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REPORT

Landowner Participation in Carbon Dioxide Removal Credit Markets via Biochar

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Summary

The urgent need to reduce greenhouse gas emissions and concentration in the atmosphere motivated first the creation of forest carbon offset credit markets and more recently carbon dioxide removal (CDR) markets. Biochar, a material made by heating an organic feedstock in the absence of oxygen, can store carbon for long periods of time and so is a viable CDR pathway. Biochar has additional benefits when added to soil and can provide a market for wood with few other uses.

How biochar is produced and at what scale affects costs and potential uses. Small-scale production requires little investment in equipment or expertise but produces minimal quantities at low efficiency. Biochar-specific equipment allows for intermediate-scale production at the source of the feedstock, such as in a forest, but presents logistical complications. Industrial-scale production generates large volumes of biochar rapidly but requires significant investments and coordinated transportation of the feedstock to a central facility.

CDR credits from qualified biochar production can provide landowners with additional revenue and markets for low-value wood. Barriers to widespread biochar production and engagement in the CDR market include landowner awareness, skepticism of new markets, inconsistent regulations, economic constraints, and challenging logistics. The final section of this report presents potential solutions to help landowners take advantage of biochar and CDR markets.

Disclaimer

The intent of this report is to provide an introductory overview of biochar and carbon credit markets, not to serve as a comprehensive guide for investment. The information contained is provided on an "as is" basis with no guarantees of completeness and reflects a moment in time as biochar and carbon dioxide removal credit markets are in constant flux. Externalities, including federal, state, and local policies, greatly impact markets, adding to uncertainty. Readers interested in engaging biochar or credit markets should verify current policy and market conditions. Any company or product referenced is for informational purposes only and is not an endorsement.

Introduction

Since 1990, the Earth's land surface has warmed by about 1.6°C (IPCC, 2023). The scientific consensus, as summarized by the Intergovernmental Panel on Climate Change, overwhelmingly indicates that the climate is changing rapidly primarily because of human-caused emissions of carbon dioxide (CO_2) and other gases. The cascading impacts of climate shift are wide-ranging and severe (Summerhayes, 2024), which has motivated efforts to reduce carbon emissions and remove carbon from the atmosphere.

One tactic for reducing carbon concentrations in the atmosphere, and thereby reducing global changes in temperature and precipitation, is carbon offset credits. Another approach built on the same underlying concept is carbon dioxide removal (CDR) credits. CDR credits have in turn created renewed interest and even active markets for biochar, a carbon-rich material made by heating biomass such as wood. This report introduces biochar as an alternative forest product (to traditional products such as lumber) which may provide supplementary income streams via CDR markets. The focus of this report is on non-industrial private landowners and therefore attempts to consider the real-world limitations they experience, such as limited capital or market access. All monetary figures in this report are in U.S. dollars.

The *Market Motivation* section of this report briefly describes the carbon offset and CDR markets. The *Biochar* section provides background on biochar properties, production methods, production scale, and biochar-specific CDR options. The third and fourth sections, *Potential Opportunities for Landowners* and *Barriers to Producing Biochar and Accessing CDR Credits*, address opportunities and barriers for forest landowners to use or profit from biochar. The final section, *Barrier Breakers*, addresses potential ways to break down barriers for landowners to benefit from biochar and highlights research gaps.

Market Motivation

Carbon Offset Credits

Carbon offset credits are being marketed as one solution to reduce carbon concentrations in the atmosphere. While the idea of market-based solutions to reduce environmental degradation is much older, the 1995 Kyoto Protocol helped bring carbon offset credits to the forefront of climate policy (Waldegren, 2012). The basic concept that underlies markets for carbon offset credits is that multiple entities balance out one another's emissions; carbon emitters (i.e., carbon credit buyers) pay another entity (i.e., carbon credit producers) to avoid or reduce carbon emissions. Credit Producers undertake projects which reduce or avoid carbon emissions, ranging from planting trees to establishing or utilizing renewable energy, which enables them to sell credits to emitters.

There are dozens of entities, both for-profit and nonprofit, that have become carbon offset credit project developers. Project developers serve multiple roles and represent one of the fastest evolving pieces of the overall carbon market puzzle. Activities undertaken by project developers include project identification, development, implementation, monitoring, verification, and registration. Identifying suitable projects involves targeting opportunities that have the potential to reduce or avoid carbon emissions such as reforestation, renewable energy, or projects that improve land management practices. Other steps in project development include creation of detailed plans outlining the project's objectives, methodologies, and how the project will reduce or remove emissions; securing funding; and working with interest holders, such as landowners or neighboring communities. Implementation of carbon offset projects must be paired with monitoring and measuring emissions reductions. Some project developers are vertically integrated, meaning they can provide all support services required by carbon credit producers and buyers (from project conceptualization to credit sales), while other developers focus on only one aspect of the process.

Because carbon offset credits can be used to allow other greenhouse gas emissions, if the offset projects are not actually sequestering or storing additional carbon, the net result is increased warming (Ruseva et al., 2017). To effectively reduce the amount of carbon in the atmosphere, carbon offset credits must be additional, permanent, and verifiable. In other words, carbon offsets credits should:

1. Constitute a real and substantial addition to the carbon sequestered or stored relative to the continuation of existing practices (**additionality**);
2. Ensure that forests in which the offset credits are generated are not converted to other land uses and the carbon represented by the offset credits remains stored for the long term, i.e., at least 100 years (**permanence**); and
3. Be rigorously verified by a third party against public science-based standards which are backed by an independent registry (**verifiability**) (Forest Stewards Guild, 2022).

Carbon Offset Markets

There are two different (though sometimes overlapping) carbon offset markets: compliance and voluntary. Compliance markets are driven by government regulation while voluntary markets are created by organizations or individuals seeking to demonstrate their commitment to reducing the threat of a changing climate. Emissions regulations in California drove the creation of a compliance market in the state, but the U.S. federal government has yet to establish regulations that would create a national compliance market. In the absence of a widespread compliance market, the voluntary carbon offset credit market has grown to over $4 billion dollars and is projected to expand six-fold by 2030 (Grand View Research, 2024).

Like with carbon offset credits, an essential element of carbon offset credit markets is verification and registration. To ensure their credit purchases are trustworthy, carbon credit buyers first rely on established offset project registries. Carbon credit registries create science-based rules (i.e., program standards and sector-specific protocols or methodologies) for measuring, monitoring, and accounting for emissions. Ideally, registries ensure that credits are similar enough to be interchangeable, even if developed under different protocols. Julius Pasay from the Climate Trust points out that "consistency is essential for creating a liquid and fungible market." (CFN, 2025).

While project developers ensure projects adhere to the standards and regulations set by carbon credit programs, verification organizations collaborate with independent third parties to validate and verify a project's emissions reductions. Forest carbon offset credits are measured and verified by following a protocol to establish initial carbon stocks; estimate business-as-usual emissions; and document stock changes related to the project (e.g., CAR, 2023). Once the emissions reductions of a project have been validated and verified, the project can be registered and request issuance of those credits from the offset project registry. Numerous carbon credit registries have emerged with which projects can be registered (e.g. the ACR at Winrock International (acrcarbon.org), Climate Action Reserve (CAR - climateactionreserve.org), Verra (verra.org), Gold Standard (www.goldstandard.org), Puro.earth (https://puro.earth), and many others). Credits must also be tracked and monitored, particularly if the project could experience 'reversals' - the release of carbon dioxide stored by the project (e.g. a fire burning trees planted by an offset project). After a project has been registered and receives issuance of credits from the registry, companies and individuals can purchase the credits from the project proponent. Interest in credits is increasing; since 2015, projects in the U.S. have generated 326 million carbon offset credits and the volume of voluntary carbon offsets increased to 7.9 million metric tons of CO2 equivalent (MMtCO2e) in 2022 (Baral et al., 2025).

Recent research has called into question the positive contribution of some carbon offset credits (Romm et al., 2025; Sanders-DeMott et al., 2025). For example, Badgley and colleagues identified systematic over-crediting in California's forest carbon offset program (Badgley et al., 2022) and the growing impact of wildfire on the durability of some types of carbon storage (Badgley, 2024). Other researchers have also identified issues with over-crediting (Haya et al., 2023; West et al., 2023) and carbon storage losses from disturbances (Dye et al., 2024) and taken the opportunity to propose potential solutions to these problems (Anderegg et al., 2025). Media reports that call forest carbon offsets into question have been equally impactful since public perception and trust in the system is an important part of the carbon market. Articles like The Great Cash-for-Carbon Hustle (Blake, 2023) or These Trees are Not What They Seem (Elgin, 2020) sow doubt with potential offset credit purchasers. Similarly, carbon credit companies and programs have advertised big opportunities and then collapsed. The forest carbon project developer NCX went from announcing $50 million in funding to discontinuing their flagship 1-year carbon crediting program within a few months (Trendafilova, 2022).

The ongoing controversy about the true climate impact of forest carbon offset credits is a prime example of the field's complexities. Carbon markets continue to evolve with frequent new entrants, mergers, acquisitions, closures, and restructurings. Interested readers should supplement this brief introduction with in-depth and unbiased resources such as offerings from Michigan State University's Forest Carbon and Climate Program (www.canr.msu.edu/fccp/).

Landowner Perception and Participation

An essential part of any forest carbon offset projects is a willing landowner. To date, carbon programs have struggled to attract forest landowners and managers. In 2018, less than 0.1 percent of family forest owners in the U.S. were engaged in carbon programs (Sass et al., 2022). Barriers to participation in carbon programs include awareness, skepticism, and economics (Brumberg et al., 2025; Khanal et al., 2019; Sharma and Kreye, 2022).

In general, forest landowners and managers are conservative, in part because of the decades forests take to grow and mature. In contrast to farming an annual crop, forest management mistakes can take decades to correct. Surveys have found that family forest owners' attitudes tend to be stable over time (Sass et al., 2023). Reticent to make rapid change means awareness and perception of forest carbon offset projects and other natural climate solutions is a key predictor of landowner engagement (Khanal et al., 2019). For example, in West Virginia, most landowners do not have sufficient knowledge of carbon offset programs and/or the credit generation process to engage (Gazal et al., 2024). Information on starting and managing natural climate solutions projects are top barriers to adoption in the US (Brumberg et al., 2025).

The landowners' perceptions, regardless of data, are important in their choices in wide range of decisions including conservation program participation (Batame et al., 2025) , wildfire risk reduction (Fischer et al., 2026), and response to forest pests (Adhikari et al., 2023). Many landowners and managers are skeptical of carbon programs and lack confidence in the protocols and proponents (Schofield et al., 2024). For example, focus groups in Minnesota compared carbon markets to the "Wild West," highlighting inconsistent carbon accounting protocols (Moser et al., 2022).

Economics are another main driver of participation in carbon programs (Moser et al., 2022). Similarly, a review of landowner interest in natural climate solutions (NCS) found funding was the top participation constraint for all natural climate solutions projects in North America and Europe and for forest-based projects globally (Brumberg et al., 2025). Economic issues include size of payments, contract length, and costs of program participation (Graves et al., 2022). Sharma and Kreye (2022) found some landowners need payments of $22.50 per acre per year to be enticed in a carbon program. The same study found that the per-year price needed to attract a landowner for a 50-year contract was three times greater than the per-year price for a one-year contract (Sharma and Kreye, 2022). In another study, extending the time commitment required for program enrollment from 5 years to 40 years reduce likely participation by ten percent (Gazal et al., 2024).

Of course, barriers to participation vary because of wide diversity of forest landowners across the country. For example, the price necessary to attract participation may be as much as four times greater for small (<20 ac) landowners than for large (>1,000 ac) landowners (Sharma and Kreye, 2022). In general, landowners who participate in carbon programs tend to be richer, more educated, relatively younger, participate in other incentive programs, and to own more land than non-participants (Khanal et al., 2019; Sass et al., 2022).

Carbon Dioxide Removal Credits

In addition to the markets for carbon offset credits, a market for the removal of carbon from the atmosphere has emerged. This market, known as the Carbon Dioxide Removal (CDR) credit market, responds to the need to not only reduce carbon emissions into the atmosphere, but also the current need to reduce atmospheric concentrations of carbon dioxide. In fact, nations will need to employ significant CDR to stay below the 1.5°C temperature limit (Jeffery et al., 2020). CDR is important in part because of the uncertainty related to projected future emission reductions inherent in many carbon offset credits. A 2024 report estimates a current rate of two GtCO2 per year of CDR and the need for seven to nine GtCO2 per year of CDR by 2050 to meet Paris Agreement goals (Geden et al., 2024).

The essential focus of CDR projects is to create a net flux of CO2 from the atmosphere to permanent, verifiable storage. Generally, CDR projects seek to store carbon for hundreds or thousands of years to achieve long-lasting climate benefits (Belmont and Sanchez, 2025). CDR projects can be split into biological options, such as tree planting, biochar, and soil carbon sequestration, and other approaches such as direct air capture, enhanced terrestrial weathering, and bioenergy with carbon capture and storage (Jeffery et al., 2020). Because of the variety of approaches, building trust in CDR requires a standardized process for quantifying net CO2 removal (Nordahl et al., 2024). As with carbon offsets, there are a range of policy tools to encourage CDR such as market-based, public procurement, subsidy, and tax credits, each having their own benefits and limitations (Hickey et al., 2023). In the U.S., market-based approaches have the greatest potential for growth, though the current CDR market relies on public infrastructure and public funding or subsidies (Grubert and Talati, 2023). It is estimated that the CDR market has potential to expand to $2.1 billion by 2032 and up to $1.2 trillion by 2050 (Stevenson and Kane, 2025).

Biologically based CDR, such as biochar, has the distinct advantage of offering co-benefits (see the section Benefits of biochar below). In addition, a review of CDR methods indicates that biochar has a higher technological readiness rating and lower costs than other removal options like direct air capture or enhanced weathering (Michaelowa et al., 2023).

Biochar

Background

Biochar is made from organic material (such as plant matter) that is heated in the absence of oxygen, a process also known as pyrolysis. When biomass is exposed to high heat, water within the material evaporates and volatile gases that contain carbon, hydrogen, and oxygen are released. These gases burn, providing the heat that turns the remaining carbon into char (Page-Dumroese et al., 2024). Unlike combustion, where the fuel source reacts with oxygen and releases gases, pyrolysis keeps most of the carbon trapped. This thermochemical breakdown of biomass creates a carbon-rich, porous material that is highly resistant to further decomposition. Biochar is usually created from unmerchantable woody residues or as a byproduct of other production systems (Rodriguez Franco et al., 2024).

For more than 2,500 years, farming communities in the Amazon basin created soil rich in nutrients, minerals, and microorganisms by adding a mixture of charcoal, bones, broken pottery, compost and manure to the area's low fertility soil (Palviainen et al., 2025). Called 'terra preta', this biochar was produced by smoldering agricultural waste (i.e., covering burning biomass with soil) in pits, combining it then with other materials and incorporating it into the land to boost agricultural outputs. One study estimated over 1000-year residence times of biochar in soils (Fang et al., 2015), though the longevity of biochar in soil is an area of active research (Belmont and Sanchez, 2025).

Biomass feedstocks for biochar production can vary greatly, often including agricultural or forest management residuals; biochar can be produced from forest biomass, crop residues, animal manure, sewage sludge, and food waste (Janiszewska-Latterini et al., 2025). Biochar can be generated by slow pyrolysis, fast pyrolysis, gasification, and torrefaction, with the pyrolytic process typically occurring at temperatures between 350°C to 1000°C. Torrefaction uses temperatures in the 200°C to 300°C range, while slow pyrolysis applies temperatures of 300°C to 700°C (Wang et al., 2020). Biochar as a byproduct of fast pyrolysis and gasification usually focuses on bio-oil and syngas (excess pyrolysis gas) respectively (Wang et al., 2020). During gasification, more of the biomass is lost to reactions with oxygen so biochar yields are lower (Belmont and Sanchez, 2025). The proportion of biomass transformed into carbon in biochar varies from five percent with gasification technologies to 35 percent with slow pyrolysis (Rodriguez Franco et al., 2024).

Biochar's final properties and quality are influenced by factors such as production temperature, feedstock type, reaction time, and pre-treatment processes (Janiszewska-Latterini et al., 2025). Both the material and the process affect properties of biochar, including ingredient concentrations, density, porosity, and pH (Amalina et al., 2022). For example, the ratio of hydrogen to organic carbon influences the permanence of carbon storage in biochar (Davison et al., 2024). Greater porosity increases biochar's surface area, which facilitates absorption and retention of carbon (Li and Tasnady, 2023). Biochar surface area ranges from 1.5 to 500 m2g-1 (Fawzy et al., 2021). Wood-based biochar tends to have greater surface area, while manure-based biochar has a higher nitrogen (N) and phosphorus (P) content (Janiszewska-Latterini et al., 2025) . Biochar produced at lower temperatures (350 °C) generally increases soil CO_2 fluxes and has greater nitrogen leaching while biochar produced at higher temperatures (450 °C) appears to retain nitrogen in the soil and have little impact on CO_2 fluxes (Toczydlowski et al., 2023). Biochar produced at temperatures above 500°C tends to have higher ash content, pH values, and longer persistence in soils (Janiszewska-Latterini et al., 2025). The effect of biochar characteristics on carbon storage and other co-benefits shows that although biochar has been used since time immemorial, the modern applications and use cases may require specific feedstocks and production processes.

Soil and Plant Benefits of Biochar

Adding biochar to soils can improve the physical, chemical, and biological properties of soils. Biochar amendments have the potential to increase soil porosity due to the varying particle sizes of biochar, thus making the soil less compact. Porous soil increases the movement of water, heat, air, and other gases throughout the soil, which are essential for the growth of plant roots (Wang et al., 2020). However, soil porosity increases are dependent on the particle size of the biochar and soil type. For example, on loamy soils, biochar particles need to be 0.5-2 mm while on sandy soils, the biochar particles need to be 0.15-2 mm to increase porosity (Zhu et al., 2025). Biochar additions improve available water, infiltration rate, hydraulic conductivity, and water holding capacity of soils (Kumar et al., 2022). Biochar's increased water holding capacity maintains soil moisture for longer periods and hence can reduce drought impacts (Antonangelo et al., 2025).

Biochar increases cation exchange capacity (CEC; the measure of the soil's ability to adsorb cations) which means important plant nutrients such as potassium (K), calcium (Ca), and magnesium (Mg) are retained (Sarauer et al., 2019). Soil pH can also be altered with the application of biochar. Biochar is typically very alkaline, which means it can be useful for restoring the pH in acidic soils (Li and Tasnady, 2023). As biochar breaks down, it releases cations such as K, Ca, and Mg which can bond to form carbonates or oxides (Wang et al., 2020). These molecules can attach to positive hydrogen (H^+) ions in the soil, lowering the H^+ concentration and increasing the soil pH (Zhu et al., 2025). While biochar can neutralize the pH of the soil, this effect is contingent on the material used to produce the biochar (as noted above) and the soil type. For example, the pH in sandy loam soils increased the most using biochar made from manure and fruit peels compared to biochar made from aloe and rapeseed (Zhu et al., 2025).

Since biochar can increase soil nutrients and reduce leaching, where nutrients are washed out from the soil by rainfall or irrigation, the addition of biochar increases available nutrients, helping roots establish and grow (Wang et al., 2020). A metanalysis of 17 studies concluded that biochar additions caused strong, positive tree growth responses in a range of ecological systems and soil conditions (Thomas and Gale, 2015). Other meta-analyses have also found that, on average, biochar increases crop yield by 10 to 42 percent (Weng and Cowie, 2025). For example, application of 10 Mg ha^{-1} increased the relative growth rate of canopy oak trees (*Quercus serrata*) by 22 percent in Japan (Ohtsuka et al., 2021). Biochar additions enhanced silver maple growth, particularly when the biochar feedstock was maple rather than conifer species (Sifton et al., 2022). However, this effect is not universal. Biochar improved growth of turkey oak seedlings (*Quercus cerris*) but not European beech (*Fagus sylvatica*) seedlings (Vannini et al., 2022). Sarauer and colleagues found biochar amendment increased soil carbon content but did not affect tree

growth (Sarauer et al., 2019). Biochar is not a panacea for tree growth. A study on pine seedlings showed decline in shoot to root ratio and growth rate, but also some indications of adaptation to warmer and drier conditions (Griego et al., 2026).

Additionally, biochar can reduce pollutants in soil and water by attracting positively charged heavy metals and reducing their movement in the soil (Wang et al., 2020). For example, biochar from wood shows significant potential to improve mine sites because of its ability to bind metals, decrease contaminant bioavailability, stimulate microorganism activity, and promote revegetation (Rodriguez-Franco and Page-Dumroese, 2021). These same properties of biochar may also drive observations of biochar reducing plant pathogens in soil (Antonangelo et al., 2025). Similarly, a study in the northwestern US showed biochar additions to forest soils were not detrimental to soil microbial community composition (Sarauer and Coleman, 2023).

Silvicultural and Restoration Benefits

Beyond soil and plant benefits, biochar production can help address a persistent challenge in forest stewardship: removing low value trees from the forest. Whether landowner objectives emphasize economics or ecological integrity, good stewardship often requires removal of trees or other vegetation that is difficult to sell (Palik and D'Amato, 2023). Yet removal of this low-value material often becomes a cost for landowners (Evans and Finkral, 2009). If low-value material can be converted to biochar, the cost of removal may be reduced or even transformed into an income stream.

The growing wildfire threat is perhaps the most obvious example showcasing the need to remove trees with little economic value. Reducing the density of trees can mitigate the threat of wildfire to communities and ecosystems (Hagmann et al., 2021; Prichard et al., 2021). The trees removed to increase fire resilience are generally small, costly to handle, and difficult to transport, meaning they have low or even negative value (Evans and Finkral, 2009). Hjerpe and colleagues (2009) delineate the significant barriers to utilizing small-diameter, low-value trees that need to be removed to increase landscape fire resilience. One solution is biochar production from trees removed in fuel reduction thinning, which could offset the cost of much-needed resilience work. Biochar from forest restoration thinning can be combined with application of the biochar to mitigate soil degradation and drought (Ghosh et al., 2025).

As much as 210 million tons of low-value wood could be removed from forests in the western US and used in products like biochar (Page-Dumroese et al., 2022). The utilization of material from thinning, including biochar, could support wildfire risk reduction on over 12 million acres in California and reduce emissions by as much as 16.9 MMtCO2e per year (Cabiyo et al., 2021). Moreover, producing biochar inside of open burning of slash and other woody debris would significantly reduce carbon emissions (Puettmann et al., 2020). If biochar production can offer a cost-effective way to remove trees that increase the risk of high severity wildfire, it could help solve one of the biggest land stewardship challenges of the 21st century.

In eastern U.S. forests, invasive species may be the largest stewardship challenge. Invasive plants reduce the economic and ecological health of forests (Fantle-Lepczyk et al., 2022). As with fuel reduction thinning in fire prone forests, removing invasive plants is a difficult, costly challenge for landowners (Pile Knapp et al., 2023). Again, there is potential for biochar production to offset this cost.

Research is exploring other benefits to biochar. For instance, a study in a lodgepole pine forest demonstrated that biochar in combination with wood mulch can benefit post-fire recovery (Kaiser et al., 2025). Other research suggests that biochar may be useful in remediation of contaminated soil or water (Arabzadeh Nosratabad et al., 2024; Liang et al., 2024).

More generally, biochar has been proposed as a tool for climate-smart forestry because of its wide range of benefits (Rodriguez Franco et al., 2024). It is important to note, however, markets for low quality wood could negatively impact forest ecosystems by incentivizing removal of biomass needed for ecological processes. Guidelines are available to help landowners and stewards understand the potential risks of biomass removal to wildlife and soil properties (Evans et al., 2012; Titus et al., 2021).

Biochar Production

Hundreds of thousands of tons biochar are produced every year in a wide range of processes. The International Biochar Initiative estimates that producers made at least 352,000 metric tons (mt) of biochar in 2023, or at least 650,000 mt of CO2 removed, based on an average of 1.9 mt CO2 removed per mt of biochar (Gray et al., 2024). The U.S. produced about half of this biochar (170 mt). Total international biochar industry revenue, including producers, distributors, value-added processors, and equipment manufacturers, was $610 million (Gray et al., 2024). Many of these estimates exclude the numerous producers creating biochar at small-scale, often with simple technology.

The scale of biochar production is a crucial factor because it can range from a few pounds produced in a backyard to thousands of tons produced at industrial plants. Methods to produce biochar range from hand piles to inexpensive, lightweight kilns that can be moved by hand, to a variety of air curtain burners that are either towed to a site or moved on a trailer (Page-Dumroese et al., 2024).

Small-scale production (less than 100 mt per year)

Biochar can be created with minimal equipment. The US Forest Service publication on Mobile biochar production (Wilson et al., 2024) provides an excellent guide to a range of biochar production options from small to intermediate scale. At a small scale and with some attention, a simple pile of wood can be burned to create biochar, albeit at a low efficiency. A flame-cap kiln can improve biochar production efficiency and safety. This low-tech and affordable method utilizes a top-lit, updraft design to minimize emissions and maximize biochar yield. A flame-top kiln costs approximately $2,000 and many are built for easy transport with a modular design. For do-it-yourself enthusiasts, open-source flame-cap kiln drawings are available online. Each design has advantages and disadvantages depending on the user's intentions (e.g. volume of feedstock, loading method, etc.) and site considerations (Wilson et al., 2024). These low-cost and low-tech methods produce biochar at an efficiency rate of approximately 15 to 20 percent. Larger versions of a flame-cap kiln are also available and allow for increased scale with the same double-walled, updraft design like the big box kiln, which provides nearly 300 ft3 capacity and can be machine loaded (McAvoy, 2023).

Intermediate scale (up to 10,000 mt per year)
Scaling up biochar production requires more complex technology and more capital-intensive equipment. Air curtain burners, such as the Firebox, CharBoss, and Tigercat 6050 are insulated fireboxes with blowers that control airflow in and out of the box (Wilson et al., 2024). Air curtain burners are designed with skids, wheels, or tracks for mobilization using heavy equipment in the woods near the feedstock. Air quality impacts are reduced using this method as an air-curtain forms across the top of the box, recirculating emissions, especially useful when burning wet fuels. Conversion efficiencies of air curtain burners are less than flame-cap kilns and depend on the size and moisture content of feedstock. Starting at around $100,000, air curtain burners can produce much higher volumes of biochar, but at a significantly higher cost, due in part to the initial cost of equipment but also the higher cost of operation.

The Firebox is best suited to a centralized operation where large quantities of biomass are available near harvests, while the Charboss can move more frequently to where the biomass is (Oyier et al., 2024). Other biochar equipment manufacturers include AGICO, Beston, WasteX, and High Plains Biochar. Those interested in intermediate scale biochar production should carefully research the equipment options to ensure a fit with their scale and feedstock. There is no 'one size fits all,' as the most efficient equipment is tailored to specific sites and operations. Well organized operations are important regardless of the equipment because maintaining consistent operating conditions like stable temperatures or feed rates produces less variable biochar (Groot, 2025a).

Industrial scale (greater than 10,000 mt per year)

Commercial production of biochar lends itself to higher efficiencies and yields because the heat from the pyrolysis process is often captured to produced additional by-products (i.e., wood vinegar, bio-oil, and syngas). Commercial biochar also tends to have greater consistency than smaller scale methods. Industrial producers closely monitored and manage feedstocks and processing conditions to meet strict requirements for biochar characteristics (Groot, 2025b). Many companies supply systems to produce biochar at industrial scale. For example, Bioforcetech and FEECO supply industrial systems for pyrolysis.

In the U.S., over 70 percent of biochar production occurs at the industrial scale with a stationary auger or rotary kiln (Gray et al., 2024). Wakefield Biochar in Valdosta, Georgia produces biochar from using pine bark and sawdust from the local timber industry (www.wakefieldbiochar.com), while Pacific Biochar in Santa Rosa, California focuses on wood from fuel reduction thinnings (www.pacificbiochar.com). Wakefield and Pacific Biochar have delivered nearly 60,000 and over 55,000 tons of CDR credits respectively (www.cdr.fyi). Southwest Biochar (www.sowbiochar.com) uses wood from restoration thinning in Arizona.

Adhikari and colleagues (2024) investigated the potential site for a similar plant in New Mexico to facilitate forest resilience treatments. Freres Engineered Wood is a lumber mill that produces biochar as a by-product but it has delivered over 26,000 tons of CDR credits to the market (www.frereswood.com). Oregon Biochar Solutions (www.chardirect.com) and Biochar Now (www.biocharnow.com) both focus on biochar to meet tight quality standards for specific applications. An example from outside the U.S. is Pyrocal in Australia (www.pyrocal.com.au), which transforms macadamia and pecan shells into biochar for agricultural and urban applications. These are just a few examples, and as biochar production continues to evolve, more innovative and sustainable production methods and products are likely to emerge.

Differences in Biochar

Different technologies often lead to different carbon contents in biochar due to the thoroughness at which pyrolysis is completed (Groot, 2025a). As described in the biochar Background section above, producing biochar at low and high temperatures produces differences in physical and chemical characteristics. Generally, there is more variability in biochar produced at small-scale than biochar produced at the industrial scale. The advantages of small to intermediate scale production are low capital requirements and reduced feedstock transportation costs. Intermediate scale requires greater investment but promises increased efficiency. Industrial scale production results in greater consistency and efficiency, but requires millions of dollars in investment.

Much of the biochar currently produced is not certified. However, the most common certifications are the European Biochar Certificate and the International Biochar Initiative (IBI) standards (Gray et al., 2024). While currently voluntary, the IBI standard is used by many national biochar initiatives and the US Department of Agriculture when evaluating biochar for various soil health initiatives (Groot, 2025b). The American National Standards Institute, U.S. Biochar Initiative and the American Society of Agricultural and Biological Engineers recently released a new standard for biochar testing aimed at establishing consistent methods and improving market clarity (ANSI USBI and ASABE, 2025).

CDR Credits for Biochar

Biochar is a particularly attractive CDR credit pathway because of the abundance of low value biomass as a feedstock and biochar's ability to store carbon in soil for decades or centuries. When considering biochar CDR, it is important to understand how much of the carbon stored in the biochar initially and how much will remain stored over time without escaping into the atmosphere as CO2 (Belmont and Sanchez, 2025). CDR resulting from the conversion of biomass to biochar is determined by the biochar yield per unit of feedstock and the relative mineralization rate of the biochar carbon in comparison with the original feedstock (Weng and Cowie, 2025).

Carbon removal efforts are currently promoted via the voluntary market. To qualify for credits, biochar projects must follow existing established protocols and must be carefully tracked. Established and emerging CDR registries have been working to develop protocols and certification for biochar carbon credits. In addition to facilitating access to the carbon removal market, the certification process is a value-adding activity as it adds authenticity and credibility to the biochar producer for marketing the physical biochar (Fawzy et al., 2021). The California Action Reserve (CAR) has developed a Biochar Protocol that provides guidance on how to quantify, monitor, report, and verify climate benefits (Davison et al., 2024). CAR's protocol includes the standard requirements for additionality, permanence, and verifiability. Notably, permanence is not assumed for biochar but instead requires a molar ratio of hydrogen to organic carbon less than 0.7 based on laboratory testing (Davison et al., 2024). This aligns with the World Biomass Certificate promulgated by Carbon Standards International, which has replaced International Biochar Initiative's standards from 2015 (WBC, 2023). Other protocols for CDR credits for biochar include Puro.earth, Isometric, and Verra (Michaelowa et al., 2023; Isometric 2025; Puro.Earth, 2024; Verra, 2024).

According to the tracking website CDR.fyi, 44 MMtCO2e of CDR credits have been sold and 1.3 MMtCO2e have been delivered as of the end of 2025 (www.cdr.fyi). Biochar represents over 80 percent of the deliverable CDR credits from nearly 90 different biochar project implementers. This progress is dwarfed by future CDR potential of biochar estimated to be approximately 2,700 MMtCO2e annually (Weng and Cowie, 2025). However, the rate of CDR crediting of biochar projects is increasing rapidly. At the end of 2023 only 0.3 MMtCO2e had been delivered; this doubled to 0.7 MMtCO2e at the end of 2024; and nearly doubled again to 1.3 MMtCO2e at the end of 2025 (www.cdr.fyi). CDR.fyi's tracking indicates that CDR credits from biochar project cost $150 per MtCO2e and Fawzy and colleagues (2021) identified a similar range from $71 to $180 per MtCO2e. In general, biochar is significantly less expensive than other CDR technologies such as direct air capture and storage (Fawzy et al., 2021).

Potential Opportunities for Landowners

Because biochar can be made from wood or other biomass that has low value for other uses, landowners may be able to turn what is essentially a waste material into an income stream. Not only does biochar present a potential opportunity for forest landowners to increase revenues from their land, it also can improve ecological health and support restoration efforts after storm damage. Perhaps the simplest option for a landowner is to use biochar as a soil amendment on the same property material is removed, improving overall ecological and soil health. Biochar can provide substantial cost savings for landowners by reducing the costs of necessary forest management. As noted above, fuel reduction in forests can be very costly, but also pays large

dividends because of the reduced wildfire impacts, with the possibility for as much as a six-fold return-on-investment (Hjerpe et al., 2024).

Interest in using biochar in agricultural operations is rapidly increasing, and larger scale biochar producers are working to provide the supply needed. To generate additional income, landowners can sell biochar to local users such as farms or gardens to be used by these parties in their soil. The USDA is supporting agricultural producers with financial assistance to offset the costs of producing and adding biochar to soils, including the purchase, shipping, and application of biochar (Smith et al., 2023).

Entering more complex CDR markets requires greater commitment and planning. To offset the administrative costs of participating in a CDR credit market, landowners or project developers need to produce many tons of biochar annually. Producing enough biochar, and hence CDR credits, to achieve this economy of scale will require targeted investment in equipment, especially since biochar production machines produce a more consistent product that is able to meet CDR protocol requirements.

Barriers to Producing Biochar and Accessing CDR Credits

Awareness

Despite biochar many benefits, limited awareness among farmers and foresters about its advantages and opportunities to integrate biochar into existing practices hinders its widespread adoption (Gray et al., 2024; Janiszewska-Latterini et al., 2025; Pierson et al., 2024). Knowledge of carbon offset credit programs and natural climate solutions more generally are well-documented barrier to landowner engagement (Brumberg et al., 2025; Gazal et al., 2024).

Skepticism

Some forest landowners are suspicious of carbon offset credit programs and even the science of climate change on which offset and CDR credits are based (Grotta et al., 2013; Nelson et al., 2016). Although perceptions of climate change have likely shifted (Graves et al., 2022), landowners who are concerned about climate change are more likely to engage in carbon programs (Sass et al., 2022). The on-going questions about the strength and quality of offset credits fuels (Romm et al., 2025; Sanders-DeMott et al., 2025) along with popular media highlighting of failures (Blake, 2023; Elgin, 2020) feed landowner skepticism of carbon programs.

Rules and Regulations

Unfortunately, the lack of nation-wide standards adds to landowners' confusion and hesitancy to engage with carbon programs like CDR credits (Abrams et al., 2017; Khanal et al., 2019). In addition to barriers related to CDR regulation, there are also regulatory barriers to the production of biochar itself. Unclear and incomplete regulations discourage the use of biochar (Janiszewska-Latterini et al., 2025). For example, an air-quality permit to burn biomass requires meeting stringent requirements that can vary state-to-state (Pierson et al., 2024).

Economics

Experience and research on forest carbon offset credits is clear that the size of payments to landowners is a crucial driver of program participation (Graves et al., 2022; Moser et al., 2022). The same is true for CDR credits. CDR credit payments to landowners must cover the costs of verification and monitoring to be viable (Mercer et al., 2024; Pan et al., 2022). The costs of creating biochar are an equally large barrier. Transporting and handling the forest biomass as a feedstock for biochar is costly (Evans and Finkral, 2009; Hjerpe et al., 2009). Lack of investment, demand fluctuation, and feedstock uncertainty have limited biochar production (Pierson et al., 2024).

Logistics

As with any operations using wood with low value, the handling and transportation are major barriers for biochar (Evans and Finkral, 2009). Producing biochar requires specialized equipment and properly trained staff to operate the equipment (Pierson et al., 2024). The logistical challenges change for in-woods biochar production versus a centralized system, but in either case they present a barrier.

Barrier Breakers

Research and experience point to barrier reducers that can help CDR credits from biochar fulfill their promise.

Building awareness

A wide body of scientific literature already exists on biochar and CDR credits. Succinct, easily digestible summaries of the science that highlights specific benefits of biochar and paths to CDR crediting will help expand awareness (Pierson et al., 2024). This report adds to growing body of information from the US Forest Service and others designed for landowners and managers including:

- Biomass to biochar: Maximizing the carbon value (Amonette et al., 2021)
- Biochar: A Key Player in Carbon Credits and Climate Mitigation (Salma et al., 2024)
- Mobile biochar production by flame carbonization: Reducing wildfire risk and improving forest resilience (Wilson et al., 2024)
- Biochar Is ready for prime time: Ground-truthed decision trees for land managers (Page-Dumroese et al., 2024)

The US Biochar Initiative (biochar-us.org), US Biochar Coalition (usbiocharcoalition.org) and others are raising awareness through social media and an annual national conferences. Often the most effective path to build awareness are neighbors, colleagues, and friends (Deak et al., 2025; Kittredge et al., 2013). Efforts to encourage and support landowners and managers to share their positive experiences with CDR credits from biochar will be essential for building awareness.

Addressing skepticism

A good place to start when addressing the skepticism of landowners and managers about CDR credits for biochar is to acknowledge that their doubt is reasonable. There have been programs and projects that have started up and then collapsed in the carbon market. Project proponents must earn the confidence of landowners and managers with honest descriptions of the opportunities and challenges of CDR credits from biochar. Research from other areas highlights the common-sense result that competence, care, and credibility build trust with forest landowners (Eastman et al., 2025; Winter et al., 2004). Similarly, robust science and strong verification protocols are key elements in building trust in carbon offset credits (Pan et al., 2022), and are equally important for CDR credits from biochar.

Meeting landowners and managers where they are, in their nearby woods and forests, is a well-proven strategy for building trust, knowledge, and engagement. The power of hands-on workshops and learning networks is well documented in the scientific literature for both climate change adaptation and wildfire management (Hunter et al., 2022; Shannon et al., 2019). For example, O'Brien and colleagues (2025) identified key factors for success include "the involvement of a local champion, co-design of the workshop between facilitators and participants, and sustained engagement post-workshop." Real-world pilot projects are another useful tool to facilitate biochar adoption (Soriano Ynfante et al., 2024). Long-term, collaborative, and honest engagement with landowners and managers help engagement with CDR credits from biochar.

Clarity and consistency of rules and regulations

Regulatory clarity and consistency facilitate investment. For project developers, landowners, and managers to invest in the equipment and operational changes necessary for biochar production, they need confidence that the rules and regulations will be consistent (Vonhedemann et al., 2020). Biomass CDR project developers identified in a survey that regulatory uncertainty and a lack of standardization are larger barriers than technology and equipment (Mercer et al., 2024). Public policies coordination across different levels and agencies with the government such as regulatory legislation, industrial subsidies, and landowner assistance will aid biochar expansion (Page-Dumroese et al., 2022). For instance, air quality permits handled at the county or state level may impede biochar production encouraged by federal programs (Pierson et al., 2024).

Money matters

Studies and experience with forest carbon offset programs suggest that money matters and the amount landowners receive from biochar CDR projects will be an important determinant of participation. Incentives should be tailored to the needs of each landowner segment. For example, the price necessary to attract landowner participation in a carbon project ranged from $22.50 per acre per year for owners with less than 20 acres to $5.59 per acre per year owners with over 1,000 acres (Sharma and Kreye, 2022). Current prices and government incentives may not be enough to encourage broad adoption of biochar (Kadam et al., 2025). However, since biochar projects do not require a long-term commitment or easement as a carbon project would, adoption may be possible at lower prices.

Reducing costs for landowners would also help make the economics of CDR credits for biochar more enticing. For example, securing a consistent and reasonably priced supply of biomass feedstock would reduce financial constraints to the adoption of biochar production (Pierson et al., 2024). Establishing long-term connections between forestry and agricultural sectors can help to stabilize and expand biochar markets by reducing the fluctuations in demand and attracting investors who are seeking to build market-based relationships with commercial agriculture (Pierson et al., 2024). Reducing the costs of monitoring, reporting and verification is another opportunity to encourage more CDR from biochar projects (Mercer et al., 2024).

Logistics and technology

While creating biochar from wood is an ancient process, technological improvements are essential for modern projects to generate CDR credits from biochar. Improvements can be made throughout the process from collecting feedstock in woods to the final application of biochar. Coordinating small landowners so operations can aggregate feedstock across landownerships can create economies of scale. As with any operations using wood with low value, the handling and transportation costs for biochar feedstocks are a major barrier (Evans and Finkral, 2009). Identify the right biochar production systems to fit local conditions and feedstock types can reduce feedstock barriers. For example, large, stationary facilities are more cost-effective per ton produced but portable units can replace transporting wood with transporting the lighter, more manageable biochar (Ahmed et al., 2025; Pierson et al., 2024). The development of new biochar-specific equipment and technology may also help address the logistical challenges.

Research needs

Bridging the gap between research and practical implementation will reduce barriers to biochar projects and generating CDR credits (Pierson et al., 2024). While the number of scientific papers and reports on biochar has increased dramatically in recent years, knowledge gaps remain. Research gaps that surfaced during the creation of this report include:

- **The economics and logistics for intermediate scale production** – expanding on the US Forest Service's field testing of biochar production equipment (Oyier et al., 2024; Wilson et al., 2024) will help both landowners and project developers feel more confident in the technology.
- **The integration of biochar with harvest of other forest products** – well-documented case studies of biochar integration with other silvicultural goals in a variety of ecoregions would provide a model landowners and managers can adjust to fit their specific needs.
- **The characteristics of biochar produced at intermediate scales** – Industrial scale biochar production is designed to meet specific product specification and small scale production is unlikely to produce enough biochar to enter into CDR markets. In between, producers contend with variations in feedstock and operating conditions. Sound science to characterize key parameters such as permanence in soil would facilitate expansion of CDR credits from biochar.
- **Clear guidance to help match biochar attributes to specific uses** – Since biochar characteristics vary significantly and affect its suitability for different applications, implementors need clear guidance on the feedstock, temperatures, and residence times needed for specific applications.

Biochar presents an opportunity to turn low-value wood into a high-value product that can benefit soils, forests, and ecosystems. CDR credits expand on this benefit through the promise of additional income. Breaking the barriers to CDR credits from biochar is an opportunity to help landowners and the climate.

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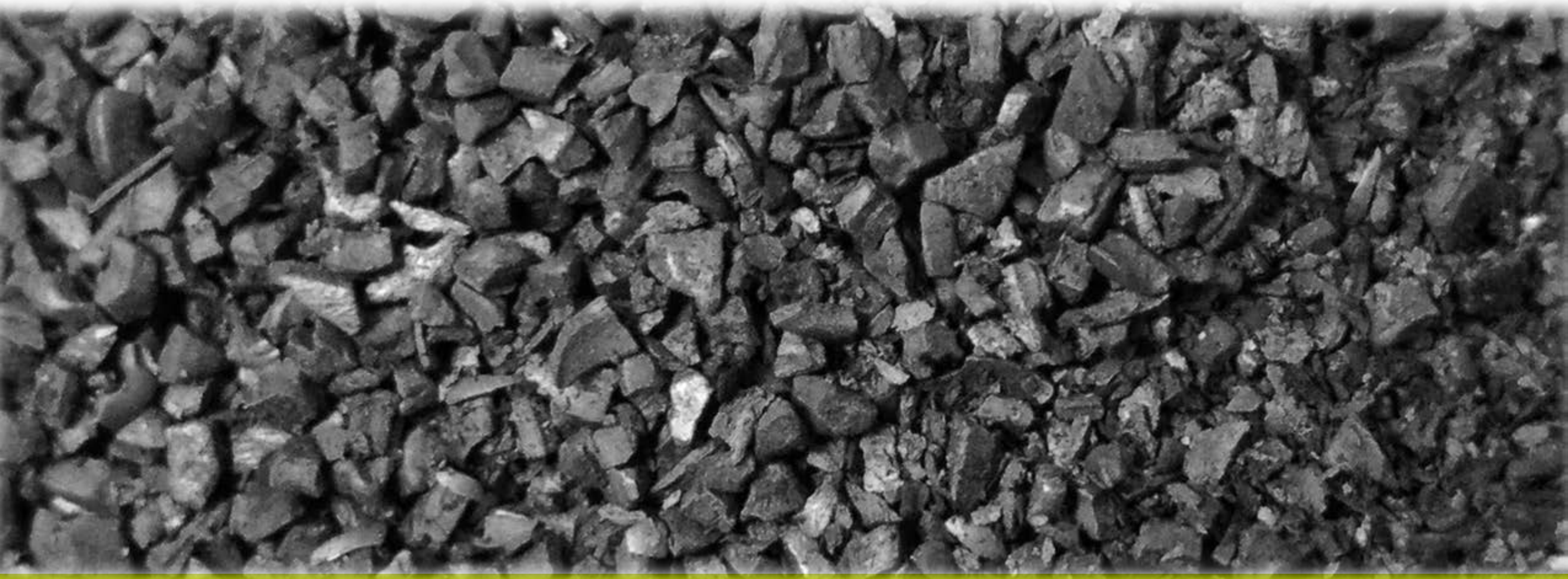

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