Review

Not peer-reviewed version

Carbon, Forests, and Biochar

Carlos Rodriguez Franco * , Deborah S. Page-Dumroese , Derek N. Pierson , Timothy Nicosia

Posted Date: 12 December 2023

doi: 10.20944/preprints202312.0785.v1

Keywords: climate change; sequestration; mitigation; reforestation

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 December 2023 doi:10.20944/preprints202312.0785.v1

Review

Carbon, Forests, and Biochar

Carlos Rodriguez Franco [a,*], Deborah S. Page-Dumroese [b], Derek Pierson [c] and Timothy Nicosia [d]

[a] U.S. Department of Agriculture, Forest Service, Washington Office. Research and Development 201, 14th Street, S.W., 2 NW Washington, DC 20250, USA; carlos.rodriguez-franco@usda.gov ORCID 0000-0002-3676-5844
[b] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1221 S. Main, Moscow, ID 83843, USA; debbie.dumroese@usda.gov ORCID 0000-0002-3095-7749
[c] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1221 S. Main, Moscow, ID 83843, USA; Derek.Pierson@usda.gov ORCID: 0000-0003-3413-1693
[d] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 240 West Prospect Road Fort Collins, CO 80526, USA; Timothy.Nicosia@usda.gov
* Correspondence: Carlos Rodriguez-Franco, USDA Forest Service, Research and Development. 201 14th Street, S.W., 2 NW Washington, DC 20250. USA. email: carlos.rodriguez-franco@usda.gov.

Abstract: Carbon (C) is one of the most abundant elements. It is part of all living organisms and is found in all states of matter (solid, liquid, gas, and plasma). It can take the form of one of the hardest and transparent materials (diamond) or it can be flexible and dark (graphite), with many carbonaceous materials at both extremes. In gaseous form, C is a component of several greenhouse gas emitted during the combustion of fossil fuels. Carbon movement between the atmosphere, land (biosphere and lithosphere), and ocean (hydrosphere) can alter total amounts in each pool. Human activities accelerate C movement into the atmosphere, causing increases in climate change. This shift from terrestrial and oceanic C pools to the atmosphere cause an increase in the intensity and duration of droughts, hurricanes, snowstorms, and other natural phenomenon. Although society hears about C emissions there is a lack of understanding of its importance and the need to decrease C in the atmospheric pool to avoid exacerbating climate change. Forests and biochar are two biological methods to retain C in the terrestrial pool for long time and at very low cost. This review details where C comes from, its relationship with forests, and biochar and their roles in increasing carbon sequestration to limit the impacts of climate change and continue having future sustainable forests and ecosystems services that we enjoy today.

Keywords: climate change; sequestration; mitigation; reforestation

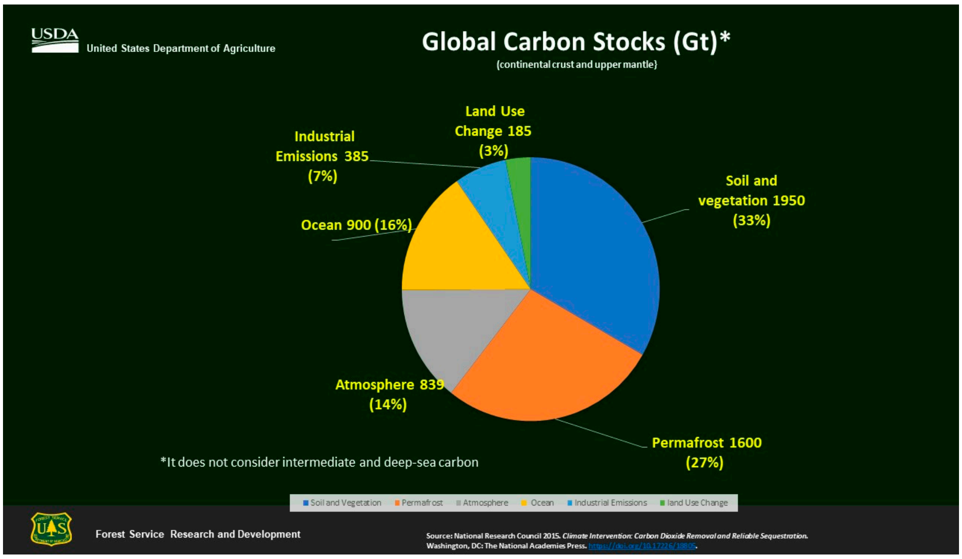
1. Introduction

Carbon (C) is one of the most common elements in the universe and on earth, is the fourth most abundant element by mass, and is the basic building block of humans, animals, plants, and soils. Carbon abundance in organic compounds and its polymers makes it the chemical foundation of all life. There are one million organic compounds containing only C and hydrogen (H). When a C atom combines with two oxygen (O) atoms it forms carbon dioxide (CO_2); one of the greenhouse gases (GHG) causing warming on earth and influencing climate change.

There is widespread recognition about climate change and the impacts on humans, plants, and animals. Increasing temperatures are linked to extreme environmental disturbances all over the world such as extreme droughts, hurricanes, snowstorms, and intense precipitation, among others. These disturbances cause environmental imbalances on forest ecosystems affecting their health, vigor, and productivity. Forest consequences are manifested as intense insect and diseases attacks, high tree mortality, and increases in extreme wildland fires with further negative effects on the soil and ecosystems services (e.g., erosion, water storage) and affecting rural communities. Further, changes in precipitation patterns may decrease soil organic C (SOC) pools, structural integrity, and nutrient cycles with adverse impacts on biomass productivity, biodiversity, and the environment (Lal, 2004).

The international Paris Agreement (2015) seeks to limit the increase in average global temperature to 2 °C with efforts to limit the increase to 1.5°C. However, there is a societal lack of awareness about the importance of C, its role in climate change, and the need to decrease atmospheric C. Controlling and mitigating CO_2 emissions are a priority for global economic development, but also for sustainable forests and soils. Forests and soils provide climate forcing feedbacks (Bonan, 2007) that help move C from atmospheric to terrestrial pools. One potential option to sequester atmospheric CO_2 is biological sequestration using the photosynthesis to remove atmospheric C and sequester it for several decades in living biomass and mass timber structures (Abed et al., 2022). Promoting photosynthesis of existing forest trees and through active forest management to increase forest ecosystem resilience through the decrease of competition between plants for growing space and its elements are among the methods available to reduce atmospheric CO_2. More options for biological C removal also could be achieved through afforestation, reforestation, and urban forestry. Moreover, utilizing forest residues from logging operations for different products like cross laminated timber, pulp for paper, wood pellets, biofuels, and biochar among others could enhance the opportunities to removal and long-term sequestration of C.

Benefits of C sequestration include the forests ability to store significant amounts of C both above and below-ground which makes it imperative to understand how humans alter C pools (Figure 1). Understanding the linkages among the various C pools and management can help reduce wildfire risk, increase water infiltration, retention, and availability, provide habitat for wildlife and other macro- and microorganisms, and sustain biodiversity.



Source: National Research Council 2015. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration.* Washington, DC: The National Academies Press. https://doi.org/10.17226/18805.

Figure 1. Global carbon stocks (Gt) in various pools. (National Research Council 2015).

Responsible and sustainable managed forests result in healthy forests with an increased resistance, resilience, and capacity to mitigate and adapt to the impacts of climate change increasing C sequestration, however, when forests are mismanaged forest degradation and deforestation occurs releasing up to 20 % of the global C emissions just because of deforestation (U.S. Forest Stewardship Council, 2023). Although, forests are not the whole solution, they are important for solving the climate change crisis together with other sustainable alternatives such as renewable energy. The objective of this systematic literature review is to highlight the importance of C, forests, and biochar including the benefits of C sequestration to decrease the impacts of climate change and promote sustainable forests and healthy soils into the future.

2. Importance of Carbon Dioxide

CO_2 importance resides in that its amount on earth atmosphere has been correlated with the increase on temperature causing global warming. Many studies have found this correlation through reconstruction studies of earth historical atmosphere characteristics using ice cores. The amount of CO_2 four billion years ago is unknown, but it is believed to have been as much as 100 times the current atmospheric level. This would have been necessary to keep earth's surface temperature above freezing, because of reduced solar luminosity (Kasting, 1984; Kasting, 1987). Although, Payne et al (2020) found out that the CO_2 constituted the atmosphere between 25 to 50 % almost three billion years ago. However, earth was not warmer, because of the presence of lower levels of N in comparison with current levels, which facilitated a global mean surface temperature low enough for glaciation to occur. The lowest CO_2 during eight glacial cycles concentration measured in an ice core covering the pre-industrial range of CO_2 concentrations during the late Quaternary (650,000 and 750,000 years before present) was by about 10 parts per million by volume (ppmv) to 172–300 (ppmv) (Luthi et al., 2008), and a study on atmospheric CO_2 concentrations measured on the Dome Concordia ice core found that before 430,000 years ago partial pressure of atmospheric CO_2 lies within the range of 260 and 180 ppmv showing that CO_2 was stable during six glacial cycles, and the relationship between CO_2 and Antarctic climate continued rather constant over this interval (Urs et al., 2005).

Since the beginning of industrialization, the amount of atmospheric CO_2 has progressively increased from ~280 parts per million by volume (ppmv) to ~368 ppmv in 2001 (Monnin et al., 2001). During the last 800 thousand years, atmospheric CO_2 ranged from a high during the interglacial period of around 300 ppm for CO_2, 800 ppb methane (CH_4) and 300 ppb nitrous oxide (N_2O) to a minimum during glacial periods of approximately 180 ppm CO_2, 350 ppb CH_4, and 200 ppb N_20. In 2011, measurements of ice cores revealed that GHG concentrations 390.5 ppm $C0_2$, 1803 ppb CH_4, and 324 ppm N_20; exceeding the range of measurements for the past 800 thousand years over (Masson-Delmotte et al., 2013). From the middle Miocene to Pleistocene, global CO_2 levels declined by more than 50 ppmv suggesting that when CO_2 concentrations decrease temperatures also decrease (Wang et al. 2015, Rae et al., 2021).

The importance of CO_2 has been reinforced by a study done by Dumitru et al (2019) that has been used as a proxy of the increase of temperature, because of the increase of CO_2 levels, which were similar to the current ones. They found out that during an interval of the Late Pliocene (3.264 to 3.025 Ma), known as the mid-Piacenzian warm period, atmospheric CO_2 concentrations were comparable to present-day values (~400 ppm), and estimated global mean temperatures were elevated by 2–3 °C relative to the pre-industrial period.

3. The Carbon Cycle

The amount of carbon on earth has not changed, as it was millions of years ago (British Geological Survey, 2023). The hydrosphere on earth was formed 4 billion years ago from water vapor condensation, resulting in oceans of water in which sedimentation occurred, where the most important characteristic of that ancient environment was the absence of free oxygen (Poderoso, 2016). Earth's earliest atmosphere must have been a mixture of the primordial gases because H is the most abundant element in the solar system, it is believed that the most abundant forms of its components like methane, ammonia, and water vapor, and neon, were also the main elements of the initial atmosphere of earth (Hayes, 2020).

Analysis of the oldest rocks on earth indicated that there are water-laid sediments with an age of 3.8 billion years containing organic carbon (OC) and carbonate minerals, in addition there were found microfossils and other sedimentary features that demonstrate convincingly that life had arisen on earth by that time, providing an indication that living organisms started the global carbon cycle from that time onward based on the distribution carbon-12 and carbon-13. The evidence of the presence of sedimentary carbonates indicated the presence of CO_2 in the earth's atmosphere at that time (Hayes, 2020).

In all forms (gas, liquid, solid) C is stored (sink) or released (source) through respiration of living organisms and by human activity primarily when fossil fuels are burned and matter transformations

doi:10.20944/preprints202312.0785.v1

occur (Bowyer et al., 2012). Movement from one C form and one C pool to another occurs when C is transformed (e.g., calcium carbonate ($CaCO_3$), dolomite ($CaMg(CO_3)_2$),bicarbonate (HCO_3), carbonate ion ($CO3^{2-}$), CO_2, methane CH_4, and formaldehyde $(CH_2O)_n$ (Dong et al., 2021). Each C pool has varying amounts of organic and inorganic C. Residence time of C in each pool also varies from years to centuries.

The lithosphere with 10^{23} g C, is the largest reservoir with the C contained in sedimentary rocks as carbonate minerals ($CaCO_3$, $CaMgCO_3$, and $FeCO_3$) and fossil fuels, which are organic compounds (oil, natural gas, and coal). Slow geological processes like weathering, vulcanism, diagenesis and sedimentation transfer the lithosphere's C to other reservoirs on a timescale of millions of years and the C is considered inactive.

Active C reservoirs contain approximately 43×10^{18} g of C, which is separated between the atmosphere with 750×10^{15} g C, the terrestrial biosphere with 2190×10^{15} g C, and the ocean with 39973×10^{15} g C. The amount of C on active carbon reservoirs is maintained in near steady state by slow geological processes, but rapid biogeochemical processes can result in the redistribution among the pools (*e.g.*, C from fossil fuels (inactive) added to the biologically active reservoirs during combustion) (Carlson et al., 2001).

In addition to geological processes C is assimilated into vegetation through photosynthesis and released through respiration. Animals, fires (wild, and prescribed) and fossil fuels also release C to the atmosphere. Another factor affecting the C cycle is that it is generally 50% of the dry weight of living organisms. Further, in the ocean sink there is passive absorption of CO_2 and associated dissolution, mixing C from algae and animal biomass, and dissolved CO_2 and carbon-containing plant and animal matter. When atmospheric C pools increase, particularly with CO_2 and CH_4, then these GHGs increase global temperature (Houghton, 2003; Hannah, 2011).

The degree that GHGs affect the climate is dependent on how much heat that particular gas absorbs and reradiates (Stephenson (2021). The atmosphere naturally contains GHGs, but they are increased by human activities. The most influential GHGs on the global warming potential (GWP) are H_2O vapor, CO_2, nitrous oxide (N_2O), CH_4 and ozone (O_3). Methane (23x) and N_2O (296x) have greater potential than CO_2 to increase earth's temperature. In the absence of a natural greenhouse effect, the heat emitted by the earth would go directly into space and the earth's average surface temperature of 14°C would be as low as -18°C (Stephenson 2021). Global atmospheric CO_2 concentrations are greater than 400 ppm and the magnitude of climate change beyond the next few decades will depend on the amount of GHGs (especially CO_2) emitted globally (U.S. Global Change Research Program, 2017). Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less. NOAA (2023) pointed out that in 2022 global average atmospheric carbon dioxide was 417.06 ppm, setting a new record high. Based on current assessment global atmospheric carbon was at 424 ppm in May 2023 (NOAA, 2023). In addition, NOAA (2023) point out that since the 1950s annual emissions from burning fossil fuels have increased every decade, from close to 11 billion tons of CO_2/yr. in the 1960s to an estimated 36.6 billion tons of CO_2 in 2022.

One way to reduce atmospheric C is through carbon sequestration using a variety of methods to store C in the other C pools , such as trees, soils, oceans, and underground geologic formations. One form of C sequestration involves removing the CO_2 from the atmosphere, primarily through biological means. This is also referred to as enhancing natural sinks (Herzog, 2015).

4. Forests

Forests in the world account for 92% of all terrestrial biomass globally, storing approximately 400 Gt of C (Kayleret al. 2017). They are a large C sink, and they absorb a large portion of anthropogenic CO_2 emissions (Pugh et al. 2019). This is an ecosystem service with both social and economic value as they can help limit climate warming (Grassi et al., 2017). Forests are estimated to cover 4.5 billion ha and equals approximately 31 % of the earth's total land area (Birdsey and Pan, 2015; Keenan et al., 2015; Bastin et al., 2017). Tropical forests are 45% of the total area, followed by the boreal forests with 27%, temperate forests with 16% and subtropical with 11% (FAO, 2020).

Forests are an important means of capturing large amounts of C at low cost, because carbon can be sequestered through the growth of trees (Woodall, 2015), especially when compared to other C sequestration options such as geologic sequestration. Globally, soils store two-to-three times as much C in organic form as C in the atmosphere and soil stocks exceed those in plants in most climatic regions (Scharlemann et al., 2014). The manner and intensity in which forests are managed can influence both above and belowground C stocks (Jandl et al., 2007; Noormets et al., 2015). With the goal of increasing both soil and vegetation C stocks, we examine management practices that can lead to increased C.

In the case of forest management, the sustainability and long-term capacity of forest ecosystems to capture and store carbon depends in large part on their health, productivity, resilience, and adaptive capacity. Forest ecosystems are dynamic, and are affected by multi-year droughts, insect and disease epidemics, wildfires, and catastrophic storms, and human activity. For example, storing carbon in overly dense forests that remain unthinned increases the risk of losing the carbon through fire and decomposition of fire-killed trees following large wildfires, as well as affecting the vegetation dynamics and influencing the future forest vegetation composition. Dense unthinned stands are less vigorous and more susceptible to insect attack (this has been largely documented in the text of vegetation dynamics by Chadwick and Larson (1996).

Traditionally forest management was focused in optimizing volume harvested per surface unit. In the case of carbon, the same approach can be taken, and therefore, optimizing, not maximizing, carbon capture in forest ecosystems can be a sustainable, long-term solution for responding to climate change to sustain other forest ecosystem services. Forest ecosystems capable of adapting to changing conditions will capture carbon and store it more securely over the long term, while also furnishing woody materials to help reduce fossil fuel use when one the uses is for producing bioenergy (Janowiak et. al., 2017).

Natural disturbances, especially wildfire and insects, threaten resource sustainability and increasingly disrupt our nation’s ability to implement management programs. Land management programs that restore forests to healthy and productive conditions will help ensure the long-term maintenance and transformation of forest carbon stocks. Forest management activities play a critical role in ensuring that forests remain a net carbon sink. The Forest management response on the ground is already happening in a threefold approach: adaptation, mitigation and restoration of forest ecosystems conditioning and repairing the key functions of ecosystems across landscapes and increasing their resilience to withstand the stresses and uncertainties associated with extreme changing climatic patterns.

According to the National Academy of Sciences (2019), fossil fuel consumption, agriculture, land-use change, and cement production are the dominant anthropogenic sources of CO_2 to the atmosphere. The focus of climate mitigation is to reduce energy sector emissions by 80-100 percent, requiring massive deployment of low-carbon technologies between now and 2050. Some examples of adaptation and mitigation actions that can be implemented are restoring healthy, resilient forest and grassland ecosystems and actively managing carbon stocks in forests, grasslands, and urban areas over time by doing the following:

- Manage stand density to decrease stocking of forests to decrease competition for growing elements and growing space as well as increase resilience to droughts, insects and disease attacks, help to decrease mortality and wildland fires intensity. less vulnerable to wildfire, pathogens, and insect attack.
- Controlling outbreaks of pests when they occur outside the norm.
- Restore forest ecosystems impacted by catastrophic disturbances such as wildland fires, hurricanes, and other disturbances, consistent with land management laws and regulations.
- Providing technical assistance for programs designed to enhance carbon sequestration potential through afforestation, reforestation, and practices that increase and maintain productivity and ecosystem health.

- Encouraging cities to retain green space and to plant and maintain trees.
- Using available tools to understand the impacts of management actions on carbon stocks and fluxes.

Overall, land use practices have the potential to alter the global distribution of C, contributing as much as 20% of global carbon emissions (Failey and Dilling, 2009). Deforestation is one activity that can increase atmospheric CO_2. Annual forest loss from 2010 to 2020 globally was 4.74 million ha per year (FAO, 2020), and the projected amount of CO_2 released by deforestation was estimated 3.9 billion tons per year in 2022.

The afforestation of degraded land can restore ecological functions and sequester atmospheric C. In addition to C sequestration, afforestation helps many communities restore a source of food and fiber while also supplying a source of firewood for cooking (Mahapatra and Schackleton, 2012). Afforestation on cropland may result in significant C stocks over 100 years (Bárcena et al., 2014) with ~15% increase in soil C stocks at the end of the first century (Nave et al., 2013). The main reason for the increase in soil C is the development of surface organic horizons, but mineral soil C sequestration can be high when broadleaved species are planted (Laganiere et al., 2010).

5. Biochar from Low-Value Woody Residues

To mitigate atmospheric GHGs and particularly CO2, sustainable harvesting can be coupled with biochar applications on forest, range, or agricultural lands. Biochar is a carbon-rich material formed by thermal decomposition at high-temperature (<700°C) of biomass under reduced oxygen conditions (Lehmann, and Joseph, 2009; Greco et al., 2019; Lefebvre, et al., 2023). When producing biochar from organic matter, the proportion of the amount of biomass transformed into carbon as total solid carbon in biochar varies from approximately 5% when using gasification technologies to approximately 35% when using slow pyrolysis technologies (McHenry, 2014). This carbonaceous material is added to the soil and is relatively stable for a long period of time (Blackwell et al., 2009). Biochar can improve soil physical, chemical, and biological properties while also reducing GHG emissions from the soil and stabilizing C pools (Wang et al., 2014). Using biochar to enhance or restore on- or near production site forest or adjacent degraded soils is one strategy that, when combined with various silvicultural treatments, can restore a variety of ecosystems services in addition to building the soil C stock. Biochar can improve water quality, bind heavy metals, or decrease toxic chemical concentrations, and improve soil health to establish sustainable plant cover, resulting in preventing soil erosion, leaching, or other unintended, negative environmental impacts (Rodriguez and Page-Dumroese, 2021). Biochar also has potential applications in waste management, renewable energy, C sequestration, GHG emission reduction, and soil and water remediation, as well as its potential for enhancing soil quality and agricultural crop productivity. In addition, C sequestered after biochar application, in combination with sustainable biomass production, can be C-negative and therefore used to actively remove CO_2 from the atmosphere, with potentially major implications to mitigate climate change (Lehmann and Joseph, 2015). Because biochar can last into the soil for many years due a large proportion of condensed aromatic C it can sequester C for many centuries (Ali et al., 2023). Biochar effects on soil health and the extent of ecosystem services depends on soil type, biochar type and application rate, and environmental parameters that affect plant productivity (Amonette et al., 2021).

Biochar production from low- or no-value woody residues can occur at a variety of scales that range from conservation burns to fixed bioenergy facilities. There are also forest management technologies to increase carbon sequestration. As noted previously, carbon retention and silvicultural practices that manage forest growing space to promote optimum vegetation growth increases aboveground C sequestration while the biochar increases belowground sequestration. For example, improved forest management can increase C sequestration from 0.03 to 1.6 Gt/y and afforestation and reforestation efforts can increase C sequestration in a range of 0.001 to 2.25 Gt/y CO_2 for the United States (NAS, 2019). Other C sequestration opportunities include combining bioenergy production with C capture and sequestration that can lead to net negative emissions as C stored by photosynthesizing biomass is sequestered rather than released to the atmosphere (NAS, 2019).

Large amounts of charcoal remain in soils today from , hundreds and thousands of years after they were abandoned. The total C storage is as high as 250 Mg C ha^{-1} m^{-1} compared to typical values of 100 Mg C ha^{-1} m^{-1} in Amazonian soils derived from similar parent material (Glaser et al., 2001). Globally, up to 12% of anthropogenic C emissions (0.21 Pg C) can be off-set annually in soil, if slash-and-burn is replaced by slash-and-char (Lehmann, et. al., 2006). In addition, these authors provide projections for the use of renewable fuels by 2100 and conclude that biochar sequestration could vary from 5.5 to 9.5 Pg C yr^{-1} if energy demand is met through pyrolysis, which would exceed current emissions from fossil fuels (5.4 Pg C yr^{-1}). In addition, Lefebvre et al. (2023) found that biochar plays an important role in global CO_2 removal; with a potential of 6.23 ± 0.24% of total GHG emissions removed in the 155 countries studied over a 100-year timeframe (base year 2020). They also pointed out that biochar could remove more than 10% of national emissions in 28 countries.

Biochar systems can generate heat, create negative C emissions, and sequester carbon. Biological C sequestration can be achieved through afforestation, changes to agricultural practices, soil carbon sequestration, application of biochar to soil, and the combination of biochar addition to soil and bioenergy with C capture and storage (BECCS) technology where biochar has moderate potential for delivering negative emissions estimated about 0.7 Gt Ce per year (National Academy of Sciences, 2018). In addition to its potential soil benefits, biochar, bio-oil, and bio-gas have also been studied for its potential climate change mitigation benefits.

6. Discussion

The combination of silvicultural prescriptions for wildfire risk reduction with biochar production and use at a variety of scales are promising methods to reduce atmospheric CO2. Consideration of promoting maximum vegetative cover and improved soil health to achieve healthy, productive, and resilient forest stands into the future. In addition, maintaining healthy forests creates growing conditions that will enhance forest ecosystem resistance to climate change impacts.

Dynamic land management considers cumulative effects across time and factors in risk, severity, scale, and likely outcome of disturbances. From 3 to 5 million km^2 per year are affected by landscape fires globally, emitting 2.2 Pg/yr. to the atmosphere, however a significant portion of the burned vegetation biomass remains as pyrogenic carbon. This pyrogenic C is accumulated in soils contributing to C sequestration; which has been estimated to be 12 % of the total C emissions from landscape fires in the world (Jones et al., 2019). According to Zheng et al (2023) boreal forests are being affected by fires, because of emerging warmer and drier fire seasons. Boreal fires normally account for 10 % of the global C emissions, but in 2021 they increased to 23 % (0.48 billion metric tons) of global emissions, being the highest increase on the last 21 years. A recent example was the 2023 Canadian wildfire that burned nearly 20 million hectares and resulted in a release of 290 megatons C from May to August. This represents over 25% of the global total for 2023 when reported in August (European Union, Atmosphere Monitoring Service, 2023). Therefore, sustainable C management involves effectively managing forest and soil C stocks by restoring, maintaining and enhancing health and productivity. This includes using management practices such as prescribed burning or other practices aimed to increase C sequestration or offset C emissions like taking into account forest products C, and when possible, considering the location, accessibility, established forest industry among other considerations to implement Climate smart actions.

The National Academy of Sciences (2018) and several other authors (Depro et.al., 2007; Ryan et. al., 2010; McKinley, et. al., 2011; Chadwick, et. al., 2014; and Janowiak et al., 2017) have pointed out that the strategies for managing forests, grasslands, and soils influence their ability to absorb carbon from the atmosphere and sequester carbon. These management options, include reforestation, afforestation (establishing a forest on land that had no previous tree cover), reducing deforestation, Climate smart forest management, using biomass as an energy source to substitute for fossil fuels, application of biochar to soil, reducing forage consumption by grazing, and employing practices that improve soil health.

Land management programs that restore forests to healthy and productive conditions will help ensure the long-term maintenance and transformation of forest carbon stocks. Ecosystems managed to adapt to changing conditions will capture carbon and store it more securely over the long term, and it will decrease the potential impact of wildfires or at least will change fire behavior decreasing its impact. However, like in the United States of America when silvicultural practices are applied for restoring forest stands not all trees removed have the required characteristics for the traditional forest industry, because of limitation in size and quality, especially when the trees come from salvage cuttings, they have limited use and value. This situation often leads to large piles of woody residues that are burned without the possibility of creating byproducts (Page-Dumroese et al. ,2017).

Biochar can be part of the solution when produced on- or near-site instead of leaving large piles of biomass that, under current open burning methods, increase C. Options for using biochar range from the local forest soil or abandoned mine lands or transported to agricultural sites with the associated benefits.

The main advantage of having active forest management in place will bring additional benefits to communities like sustainable ecosystems services and jobs generation and healthy forest industry, while also furnishing wood-based materials as biochar and others for many purposes such as renewable energy, biobased products and house constructions .

Biochar is another tool to sequester carbon on soil when used as a soil amendment for agricultural purposes, abandoned mine land and oil wells restoration, or putting back to the forest after disturbances. According to Grand View Research, Inc. (2019) the global biochar market is expected to reach USD $3 billion by 2025. The Grand View Research, Inc. (GVRI) report indicates that increasing consumption of organic food has been a major factor driving market growth, and the growing awareness regarding the advantages of biochar as soil amendment is further supplementing demand for the global market. Although, more recent assessments indicated that the global biochar market was valued at $1.654 billion in 2021 and is expected to reach $5.158 billion in 2030, growing with a compound annual growth rate (CAGR) of 13.53 % for the forecasted period (Inkwood Research, 2023). These studies show the potential importance of producing biochar for agricultural applications only.

7. Conclusions

- Better understanding of C importance, its management and relationship with forests and biological sequestration is needed to mitigate the impacts of climate change and support the adaptation of forest ecosystems to the changing climate conditions from now on.
- Biochar contribution to increase C sequestration as a soil amendment is part of the solution to promote heathy forests, that can enhance their C sequestration capability with Climate smart forest management, with additional benefits from sustainable ecosystems services on times of environmental change.

8. Future Directions

There is a need for increasing societal awareness about climate change, natural resources and their relationship with human life, and the benefits of preserving healthy forest ecosystems through active forest management. Biological C sequestration is a critically important tool to increase C storage utilizing the different technological alternatives for establishing and manipulating vegetation for enhancing C sequestration and the posterior utilization of byproducts that could keep that C out of the atmosphere as long as possible.

To achieve this goal, through forest management additional research is needed to identify the potential C sequestration options with the utilization of raw materials coming from forest management and processing mills, in addition to optimize forest operations, decrease transportation costs from the forest to the mill, and developing the markets for those products including biochar. Additionally, other studies are needed to develop a comprehensive overview of the potential for raw materials, locations, and time availability for planning purposes and complementing this information with an assessment of the current policies and regulations in place for identification of potential barriers that can be modified when designed streamlined process for operation of the whole supply chain.

In case of afforestation and reforestation there is a need of assessing the current possibilities of species survival established under current environmental conditions and assess the future environmental conditions for establishing of vegetation and assess if the current species will adapt to the new growing conditions and start to identify potential substitute species into the future that can continue their contribution to the C cycle and provide ecosystem services.

Author Contributions: Carlos Rodriguez Franco. Conceptualization, Methodology, and Writing Original draft. Deborah Page-Dumroese. Validation, Writing, Reviewing, and Editing.Derek Pierson. Validation, Writing, Reviewing, and Editing.Thimothy Nicosia. Writing, Reviewing, and Editing.

Funding: The USDA Forest Service supported this work.

Data Availability Statement: All data in the manuscript were previously published.

Acknowledgments: We are thankful to Dr. Thomas Schuler from Forest Service Research and Development, who conducted the policy review of this article

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer: The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

References

1. Abed, J., Rayburg, S., Rodwell, J. and Neave, M., 2022. A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability*, *14*(9), p.5570.
2. Ali, M. *et al.* (2023). Use of Biochar for Biological Carbon Sequestration. In: Jatoi, W.N., Mubeen, M., Hashmi, M.Z., Ali, S., Fahad, S., Mahmood, K. (eds) Climate Change Impacts on Agriculture. Springer, Cham. https://doi.org/10.1007/978-3-031-26692-8_23.
3. Amonette, E. J., Blanco-Canqui, H., Hassebrook, C., Laird, A.D., Lal, R., Lehmann, J. and Page-Dumroese, D. 2021. Journal of Soil and Water Conservation, January 2021, 76 (1) 24A-29A; DOI: https://doi.org/10.2489/jswc.2021.1115A
4. Blackwell, P., Riethmuller, G., Collins, M. 2009. Biochar application to soil. In: J. Lehmann, S. Joseph (Eds.), Biochar for Environmental Management: Science and Technology, Earthscan, London, United Kingdom (2009), pp. 207-226. https://www.taylorfrancis.com/books/edit/10.4324/9781849770552/biochar-environmental-management-johannes-lehmann-stephen-joseph
5. Bárcena, T.G., Kiær, Vesterdal, L., Stefánsdóttir, H., Gundersen, P., and Sigurdsson, B. 2014. Soil carbon stock change following afforestation in Northern Europe: a meta-analysis. Glob. Change Biol., 20 (2014), pp. 2393-2405. https://doi.org/10.1111/gcb.12576
6. Bastin JF, Berrahmouni N, Grainger A, Maniatis D, Mollicone D, Moore R, Patriarca C, Picard N, Sparrow B, Abraham EM, Aloui K, Atesoglu A, Attore F, Bassüllü Ç, Bey A, Garzuglia M, García-Montero LG, Groot N, Guerin G, Laestadius L, Lowe AJ, Mamane B, Marchi G, Patterson P, Rezende M, Ricci S, Salcedo I, Diaz AS, Stolle F, Surappaeva V, Castro R. The extent of forest in dryland biomes. Science. 2017 May 12;356(6338):635-638. https://doi.org/10.1126/science.aam6527. PMID: 28495750.
7. Birdsey, R., Pan, Y. 2015. Trends in management of the world's forests and impacts on carbon stocks For. Ecol. Manage., 355 (2015), pp. 83-90. https://doi.org/10.1016/j.foreco.2015.04.031
8. Bonan, G.B. 2007. Forests and climate change: Forcings, feedbacks, and the climate benefit of forests. Science. 320: 1444-1451.
9. Bowyer, J., Bratkovich, S., Frank, M., Howe, J., Stai, S., and Fernholz, K. 2012. Carbon 101: Understanding the carbon cycle and the forest carbon debate. Dovetail Partners, Inc., 13p. https://www.dovetailinc.org/upload/tmp/1581622918.pdf.
10. Chadwick, D.O, and Larson, B. 1996. Forest Stand Dynamics. John Wiley and Sons Inc. 520p.

doi:10.20944/preprints202312.0785.v1

11. Chadwick Dearing Oliver, Nedal T. Nassar, Bruce R. Lippke & James B. McCarter (2014) Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests, Journal of Sustainable Forestry, 33:3, 248-275, http://www.tandfonline.com/action/showCitFormats?doi=10.1080/10549811.2013.839386
12. Carlson, C.A., Bates, N.R., Hansell, D.A., and Steinberg, D.K. 2001. Carbon Cycle. In: Encyclopedia of Ocean Sciences (Second Edition), Editor(s): John H. Steele. Academic Press, 2001, Pages 477-486, ISBN 9780123744739. https://doi.org/10.1016/B978-012374473-9.00272-1
13. Depro, B.M., Brian C. Murray, B.C., Ralph J. Alig, R.J., and Shanks, A. 2007. Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands. Forest Ecology and Management 255 (2008) 1122–1134. https://www.fs.fed.us/pnw/pubs/journals/pnw_2008_depro001.pdf
14. Dong, Y., Cui, Y., Wang, J., Chen, H., Zhang, F., Wu, Y., Li, Z., Zhu, P., and hijun Jiang, S. 2021. Paleozoic carbon cycle dynamics: Insights from stable carbon isotopes in marine carbonates and C3 land plants. Earth-Science Reviews, Volume 222, 2021, 103813, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2021.103813.
15. Dumitru, O.A., Austermann, J., Polyak, V.J. *et al.* 2019. Constraints on global mean sea level during Pliocene warmth. *Nature* 574, 233–236 (2019). https://doi.org/10.1038/s41586-019-1543-2.
16. European Union, Atmosphere Monitoring Service. 2023. A record-breaking boreal wildfire season. A record-breaking boreal wildfire season | Copernicus (Accessed November 15, 2023).
17. Failey, E.L., and Dilling, L. 2010. Carbon stewardship: land management decisions and the potential for carbon sequestration in Colorado, USA. Environ. Res. Lett. 5 (2010) 024005 (7pp). doi:10.1088/1748-9326/5/2/024005
18. FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en.
19. Glaser, B., Haumaier, L., Guggenberger, G. and Zech, W.: 2001, 'The Terra Preta phenomenon – A model for sustainable agriculture in the humid tropics', *aturwissenschaften* 88, 37–41. https://doi.org/10.1007/s001140000193.
20. Grand View Research, Inc. 2019. Biochar Market Size, Share & Trend Analysis By Technology (Pyrolysis, Gasification, Others), By Application (Agriculture (Farming, Livestock) By Region & Segment Forecasts, 2012 – 2025. https://www.grandviewresearch.com/industry-analysis/biochar-market (accessed 05/21/2018)
21. Grassi, G., House, J., Dentener, F. *et al.* The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Clim Change* **7**, 220–226 (2017). https://doi.org/10.1038/nclimate3227
22. Greco, G., B. Gonzalez, and J.J. Manya. 2019. Operating conditions affecting char yield and its potential stability during slow pyrolysis of biomass: A review. *In* Advanced Carbon Materials from Biomass: An Overview, ed. J.J. Manyà. GreenCarbon Project and Consortium. http://dx.doi.org/10.5281/zenodo.3233733
23. Hannah, L. 2011. Chapter 2 - The Climate System and Climate Change. In: Editor(s): Lee Hannah, Climate Change Biology, Academic Press, 2011, pages 13-52, ISBN 9780123741820, https://doi.org/10.1016/B978-0-12-374182-0.00002-9.
24. Hayes, J.M. 2020. Evolution of the atmosphere. Britannica. https://www.britannica.com/topic/evolution-of-the-atmosphere-1703862 (Accessed September 25, 2023).
25. Herzog, H. 2015. Carbon sequestration. In: Dictionary of energy. Editors: Cleveland, C.J, and Morris, C. Elsevier, Ltd. https://www.sciencedirect.com/topics/engineering/sequestration (accessed May 30, 2019).
26. Hibbard, K.A., F.M. Hoffman, D. Huntzinger, and T.O. West, 2017: Changes in land cover and terrestrial biogeochemistry. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.). U.S. Global Change Research Program, Washington, DC, USA, pp. 277-302, doi: 10.7930/J0416V6X.
27. Hines, S.J.; Daniels, A. 2011. Private Forestland Stewardship. (October 10, 2011). U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. www.fs.usda.gov/ccrc/topics/forest-stewardship/
28. Houghton,R.A. 2003. 8.10 - The Contemporary Carbon Cycle. In: Editor(s): Heinrich D. Holland, Karl K. Turekian. Treatise on Geochemistry, Pergamon, 2003, Pages 473-513, ISBN 9780080437514. https://doi.org/10.1016/B0-08-043751-6/08168-8.
29. Inkwood Research. 2023. Global biochar market forecast 2022-2030.
30. https://inkwoodresearch.com/reports/biochar-market/#:~:text=Report%20Summary,13.53%25%20during%20the%20forecast%20period. (Accessed October 20, 2023).

31. Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A. 2007. How strongly can forest management influence soil carbon sequestration? Geoderma, 137 (2007), pp.253-268. https://doi.org/10.1016/j.geoderma.2006.09.003
32. Janowiak, M.; Connelly, W. J.; Dante-Wood, K; Domke, G. M.; Giardina, C.; Kayler, Z.; Marcinkowski, K.; Ontl, T.; Rodriguez-Franco, C.; Swanston, C.; Woodall, C. W.; and Buford, M. 2017. Considering forest and grassland carbon in land management. USDA, Forest Service. General Technical Report WO-95. 69 p. https://www.fs.fed.us/sites/default/files/fs_media/fs_document/update-considering-forestandgrassland-carbonin-landmanagement-508-61517.pdf
33. Jones, M.W., Santín, C., van der Werf, G.R. *et al.* Global fire emissions buffered by the production of pyrogenic carbon. *Nat. Geosci.* 12, 742–747 (2019). https://doi.org/10.1038/s41561-019-0403-x
34. Kayler, Z.; Janowiak, M.; Swanston, C. 2017. Global Carbon. (June 2017). U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. https://www.fs.usda.gov/ccrc/topics/global-carbon.
35. Kasting, J.F., 1984. The evolution of the prebiotic atmosphere. *Origins Life Evol Biosphere* **14**, 75–82 (1984). https://doi.org/10.1007/BF00933642.
36. Kasting, J.F., 1987. Theoretical constraints on oxygen and carbon dioxide concentrations in the Precambrian atmosphere. Precambrian Res., 34: 205--229. https://doi.org/10.1016/0301-9268(87)90001-5
37. Keenan, J.R., Reams, A.G., Achard, F., de Freitas, V.J., Grainger, A., and Lindquist, E. 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015 For. Ecol. Manage., 352 (2015), pp. 9-20. https://doi.org/10.1016/j.foreco.2015.06.014
38. Laganiere, J., Angers, D.A., and Pare, D. 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Glob. Change Biol., 16 (2010), pp. 439-453. https://doi.org/10.1111/j.1365-2486.2009.01930.x
39. Lal, R., 2004. Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1-2), pp.1-22.
40. Lefebvre, D., Fawzy, S., Aquije, C.A. *et al.* Biomass residue to carbon dioxide removal: quantifying the global impact of biochar. *Biochar* **5**, 65 (2023). https://doi.org/10.1007/s42773-023-00258-2
41. Lehmann, J., Gaunt, J., and Rondon, M. 2006. Bio-char sequestration in terrestrial ecosystems: a review. Mitigation and Adaptation Strategies for Global Change (2006) 11: 403–427. https://doi.org/10.1007/s11027-005-9006-5
42. Lehmann, J., and Joseph, S. 2009. Biochar for Environmental Management: An Introduction. In: Biochar for Environmental Management, Johannes Lehmann and Stephen Joseph Editors. Earthscan, UK and USA. 438p. https://www.taylorfrancis.com/books/edit/10.4324/9781849770552/biochar-environmental-management-johannes-lehmann-stephen-joseph
43. Lehmann, J., Joseph, S., 2015. Biochar for environmental management: an introduction. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science, Technology and Implementation, 2nd ed. Earthscan from Routledge, London, pp. 1–1214. https://www.book2look.com/embed/9781134489602
44. Liu, Z., Deng, Z., Davis, S. *et al.* Monitoring global carbon emissions in 2022. *Nat Rev Earth Environ* 4, 205–206 (2023). https://doi.org/10.1038/s43017-023-00406-z.
45. Lüthi, D., Le Floch, M., Bereiter, B. *et al.* High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* 453, 379–382 (2008). https://doi.org/10.1038/nature06949.
46. Mahapatra, A.K., Shackleton. C.M. 2012. Exploring the relationships between trade in natural products, cash income and livelihoods in tropical forest regions of Eastern India. Inter. For. Rev., 14 (2012), pp. 62-73. https://doi.org/10.1505/146554812799973217
47. Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao and A. Timmermann, 2013: Information from Paleoclimate Archives. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter05_FINAL.pdf
48. McHenry, P.M. 2014. Chapter 26 - Biochar Processing for Sustainable Development in Current and Future Bioenergy Research. Editor(s): Vijai K. Gupta, Maria G. Tuohy, Christian P. Kubicek, Jack Saddler, Feng Xu, Bioenergy Research: Advances and Applications. Elsevier, 2014, Pages 447-456. https://doi.org/10.1016/B978-0-444-59561-4.00026-7.

49. McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., , Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E., and E. Skog, K.E. 2010. A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications, 21(6), 2011, pp. 1902–1924. https://www.fs.fed.us/rm/pubs_other/rmrs_2011_mckinley_d001.pdf
50. Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J.M. (2001). Atmospheric CO_2 Concentrations over the Last Glacial Termination. Science, 291(5501), 112–114. https://doi.org/10.1126/science.291.5501.112
51. National Academies of Sciences, Engineering, and Medicine. 2018. *Land Management Practices for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop—in Brief*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/25037.
52. National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/25259.
53. National Research Council 2015. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/18805).
54. Nave, L., Swanston, C., Mishra, U., and Nadelhoffer, K. 2013. Afforestation effects on soil carbon storage in the United States: a synthesis. Soil Sci. Soc. Am. J., 77 (2013), pp. 1035-1047. https://doi.org/10.2136/sssaj2012.0236
55. NOAA. 2023. Climate Change: Atmospheric Carbon Dioxide. Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=In%20May%202023%2C%20carbon%20dioxide,people%20are%20burning%20for%20energy.
56. Noormets, A., Epron, D., Domec, J.C., McNulty, S.G., Fox, T., Sun, G. and King, J.S., 2015. Effects of forest management on productivity and carbon sequestration: A review and hypothesis. Forest Ecology and Management, 355, pp.124-140. https://doi.org/10.1016/j.foreco.2015.05.019
57. Page-Dumroese, D.S., M.D. Busse, J.G. Archuleta, D. McAvoy, and E. Roussel. 2017. Methods to reduce forest residue volume after timber harvesting and produce black carbon. Scientifica 2745764. https://doi.org/10.1155/2017/2745764
58. Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104
59. Payne, C.R., Brownlee, D., and Kasting, F.J. Oxidized micrometeorites suggest either high pCO_2 or low pN_2 during the Neoarchean. PNAS Vol. 117 No. 3. Pages 1360-1366. https://doi.org/10.1073/pnas.1910698117
60. Phys.org. 2022. Global carbon emissions at record levels with no signs of shrinking, new data shows. Global carbon emissions at record levels with no signs of shrinking, new data shows (phys.org) (Accessed October 13, 2023).
61. Poderoso, J.J. (2016). The Evolution of the Earth and Its Atmosphere. In: Gelpi, R., Boveris, A., Poderoso, J. (eds) Biochemistry of Oxidative Stress. Advances in Biochemistry in Health and Disease, vol 16. Springer, Cham. https://doi.org/10.1007/978-3-319-45865-6_2
62. Pugh, T. A. M. et al.2019. Role of forest regrowth in global carbon sink dynamics. *Proc. Natl Acad. Sci. USA* 116, 4382–4387 (2019). https://doi.org/10.1073/pnas.1810512116
63. Rae, W.B.J., Zhang, G.Y., Liu, X., Foster, L.G., Stoll M.H., and Whiteford, D.M.R. 2021. Atmospheric CO_2 over the Past 66 Million Years from Marine Archives. Annual Review of Earth and Planetary Sciences 2021 49:1, 609-641. https://doi.org/10.1146/annurev-earth-082420-063026.
64. Rodriguez-Franco, C., Page-Dumroese, D.S. Woody biochar potential for abandoned mine land restoration in the U.S.: a review. *Biochar* **3**, 7–22 (2021). https://doi.org/10.1007/s42773-020-00074-y.
65. Ryan, M.G., Harmon, M.E., Birdsey, R.A., Giardina, C.P., Heath, L.S., Houghton, R.A., Jackson, R.B., McKinley, D.C., Morrison, J.F., Murray, B.C., Pataki, D.E., and E. Skog, K.E. 2010. A Synthesis of the Science on Forests and Carbon for U.S. Forests. Issues in Ecology. Ecological Society of America. Report 13.
66. Scharlemann, PW.J., Tanner, VJ.E., Hiederer , R., Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool, Carbon Management, 5:1, 81-91, DOI: 10.4155/cmt.13.77
67. Stephenson, M. 2018. Chapter 1 - The Carbon Cycle, Fossil Fuels and Climate Change, Editor(s): Michael Stephenson. Energy and Climate Change, Elsevier, 2018, Pages 1-26. ISBN 9780128120217. https://doi.org/10.1016/B978-0-12-812021-7.00001-4.

68. Urs Siegenthaler et al. 2005. Stable Carbon Cycle Climate Relationship During the Late Pleistocene. *Science* 310,1313-1317 (2005). DOI:10.1126/science.1120130.
69. U.S. Biomass R&D Board. 2016. Federal Activities Report on the Bioeconomy. Joint Agency Report. (https://biomassboard.gov/pdfs/farb_2_18_16.pdf)
70. U.S. Department of Agriculture, Forest Service. 2012. Future of America's Forest and Rangelands: Forest Service 2010 Resources Planning Act Assessment. Gen. Tech. Rep. WO-87. Washington, DC. 198 p.
71. U.S. Environmental Protection Agency. 2019. Inventory of US Greenhouse gas emissions and sinks 1990 – 2017. Chapter 6. Land Use, Land Use change, and Forestry. . https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-chapter-6-land-use-land-use-change-and-forestry.pdf https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-chapter-6-land-use-land-use-change-and-forestry.pdf (Accessed May 28. 2019).
72. U.S. Forest Stewardship Council. 2023. Towards climate smart forestry. Increasing carbon storage in the working forests of Canada and the United States. preview.fsc-us-forest-carbon-storage-study-towards-climate-smart-forestry.a-879.pdf
73. Wang C, Tu Q, Dong D, Strong PJ, Wang H, Sun B, Wu W (2014) Spectroscopic evidence for biochar amendment promoting humic acid synthesis and intensifying humification during composting. J Hazard Mater 280:409–416. https://doi.org/10.1016/j.jhazmat.2014.08.030
74. Wang Y, Momohara A, Wang L, Lebreton-Anberrée J, Zhou Z. 2015. Evolutionary History of Atmospheric CO_2 during the Late Cenozoic from Fossilized Metasequoia Needles. PLoS One. 2015 Jul 8;10(7):e0130941. https://doi.org/10.1371%2Fjournal.pone.0130941
75. Woodall, C. W.; Coulston, J. W.: Domke, G. M.; Walters, B. F. Wear, D. N.; Smith, J. E.; Andersen, E. H.; Clough, B. J.; Cohen, W. B.; Griffith, D. M.; Hagen, S. C.; Hanou, I. S.; Nichols, M. C.; Perry, C. H.; Russell, M. B.; Westfall, J. A.; and Wilson, B. T. 2015. The U.S. Forest Carbon Accounting Framework: Stocks and Stock Change, 1990-2016. General Technical Report NRS-154. 50p. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs154.pdf
76. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver, 2017: Executive summary. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 12-34, doi: 10.7930/J0DJ5CTG.
77. Zheng, B., Philippe Ciais, P., Chevallier, F., Yang, H., Canadell, G.J., Chen, Y., van der Velde, R.I., Aben, I., Chuvieco, E., Davis, J.S., Deeter, M., Hong, C., Kong, Y., Li, H., Li, Hui., Lin, X., He, K., and Zhang, Q. 2023. Record-high CO_2 emissions from boreal fires in 2021. Science 379, 912–917 (2023). DOI: 10.1126/science.ade0805