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Review

Carbon Sequestration for Global-Scale Climate Change Mitigation: Overview of Strategies Plus Enhanced Roles for Perennial Crops

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Abstract: Climatic changes threaten many forms of crop production as well as adversely affecting global ecosystems and human activities. There are two principal ways in which the balance of the global carbon cycle can be restored, firstly to decrease anthropogenic CO_2 emissions and secondly to increase rates of carbon sequestration. Even if emissions are successfully reduced to net zero, which seems increasingly unlikely over the coming decades, it will still be essential to reduce atmospheric CO_2 concentrations to preindustrial levels, which can only be achieved by global-scale carbon sequestration of the order of gigatonnes (Gt) of CO_2 annually. Over recent decades engineering approaches have been proposed to tackle carbon sequestration. However, their technological effectiveness have yet to be demonstrated at global scale with even the most optimistic current values at less than 0.1 Gt CO_2 /yr, i.e. 50-100-fold less than required to meet IPCC targets for 2050. In contrast, biological carbon sequestration already operates as a proven global mechanism that also has the potential for increased effectiveness by harnessing high-yield tropical vegetation including perennial crops with carbon sequestration values already exceeding 1 Gt CO_2 /yr. This review will contrast engineering and biological approaches to carbon sequestration with a particular focus on the potential for perennial crops, especially in the tropics. The major conclusions are that (i) the capacity of biological carbon sequestration already dwarfs that of all engineering approaches combined, (ii) biological sequestration is already proven to operate at global scale, and (iii) compared to engineering approaches it will be orders of magnitude less expensive to upscale further in the coming decades.

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1. Introduction

The global carbon cycle is one of the major bio-geochemical processes that has shaped the development of the earth over the past 4.54 billion years [Murphy, 2024a]. This cycle involves the dynamic creation and interconversion of different forms of carbon and their movement between different terrestrial and aquatic locations across the globe. Over 99% of terrestrial carbon is locked up in the earth's crust and oceans in the form of stable mineral deposits, such as limestone which was originally formed from calcified remains of marine organisms. These carbon deposits, totaling about 65.5 teratonnes (Tt, 10^{12} tonnes) are now largely inaccessible as carbon sources and have little role in the ongoing dynamics of the global carbon cycle [NASA, 2011]. In addition, a further 2.4 Tt of carbon is present in the biosphere and about 0.9 Tt in the form of atmospheric CO_2. The latter are the two main participants in the global carbon cycle in which their impacts on the climate and biosphere have been immense and far reaching [Schlesinger et al, 2013].

For example, the explosion of arborescent vegetation during the late Carboniferous Period led to the sequestration of 100 gigatonnes (Gt, 10^9 tonnes) of atmospheric carbon per year. Because this carbon became buried as anaerobic deposits, it could not readily be re-emitted to the atmosphere. This eventually led to the depletion of atmospheric CO_2 to a low point of ~100 ppm, which greatly reduced its greenhouse function and came close to ushering in a catastrophic global cooling event that could have caused the widespread extinction of many life forms [Fuelner, 2017]. Meanwhile, those same anaerobic carbon deposits eventually became fossilized in the form of several teratonnes of coal, oil and gas, which effectively removed them from the main carbon cycle for over 300 million years. Since the mid-20th century, however, combustion of vast amounts of this fossil-derived carbon has released much of it back into the cycle in the form of immense quantities of gaseous CO_2. In turn, the emission of this excess CO_2 has exceeded the long-term sequestration capacity of the carbon cycle, resulting in a >50% increase in atmospheric CO_2 concentrations since the 1950s.

For the past million years, atmospheric CO_2 levels have remained below 300 ppm, but for the past 70+ years there has been a sustained annual increase of 1.42 ppm. Indeed there is evidence that the rate of this increase is rising further as emissions continue to rise while natural (mainly biological) sequestration rates diminish due to factors such as deforestation. In 2025, the atmospheric CO_2 level is forecast to reach a seasonal peak of >429 ppm, with every likelihood that it could reach 440 ppm by 2030, 500 ppm by 2050, 700 ppm by 2070 and 950 ppm by 2100 [Betts et al, 2025; Möller et al, 2024]. This is important because CO_2 is a powerful and persistent greenhouse gas (GHG) and it is no coincidence that global temperatures have increased by 1.5° C over the past 50 years. It is evident, therefore, that the global carbon cycle is now significantly out of balance and many aspects of the climate system are being affected in ways that threaten, not just agriculture, but the entire future of our complex technological and urban-based societies.

Most geo-climatic models show CO_2 levels continuing to increase to >1,000 ppm by the early 2100s, even if some reduction in emissions is achieved. More troublingly, 'business as usual' scenarios could result in CO_2 levels of >2,000 ppm later in the 2100s, which would have a high probability of triggering catastrophic climatic effects [Betts et al, 2025; Möller et al, 2024]. Even at the lower levels of 900-1,000 ppm that are predicted for the end of the 21st century, deep-time climate simulations of the global water cycle predict that the cycle will experience hyperactivity in terms of extreme rainfall events, which is in accordance with separate data from paleoclimate proxy analysis [Kiel, 2019; Kiehl et al, 2018]. Despite such predictions, it is evident that many countries and businesses are actually reducing their commitments to emissions reductions as was also evident from the outcome of COP29 in 2024 and the rollback in many sustainability and climate targets that has accelerated during 2025 [Wray, 2025; Climate Backtracker, 2025; Fursman, 2025].

This makes it even more important to examine the potential for improved capacities for carbon sequestration alongside emissions reductions [Lal et al, 2018; Nayak et al, 2022]. Global-scale carbon sequestration already occurs via photosynthesis with annual rates of about 677 Gt CO_2 [Salk Institute, 2025; Murphy & Cardona, 2022]. Of this total, about 660 Gt/yr of CO_2 is re-released to the atmosphere in the short term via respiration by plants and animals, meaning that in a balanced carbon cycle there would be a modest net annual CO_2 sequestration of 17 Gt [1]. Unfortunately, however, anthropogenic CO_2 release, mainly from fossil fuels, emits a further 34-37 Gt/yr into the atmosphere, meaning that instead of a modest annual CO_2 sequestration there is an ever-increasing net CO_2 emission rate of 16.3 Gt/yr [NASA, 2024]. It is this net release of CO_2 into the atmosphere that has driven its inexorable rise over recent decades from 300 ppm to 429 ppm by 2025, which is regarded as a major contributor to global climate change [Murphy, 2024a].

Recent research has highlighted the carbon sequestration potential of terrestrial vegetation as a way of restoring the global carbon cycle alongside the ongoing efforts to reduce anthropogenic emissions [Murphy, 2024a; Lal et al, 2018; Mo et al, 2023]. This concept has been termed 'recarbonization of the terrestrial biosphere' and the conservation and expansion of both natural ecosystems and agroecosystems with high carbon sequestration potential are important components of such a strategy [Smith et al, 2024; Mahli & Grace, 2000; Mendelsohn et al, 2012; Lewis et al. 2009; Murphy 2024b; Ratnasingam et al. 2015]. Such measures have an estimated capacity of 367 Gt C capture by the end of the 21st century, which could reduce atmospheric CO_2 levels by 156 ppm [Lal et al, 2018]. To put this into context, atmospheric CO_2 levels remained below 300 ppm throughout human history until the anthropogenic releases after the mid-20th century resulted in an unprecedented rise to 429 ppm in 2025 [Murphy, 2024a]. Alongside the role of terrestrial vegetation

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in carbon sequestration, other biological sources include sub-surface (mostly soil) and aquatic (mostly oceanic) systems, both of which have significant capacity to contribute to biologically-mediated carbon storage [Muller, 2023; Bar-On et al. 2025; Amelung et al. 2020; Angermayr et al, 2015; Olajire & Essien, 2014]. In addition to improving these existing biological systems, numerous engineering approaches aimed at increasing carbon sequestration have been proposed and are the subject of a great deal of ongoing research, much of which is funded by companies and governments involved in carbon emissions [Goren et al, 2024; Zhao K et al. 2023; Boele, 2024; Wang et al, 2021; Anderson, 2025; Moriarty & Honnery, 2019; Bisotti et al, 2024; Majid & Almulla, 2025].

In this review, the roles of carbon sequestration will be considered alongside reduction in carbon emissions to address the impending crisis of a seemingly inexorable rise in atmospheric CO_2 levels. The technical potential for large-scale industrially-driven carbon sequestration, alongside the considerable costs, lengthy timescales, and overall real-world feasibility will also be considered. This will be followed by discussion of enhanced roles of the major biological mechanisms sequestration including natural vegetation, soils, and aquatic systems. We will then consider often-ignored roles of agro-ecosystems, and particularly high-yield perennial crops, as realistic contributors to carbon sequestration on a global scale. Finally, policies for incentivizing use of crop- and natural landscape-based approaches, such as Carbon Credit schemes, to achieve the more effective use of global-scale sequestration capable of restoring balance to the carbon cycle will be discussed.

2. The Importance of Both Increasing CO_2 Sequestration and Reducing GHG Emissions

In order to restore the global carbon cycle it is desirable to avoid contributing to anthropogenic processes that lead to major oscillations in atmospheric CO_2 levels. The current trajectory that has only been evident over the past 80+ years has resulted in large increases in carbon emissions and a reduction in sequestration. Hence the restoration of a stable global carbon cycle will necessarily involve a combination of reduction in anthropogenic CO_2 emissions and increasing CO_2 sequestration. While this review is mainly concerned with carbon sequestration strategies, it is also important to consider the topic of emissions reductions, not least because that is the major focus of much of the current debate about how to mitigate the effects of climate change.

Despite many pronouncements and promises from governments and private sector organizations around the world, there is little evidence of any slowdown in global anthropogenic CO_2 emissions (apart from a brief leveling off in 2020 during the covid pandemic). In 2024 these emissions were an estimated about 40 Gt CO_2. The current prognosis for anything approaching a reversal of the 1950 inflection point when global carbon emissions and temperature rises started their current rapid increases appears remote. While some public and private actors are gradually implementing strategies to decrease anthropogenic CO_2 emissions these initiatives are nowhere near likely to be at the scale required to halt the inexorable rise of both carbon emissions and the related adverse climatic consequences. Over 90% of anthropogenic CO_2 emissions come from fossil sources (coal, oil, gas), while a much smaller and decreasing amount of <10% comes from various forms of land-use change that mainly involve deforestation or drainage of peat soils.

The strategies for GHG emissions reductions have been well rehearsed elsewhere but, as of the mid-2020s, there appears to be an increasing tendency by vested interests and their populist supporters to downplay the need for or effectiveness of such approaches. In extreme cases they also challenge the well-founded scientific case for the association between anthropogenic emissions and climate change [Feigin et al, 2023]. Also, while there are emissions from natural systems, including forest fires, oceans, wetlands, permafrost, mud volcanoes, volcanoes, and earthquakes, these collectively amount to 29 Gt/yr C, while anthropogenic CO_2 emissions are 40 Gt/yr and rising [Yue, 2018]. In some cases, the reality of the risks posed by high atmospheric CO_2 concentrations may be acknowledged by emissions critics, but an alternative panacea is then proposed in the form of various carbon dioxide removal (CDR) strategies [24-31]. Note that the term CDR used in this review refers to the mainly industrially based strategies as discussed in section 3. In contrast, sections 4-6 discuss biologically based methods of carbon removal, which are sometimes also referred to as conventional (in contrast to novel) CDR in parts of the literature [Smith et al, 2023]. As we will see, some proponents of the (novel) CDR approach hope that it can result in the continuation of some activities, such as use of fossil fuels that still emit CO_2. This is combined with the hope/expectation that fully scaled-up CDR technologies at some point in the future will enable all of these emissions, and more, to be recovered from the atmosphere and thereby gradually reduce CO_2 levels and hence mitigate climate change while carrying on with a form of 'business as usual' for industry [Goren et al, 2024; Zhao K et al. 2023; Boele, 2024; Wang et al, 2021].

An important point to make here is that, even if emissions reductions in the coming decades are spectacularly successful, which is increasingly doubtful, atmospheric CO_2 levels of ~430 ppm might 'only' rise above to ~500-1,000 ppm [NASA, 2024]. However, the current natural carbon sinks only absorb CO_2 very slowly and it would be many centuries before pre-industrial levels in the region of 300 ppm could be reached [32]. Even if the current (optimistic) emissions reduction policies can be maintained until 2100 and even if long-term temperatures return to 1.5 °C by 2300, recent modeling studies show that there are still high risks of potentially catastrophic climate tipping events with planetary-wide impacts [Möller et al, 2024]. Therefore, simply reducing CO_2 emissions, even to zero, will not be sufficient to restore the global carbon balance. Hence, effective global-scale carbon sequestration strategies will also be required. In the remaining sections of this review we will focus mainly on the various industrial and biological approaches to increasing the amount and scale of CO_2 sequestration from the atmosphere as a key element of reducing GHG effects of global climatic systems. However, these measures can only be one part of the effort to restore the carbon cycle and, certainly in the near term, by far the consensus of the scientific and engineering communities is that the principal and urgent focus should be on reducing anthropogenic emissions.

3. Industrial Carbon Sequestration

In order to limit average global warming to 1.5°C above pre-industrial levels, the IPCC recently estimated that the rate of CO_2 extraction needs to rise to between 7-9 Gt/yr by 2050 [IPCC 2024a]. About 2 Gt/yr CO_2 extraction is already occurring via biological carbon sequestration methods (sometimes called conventional CDR), such as reforestation/afforestation, wetland restoration, soil carbon replenishment etc, and these will be discussed in section 4 below. The 1.5°C warming threshold had already been exceeded by 2024 and, while this could have been an anomaly, it has amplified concerns that unless urgent steps are taken to reduce emissions and increase rates of carbon sequestration there would be a higher probability in the near-term of warming approaching 2.0°C and beyond [Bevacqua et al, 2025]. A recent survey of >200 IPCC climate scientists showed that 86% of them estimated maximum global warming would exceed 2°C by or before the year 2100, while 58% of the sample believed that there was at least a 50% chance of reaching or exceeding 3°C by or before 2100 [Wyne et al, 2025]. In terms of a realistic carbon sequestration target required to limit global warming, a range of 7-9 Gt/yr CO_2 removal was recently proposed [Smith et al, 2024]. This is an ambitious target, but the prospect of an engineering solution to address this side of the disrupted carbon balance (the other side being emissions reductions) has resulted in the deployment of vast investments into R&D funding, often involving by tax breaks or other inceptives totaling many $ billions, from both public and private bodies.

There are numerous industrial technologies that have been proposed for the capture of CO_2, either before it is released into the atmosphere, e.g. carbon capture (utilization) and storage (CCS or CCUS) [Goren et al, 2024; Zhao K et al. 2023; Anderson, 2025; Davoodi et al, 2023; Global CCS Institute 2024], or CO_2 removal from the atmosphere after its release, e.g. direct air capture and storage (DACS) [Smith et al, 2024; Bisotti et al, 2024; Fu et al, 2022; BCG, 2023; Krishnan et al, 2023]. These technologies are also sometimes referred to generically in the literature as carbon dioxide removal (CDR) [IPCC 2024a; 2024b, McLaren & Corry, 2025]. CCS or CCUS systems can be used to remove CO_2 following their anthropogenic emission from fossil sources such as coal, gas or oil-fired power stations. Alternatively the CO_2 could be removed from power stations fired by biofuels such as biodiesel, bioethanol or by bulk biomass such as coppiced vegetation or woodchips, in which case it is referred to as BECCS (bioenergy carbon capture and storage). The majority of the R&D behind these technologies is taking place in the USA, largely thanks to multi-billion $ government initiatives, such as the Inflation Reduction Act, and the alluring prospect of monetizing CO_2 capture systems via carbon trading, as well as offset processes that facilitate continued use of fossil fuels by a company or by its associates [Elsener, 2024]. Other important R&D centers include Europe and increasingly in Asia and these include some of the major oil companies. One example is the world's largest oil company, Saudi Aramco (market capitalization $1.7 trillion), which is investing $4 billion in low-carbon technologies including partnerships with several European companies to develop DAC/S facilities in its Arabian oil fields [Economist, 2004a]. As we will see below, however, recent political developments and regulatory hurdles may slow down development of these technologies, at least in the short to medium term [Lima, 2024].

Many approaches to industrial carbon sequestration, i.e. CDR, involve geological technologies using largely experimental processes that have only been studied or implemented on a relatively small scale. Examples include mineral carbonation [Neeraj & Yadav, 2020], graphene production from CO_2 [Liu at al, (2018)], Carbon Capture and Storage (CCS) [Goren et al, 2024; Zhao et al 2023], and use of engineered molecules such as MXenes (ternary carbides, nitrides, or carbonitrides), MBenes (transition-metal borides) [Ozkan et al, 2024] and tetrahedral organic cages [Zhu et al, 2024]. In the future some of these approaches might become scalable to global significance, but for the time being they are of only minor practical use for the urgent reduction of the ever-increasing levels of atmospheric CO_2 and methane [Robertson & Mousavian, 2020]. Some medium-scale initiatives are already operational at levels of 10+ Mt/yr, but face uncertainties such as government funding cutbacks, slow planning approval, and a lack of commitment in most countries to scale-up methods such as biochar, DAC and BECCS [Lima, 2024; Lamb et al, 2024]. As of late 2024, the entire global CCUS industry was capturing a mere 50 Mt/yr CO_2 (0.05 Gt/yr) of which the vast majority was being used to support the fossil fuel industry in the form of enhanced oil recovery [IEEFA, 2024]. Meanwhile in Europe the CCUS industry captured a paltry 2.7 Mt/yr CO_2 in 2024 (mostly for natural gas processing in Norway), but nevertheless projected an astonishing 200-fold increase to 560 Mt/yr CO_2 by 2050 [IEEFA, 2024].

The viability of industrial carbon sequestration, at least in terms of addressing the ambitious 7-9 Gt/yr CO_2 removal target from IPCC is also facing increasing skepticism among many experts ranging from engineers and geologists to economists and financiers [Moriarty & Honnery, 2019; Wang et al, 2021, Boele, 2024; IEEFA. 2024; Kazlou et al, 2024; NOAA, 2024; Anderson et al, 2025; Mendez et al, 2025]. For example it is estimated that CCUS technology alone will require a global total investment of almost $ 200 billion in the next nine years, mostly to be raised in the USA, which is hugely in excess of currently available funding levels that are already under strain as the global economy falters and some incentive schemes are scaled back [Wood Mackenzie, 2024]. The same report highlights the most optimistic projections of a rather modest carbon capture target of 0.64 Gt by 2034 and even this is likely to have a shortfall of 0.2 Gt/yr, partially due to a very slow rate of uptake in major Asian economies that was not foreseen in previous more optimistic estimates from the sector [Lamb et al, 2024; Wood Mackenzie, 2024]. A more recent report also stresses that the industry CDR target for 2050 of 6-10 Gt/yr is over 100-times greater than current projections of rollout potential, and that this will also need to be matched by the decarbonization of 15-20% of current energy-related emissions [Majid & Almulla, 2025]. This report also lists a drastically scaled-down CDR target for 2030 of only 0.43 Gt/yr, although even this rather minimal target is still based on the highly optimistic assumption that all the currently announced projects worldwide are completed on schedule and operate at full capacity, an achievement that has never previously happened in the sector.

In a wide-ranging analysis of the feasibility of engineering approaches realistically achieving Gt-scale carbon storage by 2050, a team from Imperial College, UK expressed serious reservations about prospects for such aspirations [Zhang et al, 2024]. It was concluded that in making their projections,

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industry analysts had overlooked factors such as geological, geographical, and techno-economic limitations to growth and, equally importantly, to their capacity to scale-up what is still largely a series of experimental small-medium scale technologies to become globally-encompassing mega-technologies that would almost certainly be trans-national and therefore requiring complex regulatory and supply chain structures. The report also mirrored previous concerns about the ongoing slow deployment in Asia and the increasingly unlikely prospect that the USA would really be able to contribute 60% of the total carbon storage by 2050 [Wood Mackenzie, 2024; Ganti et al, 2025]. Instead, a more likely projection that was consistent with known government roadmaps suggested a maximum global carbon storage rate of 5-6 Gt CO_2/yr, with the USA contributing a more modest 1 Gt CO_2/yr [Zhang et al, 2024]. Note that this projection is ten-fold higher than the industry CDR projected target for 2030 [Majid & Almulla, 2025], and it seems unlikely that a ten-fold increase in capacity at a much increased scale and geographical range would be forthcoming over the following two decades.

Given the skepticism about the realistic capacity to achieve sufficient carbon removal to meet IPCC guidelines by 2050, and even the reduced projected targets mentioned above, there are increasing concerns that these CDR technologies are being used by some actors as a way to delay already planned emissions reductions via decarbonization [Ganti et al, 2025; McLaren, & Corry, 2025]. This has been referred to as 'mitigation deterrence' and involves delays in what might be politically unpopular near-term actions to reduce such emissions with the justification of future CDR deployments that are themselves based on exaggerated expectations (Andreoni et al, 2023; Brad & Schneider, 2023; Carton et al., 2023; Deprez et al, 2024, Stuart-Smith et al, 2023). Instead, it is suggested that reducing residual emissions from long-lived (e.g. CO_2 and N_2O) and short-lived climate forcers (e.g. CH_4) should be the primary target that is also achievable within the 2050 time window and success in achieving this could significantly reduce the scale and the amount of CDR required [Schleussner et al, 2024; Ganti et al, 2025].

To conclude, over the past several decades investments totaling many $ billions have been deployed into industrial carbon sequestration, often using public funds that could arguably be better used for other sustainability-related projects. Over recent years several authoritative reports and analyses from independent academic and industry groups have been published that indicate uncertainty about the prospects for industrial carbon sequestration on a scale sufficient to address the required reduction in CO_2 levels, possibly by a factor of 100 or more. As shown in Figure 1, which is derived from 2024 data, the authors estimate that ~2 GtCO_2/yr of CO_2 sequestration is already occurring but nearly all of this is derived from conventional, i.e. biological, CDR methods. These methods, which will be discussed in section 4, include land-use change and forestry activities, especially afforestation/reforestation. These methods have delivered a relatively stable rate of sequestration over the past two decades whereas the so-called novel (i.e. industrial) methods only contribute 0.0013 Gt of CO_2 removal per year.

It is evident that 'deep uncertainty' exists about the prospects for CDR technologies at the required scale [Mendez et al, 2025]. Another issue is the eventual economic cost of their deployment, which is estimated at between $1 and 2 trillion/yr depending on the intensity of the CCS pathway [Bacilieri et al, 2023], with no idea of how and by whom such costs would be paid and how such investments could ever be recouped. In contrast, land plants can already sequester about 4 Gt CO_2/yr and strategies such as afforestation and reforestation plus soil carbon sequestration and improved wetland management have been suggested as viable cost-effective alternatives that involve globally scalable sequestration targets in the range of 1-10 Gt/yr C [Mendez et al, 2025]. Moreover, newly developed forms of these biological options can be deployed at modest cost via a range of bio-based strategies as we will consider in section 4.

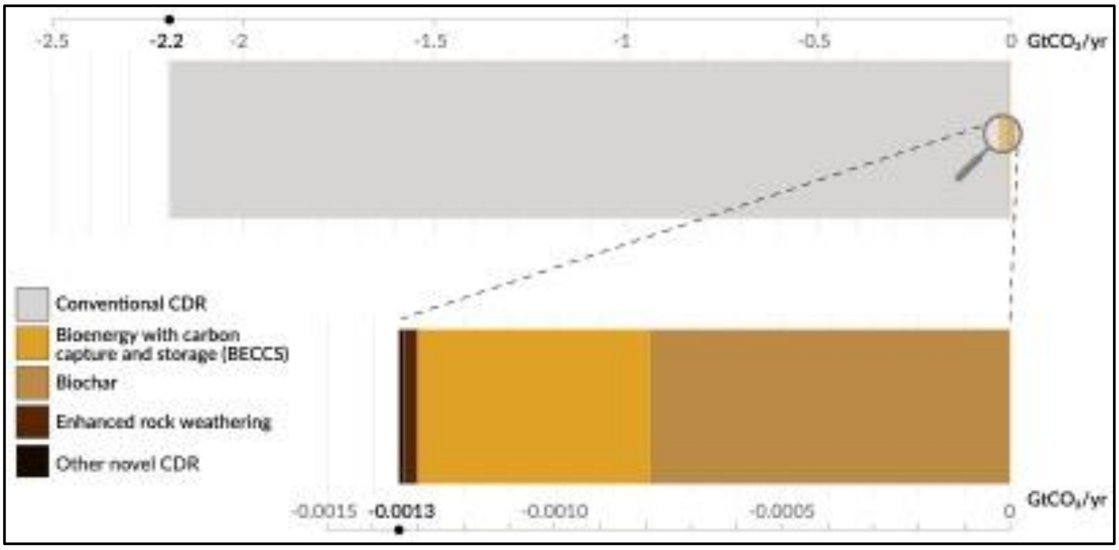

Figure 1. Comparison of CO_2 sequestration by 'conventional' (biological) and 'novel' (industrial) CDR methods as measured in $GtCO_2$/yr. Note that only a tiny fraction of CO_2 sequestration, amounting to <0.007% of total CDR, is currently delivered by the industrial methods, known as novel CDR. Source: Smith et al 2024.

4. Biological Carbon Sequestration

Biological carbon sequestration occurs in photosynthetic organisms via the fixation of CO_2 and its conversion into more reduced compounds, such as sugars, amino acids, nucleotides etc. This process requires energy, which can be derived from light in the case of photoautotrophs or from chemical compounds in the case of chemoautotrophs [Garritano et al, 2022]. The total CO_2 fixation capacity of photoautotrophic organisms on earth is about 375 Gt/yr (Angermayr et al, 2015). On land, this process is mainly carried out by higher plants, while in the oceans it is mainly driven by microscopic phytoplankton, including microalgae and cyanobacteria (Olajire & Essien, 2014). In all cases these organisms employ the RPP (reductive pentose phosphate) cycle whereby CO_2 is fixed into triose phosphates that are then converted into sucrose and starch (Murphy & Cardona 2022). Besides the RPP cycle, which is responsible for 90% of global CO_2 fixation, there are six other known carbon fixation pathways found in bacteria and archaea (Garritano et al, 2022). Sucrose and starch are then metabolized to form the basis of most of the global biomass, including some many organic carbon-based structures that can persist for centuries or millennia as long-term carbon stores, especially in the soil [Lal et al, 2018].

Major carbon stores ultimately derived from biological CO_2 fixation include living vegetation that includes centuries-old or millennia-old trees, the vast reserves of soil organic carbon (SOC) from the remains of flora, fauna, fungi and microbes, plus considerable quantities of living and dead oceanic biomass. In this section we will look at the potential of these various systems as important contributors to global-scale biological carbon sequestration as summarized in Figure 2.

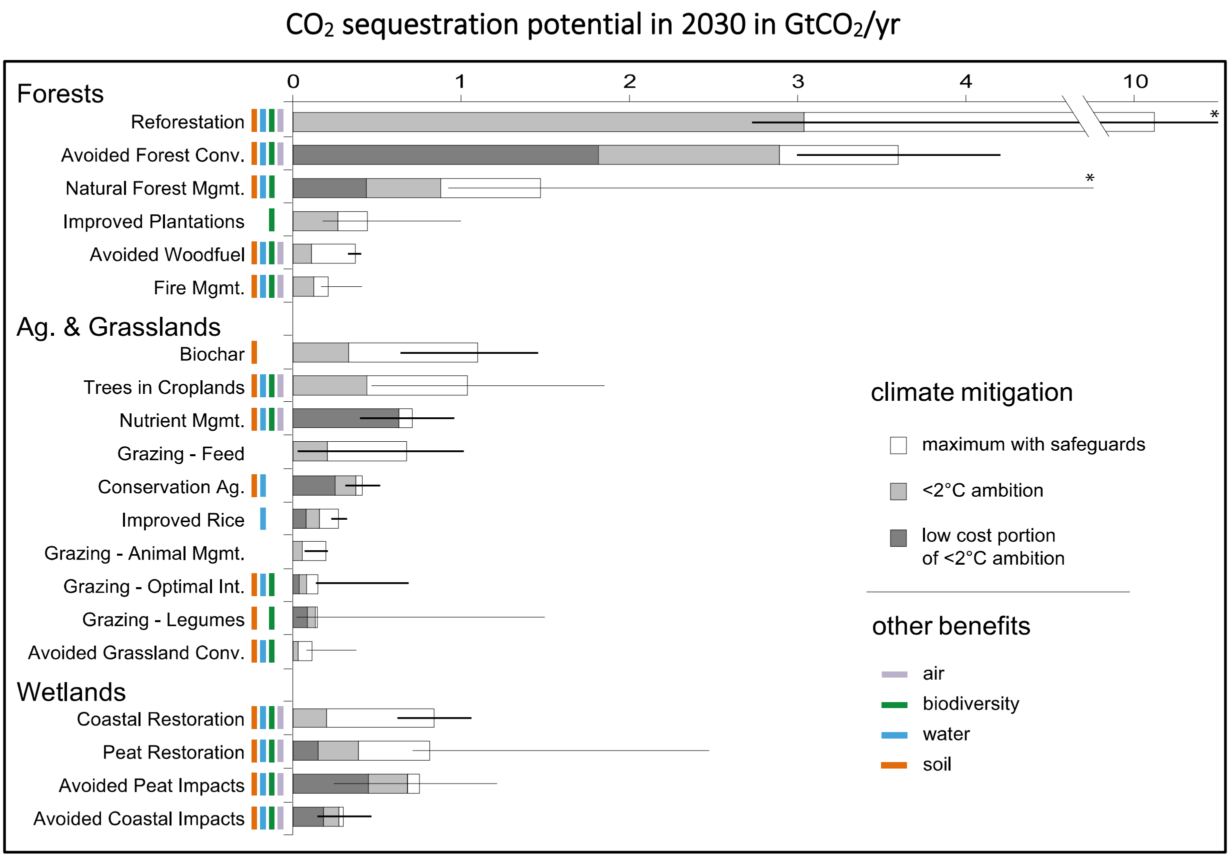

Figure 2. Projected CO_2 sequestration potential of 20 biological pathways by 2030. Note that in this study, forest-related activities, including managed forests, have the highest sequestration potentials while trees in croplands have moderate potentials. As discussed in sections 4 & 5 below, it is likely that the contribution of perennial crops and agroforestry has been underestimated in the study and it could be higher then the extreme range of about 2 $GtCO_2$/yr that is shown here. Adapted from Griscom et al. 2017 and Bailey et al, 2018.

4.1. Re-Engineering Biological CO_2 Fixation

Before considering the capacity of existing and well established biological systems for CO_2 sequestration that have been operating for billions of years, we will briefly consider some of the recent research advances that are exploring new and exciting bioengineering approaches to radically redesigning the fundamental process of biological CO_2 fixation. This research involves combinations of various cutting-edge biological and biotechnological methods aimed at manipulating and upgrading the existing biological process of CO_2 fixation and oxygenic photosynthesis that evolved over 3 billion years ago [Murphy & Cardona 2022, Nayak et al, 2022; Taylor-Kearney et al, 2024]. Naturally-occurring photosynthesis already sequesters vast quantities of atmospheric CO_2 that dwarfs even the currently high rate of anthropogenic emissions. However, >97% of biologically fixed CO_2 is quickly re-emitted to the atmosphere due to photorespiration and wasteful side-reactions [Murphy & Cardona 2022].

The enzyme responsible for the initial fixation of CO_2 into organic carbon compounds is rubisco (ribulose bisphosphate carboxylase) that generates triose phosphates via the RPP cycle. The importance of rubisco in plants is shown by its abundance; it makes up 30–50% of the total soluble protein of leaves and it is estimated that there are 5 kg of the rubisco protein for every person on the Earth [Murphy & Cardona 2022, Taylor-Kearney et al, 2024]. Despite its vital role in photosynthesis, however, rubisco is highly inefficient as a biological catalyst. This is because in addition to its main catalytic reaction of carboxylation, it has an alternative oxygenation reaction that only generates half of the yield of triose phosphate product compared to the main reaction. This wasteful side reaction occurs about one-third of the time and greatly reduces the overall catalytic efficiency. Moreover, oxygen now makes up 21% of the Earth's atmosphere whereas CO_2, despite its problematic GHG properties, is far less abundant at a mere 0.045%. Because of this oxygen-dependent side reaction, therefore, rubisco is relatively compromised in its efficiency for CO_2 fixation.

To make things worse, rubisco is also a very sluggish enzyme with a turnover frequency that is up to one million-fold slower than most other enzymes. Part of the reason for the inefficiency of rubisco is that it originally evolved in a highly anaerobic environment that persisted for as long as 1.5 billion years. This meant that the competing oxygenation reaction did not become problematic until photosynthetic organisms had already become locked into an absolute dependence on rubisco, despite the resultant oxygenation of the Earth's atmosphere [Erb & Zarzycki, 2018; Murphy & Cardona 2022, Taylor-Kearney et al, 2024]. Thanks to recent advances in our knowledge of the molecular structure and catalytic activity of rubisco, many researchers are now investigating strategies aimed at improving this key enzyme [Lin et al, 2014; Bouvier et al, 2024; Zhao et al, 2024]. Approaches include transferring a more efficient version of rubisco from cyanobacteria to crop plants, or using molecular engineering approaches to redesign a completely new form of the enzyme. If successful, future improvements in the activity and specificity of rubisco in model systems, such as simple plants, could then be transferred into more complex plants, including major crop and forestry species [Nayak et al, 2022].

As an alternative to improving rubisco function, other researchers are investigating ways to bypassing the enzyme with several synthetic biology projects now aimed at creating completely novel CO_2 fixation pathways [Schwander et al, 2016; Naseem et al, 2020; Nayak et al, 2022; Santos Correa et al, 2022]. These include hybrid synthetic/biological systems whereby oxygen-insensitive, self-replenishing CO_2 fixation occurs in vitro where it is uncoupled from organism growth and cellular regulation [Luo et al, 2022]. The ultimate aim of these strategies would be to boost the photosynthetic performance of selected plants or dramatically scaled-up cell-free systems, leading to increased rates of CO_2 fixation and hence carbon sequestration into useful biomass and higher crop yields. Nevertheless, it needs to be acknowledged that, as with the industrial engineering approaches discussed above in section 3, it will be challenging to scale up such bioengineering processes to globally relevant values in the range of several Gt C/yr in the next dew decades. However, given the existing global biological CO_2 fixation capacity of 375 Gt/yr [Angermayr et al, 2015], even a modest 2% increase due to bioengineering would deliver additional carbon sequestration in the range of the 7-9 Gt/yr CO_2 IPCC target required to limit global warming to 1.5°C [Smith et al, 2024, IPCC, 2018]. This would put bioengineering in the category of high-risk but potentially high-reward R&D that should justify at least a fraction of the $ billions of funding currently channeled to the industrial engineering approaches discussed above.

4.2. Natural Vegetation

Natural vegetation is considered to include biomes such as forests, grassland/prairie, and mixed habitats with low levels of human disturbance and it excludes cultivated cropland, including commercially managed woodlands. However, there are many examples of mixed-use systems, such as agroforestry, where crops might exist alongside native vegetation. As discussed below, it is also the case that there are few if any parts of the land surface that have not been affected by human activity either directly or indirectly. Although the current global climate is generally regarded as relatively benign in comparison with deep geological time, its net primary productivity is actually much lower than previous eras [Murphy & Cardona 2022]. For example, during the late-Jurassic era at about 155 Myr ago plant-led net primary productivity was 118 Gt/yr C while by the mid-Cretaceous era at 100 Myr ago a cooler climate and lower levels resulted in a slight reduction to 107 Gt/yr C. However, and despite the activity of today's highly efficient angiosperm-dominated flora, the global net primary productivity is a mere 57 Gt/yr C. This means that we currently live in a world where the photosynthetic net primary productivity is less than half the amount when dinosaurs were at their peak.

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A major reason for this impoverished photosynthetic performance is recent human activity, especially agriculture. This has removed 40% of natural vegetation from the most productive parts of the land surface and substituted low-biomass crops that have far inferior levels of carbon sequestration. This process has continued to accelerate with estimates that global biomass has been halved over the past 12,000 years [Erb & Zarzycki, 2018; Crowther et al, 2015]. Interestingly, despite the wholesale removal of natural vegetation, most of it arboreal, and its replacement with non-woody cultivated plants, the total biomass of ~10 Gt C grown by humans is only a mere 2% of the total existing plant biomass [Erb & Zarzycki, 2018]. This illustrates that although the majority of natural, mostly woody, vegetation has been replaced by crops, the remaining natural vegetation is so much more effective at carbon sequestration than crops that it still constitutes 98% of global plant biomass. The replacement of natural vegetation by domesticated crops is mirrored even more dramatically in the case of animals. Hence, the global livestock biomass, which comes from a tiny number of species such as cattle, pigs and poultry, is ~1 Gt C, which is about 150-fold more that the total biomass of all wild mammals (0.007 Gt) [Joyard, 2025]. Of course, the massive proliferation of livestock was only made possible by the conversion of natural vegetation to pasture and cropland to feed these animals.

The total global land area (excluding Antarctica) is ~13 Mha of which 4.1 Mha is forest and 4.8 Mha is agricultural, both arable and pastoral [FAO & UNEP 2020; FAO 2023]. Terrestrial vegetation with its huge potential for carbon sequestration potential is increasingly being recognized as having a role in restoring the global carbon cycle alongside the complementary efforts to reduce anthropogenic emissions discussed above [Murphy, 2024a; Lal et al, 2018; Mo et al, 2023]. Within this total area of land vegetation, tropical forests, which make up 69 % of terrestrial biomass, have a particularly strong sequestration potential (Mo et al, 2023). Terrestrial vegetation currently sequesters 112–169 Gt C/yr and already plays a vital role in the global carbon cycle. Moreover, if tailored optimal land management practices are implemented it is estimated that an extra 13.74 Gt C/yr sequestration potential can be unlocked [Sha et al, 2022].

The major global vegetative carbon stocks are found in three highly forested regions in the tropics, namely Central Africa, the Amazon River basins and the Indo–Malay Archipelago. A large proportion of terrestrial photosynthesis occurs in these regions, which are highly productive due to the year-round hot and moist conditions that favor rapid and continuous growth. The total global forest cover is 4060 Mha, of which 1800 Mha (or 45%) is in tropical regions [FAO, 2020a]. Globally, forests at various levels of intactness cover 31% of land area, but only one-third can be classified as primary forest and 9% is highly fragmented [FAO & UNEP, 2020]. The current FAO definition of primary forests, which has been challenged [Murphy, 2024a & references therein], is as follows: '*naturally regenerated forests of native tree species where there are no clearly visible indications of human activity and the ecological processes are not significantly disturbed*'. In reality, of course, there are few, if any, forested biomes that are completely devoid of human activity or influence when closely examined [Fletcher et al, 2021].

It is estimated that intact tropical forests globally sequester an average 0.5 t C/ha/yr and that they collectively store ~1 Gt/yr C [Lewis et al, 2009], although other estimates range from 2-4 Gt/yr C [Mahli & Grace, 2000]. Tropical forests store captured carbon in their foliage and woody biomass and in organic litter on the ground or buried in the soil layers that can extend to over a meter in depth. Carbon makes up about half of the dry weight of living tree biomass and 70% of this biomass is in woody structures, while only 30% is present in vegetative tissues such as leaves [Joyard, 2025; Ratnasingam et al, 2015]. In a study of a tropical forest in Amazonia, the newly fixed carbon was initially stored mainly as above-ground biomass (such as leaves) and later in the woody structures, but after about 16 years much of it was present in the form of below-ground biomass (such as roots and mycorrhizae) where it remained in the rhizosphere for a further 13 years [Mahli & Grace, 2000]. Following tree death the lignified biomass can persist for many years, and even centuries, according to the nature of the wood, climate, moisture and the presence of the appropriate soil-dwelling wood-decay fungi [Manici et al, 2023]. For example, in the boreal forests of Canada, as much as 80% of total carbon is present as non-living SOC [NRC, 2007].

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4.3. Afforestation and Reforestation

Afforestation and reforestation both refer to establishment of trees on land from which trees are currently mostly absent. Afforestation is the conversion of land that has been non-forested for a considerable time (50 years according to UNFCCC) into forest. Reforestation can refer to any form of tree planting but often refers to the planting of native trees into an area in which trees have become scarce or where it is used for the replacement of commercial tree plantations with a native woodland. An example of the latter would be the felling of a coniferous plantation and its substitution by a mosaic of tree species that are indigenous to the region. There are many reasons for such large-scale tree planting including a desire to restore biodiversity by replacing a monoculture once the plantation has reached the end of its useful life, the necessity to fell large tracts of diseased trees, and a desire to remove fire-prone commercial plantations, such as eucalypts, with more suitable tree cover.

The global forest area declined considerably during the 20th century as felling greatly outstripped new plantings. By its nadir during the 1990s, net forest losses reached 7.8 Mha/yr. Since the start of the 21st century, however, a combination of reduced felling and both natural and managed growth of remaining and newly planted forests has turned the tide with much-reduced net losses of 4.7 Mha/yr during the decade of the 2010s [FAO & UNEP, 2020]. In absolute terms, the world has lost 178 Mha forest during the three decades from 1990-2020, an annual average loss of 6 Mha. While these statistics are grim, there is some room for optimism in the 40% decrease in rates of forest losses. These are due to a combination of reduced felling, natural regeneration, and significantly increased rates of afforestation and reforestation [Hua et al, 2016; Ahrends et al, 2017; Cook-Patton et al, 2020; Harris & Gibbs, 2021; Harris et al, 2021]. It was recently reported that the carbon sink (i.e. net sequestration) value of global forests was relatively steady from the 1990s to the 2010s at ~3.5 Gt C/yr, but much of this was negated by tropical deforestation totaling ~2.2 Gt C/yr, which further emphasizes the importance of reforestation (Pan et al, 2024) as summarized in Figure 3.

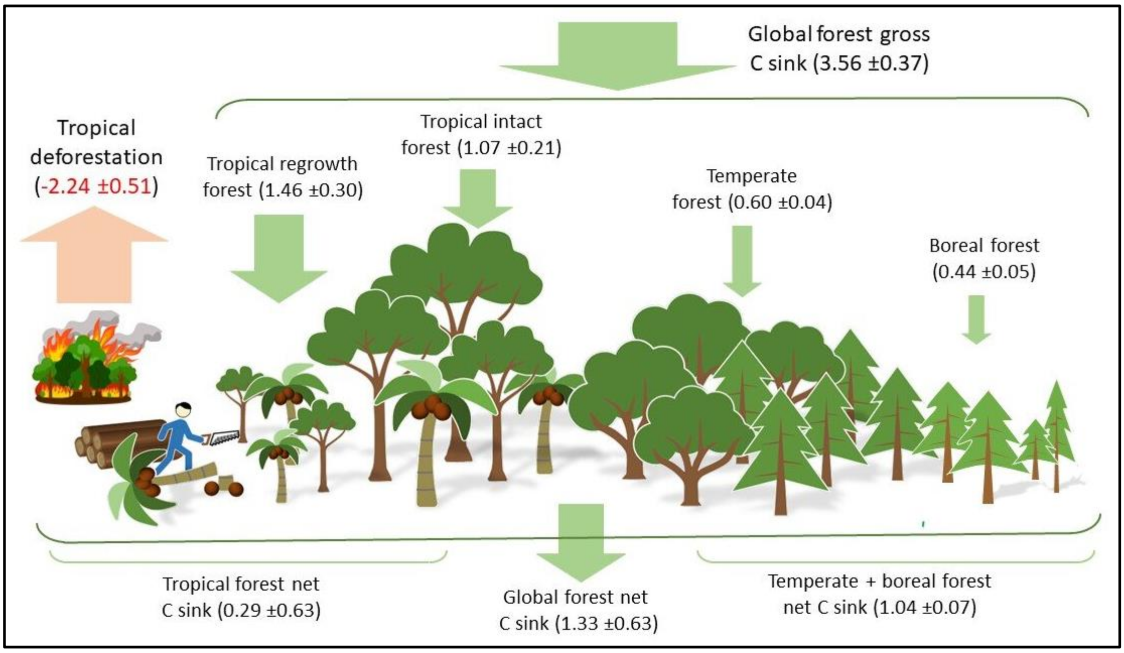

Figure 3. Carbon sinks and sources in global forests. Values cover the period 1990-2019 and are expressed in Gt C/yr. Green = C sinks, red = C sources (i.e. emissions). Source: Pan et al, 2024, which has further details on methodology.

As noted by FAO, forest restoration, when implemented appropriately, helps restore habitats and ecosystems, create jobs and income, and can be an effective nature-based solution to climate change [FAO & UNEP 2020]. It is estimated that there are some 1700-1800 Mha of potential forest land (defined as land that could sustain more than 10% tree cover) in areas dominated by sparse vegetation, grasslands and degraded bare soils (Bastin et al, 2019). If replanted as natural forests or high-productivity commercial treescapes such as perennial agroforests, these regions could collectively sequester and store an additional 205 Gt C at maturity (Bastin et al, 2019). Over a timescale of several decades this would considerably reduce the current anthropogenic carbon burden that is of the order of 300 Gt. In another study the amount of global forest carbon storage was found to be even more below its natural potential, with a total deficit of 226 Gt [Mo et al, 2023].

One challenge is to accurately assess the land area that is suitable for afforestation and/or reforestation [Walker et al, 2022; Lewis et al, 2022]. Current estimates are mainly based on a combination of ground-based measurements, remote imagery, and a suite of modeling tools that enable extrapolations up to global levels. All estimates carry uncertainties and require modification as improved data-generation techniques emerge, which is one reason why figures can vary in different studies. An interesting recent technological development was the launch of the Biomass satellite by the European Space Agency in May 2025. This satellite is designed to provide P-band synthetic aperture radar (SAR) measurements for a much more accurate high-resolution determination of the amount of biomass and carbon stored in forests plus an experimental 'tomographic' phase that is hoped to provide 3D views of forests [European Space Agency, 2025].

The IPCC suggests that increasing the total area of the world's forests, woodlands and woody savannas by 9% by 2030 could sequester one quarter of the necessary atmospheric carbon on land to comply with its suggested 1.5°C pathways. In practice this means adding new forest totalling about 350 Mha. Currently, three major approaches are being taken as follows: (i) leaving degraded and abandoned agricultural land to regenerate to natural forest; (ii) largely allowing plant succession to proceed on its own, although some areas are planted with native species to accelerate recovery rates; (iii) converting marginal agricultural lands into plantations of valuable trees like *Eucalyptus* (for paper) or *Hevea braziliensis* (for rubber); and fostering agroforestry, the growing of agricultural crops and useful trees together.

In 2019, the US National Academies published a research agenda for advancing the understanding of a variety of land- and coastal-based CDR approaches and specifically, for assessing their benefits, risks, and sustainable scale potential [National Academies, 2019]. The study found that, to meet climate goals, biological methods were the most cost effective and scalable [National Academies, 2019]. In particular, approaches based on afforestation/reforestation, changes in forest management, uptake, and storage by agricultural soils incurred carbon at costs below \$100/t CO_2 captured, and sometimes as low as \$10-60/t CO_2 captured. Estimates for the potential carbon removal from afforestation/reforestation ranged from 2.7 to 17.9 Gt CO_2 annually depending on different assumptions and modeling approaches, and variable prices or incentives for implementing activities. At the low end of the range, the assumed price of carbon is low and secondary impacts are few but at the high end, the price of carbon would be as high as \$100/t CO_2 and tens of millions of hectares would be incentivized to convert from crop or grass production to forest.

4.4. Soil-Carbon Sequestration

Soil organic carbon (SOC) constitutes the largest terrestrial carbon pool and globally the top 30 cm of soil contains more carbon than the atmosphere and vegetation combined. The stock of SOC in the terrestrial biosphere is linked with ambient atmospheric CO_2 concentrations [Trenberth & Smith, 2005]. Subsoil layers at >30 cm depth are another important reservoir of long-term sequestered carbon that can be thousands of years old (Button et al, 2022). Estimates of the CO_2 sequestration potential of global soils have been variously estimated as 0.90-1.85 Gt C/yr [Zomer et al, 2017]; 1 Gt C/yr [Paustain et al, 2019]; 0.79-1.45 Gt C/yr [Amelung et al, 2020]; 0.28-0.43 Gt C/yr [Lessman et al, 2022]; 0.14–0.57 Gt C/yr (FAO, 2025), i.e. a range of 0.14-1.85 Gt C/yr. To date, 33% of global soils have been degraded and to the extent that they have lost as much as 50-75% of their SOC due to the historical expansion of agriculture and pastoralism and subsequent land-use conversion from native ecosystems (e.g., peatlands, forests, grasslands) to arable land [Sanderman et al 2017; Kabato et al, 2025].

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It is estimated that since the invention of agriculture over 10,000 years ago soil disturbance associated with arable and pastoral farming has resulted in the release of ~110 Gt C from the top layer of soil [Melillo et al, 2017; 2021], while another group reported a lower 31 Gt C [Sanderman et al, 2017], although this has been questioned [Padarian et al, 2022]. A major part of any recarbonization of the terrestrial biosphere (as mentioned above) will involve, not only increased C sequestration via photosynthesis, but also the more effective long-term storage of this material in the form of biomass or SOC [Lal et al, 2018; Nayak et al, 2022].

The expansion of agriculture between 1850 and 2015 CE has also involved the drainage and loss of 50 Mha peatland areas, resulting in the release of 80 Gt CO_2-eq. In the absence of altered management approaches, by the end of the 21st century, cumulative emissions from drained peatlands may reach 250 Gt CO_2-eq [Leifeld et al, 2019]. Historically, the vast majority of peat-related emissions were derived from the temperate zones, but in the past few decades drained tropical peatlands, particularly in SE Asia, have been responsible for the majority of current emissions [Prananto et al, 2020]. On the plus side, however, the pace of peatland conversion has significantly reduced over recent years [Murphy, 2024b]. There is also evidence that amelioratory measures, such as rewetting to raise water tables, can substantially lower peat-related GHG emissions [Armentano & Menges, 1986; Wilson et al, 2016] and could eventually even reverse them [Knox et al, 2015]. Such measures do not increase carbon sequestration *per se* but they can reduce future carbon emissions. Among the numerous challenges in tackling the issue of soil C on a global basis is the lack of data in many parts of the world and this applies particularly in many regions there where high yield gaps and historical SOC impoverishment mean that any ameliorative measures that are eventually taken would have the greatest impact [Amelung et al, 2020].

Global cropland totals 1,410 Mha and these soils also hold great potential for expanded carbon sequestration, with a capacity of 16-19 Mt C/yr even in the relatively small area (100 Mha) occupied by the EU [Freibauer et al, 2004]. Globally, the potential of agricultural soils is of the order of 1-2 Gt/yr, a figure that is comparable with the most optimistic current projections for industrial carbon sequestration [Murphy, 2024a]. The precise potential for agricultural soils to regain some or all of their lost carbon content will vary according to factors such soil type, climate, management and the nature of their previous and future uses [Button et al, 2022; Lessman et al, 2022]. As much as 1.4 Mha of relatively C-poor cropland is readily available for improvement, the majority of which is in warm climatic zones, such as the tropics and subtropics and Mediterranean regions. Using a neural network model it was estimated that the topsoils (0-30 cm) of the 1.4 Mha of global cropland contains 83 Gt C [Padarian et al, 2022]. With the use of remediation strategies this could be increased by a further 29-65 Gt C, albeit over a period of between 9 and 20 decades at a still-impressive annual C sequestration rate of ~0.3 Gt.

The most impactful strategy to restore soil C levels is a greater use of organic fertilization with others including low- or no-tillage and no-burning of crop resides. Interestingly, some of the existing major tropical perennial crops that will be discussed later (see section 5) fall into these categories. For example, perennial tree crops such as oil palm can be used to improve soil C stocks following conversion from other uses such as grassland pasture [Goodrick at al, 2015; Borchard et al, 2019; Amelung et al, 2020; Brindis-Santos et al, 2021]. In general, agricultural systems with high levels of crop diversity and the presence of perennial species, as in agroforestry, have been shown to have enhanced levels of soil C and therefore greater biological health and resilience [Sprunger et al, 2020]. With improved management practices it should be feasible to restore between 228 and 418 Mha of cropland, which is 16-30% of the total area [Padarian et al, 2022]. While the total amount of additional carbon that can be sequestered into agricultural soils is small in the context of anthropogenic emissions it is critical in terms of long-term soil health and hence sustainable crop productivity and food security.

4.5. Ocean Fertilization

The global oceans directly take up ~30% of anthropogenically emitted CO_2 in the form of dissolved gas, removing ~1 Gt /yr [Muller et al, 2023]. In addition, the oceans contain extensive pools of organic carbon in the form of living marine biomass totaling 1-3 Gt C, plus long-term stores of non-living dissolved organic carbon (DOC) totaling 600 Gt [NASA, 2011; Muller & Decanadal, 2023; Olajire & Essien, 2014; Fakhraee et al, 2021; Muller et al, 2023]. Marine DOC can be regarded as the aquatic equivalent of the terrestrial SOC considered in the previous sub-section, with both pools derived from the dead remains of living organisms and with both having a lengthy persistence time. Unlike plant-dominated terrestrial systems, however, plants only make up 8% of the living marine biomass (0.5 Gt C), while the major primary producers are the photosynthetic algal and bacterial organisms that make up 54% of the biomass (3.5 Gt C). Depending for nourishment on these primary producers are the heterotrophic consumers, such as animals, protists and bacteria that make up 36% of the marine biomass (3.5 Gt C), giving a grand total of 7 Gt C [Bar-On et al, 2019]. For reference, terrestrial plants, many of which are arboreal, highly lignified and hence carbon-rich organisms have a biomass of 450 Gt [Bar-On et al, 2019]. Despite the relatively small amount of marine biomass, the concept of developing technologies for ocean fertilization to increase this biomass has gained some traction and funding in recent decades.

Ocean fertilization involves stimulation of the growth of major primary producers, i.e. phytoplankton, by adding exogenous minerals such as iron that might be present in limiting quantities in current aquatic systems. Theoretically, any resultant increase in phytoplankton biomass would also lead to a corresponding increase in heterotrophic biomass and a possible additional oceanic C sink of the order of 1-2 Gt C. However, the technology has always been controversial, both in terms of feasibility, cost, the risk of undesirable and irreversible side effects on oceanic systems, and a lack of accountability/regulation in operations in international waters [Lauderdale et al, 2020; Hance et al, 2023]. Indeed, there have been several attempts at international regulation including the UN Convention on the Prevention of Marine Pollution that mandated strict regulation of ocean fertilization activities and a *de facto* banning of commercial deployment [Silverman-Roati et al, 2022]. Although ocean fertilization involves biological carbon sequestration, it is different to other biological methods considered here in that it is still a largely theoretical technology that aims to increase the capacity of oceanic regions that currently have low productivity.

At its simplest, the process of ocean fertilization entails adding nutrients to the upper photic zone layers of the ocean with the aim of stimulating photosynthesis by phytoplankton such as algae and cyanobacteria. Depending on turbidity, the photic zone, defined as receiving <1% of surface sunlight, can be as shallow as a few cm near major land masses to as deep as 200 m in the open ocean. In most oceanic photic regions, phytoplankton growth is strongly limited by the availability of elements such as iron, nitrogen or phosphorus. If substantial amounts of such micro-or macro-nutrients are released into these areas, the phytoplankton can increase their growth rates, hence absorbing CO_2 (ultimately from the atmosphere) and sequestering it as organic carbon, some of which will remain in the long-term DOC pool, possible for millennia or longer. There is some support for this approach, for example based on paleoclimatic data from ice cores that link high iron levels with lower historic levels of atmospheric CO_2 [Petit et al, 1999]. In its earlier iterations, this experimental technology quickly ran into several problems including lower than predicted CO_2 uptake by phytoplankton, a lack of the expected coupling with long-term DOC pools, reduction in O_2 levels, altered marine biodiversity that can lead to toxic algal blooms, and the emergence of other undesirable marine flora and fauna [Strong et al, 2009; Martin et al, 2013; Bach et al, 2019; Goldenberg et al, 2024].

Another proposed way of achieving ocean fertilization is to use a still largely theoretical carbon sequestration technology known as artificial upwelling [OceanNets, 2020]. This involves enhancement of the upward transport of nutrient-rich deep waters using pipes or wave pumps. The technology has never been tested at scale and remains controversial. For example, it is stated that even a persistent and effective deployment of the millions of functional pumps required across the global ocean would still not meet CDR goals for sequestration or permanence [National Academies

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of Sciences, 2021; Jurcott et al, 2024]. Moreover, natural occurrences of upwelling generally act as net sources of CO_2 to the atmosphere rather than as net sinks [Takahashi et al, 1997]. Despite these concerns, there is still considerable interest in the concept of ocean fertilization via either mineral supplementation or artificial upwelling and research funds are still being committed to such projects, albeit with persistent reservations about their feasibility and safety [Castañón, 2021; Doney et al, 2021; Lubofski, 2021; Goldenberg et al, 2024; Jurcott et al, 2024; Maribus, 2024].

4.6. Biomass

The final group of biological carbon sequestration techniques to be considered in this section relates to the creation and exploitation of various forms of high-carbon biomass [Denvir & Leslie-Bole, 2025]. All forms of biologically generated materials, including human bodies, can be regarded as biomass, but in most cases these materials are complex mixtures of a wide variety of different elements in addition to carbon and they often have high water contents that renders them unsuitable in the context of effective carbon sequestration and storage. For example, adult human bodies contain 60% water but only 16.5% carbon by weight. In contrast, dried woody plant biomass contains ~50% carbon, although this figure varies according to the source, especially between dense tropical hardwoods and much lighter temperate coniferous woods [Lamlom & Savidge, 2003]. Plant-based biomass has been used as a fuel and other purposes for millennia but, due to its relatively high weight and difficulties in transport, this has generally been on a small scale and only for local consumption. Among some of the more common forms of plant biomass are wood chips, logs and pellets, charcoal, biochar, and several fast-growing grasses such as miscanthus, bamboo and switchgrass. Improved biomass recovery has also been proposed as part of the decarbonization agenda, e.g. for oil palm (Rajakal et al, 2024). The discussion here will be limited to several examples of the use of plant biomass in the context of carbon sequestration, namely biochar and wood chips/pellets.

Biochar

The informal use of biochar for soil improvement dates back to the earliest days of Neolithic farming with one of the best known examples being for the generation of the anthropogenic dark earths in pre-Columbian Amazonia [Glaser & Birk, 2012]. Nowadays biochar has many other applications including soil improvement, enhancing crop yields, carbon sequestration and the use of its pyrolysis products to generate carbon-neutral biofuels [Lehman et al, 2015], not to mention its potential use in generation carbon offsets and credits as part of carbon trading systems [De Gryze et al, 2010], as discussed further in section 7 below. Biochar is rapidly emerging as a useful form of biomass that can be obtained from a wide variety of plant sources [Varkolu et al, 2025]. It is a solid, charcoal-like substance containing 70% carbon with a long history of use as soil enhancer to increase fertility, prevent soil degradation, a concrete additive, and to sequester carbon in the soil [Zhang et al, 2022; De Gryze et al, 2010].

Biochar is produced using pyrolysis. i.e. heating the plant material under anoxic or low-oxygen conditions to generate a solid charred mixture that contains aromatic and reduced carbon compounds, plus liquid and gaseous byproducts known respectively as bio-oil and bio-gas [Saxena, 2025]. This renders biochar far more recalcitrant to breakdown than the original plant material and some biochars can remain undisturbed in the soil for centuries, which makes them ideal for long-term sequestration [Lehman et al, 2015]. From 2018-2022 biochar R&D had generated several dozen high-value patents and incoming funding was a respectable $144 million, although this was still much lower than the $390 million allocated to BECCS and DACS [Smith et al, 2024]. The technology is gradually being upscaled, for example with the $8 million CARBONITY facility in Quebec, Canada beginning production in 2025 [Paper Advance, 2025]. In some senses the modern upscaled version of biochar technology resembles industrial methods of carbon sequestration and it is interesting to compare their respective CO_2 removal capacities. In 2024, biochar operated at 0.79 Mt.CO_2/yr while BECCS achieved 0.51 Mt.CO_2/yr and DACS was a mere 0.03 Mt.CO_2/yr [Smith et al, 2024]. In contrast, afforestation/reforestation currently operates at a three orders of magnitude greater scale in the region of ~2 Gt/CO_2/yr, i.e. ~2,000 Mt.CO_2/yr [Smith et al, 2024].

Wood Chips/Pellets

The combustion of wood chips/pellets in large-scale energy production, normally as part of electricity generation, is one of the many examples of biofuel use. Some liquid biofuels, such as biodiesel and bioethanol are lightweight energy-dense liquids that can be used in transport settings such as road vehicles and airplanes. In contrast, wood-based fuels are heavy, bulky, solid materials that have far lower energy densities (measured as GJ/t) that are only 25-35% of values of liquid biofuels. This constrains the practical commercial uses of solid biomass fuels to operating on fixed sites for the large-scale generation of heat energy that is then typically used to generate electricity. The large-scale use of wood-based plant biomass for energy generation has been controversial, particularly when the process is claimed to be carbon-neutral, or even involve negative CO_2 emissions, such as if effective CO_2 capture technologies are deployed to remove the end-of-pipe combustion products when the wood is burned, as in the case of BECCS or combined BECCS-DAC [Camia et al, 2021]. In 2023 the European Academies Sciences Advisory Council stated that using woody biomass for power generation "*is not effective in mitigating climate change and may even increase the risk of dangerous climate change*".

Such concerns are compounded when the biomass is transported vast distances from its woodland source to its ultimate site of use in power plants that might be thousands of miles away on another continent [Sterman et al 2018; Booth, 2019; Wang et al, 2021; Sterman et al, 2022; Snowdon, 2024]. Clearly the life-cycle implications of felling, chipping/pelletization, and transporting such vast quantities of wood products need to be taken into account when trying to make a case for carbon-neutrality of their use in power generation. Because combustion and processing efficiencies for wood fuels are much less than coal, the substitution of wood for coal incurs a carbon debt that lasts between 44–104 years after the wood is felled, as long as the land is immediately replanted with a similar type of forest [Sterman et al, 2018; 2022]. In terms of distances, transportation of woody biomass over ~500 km is problematic, as are their net emissions footprints. For example in a US study it was found that power stations using wood pellets emitted an average 2.8-times the amount of pollutants than comparable facilities using coal, oil or natural gas [Tran et al, 2023]. A recent high profile example that is ongoing is the felling of mature trees in North America for the production of wood pellets that are then shipped to former coal-fired power stations in Europe, where they supposedly act as a carbon-neutral fuel, a claim decisively at variance with most scientific evidence [Sterman et al 2018; Booth, 2019; Buchholz et al, 2021; NRDC, 2021; Wang et al, 2021; Sterman et al, 2022].

The practice of burning wood chips/pellets derived from mature trees thousands of miles away has recently become a *cause célèbre* in the UK. In this case, the operators of the government-subsidised (but privately owned) Drax power station in 2022 imported 8.2 Mt of North American wood pellets while benefiting from a $780 million state handout [Snowdon, 2024]. Somewhat belatedly, the UK government issued a report in early 2024 in which their support for tree biomass was questioned, both in terms of its cost in public subsidies of over $8 billion since 2002, and its questionable sustainability criteria [National Audit Office, 2024; Lawson, 2023; Mavrokefalidis, 2024; Millard, 2024]. It was reported that Drax held logging licences in British Columbia, Canada, and used wood, including whole trees, from primary and old-growth forests for its pellets. While Drax admitted it had taken wood from old-growth forests, it was also found that the company had not disclosed using wood from several natural forests both in Canada and the USA [Crowley 2025; Muirhead 2025; This is Money, 2025].

Matters were not helped when in 2023 it was revealed that the Drax power station has by far the highest net GHG emissions of any industrial enterprise in the UK. The Drax figures of 11.5 Mt CO_2e compared with far lower values for all of the oil- and gas- fired power stations in the country and were 85% higher than the largest coal-fired steelworks at Port Talbot [Mayo, 2024]. Unfortunately in

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2025 the Drax power station continued to benefit from a $9 billion public subsidy that was renewed despite the previously expressed concerns of scientific experts [Anderson et al, 2024], elected parliamentarians [National Audit Office, 2024; UK Parliament, 2024; Pratley, 2025], and many in civil society [Lawson, 2023; PFPI, 2025]. The company was also fined and had some of its subsidy withdrawn, but this long-running case does nothing to enhance the reputation of biomass technologies and their potential, if any, to make meaningful large-scale contributions to sustainable carbon sequestration.

5. The Potential of Tropical Perennial Crops

So far we have mainly considered natural sources for biological sequestration but there is another largely overlooked source, namely from crops [Ilakiya et al, 2024]. As noted above, most crops are derived from small non-woody annual plants, such as cereals, legumes and roots that sequester relatively small amounts of CO_2. However, there is another crop category, namely woody perennial species where there may be options for developing improved carbon sinks. In this section we will focus on tropical perennial crops.

Tropical cropland occupies >700 Mha and is an important potential source of additional carbon sequestration [Phalan *et al*, 2013]. However, many of these species, such as soybean, maize, rice and sorghum, are short-season annual that are poor in their sequestration potential with high net CO_2 emissions are due to factors such as respiration, soil disturbance, use of energy-rich inputs, such as fertilisers, and land-use conversion (Mahli & Grace, 2000; Patthanaissaranukool & Polprasert, 2011). In contrast with annual crops, tropical perennial crops have considerable potential for additional carbon sequestration.

In the tropics, forests and agricultural production systems often overlap to varying degrees, especially in the case of perennial crops that are frequently cultivated alongside other tree species, not all of which are crops but which are used primarily as shade cover. Agriculture is one of the key elements that can play a part in improved sustainability and climate change mitigation [Ag Policy Eval, 2022]. As in the case of agroforestry systems, many tropical perennial crops are being increasingly cultivated to create high-carbon-stock landscapes that have greatly increased carbon sequestration that are provided in addition to their many other benefits [Martinez-Nuñez et al, 2024; Albrecht et al, 2003]. Indeed, ~40% of global agricultural land has more than 10% tree cover (Zomer et al, 2009). In Figure 4, the estimated carbon sequestration potentials are shown for both above-ground and below-ground locations in four contrasting crop types, two of which are perennial and two annual. As expected the lower-biomass annual crops have much reduced capacities for carbon sequestration [Ilakiya et al, 2024. In this section, therefore, case studies of six tropical perennial crops, cocoa, coffee, banana, coconut, rubber, and oil palm are presented. As we will see below, five of the six tropical perennial crops have potential carbon sequestration values in the range of 10 Mt/yr to >1000 Mt/yr with a possible total exceeding 1 Gt/yr C.

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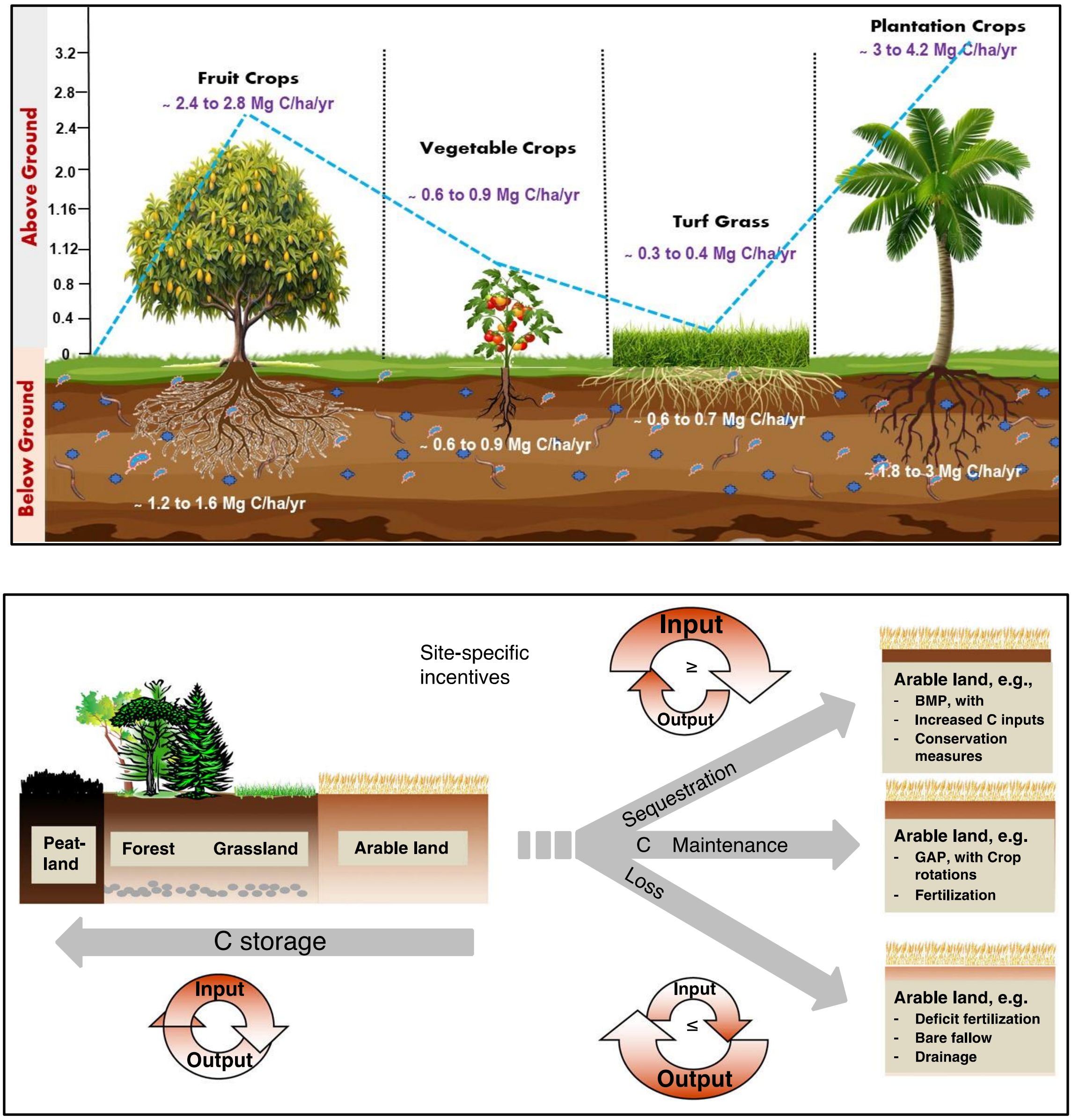

Figure 4. Carbon sequestration in different cropping systems. Upper panel: C sequestration in various crop types showing tree crops ranging from 2-4 Mg/ha, equivalent to 2-4 Gt/Mha. Source: Ilakiya et al, 2024. Lower panel: Potential for improved C sequestration in some types of arable land via improved measures such as best management practice (BMP), organic inputs and conservation measures. Source: Amelung et al, 2020.

5.1. Cocoa

Cocoa, *Theobroma cacao*, is a lowland tropical tree crop grown globally on about 6 Mha with an annual production of ~4.5 Mt beans. The main center of cultivation is in West Africa which accounts for 65% of global production, half of which is grown in the country of Cote d'Ivoire. Over 90% of the crop is cultivated on smallholder farms that total at least six million units. The lack of effective market control by the growers and local governments has led to considerable volatility with cycles of overproduction and scarcity that are exacerbated by climatic factors, low prices offered to producers, increased intensification, pest/disease outbreaks, and deforestation (Miharza et al, 2023; Martinez-Nuñez et al, 2024; Michel et al, 2024). In early 2025, commodity prices of cocoa reached record highs with a 14% decline in annual production during the 2023-24 season from 4.9 to 4.2 Mt [Robinson, 2025]. Unfortunately, the cycles of 'boom and bust' in cocoa cropping systems regularly lead to deforestation during periods of higher prices followed by severe economic hardship for farmers during periods of lower prices, all of which have been exacerbated by recent climate change that has mainly affected Côte d'Ivoire and Ghana.

Cocoa seedlings are typically grown as understory plants in the shade of various tree species. Mature cocoa trees can range from 6-12 m in height and can be grown as monocultures in full sunlight, although they are increasingly cultivated in agroforestry systems. Cocoa plantations are often located in valleys or coastal plains where they require evenly distributed rainfall and nutrient-rich, well-drained soil. The main harvesting season of the cocoa pods is between October and March, but in some cases a secondary harvest is possible from May to August, especially if there has been plentiful rainfall.

Cocoa trees have a useful economic life of about 25 yrs before a new generation of seedlings is planted. Cocoa is exclusively a cash crop, so smallholders often grow additional subsistence food crops, such as sweet potatoes, maize and cocoyams, as part of the shade vegetation (Artenaga et al, 2014). Other useful shade species include various alternative cash crops such as banana, coconut, rubber trees, and in some cases parts of the original forest vegetation can also serve as a shade component (Somarriba et al, 2013; Nguyen-Duy et al, 2018; Thomson et al, 2020; Miharza et al, 2023; Michel et al, 2024). Example of monoculture, mixed culture and shade cropping systems in Sierra Leone, Peru and Ecuador are shown in Figure 5.

There is an increasing body of research on the benefits of agroforestry and low-input systems for cocoa cultivation. This has established, not only the absolute requirement for 70% shade for young plants but also the benefits of about 25% shade for cocoa trees of five to seven years. While this level of shade can be reduced for older trees, the downside is that the plants will require additional nutrients and water. In contrast, by keeping the shade trees there would be less dependence on such inputs and increased overall resilience of the cocoa cropping system (Thomson et al, 2020; Michel et al, 2024). In the important cocoa-growing countries of Côte d'Ivoire and Ghana much of the original forest has already been converted to agriculture. However, although cocoa agroforestry cannot completely replace natural forests, it is a valuable tool for conserving and protecting biodiversity while maintaining high levels of productivity of an economically essential cash crop for indigenous farmers [Schroth et al, 2016; FAO & UNEP, 2020].

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Figure 5. Cocoa cropping systems. Upper panel: Commercial monoculture in Ecuador. Mid panel: mixed culture in Peru. Lower panel: shade-grown cocoa plantation in Sierra Leone.

Because perennial cocoa trees have a greater biomass than annual crops, such as maize or rice, even when grow as monocultures cocoa trees are more effective in terms of carbon sequestration. This effect is greatly amplified when cocoa is grown within a well-planned agroforestry system where good yields of the cocoa crop and canopy vegetation can be achieved at high carbon densities (Somarriba et al, 2013). In a study from Central America, the crop system contained an average total carbon content of 117 t/ha of which 42% was fresh aboveground biomass. The cocoa trees stored 18%

of carbon in the aboveground biomass while the companion trees store 65% with an annual rate of carbon accumulation in the range of 1.3–2.6 t/ha/yr (Somarriba et al, 2013). Most of the sequestered carbon was stored in trees, especially the taller companion trees, and in the soil.

A study of different intercropping systems in Indonesia showed that there were both advantages and drawbacks in each system, but overall cocoa performance was good (Nguyen-Duy et al, 2018). Interestingly, despite its utility as a both a shade tree and an additional cash crop, banana played an insignificant role in carbon sequestration within cocoa agroforestry system in comparison with other shade species. In general, the annual rate of carbon accumulation in the agroforestry systems was between 2–3 t/ha/yr, of which between 25-35% was contributed by the cocoa trees while the remainder was generated by the shade trees (Nguyen-Duy et al, 2018). In terms of GHG emissions in the intercropping systems, the major component was the crop residue with relatively little contribution from fertilizer use. The GHG emissions were mostly methane produced due to the anaerobic conditions of crop residue decomposition, although this could be reduced by appropriate treatment of the residue prior to decomposition. In the three intercropping systems compared, there was a net negative carbon emission C_{eq} footprint of between 0.8 and 2.5 t/ha. In all cases, therefore, different forms of cocoa agroforestry resulted in significant levels of carbon sequestration, which are in addition to their manifold economic and environmental benefits (Nguyen-Duy et al, 2018).

In another study in Indonesia, there was considerable variation in carbon stock accumulation between different production systems and in different habitats, as would be expected. However, even in cocoa monocultures, the total carbon stocks averaged 105 t/ha and the best agroforestry systems reached as high as 195 t/ha (Miharza et al, 2023). The agroforestry systems also had lower C footprints in terms of GHG emissions with values of 0.93 t C_{eq}/ha in contrast with 1.9 t C_{eq}/ha for monoculture systems. In summary, the deployment of the most effective agroforestry systems that combine high crop yields with low inputs and increased environmental resilience is already delivering significant amounts of net carbon sequestration. If these systems are applied across most of the global cocoa production of 6 Mha, well over 10 Mt of CO_2 could be extracted annually from the atmosphere by this crop alone. In contrast, as discussed in section 3 above, the current rates of all of the industrial CO_2 sequestration schemes (known as carbon dioxide removal or CDR) are only 2 Mt CO_2/yr.

5.2. Coffee

Coffee is a highly valuable tropical crop that is grown globally on about 11 Mha with an annual production of 10.5 Mt beans. Two major species are grown commercially, namely *Coffea arabica* (60-70% global production), which is an understory montane shrub typically grown at elevations of 1300-2000 m, for example in Ethiopia and Kenya, and *Coffea canephora* (30-40% global production), which is native to humid tropical lowlands in Africa and now cultivated globally. The plants generally grow as shrubs, but can sometimes reach heights of 4-8 m when they resemble small trees that can be productive for >30 yrs. Between 70-80% of the crop is grown on as many as 12 million smallholder farms with three countries, namely Brazil, Vietnam and Colombia responsible for 62% of global bean production. Over recent years, climate-related factors, such as drought and disease, have resulted in substantial decreases in crop yields and during the year from 2023-24 retail prices of coffee doubled across the world with the prospect of further yield decreases in the future (Grüter et al, 2022; Murphy, 2022).

The fact that coffee plants are shade-adapted perennials makes them particularly amenable to cultivation in agroforestry systems (Haggar et al, 2021; Vallejos-Torres et al, 2024). Indeed, coffee-based agroforestry has been shown to deliver benefits such as higher carbon sequestration and biomass accumulation, as well as increased biodiversity, and other ecosystem functions (Buechley et al, 2015; Hylander et al, 2013; Koutouleas et al, 2022; Tesfay et al, 2022; Tilden et al, 2024). Coffee-based agroforestry systems are often based on single partner tree species, such as *Inga spp.*, but they can also host numerous additional tree species that can provide further ecosystem services such as increased biodiversity and forest connectivity. Such systems are becoming increasing used for commercial crop production, especially in view of their greater capacity to buffer against climatic

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episodes such as the recent droughts that have dramatically reduced yields in many regions (Lara-Estrada et al, 2021; Grüter et al, 2022; Murphy, 2022). The five principal coffee crop landscapes, as defined in Toledo et al, 2012, range from unshaded monocultures to highly forested polyculture and 'rustic' systems as shown diagrammatically in Figure 6 with further pictorial examples shown later in Figure 7.

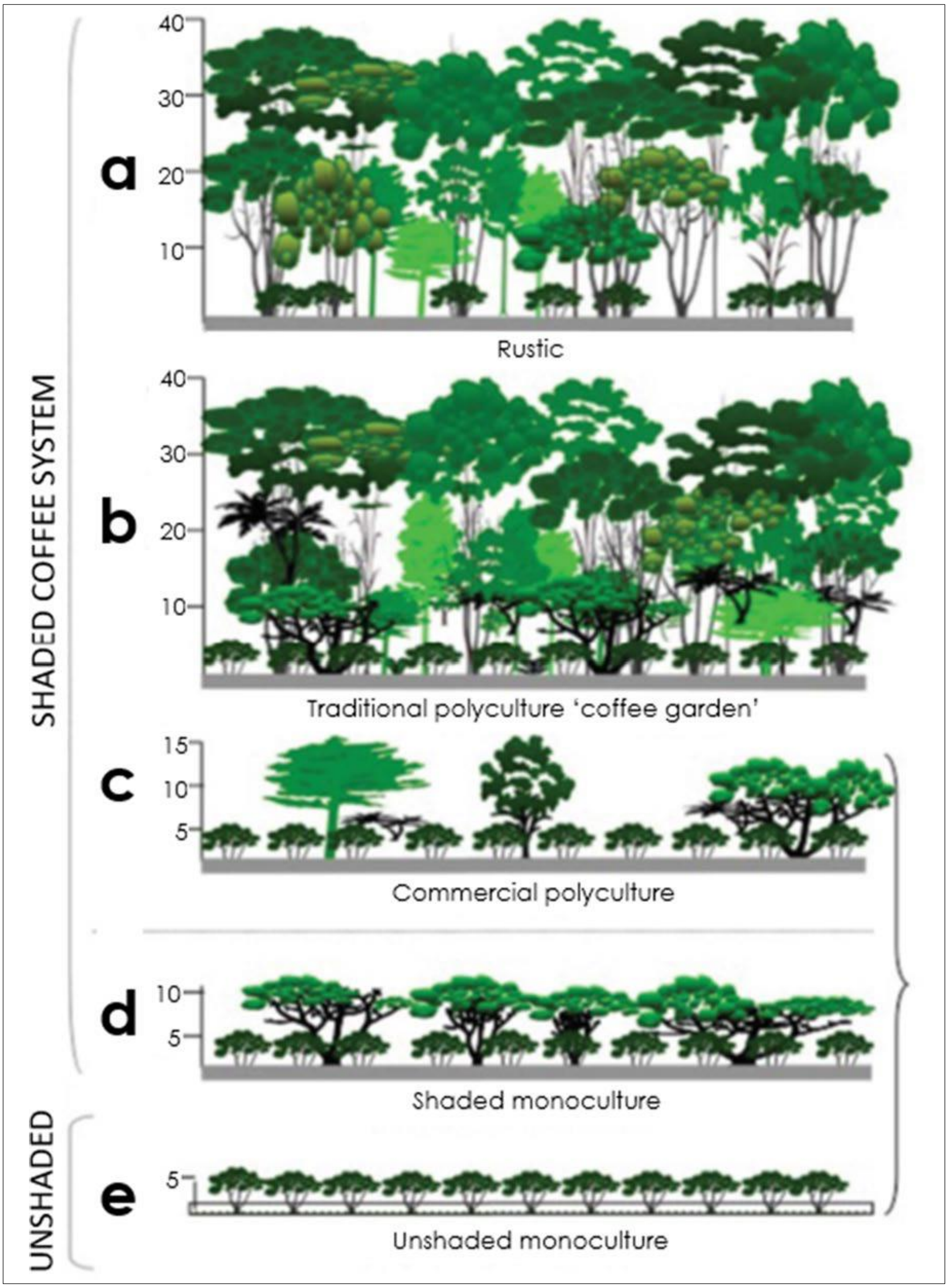

Figure 6. The five main coffee producing landscapes distinguished by vegetation structure, species variety, and composition, as well as by the impact of human manipulation. Source: Toledo & Moguel 2012.

With a growing interest by many consumers in specialty, sustainability-certified, and 'fair trade' brands of coffee, there are increasing economic as well as environmental benefits in the use of coffee-based agroforestry systems (Tilden et al, 2024). In addition to their many ecosystem services, such systems can deliver broader benefits in terms of carbon sequestration and GHG emission reduction, thereby increasing the carbon stock of the crop system on a long-term basis. For example, in a recent study in Peru, the effects of coffee cultivation in the presence of shade trees of *Inga spp*. were analyzed (Vallejos-Torres et al, 2024). These nitrogen-fixing trees can grow as tall as 15 m and are widely used in conjunction with either coffee or cocoa crops in agroforestry systems. As a control, the carbon stock in nearby secondary forests was also measured. The carbon stock biomass in the secondary forests was 132.2 t/ha, while in coffee plantations with *Inga spp.* shade trees was biomass was an impressive 118.2 t/ha. Carbon stocks were 76.5 t/ha in agroforestry systems with much lower values of 31.1 t/ha found in shade-less monoculture. In all agroforestry systems examined the coffee plants sequestered an average of 2.65 t/ha, corresponding to 4.63% of the total carbon sequestered, with the rest being fixed by the companion vegetation. The highest amounts of carbon storage were found in coffee systems intercropped with *Inga* spp. shade trees. Other tree-intercropping examples are shown in Figure 7.

Similar studies on a variety of coffee shade-tree systems in Ethiopia and Central America have shown broadly similar findings (Birhanu et al, 2022; Niguse et al, 2022; Lugo-Pérez et al, 2023 Gelaye et al, 2024). For example, in Ethiopia *Syzygium* shade-tree systems had carbon stocks of 254.9 t C/ha while *Albizia* shade-tree systems had stocks of 321.8 t C/ha. Within these coffee agroforestry systems, the coffee plants contributed 37.5 t C/ha, accounting for approximately 12.8% of the total carbon sequestered in the systems (Niguse et al, 2022). These two shade trees are widely used in coffee agroforestry in Africa and Asia. In Puerto Rico it was estimated that shade-tree incorporation could increase the average storage capacity of coffee systems by 40 t C/ha and provide a sequestration of 0.15 Mt of C in the coming decades (Lugo-Pérez et al, 2023). In Costa Rica, shade trees were reported to sequester between 1-3 t C/ha/yr, and when mixtures of large native timber trees were used as shade species their C storage capacity was almost as high as an undisturbed forest (Harmand et al, 2006).

In terms of reducing net CO_{2e} emissions within the overall coffee supply chain, there are clear advantages to considering the entire 'cradle to grave' life cycle analysis (LCA) in addition to just the crop cultivation. For example, in a study of Arabica coffee imported from Brazil and Vietnam to the UK, the average carbon footprint from both countries was calculated as 15.33 (±0.72) kg CO_{2e}/kg of green coffee for 'conventional' coffee production and 3.51 (±0.13) CO_{2e}/kg for 'sustainable' coffee production [Nab & Maslin, 2020]. In this case, the 77% reduction in carbon footprint for 'sustainable' coffee production in comparison to 'conventional' production was due to export of coffee beans via cargo ship rather than airfreight as well as the reduction of agrochemical inputs.

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Figure 7. Coffee cropping systems. Upper panels: Coffee crop under shade. (A) Arabica coffee with mixed tree species. (B) *C. canephora* intercropped with a single shade tree species, Source: Koutouleas, 2022. Lower panels: Left, With eucalyptus & erythrina trees Costa Rica. Right, Intercropping in Colombia.

It would be interesting to perform more detailed LCA studies of a wider range of coffee supply chains, particularly for the expanding markets for 'fair trade' and artisanal brands that are increasingly prominent in many consuming countries [Henderson et al, 2025; Technavio, 2025]. One aspect ignored in many such studies is the carbon sequestration potential of coffee crops, especially within agroforestry systems. For example, a recent study from two states in Brazil found that the average CO_{2e} removal from the plantations analyzed was 0.43 tCO_{2e}/ha while emissions were 2.4 t CO_{2eq}/ha giving a net carbon balance of 1.97 tCO_{2e}/ha, but data on carbon sequestration, including from partner tree crops, was not included in the audit (Solidaridad et al, 2024).

To summarize, in the case of coffee there are numerous agroforestry systems currently in use or being trialed around the world and, as expected, these have diverse performance characteristics with regard to CO_2 sequestration and C storage. For example, in Costa Rica values as high as 70-80 t C/ha have been reported for well managed agroforestry systems, while crops grown without shade only sequester ~10 t C/ha. In all cases the carbon sequestration potential of coffee crops dwarfs the emissions footprint associated with their cultivation, and probably also offsets the additional emissions in the rest of the coffee supply chain, although this remains to be verified by more comprehensive LCA studies.

5.3. Banana

Bananas, *Musa spp.*, are widely grown in the tropics either as locally consumed food crops or as exported dessert fruits [FAO, 2025a; 2025b]. The *Musa acuminata* variety, Cavendish, is used for dessert bananas while a *Musa balbisiana* x *acuminata* hybrid is the major plantain variety that often serves as a staple food. The global banana crop area is >12 Mha of which 7 Mha is the sweet Cavendish variety used for export while another 5 Mha is grown as plantains or 'cooking bananas' that are not eaten raw but instead cooked to make starchy vegetable foods. Global annual production is 105 Mt fruit, of which 43 Mt is the dessert Cavendish variety and 45 Mt plantain varieties. Despite appearances, bananas are neither trees nor palms but are the largest extant form of herbaceous

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flowering plant. They can reach 2 to 9m in height with the large leaves borne on a pseudostem consisting of leaf stalks. Production of the commercial Cavendish mainly occurs in Latin America and the Philippines, with the four countries of Ecuador, Philippines, Costa Rica, and Guatemala responsible for >75% of global fruit exports.

Commercial banana fruit yields range between 40 and 60 t/ha and they can produce fruits within 1-2 yrs of planting, after which the fruits can be harvested all year round. The plants are typically grown in 2x2 m rows and can support a prolific understory vegetation with a maximum density of ~400 plants/ha. As noted previously, the crop is sometimes interplanted or is used as a nurse crop for other perennial crops such as cocoa and coffee. In Figure 8, several examples of banana monocrop and groundcover-intercrop systems are shown plus a monocrop plantain system grown for local consumption as a subsistence vegetable rather than a fruit crop.

One of the downsides of commercial banana cultivation is the almost total reliance on a single clonal variety. At present the *Musa acuminata* variety, Cavendish, supplies ~99% of all dessert banana exports to developed countries. Despite its high yield, long shelf-life and good consumer appeal, however, Cavendish is a sterile triploid clone with essentially no genetic diversity which renders it highly susceptible to disease. In recent years new strains of the fungal pathogen, Fusarium wilt (also called Panama disease), have spread globally and are now threatening the future of Cavendish in a similar manner to the previous triploid variety Gros Michel that was eradicated by Fusarium wilt in the 1950s (Turrell et al, 2024; Zhang et al, 2024). As expected, numerous programs are currently underway to use a variety of breeding strategies to develop new varieties of commercial dessert bananas [Turrell et al, 2024; Zhang et al, 2024].

Although bananas often play important roles as shade crops, they are less efficient than many other tropical perennial crops, such as coffee and cocoa, in terms of their capacity for carbon storage and CO_2 sequestration in agroecosystems. This is largely due to their relatively low biomass and the absence of longer-lived lignified tissues. For example, in a study on Hainan Island, China over half of all the tissues was made up of water. The C fixed by banana plants was mainly found at fruit growing stage and CO_2 sequestration was 16, 41 and 80 t/ha at the vegetative growth, bud and fruit maturity stages respectively [Zhao et al, 2014]. Therefore, banana remains an attractive option for intercropping with cocoa or coffee trees during the first 2-3 years of establishment stage to provide shade (Leonel et al, 2024). However, once these trees have grown as tall as the banana plants the latter no longer provide either shade or effective carbon storage.

Figure 8. Banana cropping systems. Upper panel: Monocrop in Thailand. Middle panel: With groundcover in Dominica. Lower panel: Plantain plantation grown for local vegetable consumption in Nigeria.

This means that their replacement with alternative shade tree species is a more efficient way to increase the overall C stock of the system. A further challenge to commercial banana cultivation is the potential impact of climate change and its restricted geographical range that depends on ready access to export infrastructure and a shrinking labor supply (Varma et al, 2025). In conclusion, and unlike true trees such as cocoa and coffee, banana crops can be grown a components of some agroforestry systems where they can usefully serve as additional sources of income for smallholder.

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However, because they are non-woody herbaceous plants they do not contribute as effectively to carbon sequestration in comparison with the aforementioned lignified perennial crops.

5.4. Coconut

Coconuts, *Cocos nucifera*, are cultivated throughout the humid tropics and are even grown in isolated Pacific atolls where they have displaced many native trees (Burnett 2024). The trees flourish best in warm, low-elevation habitats that are close to coastal regions with low daily and seasonal temperature fluctuations. Mapping studies showed that three major areas of coconut cultivation were in Indonesia (1.73 Mha), the Philippines (1.54 Mha), and India (1.47 Mha), which together represent 82 % of the global coconut mapped area [Descals et al, 2023]. In 2022, Indonesia emerged as the largest global exporter, just ahead of the Philippines [FAOSTAT, 2022]. North America currently imports nearly 30% of the global coconut production, with Europe predicted to have the highest import growth trajectory at a CAGR of 10.5% that is partially driven by misguided efforts by some retailers to substitute coconut oil for palm kernel oil [Murphy et al, 2021].

Coconut trees are grown for both local subsistence consumption and as cash crops for export with an estimated global area of 11.25 Mha under cultivation as harvestable crops [Statista 2025]. In a different study, based in satellite data, the global an estimated 12.31 ± 3.83 Mha for dense open- and closed-canopy crops was estimated [Descals et al, 2023]. In addition this study also found another ~20 Mha of sparsely grown coconut crops that has hitherto been largely overlooked. Over 90% of the coconut crop is grown on smallholdings and the global annual production is 40 Mt nuts. The trees can reach 30 m in height and have a maximum productive life of 15-20 yrs, but they can sometimes be grown economically for as long as 50-60 yrs [Ranasinghe et al, 2007]. The main commercial products of the crop are the fruit oil and its dried flesh or copra, both of which are exported globally in a trade that was valued at $30 billion in 2024 with a projected increase to $55 billion by 2032. Additional crop products include coconut shell charcoal used in various industrial applications, shredded coconut used in both culinary and snack sectors, and coconut fiber with many uses in eco-friendly products and gardening applications.

Coconut crops are commonly grown as monocultures, particularly in larger commercial plantations. However, the adverse ecological effects of such cropping systems, coupled with their reduced climate resilience and lack of income diversity for smallholders, are some of the factors that are driving an increased drive towards alternative production systems such as intercropping and agroforestry [Atapattu et al 2024; Namitha et al, 2025] and also shown in Figure 9. The coconut has a carbon storage capacity of 24.1 t C/ha and it was estimated that coconut monoculture could potentially provide 102.27 t/ha of above ground biomass and 51.14 t/ha carbon stocks, meaning that some coconut cropping systems could approach natural forests in terms of carbon productivity [Bhagya et al, 2017]. In another study, coconut intercropped with mango crops sequestered 138.9 t C/ha (above + below ground), while a coconut monocrop only sequestered 98.2 t C/ha [Maheswarappa et al, 2010]. Coconut-based intercropping has been recently reviewed [Rani et al, 2024].

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Figure 9. Coconut intercropping. Both panels show the use of intercropping with maize as part of the regenerative techniques being employed in Indonesia. (Source: Haigan Murray / RCA Carbon Indonesia).

Clearly, it is challenging to estimate the existing and future potential performance of coconut crops in terms of carbon sequestration. Densely planted open- and closed-canopy crops probably occupy a global area of about 12 Mha, which is comparable with coffee or banana but only about half that of oil palm (see below). If extrapolated globally therefore, the above estimate of a carbon storage capacity of 24.1 t C/ha for coconut trees would translate to a carbon storage value ~290 Mt for the

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mainstream crops. And this value would be considerably higher once sparsely planted coconuts are taken into consideration.

Given the diversity of the different coconut cropping systems around the world, estimates of the annual CO_2 sequestration performance of the crop can only be speculative. However, if the global standing storage value in the range of 300+ Mt carbon and the trees have average lifespans of 30-50 yrs, a rough estimate for the required carbon sequestration would be ~6-10 Mt/yr. These values are probably very conservative estimates, but they are nevertheless interesting in their similarity to the estimated CO_2 sequestration rates of ~10 Mt/yr each for global cocoa and coffee crops as discussed above.

5.5. Rubber

Rubber, *Hevea braziliensis*, is cultivated across the humid tropics, most notably in Asia and Africa, with Thailand, Indonesia, Vietnam, and Ivory Coast together accounting for roughly 70% of global production. Small stands of rubber are often present as part of mixed cropping by smallholders and the crop is grown worldwide on a mixture of smallholder and commercial plantations extending to a total area of ~10 Mha. For example, in Thailand 90% of rubber production is generated by 1.7 million smallholders that make up about 25% of households involved in agriculture (Rubber Authority of Thailand, 2024). Rubber trees can be grown in smallholdings and plantations in association with ground cover and intercropping including in sloping terrain, which has allowed for cultivation in upland areas. Crop yields vary widely from 0.3-2.2 t/ha according to the nature of the land, agronomy, management and quality of the germplasm, which varies from relatively unimproved stock to highly productive material generated by modern clonal propagation techniques. Globally traded natural rubber totals ~13.9 Mt/yr, with a value of ~$2k/t or $29 billion/yr. As with most of the other tropical crops discussed here, rubber production and prices have varied considerably over recent decades due to a combination of climatic and geopolitical factors (Moss et al, 2025). Examples of plantation and wild rubber trees are shown in Figure 10.

Rubber trees produce a mixture of polymerized isoprenoids in the form of a sticky white colloidal fluid called latex that can be harvested from incisions in the tree bark. Commercial rubber trees typically grow to 20-30m in height and are productive for between 25-35 yrs after an immature period of 7 yrs, meaning that the economic cycle of a plantation is around 30-40 yrs. The latex from wild rubber trees was used for purposes such as making waterproof containers and textiles by Mesoamerican cultures for thousands of years before the development of colonial commercial plantations, firstly in South America and later in Africa and Asia. Latex is processed into so-called natural rubber, which has a large range of uses in adhesives, cements, footwear, insulation, vehicle tires to mention just a few. However, in many cases it has been replaced by synthetic rubber derived from fossil carbon, which is cheaper to produce and for some applications has better performance properties, such as resistance to weathering, abrasion, salt water, and oxidation damage. Despite this, there is still a robust market for natural rubber and it now makes up ~48% of the total global rubber production of 29 My/yr (Statista, 2024).

Historically, most commercial rubber plantations were established on various forms of forested land in the tropics. These ranged from logged-over secondary forests to more pristine habitats, although even the latter were normally used for human activities such as hunting and gathering. By the 1930s natural rubber production peaked at over 1 Mt/yr, meaning that many plantations date back well over a century. More recently, Thailand and Indonesia have emerged as major global production centers and this led to increase use of tropical forest for conversion, which was mainly done by smallholders. Eventually this led to concerns in some importing countries, for example in Europe which implemented the EU Regulation on Deforestation-Free Products (EUDR), due to take effect in 2025-6.

The EUDR specifies that EU operators dealing in natural rubber and its derivatives, such as gloves and tires, must ensure these products are deforestation-free and legal in the country of production. In response, the Thai government has focused on areas that account for 64% of rubber

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cultivation that were mostly established on agricultural land previously used for fruit production. In the remaining 36% of the area the rubber crop was planted mainly on agricultural land originally used for cassava or sugar cane cultivation or paddy fields, but also in some logged-over forests (Rubber Authority of Thailand, 2024). The aim is to ensure that little or no deforestation occurs in the future and that any rubber products exported to the EU are compliant with EUDR, particularly with regard to traceability and the welfare of smallholder producers.

Figure 10. Rubber as a plantation crop and as wild trees in Indonesia. Upper panel: Rubber plantations tend to have less profuse canopies than many other tree crops but can support a varied groundcover. Lower panel: Left, helical channels are cut into the bark to tap the latex which is harvested as a milky white liquid. Right In the wild, rubber trees can attain heights of >40 meters which is double their typical height in plantations.

There is growing interest in the carbon sequestration potential of rubber crops although there are numerous uncertainties around the difficulties in compiling such estimates and their use for policy decisions. Among these challenges are estimates of carbon stock at different levels from individual plots up to entire landscapes (Blagodatsky et al, 2016). The same authors note that assessed C values sometimes miss out components such as latex, rubber wood and soil C. The use of clonal propagation has enabled the development of rubber germplasm capable of high rates of carbon sequestration that approach the capacity of secondary forests of a similar age. For example, progeny of rubber clones in Cameroon stored between 111-187 t C/ha/yr (Menoh et al, 2022), which was comparable with secondary forests rates of between 92-257 t C/ha/yr (Adingra et al, 2016). Even more impressive figures of total ecosystem C stock densities in the range of 93-376 t/ha were reported from plantations in SE Asia (Ziegler et al, 2012). In a further study from Thailand annual CO_2 sequestration values ranging from 28 to 43 t C/ha/yr were reported with an estimate that the average rubber plantation sequestered 24.9 t CO_2 for each tonne of latex produced (Satakhun et al, 2019).

In a recent literature review the average carbon stocks present in rubber plantations were estimated at between 30-100 t/ha C dry wt in contrast to estimates of 10-50 t/ha C dry wt in the case of secondary forests and ~300 t/ha C dry wt in the case of a dense mature undisturbed tropical forest (Tiko et al, 2025). As this review points out, rubber plantations are often managed by smallholders to protect livestock, limit erosion, and provide various non-timber forest products, in addition to their more recently recognized roles as C sinks that can mitigate GHG emissions and consequent climate change (Fox et al, 2014; Pinizzotto et al, 2021; Gitz et al, Gohet et al, 2022; Zou et al, 2022). There has also been considerable interest in the use of agroforestry and other eco-friendly strategies, such as landscape mosaics and wild fauna/flora corridors, to further amplify the already considerable potential for rubber crops to play significant roles in environmental remediation in addition to their roles as C sinks (Liu et al, 2020; Tiko et al,, 2025). Finally, as with many other high-biomass tropical crops, rubber is now being considered as a candidate in the context of generating carbon credits as an additional source of income to the crop product itself as discussed below in section 7. For example, a joint Japanese-Thai venture aims to use 4 Mha of *rubber* plantations as a profitable carbon credit generating scheme (Jackson et al, 2024; The Nation, 2024).

In conclusion, rubber crops are probably among the most effective in terms of their carbon sequestration potential. There are clearly many uncertainties about the exact range of values and these will vary anyway according to local conditions such as the land/soil structure, climate, and management effectiveness. However, if we accept a range of 30 to 40 t C/ha/yr as reported in Thailand, extrapolation over the global area of ~10 Mha would generate CO_2 sequestration rates of 300-400 Mt/yr. Even if this value is drastically reduced to account for poorer yields in some regions, the global sequestration rate for rubber is likely to be in the region of >100-200 Mt/yr. As noted above, this is considerably in excess of the ~10 Mt/yr sequestration rate for each of the three tree crops discussed previously, namely cocoa, coffee, and coconut. The total CO_2 sequestration rate for these four crops alone is likely to be above 200 Mt/yr and could be much higher. In the next sub-section we will consider the final tree crop, oil palm, which is reportedly even more effective in terms of CO_2 sequestration.

5.6. Oil Palm

The African oil palm, *Elaeis guineensis*, is the most important vegetable oil crop, supplying 40% of global traded oil consumed by over two billion people [Solidaridad, 2025]. The crop is also the most widely grown of the six examples of tropical perennial crops discussed here. It occupies a total land area of 23 Mha from which it generates an annual production is 80 Mt oil that is exported

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worldwide in a market valued at an annual $77 billion. Although the crop is widely grown across the humid tropics of Africa and the Americas, 85% of global production occurs in Indonesia and Malaysia. One of the emerging centers of cultivation is Colombia where 2 Mha of former poor quality cropland is now used, including land formerly used for illicit coca production [Southey, 2022], and see also the lower panel in Figure 11. Over 80% of the global crop is used for edible purposes, plus 20% used for oleochemicals, pharmaceutical and health care products, and liquid biofuels while other parts of the crop have many other uses including as lumber, furniture, biochar, bioplastics, livestock feed, and even propellants [Abdul Rahim et al, 2024].

Oil palm is cultivated either on large commercial plantations, often run by multinational corporations employing a paid labor force or, alternatively, on small (<5 ha) typically family-run smallholdings [Murphy et al, 2021]. In Indonesia, which is the major global center of oil palm cultivation, 2.7 million smallholders manage 6.7 Mha or 41% of the total oil palm area in the country. On these smallholdings, vegetable plots and livestock often coexist with the oil palm trees, with some farmers also benefiting from additional understory cash crops, such as pineapple, banana, and tapioca, that are planted amongst the palm trees [Ariesca et al, 2023]. Commercial plantations are responsible for the vast majority of the exported palm oil products and tend to be managed as intensive monocultures, although ground-cover vegetation such as legumes can be grown for the first few years after planting when the young trees are still relatively short.

Mature oil palms grow as tall perennial trees that can reach over 10 meters in height and are able to store an annual 2.5 t/ha carbon during their productive lifetime of about 25 to 30 years, after which the old trees are felled for replanting with new seedlings. This level of primary productivity is comparable to and can even sometimes exceed that of some tropical forests (Henson, 1999; 2017; Lamade & Bouillet, 2005; Henson et al, 2012a; 2012b; Pulhin *et al*, 2014; Cheah *et al*, 2015; Daud *et al*, 2019; Uning *et al*, 2020; Alcock *et al*, 2022; Murphy, 2024b; Murphy et al, 2025). The average net CO_2 uptake of a typical oil palm plantation is 23 t/ha/yr and extrapolated over the global crop area of 23 Mha this comes to a total carbon sequestration figure of 529 Mt/y. In addition to carbon stored in the trees themselves, oil palm plantations can store 70-87 t C /ha sequestered organic carbon in the soil at depths of 20-60 cm (Brindis-Santos et al, 2021). Soil organic carbon (SOC) is higher by 16–27% in oil palm plantations compared with pastureland (Goodrick et al, 2015).

The incorporation of fallen biomass from oil palm plants acts as an organic input providing favorable conditions for soil health as evidenced by the increased amount of SOC in areas under plants that receive the largest amounts of organic residues. In other studies with different cropping systems, subsoil layers at >30 cm depth have been found to be important reservoirs of long-term sequestered carbon that can be thousands of years old (Button et al, 2022). However, the composition and age of subsoils in oil palm plantations has been little studied and could represent a hitherto unrecognized element in their capacity to store carbon. There is growing interest in adapting intensive commercial oil palm monocultures to various agroforestry systems (Rahmani et al, 2021, Rival et al, 2025). However, introduction of long-cycle food crops into newly established monocrop palm plantations has been associated with delayed production and a decrease in palm yields over the longer term (Rafflegeau et al, 2010; Koussihouèdé et al, 2020; Masure et al, 2023).

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Figure 11. Oil Palm cropping systems. Upper panel: Intercropped oil palms in Colombia. Mid panels: Left, Oil palms planted on previously low-quality rice land in Colombia Right, Large-scale commercial plantation in Malaysia. Lower panels: Left, Use of livestock for fruit transport. Right, Some oil palm plantations in Colombia were established on poor farmland previously used to grow coca for the drug trade and growers still use armed guards for security.

Despite these reservations, it is possible that agroforestry could still be used in some circumstances as part of a wider effort to increase the environmental credentials of oil palm crops (Khasanah et al, 2020; Ahirwal et al 2022; Messier et al, 2022; Zemp et al, 2023; Deines et al, 2024). For example, it was recently reported that agroforestry schemes are underway with species such as *Coffea liberica* and *Shorea balangeran*. This trial is proceeding in threatened peatland ecosystems as a way of enhancing the carbon footprint and economic value while also limiting forest conversion (Frianto *et al*, 2024). Another recent initiative is the TRAILS multidisciplinary approach involving mixed tree plantations, interplanted rows, and forest islands (Rival et al, 2025). In the latter case, oil palm intercropped with other trees within the forest zone can be sufficient to meet the threshold definition of a *bona fide* forest. Example tree species planted on an existing eight-year oil palm plantation include jengkol or dog fruit *(Archidendron pauciflorum)*, petai *(Parkia speciosa)*, durian *(Durio zibethinus)*, sungkai *(Peronema canescens)*, meranti *(Shorea leprosula)*, and jelutong *(Dyera lowii)*.

Oil palm yields and sequestration potential vary considerably according to factors such as plantation age and efficiency of agronomic and management practices (Woittiez et al, 2017; Monzon et al, 2023). For example, the latest data from Statista shows a global average oil yield of 3.3 t/ha whereas some plantations report yields in the region of 6.3 t/ha in Malaysia and 5.4 t/ha in Indonesia (Salim et al, 2024) and new breeding lines, with a claimed 9.9 t/ha are scheduled for large-scale production in 2025 (SD Guthrie, 2023). This means that the use of the latest breeding materials, alongside some considerable management improvements and more imaginative use of systems such as agroforestry could hugely increase the already impressive performance of oil palm crops in terms of carbon sequestration potential. Other examples of strategies for yield improvements by both smallholders and commercial growers include reducing the harvest cycle length from 19.6 to 8.3 days (Escallón-Barrios et al, 2020) and measures such as more effective weed management, pruning, nutrient application and using appropriate harvesting criteria such as the amount of loose fruits instead of bunch color (Lee et al, 2014; Mohanaraj Dono et al, 2016; Monzon et al, 2023) Innovative new ideas for 'smart' oil palm mills have also been advanced (Isaac et al, 2019), as well as the use of digital blockchain technologies to enhance the performance and transparency of supply chains (Keong et al, 2019).

To summarize, there is a great deal of unrealized potential for significant increases in oil palm crop yields already feasible simply by management improvements with a possible trebling to 10 t/ha in the medium term using a combination of best practices and superior breeding lines. As a perennial tree species with a 25-30 yr growing cycle, oil palm has a very high capacity to sequester atmospheric CO_2 and, in addition to its oil-rich fruits, it produces large quantities of useful lignified biomass with a total carbon sequestration figure that is possibly in excess of 529 Mt/yr. The use of improved high-yield germplasm and better agronomic and management methods could easily increase the global performance of the crop by several-fold and while such improvements would not all be translated into higher rates of carbon sequestration it is possible to envisage figures in the range of 900-1000 Mt/yr C. Finally, a recent remote sensing study concludes that there may be as much as 6-7 Mha of hitherto unreported oil palm cultivation adjacent to village smallholdings in Africa (Descals et al, 2025). Although these findings have yet to be confirmed, they imply the presence of substantial areas of undocumented oil palm cropland. This raises the possibility that the total land use, and hence the overall carbon sequestration capacity, of other tropical tree crops might also have been similarly underestimated.

6. The Potential of Selected Non-Tropical Perennial Crops

Although the tropics are by far the most productive global region in terms of plant photosynthesis and hence carbon sequestration, the 1,200 Mha of tropical forest only accounts for 8% of total land area. In terms of land coverage, the temperate and boreal regions have a greater overall surface area covering 23% of total land area. While the vegetation growth in such biomes is restricted compared to the tropics due to cool, light-poor winter seasons the longer days during their productive summers can result in impressive rates of carbon sequestration during their main growth phase. Temperate and boreal forests are mainly found in the northern hemisphere and some of these regions are used to cultivate commercial forestry crops for applications such as lumber, construction materials, and paper manufacture. Apart from such forestry crops, the vast majority of arable agriculture in temperate zones is dedicated to short-lived annual crops, such as wheat, maize and oilseeds, while an even greater land area is dedicated to grassy pasture for livestock. In both of these cases there is only a small potential for useful levels of carbon sequestration and even this cannot occur during the cooler seasons when much of the photosynthesis ceases.

Unfortunately, there are a relatively few non-tropical woody perennial crops that have been studied in detail in terms of their possible contribution to a net reduction of atmospheric CO_2 levels. In this section two arable crops, olive and grapes, will be considered as well as a brief survey of the principal temperate/boreal natural forestry and forest-cropping systems. In all three cases significant changes in the locations of these crops are predicted as a result of climate change, some of which is already underway. Hence, the optimal cultivation zones of these crops grown in the northern hemisphere are likely to move several hundred km northwards. In the case of olives and grapes this is unlikely to impact significantly on carbon sequestration potential, although unrelated agronomic changes are likely to reduce their sequestration potential. However, the extensive expansion of temperate/boreal forestry systems is predicted to result in much higher carbon sequestration although, as we will see, whether this will be sufficient to offset a predicted decline in tropical forest carbon storage remains unresolved [Bastin et al, 2019; Walker et al, 2022].

6.1. Olives

Olive trees, *Olea europaea*, are native to the Mediterranean region, but are now grown globally on ~10 Mha with an annual yield of ~3.3 Mt oil and 2.6 Mt table olives. The olive fruits are harvested once a year with the most valuable product being the best intact fruits that are processed into table olives while the remainder of the fruits are pressed to extract the oil. Table olives are often irrigated to produce a larger pulp to pit ratio and a lower oil content at 10-12% FW, while high-oil varieties have smaller fruits with an oil content of <25-30% FW. The trees are relatively short with compact foliage, typically 8–15 m in height, with some ancient specimens having rootstocks aged over 4,000 yrs, although modern commercial crops have much shorter economic lifespans in the range of 20-40 yrs. It is estimated that in Europe olive groves can store ~0.22 Gt CO_2-eq while standing trees potentially sequester ~0.03 Gt CO_2-eq/yr in soils, leading to a total annual sequestration potential for traditional long-lived trees of 0.22 Gt CO_2 (Galán-Martín et al, 2022; 2024). However, as noted below, much of the olive industry is now moving towards new short-lived, intensively managed systems that will have much lower sequestration potentials. Examples of traditional and modern olive cropping systems are shown in Figure 12 where it is clear that despite increase foliage density there is far less woody biomass in the modern intensive system.

Figure 12. Comparison of traditional and modern olive cropping systems. Upper panel: Traditional extensive cultivation of olive trees in Greece. Lower panel: Modern cultivation of 'superintensive' hedge-like plants in Spain.

During recent decades global olive cultivation has been altered drastically from the situation prior to 1991 when 92% of olive groves in a global area of 7.1 Mha were made up of traditional tree varieties. In contrast, more than half of the commercial olive crop is now grown a completely new landscape dominated by intensively managed high-yield cultivars. By 2041 it is predicted that the global area will be 14 Mha, of which only 39% will be traditional varieties, and that oil production will have risen to 4.4 Mt [Dawson et al, 2021; Rosatti et al, 2024]. The emerging picture is of a crop dominated by so-called 'intensive' and 'super-intensive' varieties with high input requirements and increasing levels of mechanization. In the 'intensive' systems, rows are planted 6m x 3-6m with drip irrigation and have a lifespan of <40 yrs with fruits harvested using vibrating machines. The 'super-intensive' plants grow as irrigated hedges of <4m tall trees in 4m x 1-2m rows that have a much shorter lifespan of 13-20 yr.

These trees grow rapidly with a high yield but suffer from stresses, including pests and diseases, that reduce their lifespan. On the plus side, crop densities of >1,500-2,000 trees/ha can be achieved, in contrast to an average of 300 trees/ha in traditional systems. Greater branching also increases resources by increasing biomass partitioning into leaves (i.e. the photosynthetic organs), relative to wood. While this will increase rates of carbon sequestration and harvest index (HI), it also results in a reduction in long-term woody and soil biomass [Rosatti et al, 2024]. The HI of such intensive olive systems is therefore very high at 77-80% and greatly exceeds that of traditional varieties, but the drawback is that they are much further removed from the HI of forest trees, which is typically below 20%. Hence, while modern olive cropping systems are very efficient at delivering high fruit yields, they are less useful in delivering high rates of carbon sequestration, particularly in comparison with the tropical crops discussed above in section 5. Another issue that will impact olive cultivation is the effects of climate change where the major crop centers in the Mediterranean basin are already being adversely affected by increasing periods of drought that are especially damaging to the new water-hungry intensive varieties (Dawson et al, 2021; Rosatti et al, 2024).

6.2. Grapes

Grapes, *Vitis vinifera*, are native to the Mediterranean region, but are now grown globally on 7.3 Mha with a gross annual yield of 80 Mt grapes. The main products from grapes are wine, table grapes used as edible dessert fruits, and dried grapes that include sultanas, raisins, and currents. Global consumption of these products is as follows: 34 Mt grapes used to make 28 billion liters of wine, musts and juices; 31.5 Mt of table grapes; and 5.7 Mt grapes used to make 1.4 Mt dried fruit (OIV, 2022). In terms of land area, the major grape-producing countries are Spain, France, China, and Italy with 45% global area, while in terms of wine production the major countries are Spain, France, and Italy with 48% of the global total. The major producers of table grapes are China, Turkey, and India with this market increasing substantially since 2000 while wine markets have remained largely static, albeit with significant short term fluctuations. Grape vines are perennial plants that have a commercial lifespan of 25-30 yrs, although in semi-arid areas they can still be productive but low-yielding after well over 100 yrs. However, unlike, olives, grape vines are deciduous and lose their foliage to become dormant for the six cooler months of each annual season meaning that they are only photosynthetically active for the warmer half of each year.

Grape vines are typically trained to grow up to a height of about 1.8 m on trellises from which the foliage and fruits hang down for about 1.0 m. Given the rather modest amount of woody biomass present in grape vines and the fact that they are more akin to annual than perennial plants in only having a six-month growing season, it is not surprising that these crops are less productive than the tropical crops discussed above in section 5. However, vineyard agroecosystems have been reported to be net C sinks, albeit to widely varying extents ranging from an annual 0.7-9.0 t C/ha (Marras et al, 2015; Venedrame et al, 2019; Chiriaco et al, 2019; Callesen et al, 2023) as recently reviewed by Xue et al, [2024]. These values are less than most temperate forests and some orchards, primarily due to the small amount of biomass in grape crops, although there was a surprising quantity of long-term carbon present in the soil that in one case accounted for >75% of C storage (Callesen et al, 2023).

6.3. Temperate/Boreal Forestry Crops

Forested biomes are often associated with the tropics, but temperate forests are surprisingly widespread and in just three countries (Russia, Canada, and USA) they occupy 1470 Mha and make up 37% of total global forest area [FAO, 2020]. In terms of living tree biomass temperate and boreal regions make up 30% of the global total with 114 Gt C currently present but a potential total of 184 Gt C if conservation and restoration measure are implemented [Mo et al, 2023]. In boreal regions most of the forestry is owned by the state, except in the Nordic countries where small private and corporate forest owners dominate. Both uneven-aged and even-aged silvicultural systems can be used to produce commercial harvests, but systems can also be designed to meet a variety of other forest management objectives including wildlife conservation, water production, fire control, and biodiversity targets [Graham & Jain, 1998]. In the temperate forest zones, large-scale corporate forest operations are to be found mainly in North America and in the Southern Hemisphere and there are also more than 20 million small-scale private forest owners, some of which operate cropping systems on their forests.

According to the FAO, many small-scale forests contain mostly indigenous tree species while larger-scale forests are often stocked with rapidly-growing introduced species that are clear-felled on rotations of several decades before replanting [FAO, 2020]. Examples of introduced species include Sitka spruce; Norway spruce; Lodgepole pine; and Douglas fir in cooler regions of Europe and Radiata pine and Eucalypts in warmer Mediterranean biomes that include Chile and New Zealand where these have recently replaced native vegetation. Management on most of the larger commercial forests is highly mechanized with contractor harvesting by clear-felling of softwood stands while in some sensitive areas various types of selective harvesting systems are practised, both in coniferous and deciduous forests. Boreal forests are even more likely to be harvested by large-scale clear felling in batches of 25-100 ha. These are likely to be primary forests in the eastern boreal regions, i.e. Siberia, where exploitation is relatively recent, but are mostly 2nd and 3rd generation forests in more westerly boreal regions such as Scandinavia and Canada where exploitation has been underway for much longer. In many cases the felled boreal forests are left to regenerate naturally although more recently deliberate planting of improved seed varieties has been used. Both natural and commercial forests in temperate/boreal zones can play roles in enhanced carbon sequestration whether as monocultures or on agroforestry contexts [Lal et al, 2012; Nair et al, 2012].

A relatively recent development that affects all forestry systems is climate change, which is predicted to have contrasting effects in tropical versus temperate/boreal regions [Bastin 2019]. This study found that warming is likely to increase tree cover in cold regions with low tree cover, such as in northern boreal regions like Siberia, whereas their model showed a high probability of consistent declines of tropical forests with high tree cover. Because the average tree cover of 30-40% in what would be an expanding boreal region is lower than the 90-100% cover in the declining tropical regions their evaluation suggests that the potential global canopy cover will decrease under future climate scenarios, even if there is a larger total forested area with >10% tree cover. The prediction is that boreal canopy cover will increase by ~130 Mha with further increases of 30 Mha each in temperate, montane, and desertic biomes, giving a total increase in forest area of ~250 Mha in these cooler regions of the world. While this might be positive for such regions, the bad news is that the models also predict a potential ~450 Mha loss of forest habitat in tropical regions, which would produce a net global loss of 223 Mha of canopy cover by 2050, corresponding to a reduction of 46 Gt in sequestered carbon [Bastin 2019]. However the effects of future climate change on global forest biomass remains highly uncertain and another report came to a rather different conclusion with a predicted potential for an overall 17% increase in global carbon stored in woody biomass by 2050 despite a 12% decrease in the topics [Walker et al, 2022].

7. The Roles of Carbon Trading Schemes

Carbon trading schemes, also called Emissions Trading Systems (ETS), are designed to encourage the net removal of CO_2 (and sometimes other GHGs) from the atmosphere either by preventing their release in the first place or by sequestration of already emitted gases. The scheme typically use a quota system to enable entities (companies or other organizations) to engage in trading aimed at encouraging a net reduction of CO_2 over time. To give a very general example, an entity that is producing more carbon emissions than are permitted by its quota can purchase the right to carry on with its surplus from another entity that is producing fewer emissions than its quota. In the case of the EU this could involve one of the >10,000 company power stations or factories that are part of the Emissions Trading System and each of which is assigned an annual quota of CO_2 emissions units where excess units must be offset by purchasing unused units from another member of the scheme [MET, 2023]. The problem with such a scheme is that a well-funded company can simply buy offset units without tackling its own emissions surplus.

There are numerous carbon trading schemes, or ETSs, that are linked to carbon sequestration and/or emissions [ICAP, 2025]. In 2025, 38 global ETSs were in operation with 20 more in development in jurisdictions covering one third of the global population. Current ETSs account for 19% of all GHG emissions, amounting to 10 Gt CO_2e worldwide, with funding of $70 billion. In general, the operation of carbon credit markets has had a chequered past with several instances of fraud that have recently affected investor confidence. For example, in the context of carbon sequestration there is evidence that emission reductions from forest conservation have been overestimated and carbon offsets are failing to address climate mitigation [Jones et al, 2023; West et al, 2023]. A recent study found that out of 1 Gt CO_2e of assigned carbon credits, fewer than 16% of them involved real emissions reductions, resulting in a huge shortfall totalling no less than 840 Mt CO_2e [Probst et al, 2024]. This has led to calls for fundamental reform of carbon crediting mechanisms and poses uncomfortable questions for the entire system, as discussed at COP29 in 2024 [Greenfield et al, 2024; Probst et al, 2024].

In late 2024, a new set of carbon market rules were agreed at COP29 to a mixed reception, with many welcoming a new start after the scandals of the past [Greenfield et al, 2025; UNFCCC, 2025] while others were more cautious about whether the reforms will really be able to help developing countries benefit from funds to drive sustainability initiatives [Gagnon-Lebrun et al, 2024; Zheng, 2025]. In terms of a practical real-world example, it was reported that the global software company Microsoft had purchased carbon credits from Brazil in order to offset some its GHG emissions as part of its planned move towards a net zero operation [Economist, 2024b]. In this case, Microsoft has bought credits to remove <5 Mt of CO_2 carbon via reforestation, meaning that it was effectively funding several reforestation in Brazil to the tune of $10-20/t C in the new trees. The carbon credit price is predicted to rise to ~$30/t in 2030, and this price is already being used or exceeded in high-quality reforestation deals. According to calculations by the McKinsey Consultancy this could make it financially attractive to reforest roughly half of the pastureland in Brazil. It was also estimated that, in contrast to the $10-40 cost to sequester 1t of CO_2 by tree planting, the use of direct air capture and storage (DACS) would cost around $1,000, i.e. 40-100 times more expensive [Economist, 2024b]. This illustrates how the use of carbon trading can potentially unlock biological carbon sequestration to serve as a cheaper and more readily implemented approach than industrial schemes like DACS.

In another example, we can consider the use of tropical perennial crops as reforestation agents.

Restored Brazilian forests could account for 15% of the world's potential for carbon removal through reforestation and Indonesia might have a comparable potential. This raises the possibility of using high-yield commercial forests, such as oil palm plantations, within such a market. It would be necessary for oil palm plantations to be classified as forests for this purpose, but this already happens in Scandinavia where commercial tree plantations are judged to be forests and are allowed into carbon trading schemes despite the fact that they capture far less carbon than tropical tree crops. It is estimated that in order to reach the IPCC target of 5-10 Gt/yr by 2050, carbon-removal markets would be worth in excess of $200 billion which could make it an attractive prospect for investors.

The regulation of such markets is already improving with the deployment of new technologies such as satellite imagery and lidar–laser scans that build three-dimensional images to estimate carbon stocks and verifiably upload data to ensure transparency. Carbon trading schemes have recently been launched in the UK and other examples are being trialed in Vietnam, Brazil and Australia.

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Opportunities also exist for expanding Malaysia's role in voluntary carbon market either by reforestation of low-quality land and/or by increased oil palm cultivation that would also avoid adverse land-use conversion costs. Another innovation is the extension of the carbon credit concept to cover so-called biodiversity credits as recently proposed by the Global Biodiversity Framework [Antonelli et al, 2024].

We have recently proposed some targets for carbon credit utilization linked to both natural and crop-based landscapes in Malaysia as summarized below [Murphy et al, 2025].

- Utilize carbon offset mechanisms and carbon credits to incentivize sustainable practices across the entire value chain, enhancing environmental responsibility.
- Monetization Opportunities: Emphasise the improved potential for stakeholders, particularly smallholders, to monetize carbon credits, creating an additional income stream and supporting their economic viability.
- Integration with International Markets: Leverage the Voluntary Carbon Exchange to facilitate global trading of carbon credits, expanding Malaysia's role in the voluntary carbon market and increasing revenue from carbon credits.
- Wetland Agriculture: Promote practices that maintain elevated water tables in peatlands to support sustainable crop cultivation, which can generate carbon credits and physical products to provide income for farmers through sustainable peatland management.
- Forest Preservation Incentives: Incentivize preservation of tropical forests by highlighting the benefits of carbon credits, biodiversity protection, and sustainable tourism to counteract drivers of deforestation.
- Address challenges associated with accurately measuring carbon sequestration and emissions to ensure effective implementation and credibility of the carbon credit system. This links with the need for more accurate baseline emissions data and land-use conversion calculations as these will feed into the value of future carbon credits.

8. Conclusions

In order to address the climate crisis resulting from excessive releases of anthropogenic CO_2 an its accumulation in the atmosphere its is necessary to both limit any future emissions and also to remove or sequester the existing surplus CO_2 already present in the atmosphere.

Until the mass emission of anthropogenic CO_2 ,mainly from fossil fuel combustion, that started in the 1950s, biologically-based CO_2 sequestration broadly kept pace with emissions meaning that the global carbon cycle remained in balance an atmospheric CO_2 concentrations stayed close to historic levels of 300 ppm.

In order to reduce atmospheric CO_2 concentrations from levels that could reach >500 ppm by the end of the century it will be necessary to significantly increase CO_2 sequestration (also called carbon dioxide removal or CDR) in the near future.

Two contrasting approaches to CDR are (i) to increase biologically-based (conventional CDT) sequestration mainly via plants or (ii) to develop new industrially-based technologies (novel CDT) such as CCS and DAC.

The industrial approach is attractive especially if long-term storage solutions can be found to sequester captured carbon for many millennia. However, the current situation is that the novel CDR approaches remain at a very early stage of development that are only able to capture <0.1% of the CO_2 already removed by biological methods such as afforestation/reforestation and soil sequestration.

Other promising biological methods include the appropriate use of biomass and the more efficient use of woody perennial plants that include crops. The contribution of major tree crops, especially in the tropics, has been largely ignored. However, as discussed here, these crops could collectively sequester amounts exceeding 1 Gt/yr C, which is greatly in excess of the novel CDR methods and of the same order of magnitude as other biological methods.

The judicious use of carbon trading schemes (also called Emissions Trading Systems or ETSs) could help release funding by monetizing some of the biological CDR approaches where the cash cost of sequestered carbon could be 10-100-fold lower than that of the novel CDR approaches, most of which are currently funded by the fossil fuel sector.

Abbreviations

C, carbon, CDR, carbon dioxide removal; GHG, greenhouse gas; Gt, gigatonne (10^9); ha, hectare; m, meter; Mt, megatonne (10^6); LUC, land-use conversion; RPP, reductive pentose phosphate (cycle of CO_2 fixation); rubisco, ribulose bisphosphate carboxylase; SOC, soil organic carbon; Tt, teratonne (10^{12}),

Note that carbon mass (C) relates to the element itself, except when expressed as CO_2, which is 3.38 times the equivalent carbon mass or C_{eq}.

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