain is released into the atmosphere in a shorter period of time. In the last decades, however, small-dimension timber has attained longer lifespans because of the development of composite timber technology (e.g., Liang et al., 2020).

Partial cutting increases forest carbon sequestration rates and maintains higher carbon storage in soils compared to clearcuts (Ameray et al., 2021). Wood harvest can lead to soil organic carbon losses, especially if it is intense and in temperate forests when compared to boreal forests (Achat et al., 2015). When forest harvesting residues (e.g., branches) are left in situ after silvicultural operations, their carbon content is transferred to the deadwood pool, increasing soil organic carbon in the long term as a direct result of the decomposition process (Achat et al., 2015). This management option also modifies fuel distribution and flammability in the stand.

The diversification of planted forests in terms of tree species, functional diversity, and structural heterogeneity is considered a promising strategy for climate change mitigation, multifunctionality, and increasing resilience to disturbances (Messier et al., 2022). There is a growing body of evidence that more diverse planted forests are as productive or more so than monospecific stands in terms of biomass (Ameray et al., 2021; Forrester and Bauhus, 2016; Huang et al., 2018), and that diverse planted forests provide a higher level of ecosystem functions and services beyond wood production (Ampoorter et al., 2020; Schuldt et al., 2018). Partial cutting can be used to transform monospecific stands into species mixtures. Underplanting or direct seeding broadleaves in coniferous stands, for example, has been used in forest restoration efforts (Stanturf et al., 2014). Variable retention harvesting, variable density thinning (VDT) (Palik and Kastendick, 2023; So et al., 2024), or creating artificial gaps (Brodie and Harrington, 2020) are alternatives to clear-cutting, row thinning, or shelterwoods. While some VDT have shown increased natural regeneration in the thinned "skips" (e.g., Nyamai et al., 2020), these areas could easily be planted with climate-adapted native species (Chakraborty et al., 2024).

The protection of carbon pools in planted stands includes management options aimed at reducing wildfire risk (i.e., number, extent, and intensity of fires), pest outbreaks, and the impact of extreme weather events. At the stand level, actions oriented to reduce fuel load include thinning, pruning, brushing out, prescribed burning, and removing harvesting residue. Also, structures to break fuel continuity, such as firebreaks and control lines, need to be clean and accessible. Diversification of tree species can break fuel continuity, and species mixtures also make planted stands less vulnerable to pest outbreaks and extreme weather events (Bauhus et al., 2017; Jactel et al., 2021). In general, promoting irregular structures and reducing forest density by thinning would reduce drought and pest effects. Trees of different sizes respond differently to meteorological conditions, making the stand more resilient to warming and water shortage, but irregular structures also promote vertical fuel continuity and might cause more intense fires. Partial cuttings can also increase post-cutting mortality that is incurred by disturbance, particularly windthrow (Montoro Girona et al., 2019).

Aboveground carbon storage in forests is unstable, and fast-growing species require timely management and harvests because the stand swiftly becomes highly vulnerable to disturbances. The current problems of declining timber production and increasing stand mortality can largely be attributed to the fact that the species selection and stand structure in planted forests are more in line with the demand for specific timber assortments or ecosystem services (e.g., soil erosion prevention) than an expression of adaptation to climatic conditions (Nabuurs et al., 2017; Yousefpour et al., 2018). Planted forests are still predominantly established and managed as monospecific and homogeneous stands, highlighting a disconnect between scientific evidence and forestry practices (Messier et al., 2022). Engaging in bridge-building efforts on this topic will contribute to the multifunctionality and long-term stability of planted forests and the forestry sector, particularly in the face of increasing uncertainty resulting from climate and socioeconomic changes.

Reducing emissions by using wood: The cyclic forestry-based system

The previous section describes management options and trade-offs to increase CO_2 sequestration in planted forests. Just allowing carbon stocks to grow in the forests, however, does not contribute to supply chains of sustainable materials and energy to substitute energy-intensive materials and fossil fuels in current societies. It is important to note that increasing the supply of wood and biomass is paramount in a world with more than eight billion people, where bioenergy from wood can help to reduce the dependency on fossil energy and create more sustainable solutions for future generations.

Using wood products is a well-recognized and known climate-mitigating tool from forests (Gustavsson et al., 2021; Oliver et al., 2014; Taeroe et al., 2017). The UN Environmental Program (UNEP) reports that the built environment is responsible for at least 37% of global CO_2 emissions (UNEP, 2023), and while there is progress on reducing the operational energy consumption of buildings, practically no progress has been achieved on the construction aspect. Thus transforming the construction sector toward renewable building materials such as sustainably produced wood holds great potential for reducing global CO_2 emissions. This underpins the need to understand the flows and changes in stocks of the entire carbon cycle (Fig. 10.1) to describe and evaluate the mechanisms, potentials, and limitations of forestry and the use of wood products and woody biomass in climate change mitigation.

Substitution effects of replacing fossil fuels and energy-intensive materials with wood

Substituting woody biofuels for fossil fuels or wood products for energy-intensive materials, such as concrete, steel, plastics, or cotton, contributes to reducing GHG emissions and to climate change mitigation. Thus, analysis of the forest carbon cycle needs to consider the substitution effects achieved by replacing materials with high levels of embedded energy (i.e., their manufacture is energy-intensive) and fossil fuels with wood materials and biofuels, respectively. Estimating the CO_2 emissions in all parts of the life cycles of alternative product systems is used to compare systems and calculate the reduced/increased emissions achieved by replacing fossil-based products and energy with wood-based ones. The reduced emissions obtained are often denoted as "substitution factors" and "substitution effects" (Leskinen et al., 2018). A substitution factor describes how much GHG emissions would be avoided if a wood-based product is used instead of another product to provide the same function, being it is a chemical compound, a construction element, an energy service, or a textile fiber. Overall, GHG substitution effects can be estimated by combining information on the quantity of wood products that are produced or consumed with product-specific substitution factors.

Numerically, substitution effects describe the ratio between reduced emissions of CO_2 from using the alternative materials and processes relative to the CO_2 equivalents of wood dry matter in the wood products used. When substitution effects are above zero, there is a CO_2-reduction impact from using wood-based materials and fuels. Substitution effects are high (e.g., >1) when substituting energy-intensive fossil-based materials with wood products, or when bioenergy is used to substitute coal in energy-efficient combined heat and power (CHP) plants. These values can vary significantly, depending on the specific products being substituted and the types of woody products replacing them (Sathre and O'Connor, 2010). Overall, substitution effects (i.e., climate change mitigation) are increased the more efficiently the substituting wood products are produced, for example, in terms of yield per year and hectare, or proportion of the total stand growth utilized for wood products.

Oliver et al. (2014) provided examples of wood materials substituting various energy-intensive materials. They reported substitution effects for fuels in the range of 0.5–1.5 kg-CO_2 kg^{-1}dry wood. When wood fuels are substituted for natural gas in energy-inefficient power plants, the substitution effects were generally low, whereas they were high in energy-efficient CHP systems (e.g., a power plant with a district heating facility), or when replacing coal as fuel. When wood building materials substituted for energy-intensive materials, the range of substitution effects was 2.0–9.5 kg-CO_2 kg^{-1}-dry wood (Fig. 10.3). The highest values of substitution effects were found for

Figure 10.3 More than 25-years-old wooden industrial buildings (9500 m^2) built in 1995 at the Velux company's production facility in Østbirk, Denmark, to demonstrate a sustainable solution in practice to the alternative of using energy-intensive construction materials like concrete, aluminum, steel, and plastics. Specifications for the buildings included the use of proactive construction solutions to avoid the need for paint or chemical treatments to support durability, to avoid the need for maintenance, and to support aesthetics and functionality of the building. *(Credit: Palle Madsen.)*

wood composite construction materials since such materials generally involve higher utilization of the total forest yield. With whole-timber construction products, higher proportions of the total forest-wood production will become waste wood and often used for energy, which is not as efficient in terms of CO_2 sequestration as when small-dimension wood is used for composite construction materials.

The literature on substitution effects has grown considerably during the last decade, and reviews (Leskinen et al., 2018; Sathre and O'Connor, 2010) on this topic tend to report lower values than Oliver et al. (2014). Lower substitution effects might be related to the fact that system analyses have become increasingly comprehensive over time, and the substitution effects of using wood will decrease over time as our resource systems and societies become more energy efficient.

Innovative pathways to improve the utilization of carbon fluxes

A fundamental prerequisite for reducing emissions by using wood is the sustainability of forestry activities in the long term. The innovations and potential improvements of the forest industry are available in all parts of the cycle, and they will, in many cases, need adjustments of current practice to overcome challenges, changes, or create synergies. For example, changing tree species in planted forests while seeking increased growth, CO_2 sequestration, and forest adaptation will typically need changes to seed procurement, nurseries, and silviculture, and to the wood processing industry and markets. Thus, mitigation efforts could also need more intensive management, particularly if industrial products increase the market value and volume of wood harvests. Also, alternatives for CO_2 sequestration other than biomass are proposed to be integrated into the forest-industry bioeconomy.

As an example of an innovative pathway in the carbon cycle, BeCCS (Bioenergy Carbon Capture Storage) involves the full carbon cycle and links forestry with the wood products and energy industries (Fig. 10.4). When biomass is used to produce energy, BeCCS systems create a negative carbon flow from the atmosphere into geological storage by using carbon capture technologies, already being implemented in the fossil fuel industry (Almena et al., 2022). If BeCCS technology develops successfully, the costs and CO_2 emissions of the process itself will be relatively small compared to the CO_2 permanently stored (Almena et al., 2022).

Measuring CO_2 sequestration and carbon storage in planted forests

While planted forests are potentially an important tool for reducing global GHG emissions and mitigating climate change (IPCC 2022), they have had a relatively small share of the international markets for trading emission reduction credits (Kaarakka et al., 2023; Van Der Gaast et al., 2018). Reasons for this mismatch are related to risks and

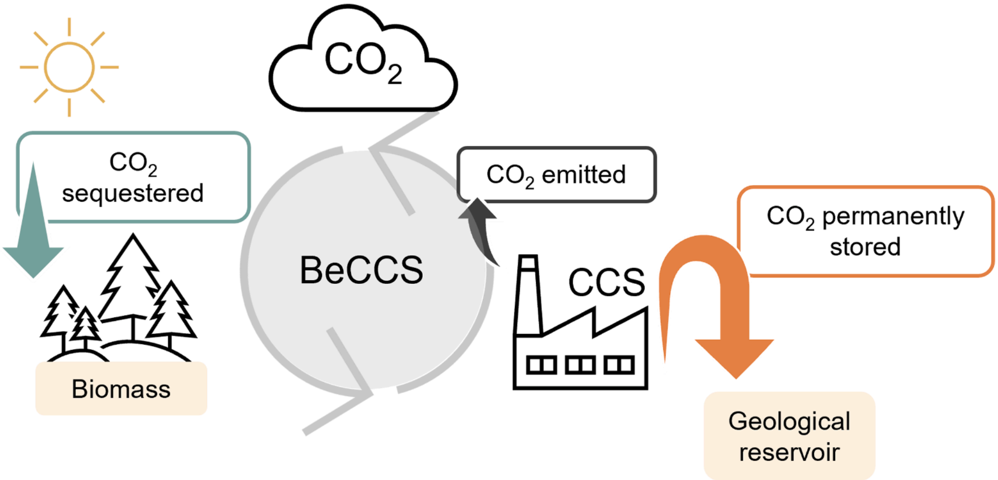

Figure 10.4 The carbon flow of bioenergy carbon capture storage (BeCCS). When BeCCS systems are used, a negative carbon flow from the atmosphere into storage is created. *(Credit: Almena et al., 2002)*

uncertainties that have surrounded forestry projects, such as how long sequestered carbon will remain in the forest or how to precisely monitor the size of the carbon sinks (Kaarakka et al., 2023; Van Der Gaast et al., 2018). In Europe, the Emissions Trading System allows industries to purchase carbon credits, including those generated through CO_2 sequestration in forests. In addition, the Nature Restoration Law sets the stock of organic carbon as one of the indicators whose trend needs to increase at the national level in restored forest ecosystems. Both normative frameworks require measurement and monitoring of carbon stocks and CO_2 sequestration in European planted forests.

Carbon stocks in planted forests can be estimated by summing up the carbon accumulated in five pools: Aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter and mineral carbon (Fig. 10.1). The IPCC proposes different methodologies for estimating GHG emissions and removals due to changes in biomass, dead organic matter, and soil organic carbon, adapted to different levels of detail according to the available information about forests in each country (IPCC, 2019; IPCC et al., 2006). Aboveground biomass especially fluctuates in planted and plantation forests; we compiled a set of available information for measuring carbon stocks and changes in this carbon pool in Europe.

Introduction to available information to measure aboveground biomass gains

There are different methods for estimating biomass and quantifying carbon content in forest biomass that comprise different spatiotemporal scales and resolutions. Inventories from forest management plans, reports on forest condition, and dendrochronological data can cover long temporal scales, while remote sensing and National Forest Inventories (NFI) provide information on forest response at large spatial scales (Ruiz-Benito et al., 2020). Dendrochronological information provides data on annual radial growth at the tree level, which is valuable for estimating ecosystem-level productivity, annual and accumulated CO_2 sequestration, and growth responses to disturbances. At the stand level, the information on stand density, tree sizes, and wood volume compiled in forest management projects provides useful data on forest changes and biomass accumulation, even over centuries (Madrigal-González et al., 2017).

NFIs and other forest inventory networks are essential tools for studying forest dynamics and thus understanding CO_2 sequestration and carbon storage at regional scales (e.g., Astigarraga et al., 2020). These inventories involve systematic or random sampling of forest areas within a given territory, conducted periodically, and include data related to tree size, species, condition (dead or alive), as well as regeneration and shrub abundance. This information allows for the direct estimation of forest biomass and the accumulation between inventories (González Díaz et al., 2020). In addition, NFIs include information on planted forests, such as soil preparation techniques or stand origin (planting, seeding) of the main tree species in the plots.

Remote sensing offers an alternative to field methods by providing information on forest response with high spatial and temporal resolution (Ruiz-Benito et al., 2020). It enables the observation and analysis of objects or areas without making physical contact, using various platforms, including ground-based devices, but typically utilizing platforms such as aircraft or satellites for vast areas (Lavender and Lavender, 2023). The limitations of traditional ground-based measurement techniques in estimating forest biomass and carbon stocks, such as covering limited spatial areas and difficulties in challenging terrain, could be overcome with remote sensing techniques (Goetz and Dubayah, 2011).

Remote sensing for monitoring planted forests

Remote sensing technology and data are incredibly valuable for monitoring planted forests (Espíndola and Ebecken, 2023). With satellite remote sensing, large areas of trees can be periodically monitored, checking on the health of the forest (Siliuk et al., 2020), how much area it covers, and any changes caused by environmental effects or human activities (Avtar et al., 2017). It makes it easy to keep track of efforts to grow more trees, reduce deforestation, and see how the forest recovers from disturbances like fires or windstorms (Güzel et al., 2021). By providing up-to-date and precise information, remote sensing helps in the careful management of forest resources and ensures that planted forests remain healthy and continue to help with carbon capture and support biodiversity (Chen et al., 2019).

Satellite remote sensing employs a variety of sensors, each designed for specific observational needs. Among these, optical sensors are predominant for Earth observation due to their ability to capture data across a wide range of the electromagnetic spectrum (Rautiainen et al., 2010). One of the most valuable applications of optical remote sensing is in monitoring vegetation, and one of the most practical ways for vegetation monitoring is through vegetation indices (Huete, 2012). Vegetation indices are mathematical combinations of different spectral bands to highlight specific properties of vegetation, such as chlorophyll content, leaf area, and health. The normalized difference vegetation index (NDVI) is a widely used index that provides insights into the photosynthetic activity of plants (Robinson et al., 2017), indicating plant health, biomass, and growth dynamics. By measuring how much red and near-infrared light is absorbed and reflected by vegetation, NDVI can help differentiate between healthy vegetation, stressed plants, and non-vegetated areas. NDVI also allows us to identify species that can benefit from climate change as for example, *Acer pseudoplatanus* (Konatowska et al., 2023).

Light detection and ranging (LiDAR) is a relatively new method with great promise. It provides detailed information on the three-dimensional structure of forests and has been used to estimate properties such as canopy height, biomass, and leaf area index. Repeated LiDAR measurements in a landscape can provide information on the dynamics of the structure and biomass accumulation across a wide range of forest ecosystems (Goetz and Dubayah, 2011).

LiDAR, with its ability to capture high-resolution 3D data, provides detailed measurements of forest canopy properties linked to biomass and carbon stocks. This technology offers a vertical insight into the forest structure that traditional methods cannot match, especially for large-scale assessments. Radar technology, particularly synthetic aperture radar (SAR), provides an alternative that can penetrate forest canopies and deliver continuous data, unaffected by cloud cover, which is a significant advantage in tropical regions. By integrating LiDAR, SAR, and optical remote sensing data, a holistic view of forest biomass can be achieved, allowing for more accurate estimations of carbon stocks across various regions and forest types. In Scandinavia, LiDAR technology has been utilized to measure forest canopy height and structure accurately in commercial timber plantations managed for both economic benefits and environmental sustainability, including CO_2 sequestration. This technology has enabled detailed estimates of carbon stocks, which are critical for optimizing forest management practices that balance timber production with CO_2 sequestration goals (Goetz and Dubayah, 2011).

The advances in remote sensing technology have fundamentally reshaped our ability to understand forests, providing us with an unprecedented wealth of data and insights. These data are crucial for accurate carbon stock estimation and for monitoring changes over time, allowing researchers, policymakers, and managers to assess the effectiveness of reforestation and afforestation efforts, to track reforestation progress, and to understand the impacts of forest management practices on carbon cycling at different scales. This information provides invaluable insights that drive informed decision-making in climate action strategies.

Guidelines: The future of planted forests in the context of rapid climate change

Planted forests play a key role in climate change mitigation. However, unlike naturally regenerated forests, their species composition and structure are not the result of natural succession, promoting the species and individuals best adapted to current environmental conditions. Rather, they are the result of a demand for specific wood products and other ecosystem services, but they are not necessarily functional ecosystems for the maximization of CO_2 sequestration. The whole carbon cycle associated with forests, including both the biological and the industrial components (Fig. 10.1), needs to be considered for climate change mitigation. Management of planted forests is key to supporting their role as nature-based solutions for climate change mitigation and to maintain their stability and the ecosystem services they provide. For that, not only management actions, but planning and decision-making should consider the following points.

1. Policies and legislation should provide an enabling environment that supports climate change mitigation objectives by creating legal and economic frameworks that encourage sustainable forest management and increased use of wood products. This could include subsidies for forestry practices that are consistent with mitigation goals and the regulation of CO_2 emissions.
2. Increased CO_2 sequestration can be achieved by bridging the gap between scientific research and silviculture practice. A growing body of scientific results on species and provenance responses to climate, planting techniques, and different monitoring methodologies can be used to inform species selection. It is important to evaluate the capacity of the candidate species to assimilate carbon in the aboveground and belowground components. Basing decisions on scientific evidence would help to select species that will be able to reach the felling age in a changing climate and thus maximize wood production, sequester CO_2, and store carbon in the soil.
3. Species and provenance selection must consider their impact on forest biodiversity, which is important for maintaining further ecosystem services and for ecosystem stability. Native species more adapted to local disturbances and related to higher soil carbon stocks should be encouraged in planted forests, provided they will be adapted to the future climate.
4. Forestation should include an assessment of species adaptation to current and future climatic conditions. Structural diversity can minimize risks from extreme climatic events. Lowering stand densities by reducing planting densities and thinning mature stands could address current and future problems of water availability and fire risk. Thinning, however, could expose stands in windy regions to windthrow risk.
5. Water shortage will be a limiting factor for CO_2 sequestration in a warming climate. Cultivation of species and their ecotypes that are more resistant to heat waves and water stress, and cultivation and planting techniques that reduce water shortage (e.

g., microcatchments), should be considered. Measures to increase water retention in ecosystems potentially can increase CO_2 sequestration in wood, as well as increase stand stability and resilience to climate change.

6. Data-driven policies that accurately reflect the state of forest carbon stocks are essential for aligning forest conservation efforts with climate change mitigation strategies. Integrating remote sensing techniques (e.g., satellite imagery and LiDAR) and on-the-ground data collection allows for a holistic assessment of forest ecosystems and their carbon sequestration potential. Remote sensing can provide information on the physiological state of forest stands at large spatial scales and may aid in identifying species that are better adapted to a changing climate.
7. The potential of climate change mitigation can be increased by cross-sectoral solutions involving the full carbon cycle that link forest management with the wood processing and energy industries. It is mandatory to consider substitution effects when replacing fossil-based materials with renewable materials.
8. Increasing carbon storage in forests is critical but insufficient to mitigate climate change. Measures to reduce the use of fossil fuels are essential and need to be complemented by increasing the use of wood in the material and energy sectors, with recycling and proper disposal. Closer integration of wood production and utilization, i.e., forestry and wood industry, should be continuously monitored to assess the balance between CO_2 sequestration and release of GHGs.
9. Innovative pathways for carbon cycling need to be seen in the light of the whole forest-wood use system and not just as isolated components of a system. Technologies in early stages (e.g., BeCCS), able to modify the forest carbon cycle and mitigate climate change, need to be supported by further research and the commitment of forest managers.
10. Education and communication are essential to raise awareness of the role of planted forests in mitigating climate change and the benefits of replacing fossil-based materials and fuels with wood-based products. Major efforts are needed to support public education, promotional campaigns, and cooperation between the forest sector and other sectors.

The potential of planted forests to sequester CO_2 on a scale that can contribute significantly to global climate goals is increasingly being recognized (Gundersen et al., 2021). Nevertheless, the complexities of natural forest ecosystems cannot be fully substituted by planted forests (Moreno-Mateos et al., 2020), even when planted forests can more efficiently absorb CO_2 and contribute to climate change mitigation. Secondary and near-natural forests continue to be important carbon sinks, and old-growth forests are essential carbon reservoirs and complement the role of planted forests, thus all play a critical role in mitigating climate change. The insights presented here emphasize the need for comprehensive strategies that integrate restoration and reforestation efforts with the sustainable management of existing forests.

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