

Perspective

Soils and Beyond: Optimizing Sustainability Opportunities for Biochar

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Abstract: Biochar is most commonly considered for its use as a soil amendment, where it has gained attention for its potential to improve agricultural production and soil health. Twenty years of near exponential growth in investigation has demonstrated that biochar does not consistently deliver these benefits, due to variables in biochar, soil, climate, and cropping systems. While biochar can provide agronomic improvements in marginal soils, it is less likely to do so in temperate climates and fertile soils. Here, biochar and its coproducts may be better utilized for contaminant remediation or the substitution of nonrenewable or mining-intensive materials. The carbon sequestration function of biochar, via conversion of biomass to stable forms of carbon, does not depend on its incorporation into soil. To aid in the sustainable production and use of biochar, we offer two conceptual decision trees, and ask: What do we currently know about biochar? What are the critical gaps in knowledge? How should the scientific community move forward? Thoughtful answers to these questions can push biochar research towards more critical, mechanistic investigations, and guide the public in the smart, efficient use of biochar which extracts maximized benefits for variable uses, and optimizes its potential to enhance agricultural and environmental sustainability.

Keywords: biochar; soil; agriculture; climate change; remediation; bioenergy; coproducts; sustainability; carbon sequestration; perspective



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1. Introduction

The rise in popularity of biochar, or pyrolyzed biomass, can be traced through multiple sectors across the globe. In the scientific community, articles mentioning the word biochar are published at a near exponential rate [1], and in the private industry, United States patent applications mentioning biochar increase nearly every year [2] (Figure 1). Surrounding this scientific and entrepreneurial activity are the many associations dedicated to biochar, from governmental groups at the federal, state, and local level, to nonprofits and trade groups. In 2021, the International Biochar Initiative (IBI) reported a 30% increase in membership revenues from 2020, comprised of both corporate and individual memberships, and a greater than 60% increase in newsletter subscribers from 2018 [3]. Perhaps most surprising is the rise in interest from the general public. “How to make biochar” workshops abound, as do YouTube videos with presentations on the “exceptional results” of biochar in home gardens, and impassioned descriptions of how biochar is the future of sustainable agriculture.

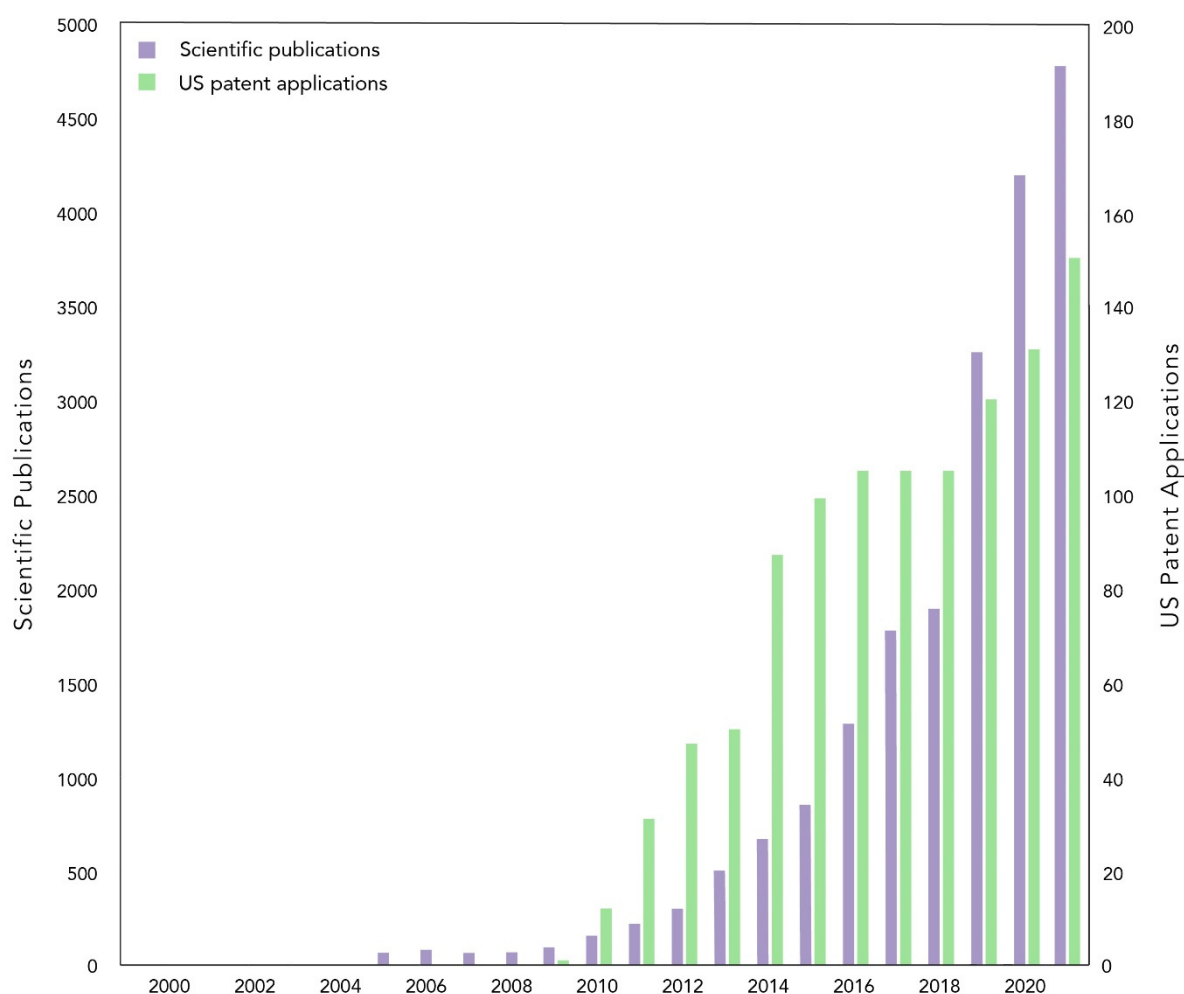


Figure 1. The rise in interest in biochar, demonstrated through the number of scientific publications per year (purple, left *y*-axis) and the number of United States (US) patent applications (green, right *y*-axis). Data located based on keyword searches of the word “biochar” [1,2].

In this regard, the study of biochar is not dissimilar to that of soil health or soil carbon sequestration, with interest spreading beyond scientific and agricultural communities and its merit debated in the public arena [4,5]. While claims that adding biochar to soils can increase soil health and sustainability are commonplace [6–8], the scientific community has yet to reach consensus on whether biochar can consistently deliver these benefits, or if it has merely fallen victim to hyperbole [9]. In agriculture, biochar is proposed as a soil amendment that can increase crop yield, soil fertility, and water holding capacity [10–13]. However, a growing number of meta-analyses and literature reviews demonstrate that these benefits are not consistently realized [13–15]. Divergent results are in part due to the fact that “biochar” is an umbrella term for many diverse carbonaceous products, created from different feedstocks at different temperatures using different methods. Once biochar has been produced, still more variables are introduced. Is biochar being added to the soil? If so, which biochar, to what soil texture, at what rate, in what climate, to what system, and for what purpose? Is biochar being used for remediation? For what contaminant and in what medium? The decision tree that accompanies the production and use of biochar can generate a myriad of possible outcomes, which will not equally deliver agricultural, ecological, environmental, or climate change mitigation benefits. This poses numerous challenges to making comparisons between biochar studies, and to creating unified recommendations for the effective and sustainable use of biochar.

Nevertheless, the idea of adding biochar to working lands is garnering attention in the policy arena. In 2018, the Intergovernmental Panel on Climate Change (IPCC) described biochar as a leading natural climate solution [6]. In 2020, the National Resource Conservation Service included biochar alongside compost and whole orchard recycling in their Soil Carbon Amendment, as a practice that can deliver a suite of agronomic and environmental benefits [16]. With the public movement for biochar surging ahead, it is essential that the scientific community begins a new era of self-awareness concerning biochar research. We must ask ourselves: (1) What do we really know about biochar? (2) What are the critical gaps in knowledge? (3) How can we best move forward? Answers to these questions can improve our work in biochar research to produce deeper, more mechanistic results, and to provide stakeholders with smart and efficient uses of biochar that optimize environmental and agronomic benefits. The enthusiasm that surrounds biochar may be useful for raising awareness, stimulating scientific dialogue, and leveraging research funding. However, the scientific community must prevent biochar from being stigmatized as a trend at best, or snake oil at worst. Instead, we can assist in the evaluation of biochars for benefits they are likely to deliver, those they are unlikely to, and the production and use parameters which optimize intended benefits for specific conditions.

2. What Do We Really Know about Biochar?

Biochar is a category of heterogeneous materials which possess unique chemical and physical properties. These properties are a function of production variables such as the method (i.e., gasification, pyrolysis, flow-through, batch), production temperature, and feedstock. Hassan et al. (2020) reviewed 533 datasets to determine that increased production temperature resulted in an overall increase in pH, surface area, pore size, ash content, hydrophobicity, and biochar stability, as determined by the oxygen to carbon vs. hydrogen to carbon ratios [17]. They also determined that biochars derived from hardwood and softwood have greater surface area and carbon content than those from manure or grass, while manure and grass biochars have more abundant oxygen-containing functional groups and mineral constituents. While there is clearly high variation amongst biochars, they are overall characterized by stable carbon (C), high surface area, reactive surface functional groups, low bulk density, and neutral to basic pH [18]. These properties endow biochar with the potential to deliver a broad range of benefits.

For the purposes of this discussion, benefits will be grouped into the following categories, though we do not claim the categories are entirely comprehensive or mutually exclusive: agricultural production, climate change mitigation, contaminant remediation, product substitution, waste management, and renewable fuel production (Figure 2). The first three categories, in order, dominate scientific investigation [15], while product substitution is an emerging but less studied use. The categories of waste management and renewable fuel production also receive less scientific investigation, but may be considered nontarget or co-benefits resulting from the production and use of biochar. Despite less research into non-soil applications, they may deliver increased environmental and economic advantages. Further investigation into strategies for optimizing co-benefits, and into new and innovative uses for biochar, is required.

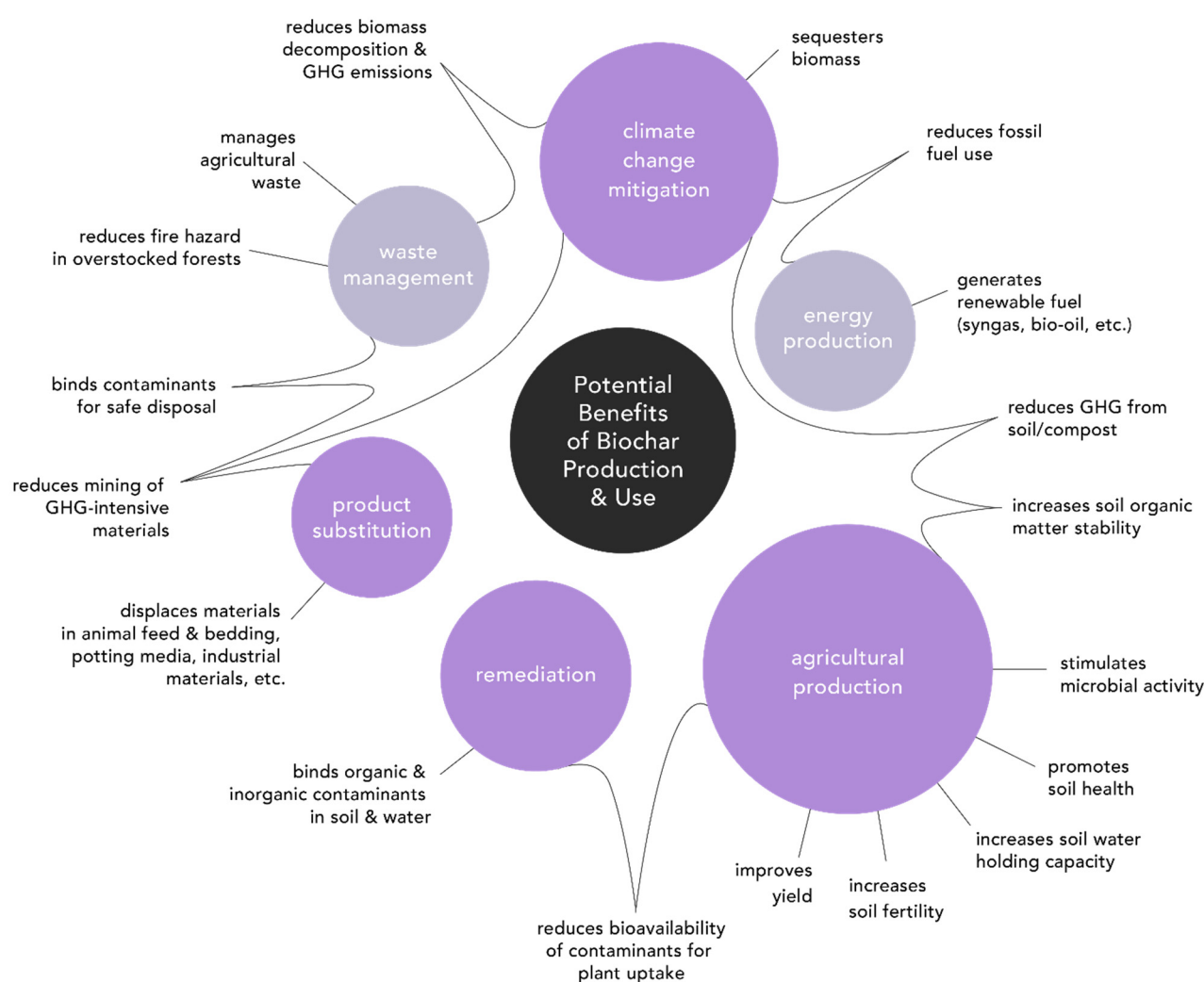


Figure 2. Conceptual diagram of the potential benefits of biochar production and use. Primary benefits (bold purple) are sized according to the number of related publications [15]. Co-benefits are rendered in light purple. Benefits included here are not exhaustive or mutually exclusive, nor will they be consistently realized depending on variables in the biochar and in the system in which they are utilized.

2.1. Agricultural Production

Adding biochar to agricultural land is its most commonly investigated use [15]. While application rates vary widely, one meta-analysis concluded that the greatest benefits were observed in studies utilizing 100 t ha^{-1} [19]. This unrealistically high rate poses obvious practical and economic challenges. More recently, Oladele (2019) developed a soil quality index using data from a three-year field trial, which concluded that a biochar application rate of $6\text{--}12 \text{ t ha}^{-1}$ was optimal, though results were constrained to acidic alfisols (USDA Soil Taxonomy) [20]. Pandit et al. (2018) conducted an economic analysis which included payments for C sequestration, to determine an optimal rate of 15 t ha^{-1} [21]. Guo (2020) made even more specific recommendations based on the results of a literature review and from greenhouse trials, concluding that biochar should be applied at a concentration of 2–5% by weight for wood- and crop residue-derived biochars, and 1–3% for manure-derived biochars [22]. While biochar is typically amended to soils by broadcasting it on the soil surface and tilling it in, subsurface banding may be a more efficient method for concentrating biochar in the crop rhizosphere and for minimizing dust emissions [23]. Unlike other soil amendments, biochar is persistent in the soil and does not need to be applied every year. As biochar will weather over time, it has been suggested it should be applied every three years to optimize potential benefits [20]. This recommendation should

be considered with caution, as there have been no long-term studies which analyze the effects of biochar application repeated every three years.

Biochar has been reported to deliver a suite of agronomic benefits when added to agricultural soils, including increased crop yields [10], soil fertility [11], soil water holding capacity [12,13], microbial biomass and activity [24,25], a shift towards more fungal-dominated microbial community composition [25], and the suppression of soil borne pathogens and disease [26]. While many studies demonstrate increased crop yield following biochar addition [21,27,28], others show little to no effect [29–31], and in some cases, negative effects have been reported [32]. The efficacy of biochar to deliver agronomic outcomes is dependent on the myriad of variables previously discussed. This has resulted in multiple researchers concluding that location- and material-specific consideration is required to optimize agronomic benefits for a particular system [14,15,19].

Biochar amendment can increase soil fertility, which in turn may increase crop yield [21,27,28], or lead to minor [30,33], temporary [31], or soil texture-specific yield increases [34–36]. Increased soil fertility is often attributed to the typically high cation exchange capacity of biochars (CEC), which can result in increased exchangeable cations such as magnesium (Mg^{2+}), potassium (K^+), calcium (Ca^{2+}) [21,34], and ammonium (NH_4^+) [37] in the soil. Biochar amendment has also been reported to benefit saline and sodic soils, through the sorption of sodium (Na^+) on exchange sites, or by releasing non-sodium base cations to decrease exchangeable sodium percentage [38–40]. The retention of anions such as nitrate (NO_3^-) is typically hindered due to unfavorable electrostatic interactions [41]; however, pores within biochar may retard nitrate leaching and make it more available for plant uptake [42–44]. Additionally, modification of biochar to increase the anion exchange capacity has been shown effective for nitrate retention [41]. Although biochars are not considered fertilizing materials, there can be temporary changes in soil fertility from the release of nutrients within biochar, particularly for animal manure-based biochars. Regardless, the use of synthetic fertilizers, compost, or manure is recommended for use in conjunction with biochar amendment [45–48].

The potential impact of biochar on soil water dynamics has led to many investigations of the material as a strategy for increasing crop water use efficiency and mitigating the vulnerability of soils to drought conditions. Recent meta-analyses concluded that biochar substantially increased soil water content at field capacity and permanent wilting point in coarse textured soils only [12,13]. Despite these observed trends, benefits have also been observed in fine textured soils, including reduced crop water stress, increased yield [49,50], and reduced crop loss during deficit irrigation [51]. Other authors have reported little to no effect, or transient effects, of biochar on soil water dynamics in both fine and coarse textured soils [29,30,52].

The conditions in which biochar appears to deliver the most consistent agronomic benefits are those in which soils require conditioning or remediation for the successful growth of crops, including low pH and sandy soils. A global meta-analysis concluded that biochar boosts yields in the tropics by 25%, but overall has no effect on yield in temperate latitudes [14]. Arable tropical soils are typically characterized by acidity, low fertility, and receive limited fertilizer inputs, and therefore may have the most to gain from the addition of biochar. Since most biochars are alkaline within a pH range of 8 to 10, they can increase soil pH to reduce aluminum toxicity and increase phosphorous availability [53,54]. However, it has been observed that up to 50 t of biochar per hectare may be required to match the liming effect of just 3 t per hectare of dolomite [55]. Biochar can also immobilize heavy metals or organic pollutants, thereby increasing yields and decreasing the concentration of contaminants in crop biomass [56,57]. Collectively, this research suggests biochar has a promising role in remediating or conditioning soils that may otherwise pose challenges for agricultural production. There appear to be fewer agronomic benefits from applying biochar to temperate and fertile cropping systems [14].

Current research regarding the use of biochar in soils demonstrates mixed results, with studies indicating that cropping systems in sandy or highly weathered soils are most likely

to benefit. Soil health and sustainability benefits are less widely studied; however, results also appear dependent on soil texture, with increased aggregation more likely to occur in fine soils [58,59], and microbial benefits in coarse soils [24]. Mixed results emphasize the need for a prescribed approach to amending agricultural soils with biochar, in which the right biochar is added, at the right rate, in the right form, in the right context to increase the probability of tangible benefits.

2.2. Climate Change Mitigation

The policy interest in biochar is driven primarily by climate change mitigation goals, as the production and use of biochar may reduce global warming potential (GWP) through multiple mechanisms. Biochar is produced through the thermochemical conversion of organic waste materials such as wood from forest thinning operations, manure, and crop residues such as corn stalks, rice hulls, and grape pomace. This process has clear waste management benefits. Depending on production parameters, energy coproducts can also be generated. Gasification and slow pyrolysis are two common strategies for the thermochemical conversion of biomass. Each process transfers the heating value from carbonaceous materials into syngas, bio-oil, and biochar [60]. Syngas and bio-oil can be utilized to displace the onsite use of regional electricity grids and therefore reduce the dependence on fossil-based fuels. Biochar can mitigate greenhouse gas (GHG) emissions by fixing C that would otherwise be emitted as biogenic carbon dioxide during biomass decomposition, into recalcitrant aromatic ring structures [61]. While biochar is commonly cited as a source of persistent C, biochar stability varies as a function of its chemistry, with lower oxygen (O) to C ratios (O/C) linked with greater stability [62]. A meta-analysis based on 128 observations estimated that 3% of biochar C has a mean residence time (MRT) of only 108 days, while 97% has an MRT of 556 years [61].

While similar coproducts are generated from gasification and slow pyrolysis, each process results in different quantities of syngas and biochar. Because gasification involves partial oxidation, less C is fixed into biochar resulting in lower biochar yields and higher syngas yields [63]. Slow pyrolysis, by contrast, occurs in low or no-oxygen conditions and optimizes for the production of biochar rather than syngas. Multiple life cycle assessments (LCAs) have been conducted to evaluate slow pyrolysis and gasification waste management systems in terms of their GHG balance and economic feasibility [63–68]. Studies frequently conclude that gasification is a more favorable waste management strategy in terms of economic viability, as syngas has a higher monetary value than biochar and is not dependent on the cost of C offset incentive programs. Because of the higher biochar yield, however, slow pyrolysis has been shown to deliver greater benefits in terms of C abatement and an overall reduction in GWP [63]. A recent literature review concluded that biochar LCAs collectively demonstrate “significant” and “obvious” climate change mitigation benefits [69], most of which are the result of direct C sequestration rather than energy production. Because of the uncertainty in the literature regarding benefits and drawbacks of biochar as a soil amendment, most LCAs do not model the performance of biochar once it has been applied to soil. This uncertainty is reflected in policy arenas as well, such as in the IPCC 2018 Special Report, which included biochar production as a negative emissions technology due to C fixation, but excluded secondary GHG benefits of biochar in the soil [6].

The purported secondary GHG benefits of adding biochar to soil are due in part due to the potential for biochar to promote the formation and preservation of soil organic C. Since biochar itself is primarily comprised of C [18], it is not surprising that many authors report increased total C following biochar addition [10,20,24,70]. Simply put, adding C to the soil increases C in the soil. Due to challenges in methods, few authors distinguish between added biochar C and secondary soil C formation or preservation that may occur due to the addition of biochar. However, methods such as dichromate oxidation [71,72] and the use of molecular markers via the benzene polycarboxylic acid (BPCA) method [73,74] are available to make these distinctions.

Biochar has been observed to increase microbial biomass C by altering the soil chemical environment through increased nutrients or changes in pH, or the soil physical environment by providing additional habitat via increased surface area or porosity [25,75]. Biochar may also shift the soil microbial community composition towards increased ratios of fungal to bacterial phospholipid fatty acids (PLFAs), and Gram positive to Gram negative PLFAs [25]. These shifts are often interpreted to indicate a bacterial community more effective at utilizing recalcitrant C or enduring soil nutrient and water shortages [25,76]. Multiple authors have observed that biochar amendments can lead to increased soil aggregate size and stability [58,59,77], which may indicate an increased ability to store and protect soil C [78]. Two proposed mechanisms for this are an increase in multivalent cations which bridge organic colloids and clays, and the increased presence of bacterial mucilage and fungal hyphae [79]. Finally, biochar has been observed to protect soil C through negative priming of soil organic matter [61]. As with other effects, the ability of biochar to influence soil aggregation or the microbial community appears dependent on a suite of biochar properties, such as pH, nutrient content, and labile C, as well as the physiochemical properties of the soil [25,58,75,80]. Furthermore, benefits may not persist over time [81], or may be overridden quickly by shifts in management practices [82].

Another potential climate benefit resulting from the use of biochar is its ability to reduce GHG emissions from the matrix it is added to. A meta-analysis of 608 observations from 88 studies concluded that, overall, biochar reduced nitrous oxide (N_2O) emissions by 32% when added to the soil, though effects were negligible after one year [83]. Results were greatest in paddy soils and sandy soils, but were not observed in grasslands or perennial crops. Reductions in soil ammonia (NH_3) volatilization have also been observed, although a meta-analysis of 144 observations concluded there was minimal response overall [84]. Biochar application to acidic soil was observed to increase the emission of NH_3 , while combining biochar with urea or organic fertilizer, or using wood-based or acidified biochar, was observed to reduce NH_3 emissions [84]. Mechanisms for biochar associated GHG reductions are poorly understood, though hypotheses frequently include the ability of biochar to alter pH or soil water and aeration dynamics, chemically or physically retain nitrate or ammonium, increase pH buffering capacity, and serve as an electron shuttle for microbes involved in the nitrogen cycle [83–86]. These hypotheses have been used to explain reductions in the emissions of N_2O , NH_3 , methane (CH_4) [46,87], and volatile organic compounds (VOCs) [88] from green waste and manure composting process, as well. Finally, biochar has been observed to reduce the GHG impacts of livestock production when added to animal feed. A literature review of 112 publications determined that in most studies, and for all investigated livestock species, adding biochar to animal feed resulted in reduced GHG emissions, as well as positive effects on parameters such as toxin adsorption, digestion, blood values, feed efficiency, and meat quality [89].

The climate change mitigation benefits of biochar can be optimized by ensuring the production and distribution of biochars with low O to C ratios for maximum stability [62]. The widespread adoption of policies such as California's AB-2511, which requires biochars to be a minimum of 60% C [90], could assist in this goal. However, this definition of biochar excludes materials with less than 60% C, and may reduce the availability and use of these potentially beneficial materials. Nuanced categories based on specific criteria may be more useful to ensuring the sustainability benefits of biochar. It is also essential to avoid generating additional GHG emissions during the biochar life cycle, by optimizing systems to minimize feedstock and biochar transportation, energy inputs, and the use of non-waste biomass products [63–66,68]. Finally, careful regional analyses should be conducted on the existing uses of feedstocks, to avoid utilizing biomass from domains where it is already providing ecosystem services, such as the return of crop residues for increased soil health or erosion control.

2.3. Environmental Remediation

Though biochar is primarily considered an agricultural soil amendment, there is great promise for its use in soil remediation. Biochars possess a range of unique chemical and physical properties which can make them highly effective materials for facilitating contaminant binding, bioremediation, and phytostabilization. Similar to activated carbon, which is commonly used in remediation, biochars typically have high surface area, aromaticity, and cation exchange capacity, making them favorable absorbents for a range of heavy metals [91,92], pesticides [93,94], and organic compounds [95,96]. In many cases, tailoring the biochar feedstock and pyrolysis conditions for specific contaminants is key for remediation efficiency [41,97]. As the costs of soil remediation are typically high, biochar can serve as a low-cost and sustainable alternative in certain scenarios.

The high affinity of organic hydrocarbons to activated carbon and charcoal has long been established. It is, therefore, not surprising that biochar can serve as a sink for a wide range of organic contaminants, with affinity typically increasing with increased hydrophobicity and aromaticity [17,56,98,99]. Thus, biochar can be utilized to immobilize pharmaceuticals in animal wastes [100], wastewater [101], and biosolids [102], reduce the mobility of pesticides [103], or serve as a sink for petroleum-based compounds [104]. Through these mechanisms, the bioavailability of contaminants to surrounding organisms can be reduced via sorption to biochar [105–107]. There is also a growing body of evidence which demonstrates that biochar can facilitate biodegradation of organic contaminants in impacted soils [108–110]. This may have enormous implications for the cost and effectiveness of organic remediation efforts. However, for these technologies to be fully developed, further investigation is required into the physical and chemical parameters of biochars which best facilitate specific contaminant binding and bioremediation of organic compounds.

Remediation of metal(oid)-contaminated soils is particularly challenging as metal(oid)s do not degrade. Numerous studies demonstrate that biochars can favorably bind heavy metals [17,111,112], due to their high surface area and cation exchange capacity, through chemisorption and electrostatic interactions. As a result, biochars applied to heavy metal-contaminated soils can reduce metal bioavailability and phytotoxicity [113,114], thus facilitating phytostabilization via establishment of plant cover and, subsequently, additional contaminant immobilization through plant uptake or through increased exudates and organic matter production [115–118]. While metal retention can contribute to enhanced food safety, it is not a perfect solution, as metals will remain in the soil and may be released as biochars age. A novel approach to remediate metal(oid)-contaminated soils is via magnetic biochars that bind metal(oid)s, and can subsequently be recovered to remove bound contaminants [119–122]. However, this approach is likely best suited for aquatic environments, as magnetic biochar is challenging to recover from drier soils.

Wastewater, stormwater runoff, and various aquatic environments can offer ideal systems in which to utilize biochar for the removal of nutrients and contaminants [123–125], especially where biochars have been modified to carry out this task [41,123,126]. Biochars are frequently modified with the aim to increase positive charge on the biochar surface, through the addition of iron [127], magnesium [128], and cationic polymers [129]; through its incorporation into layered double hydroxides [130]; and by adding oxidants, acids, or alkalis [126,131]. In scenarios where biochar remediates excess nutrients from aqueous environments, the nutrient-loaded biochar can be reutilized as a fertilizing material in agriculture [123]. Additionally, sewage sludge from aquatic systems can be converted into biochar [132] for carbon stabilization and as a potential source of nutrients.

The ability of modified and unmodified biochars to bind both organic and inorganic contaminants makes their use in remediation highly effective. Research is ongoing into successful and cost-effective strategies for tailoring biochars for bioremediation, phytostabilization, contaminant removal, and nutrient recovery. These uses likely provide greater economic and environmental benefits than its use as a soil amendment in agriculture. In summary, biochar offers a low-tech and cost-efficient option for addressing many environ-

mental challenges, with the potential co-benefits of biomass waste management, carbon sequestration, and renewable energy production.

2.4. Product Substitution

The primary carbon sequestration benefits of biochar are achieved merely through its production, and do not necessitate that biochar be added to the soil. Perhaps the least studied but most promising uses of biochar are those that employ it as a substitute for materials otherwise requiring GHG-intensive processing. In an idealized system, biochar can be created from waste biomass as a coproduct of energy production, and then utilized as a substitute for materials that would otherwise be extracted, mined, or refined.

Biochar is increasingly being studied as a substitute for the porous and low-weight materials in potting media [133]. Headlee et al. (2014) observed a biochar produced from red oak at 500 °C to completely replace vermiculite, a nonrenewable and mining-intensive material, with no negative effect to the growth or nutrient uptake of poplar trees [134]. Margenot et al. (2018) illustrated that a softwood biochar produced at 800 °C could replace 100% of the peat in a potting mix, with no negative effect on marigold growth or quality [135]. Yan et al. (2020) demonstrated no negative effects on mint yield or quality when 80% of the peat was substituted with a hardwood biochar produced from fast pyrolysis [136]. Data from these and other studies, including an LCA [137], have enormous implications for the nursery industry. Currently, potting media rely heavily on the GHG-intensive mining of peat bogs, which collectively serve as a global C sink and are part of irreplaceable wetland ecosystems [138–140]. Biochars produced from softwood and hardwood at multiple temperatures have also been observed to replace peat as an inoculum carrier in seed coatings, with increased corn yield and germination rates [141].

Because biochars are typically highly porous, have low bulk density, and contain reactive surface functional groups, it has been observed that biochar can serve as an odor control additive to various matrices [142]. Vaughn et al. (2020) determined that biochar produced from Eastern Redwood Cedar at 928 °C could replace mining-intensive clays in a low dust, odor-controlling, biodegradable cat litter formulation [143]. Flores et al. (2021) observed that biochar produced from *Miscanthus* grass at 400 °C could be added to turkey bedding at a rate of 20%, to reduce reliance on increasingly scarce pine shavings [144]. Biochar in this study resulted in increased hygienic conditions in the bedding matrix, reduced incidence of animal stress, and an increase in the growth rate and overall body weight of turkeys. When added to animal feed, biochar has been observed to reduce odor-causing NH_3 and CH_4 [89]. While biochar cannot completely displace ingredients in livestock feed, it can be added to dilute the matrix and reduce the use of non-waste ingredients overall.

Coproducts generated from the biochar production process may also serve to displace GHG-intensive materials. As described earlier, the use of syngas and bio-oil can reduce dependence on fuel mixes—fossil or otherwise—from regional utility grids. Pyrolygneous acid (PA)—an organic liquid consisting of aliphatic, aromatic, and naphthenic hydrocarbons and other oxygenated compounds such as alcohols, aldehydes, ketones, furans, acids, phenols, and ethers—may also be generated through pyrolysis [145]. The use of PA in agriculture long predates the petrochemical industry, with most contemporary scientific investigation carried out in Asia. Grewal et al. (2019) produced a detailed review of studies which have demonstrated the ability of PA to deliver benefits such as enhanced plant growth and development, use as an antifungal and insecticide, and the ability to replace synthetic chemical herbicides [145].

There is also vast potential for biochar to be used in industrial applications, though this has been minimally studied. Its low thermal conductivity and water absorption properties may make it effective at regulating temperature and humidity in building applications, where it can replace non-biodegradable Styrofoam, or dilute the use of nonrenewable clay, lime, sand, and cement mortar [146]. Bartoli et al. (2020) authored a detailed review of the potential for biochar to aid in energy storage applications, by serving as anodic material in

batteries, as fuel in direct carbon fuel cells, and, through chemical or physical activation, as an elevated surface for the double ionic layer in supercapacitors [147]. Furthermore, biochar has also been observed to reinforce plastics, epoxies, and cements when mixed into the material matrix [147]. Recent focus on the environmental challenges associated with the use of micro-plastics in cosmetics has led scientists and entrepreneurs to search for low-cost and sustainable alternatives [148]. As biochar already has a long history in the beauty industry as a detoxicant in soaps and homeopathic salves [146], it may be a promising replacement for the plastic beads in skin and teeth exfoliants.

The substantial potential of biochar to be used in the substitution of materials with high GHG emissions provides further opportunities for biochar to “close the loop” and address global sustainability. While biochar is a form of sequestered carbon, its ability to replace products that generate carbon dioxide emissions makes it a highly attractive climate change mitigation tool. Additionally, biochar represents a low-cost option as a “green” technology to replace other products which are harmful to the environment.

2.5. Potential Consequences to the Widespread Use of Biochar

Though biochar LCAs illustrate clear climate change mitigation benefits, authors of two separate analyses warn that biochar-related pollution may contribute to a larger negative effect over its life cycle, due to the potential adverse human health impacts [63,65]. Potential consequences remain critically understudied [149]. While a low bulk density and high surface area can lead to benefits such as water and nutrient retention, they also render biochar susceptible to off-site transport via surface runoff, or airborne release as particulate matter less than 2.5 or 10 μm in diameter ($\text{PM}_{2.5}$ or PM_{10} , respectively) [150,151]. This can occur during low-tech biochar production, during biochar application to the soil, or after it has been incorporated as the result of mechanical tillage or wind- or water-driven erosion. Agricultural dust is a major contributor to PM_{10} , particularly in intensively farmed regions [152–154]. Exposure to both the organic and inorganic components from agricultural PM_{10} have been linked with adverse health effects in farmworkers, including increased chronic respiratory symptoms and the worsening of lung and heart disease [155–158]. With the growing interest in biochar as a soil amendment comes an imperative to better understand potential consequences for water and air quality, and how these might affect the health of agricultural workers, neighboring farm communities, livestock, and wildlife.

The organic and inorganic chemical constituents of biochar may also present a human health risk [159,160]. Polycyclic aromatic hydrocarbons (PAHs), for example, are known to form during the pyrolysis of biomass, with concentrations heavily dependent on production methods, feedstock, and temperature [161–163]. While most biochars contain PAH concentrations well below environmental quality standards [161,164,165], others have values well beyond [161,166–169]. Other native toxicants formed or concentrated during biochar production may include heavy metals, volatile organic compounds (VOCs), dioxins, furans, and polychlorinated biphenyl (PCBs), with some biochars showing endocrine disrupting potential [170]. Heavy metals occur naturally in biomass feedstocks and are concentrated in biochar through the production process [165]. As with PAHs, many studies demonstrate biochars to have metal concentrations well below most environmental quality standards [164,165,167,171]. Biochar copper and zinc levels, however, have been observed to have phytotoxic effects in cucumber, cress, and sorghum [172]. Similarly, high levels of VOCs have been detected in biochar and observed to cause phytotoxicity in cress [173]. In contrast, observed levels of total dioxins, PCBs and furans in biochar are often very low, with bioavailable fractions below analytical detection limits [161,174].

As this is an emerging field of research, few studies have investigated potential ecological and human health consequences. While rare, the potentially toxic properties in biochar have been observed to cause phytotoxicity, cytotoxicity, and additional adverse effects such as extracellular enzyme inhibition or earthworm avoidance [175]. There are also studies which suggest biochar PAHs may be carcinogenic if ingested via vegetables grown in biochar-amended soils [176,177]. By contrast, Liu et al. (2019) determined there was

little to no release of PAHs from biochar in simulated lung fluids, even under “worst case scenario” exposure [178]. This may indicate that biochar PAHs are not readily bioavailable through inhalation pathways. Additionally, the concentration, and therefore, potential toxicity, of PAHs has been demonstrated to decrease as biochar ages [179,180], indicating that potential threats may be short-term and easily managed. Fortunately, there are a growing number of strategies for mitigating the potential consequences of the production and use of biochar.

2.6. Strategies for Mitigating Consequences

During the biochar production process, steps can be taken to create a safer, more effective soil amendment. As heavy metals and metalloids are concentrated in biochar through thermal conversion [165], the use of treated feedstocks such as chromated copper arsenate (CCA)-pressure treated wood should be avoided, along with materials from construction and demolition, and feedstocks of unknown origin. Research suggests that slow pyrolysis may minimize biochar PAH content compared to gasification, and that increased residence time [161] and rate of carrier gas flow [163,181,182] can offset PAH formation under high temperatures. There may also exist simple pre- and post- production modifications that reduce levels of contaminants. Studies indicate that drying feedstock biomass prior to pyrolysis may reduce production-related PM₁₀ emissions, as well as PM-bound PAHs, as the presence of moisture encourages the incomplete combustion of volatile compounds formed during pyrolysis [183]. Research has also demonstrated that biochars can be dried at temperatures between 100 and 300 °C, effectively removing PAHs through thermal desorption within 24 h [184]. Efforts have also been made to improve the physical properties of biochar during its production. An increasingly popular technique is to pelletize biochars to increase resistance to abrasion [185]. Addition of binders during pelletization, such as lignin and Ca(OH)₂, can further enhance the mechanical strength of biochars [186]. With increased mechanical strength and abrasion resistance, biochar may emit less dust compared to those that have not been compressed.

Major (2010) summarizes various biochar application methods and recommends combining biochar amendment with other on-farm processes to reduce costs and to minimize the potential for dust emissions [23]. Suggestions include adding biochar to compost or liquid fertilizer. To reduce dust emissions, recommendations for applying biochar with high moisture content or in liquid slurries are common, as are warnings to avoid application on windy days [159,187,188]. While most biochar field trials utilize a broadcasting application technique (Figure 3d), Major (2010) suggests that subsurface banding (Figure 3a–c) may have the greatest potential to reduce wind and rain-driven biochar losses. Regardless of application method, the use of appropriate respirators, eye protection, gloves, long sleeves, and pants is recommended for farm operators and workers while handling biochar [189].

Governments can play a key role in developing and enforcing policies that ensure the safe production and handling of biochar. The United States has not yet adopted required regulatory standards for biochar contaminant levels (e.g., PAHs, heavy metals), though maximum threshold values for a limited number of toxicants have been established in frameworks proposed by the European Biochar Certificate (EBC) [187] and the International Biochar Initiative (IBI) [190]. As of June 2021, IBI lists four biochars certified to meet their safety and quality standards, all of which are in the United States [191]. EBC lists 27 certified biochars from Austria (3), Finland (1), France (1), Germany (11), Romania (1), Serbia (1), Sweden (4), and Switzerland (5) [192]. Differences in these standards have led to inconsistencies in both scientific and legislative literature. There is a pressing need for a unified regulatory framework, which would facilitate communication in academic fields and in the emerging biochar market. Furthermore, outreach and education efforts could assist in ensuring the safe application of biochar to working lands. This may be particularly relevant when biochar is paid for by government cost-share or incentive programs as part of climate change mitigation strategies. In these cases, agencies could require producers

and land managers to review simple best management practices for the safe and effective use of biochar.

Recommended



Not Recommended



Figure 3. Practices that are recommended (**left**) and not recommended (**right**) for the application of biochar to agricultural lands. On the left, a biochar is applied to the field at 40% moisture content (**a**), using a subsurface banding technique (**b**) in which biochar is immediately covered by soil (**c**) so it is less likely to contaminate air or water as the result of wind- or rain-driven erosion. On the right, a biochar is applied at 0% moisture content (**d**), on a windy day (**e**), and left on the soil surface where it became airborne (**f**). Photo credit for (**a–c**) to Sanjai J. Parikh, (**d**) to Brian Kozlowski at the University of Tennessee, and (**e,f**) to Iris Holzer at the University of California, Davis.

3. What Are the Critical Gaps in Knowledge?

While there has been an extraordinary rise in scientific studies concerning biochar, there has not been a proportional rise in understanding. In Figure 4, we propose a conceptual diagram of how biochar investigation and the accrual of knowledge about biochar have advanced at different rates. In the earlier stage of research (Stage I), each publication contributed to an understanding of biochar and its various uses. In the current phase (Stage II), there has been a decrease in the rate of knowledge accrual, despite the near exponential increase in research (Figure 1). Though Stage I and II are likely present in many burgeoning fields of study, we believe it is particularly relevant for biochar, where the accrual of knowledge for optimizing its practical and sustainable use has stagnated behind the number of publications. This is in part due to biochar's numerous variables, which enable scientists to repeat similar experiments with slight alterations in biochar properties or experimental conditions. It is also due to a lack of sufficient mechanistic investigation. Biochar studies are not frequently designed to provide mechanistic explanations behind observed results, and thus, further insight remains in a "black box". While biochar is known to have a broad range of unique physicochemical properties, it is not sufficient for authors to mention these in passing as a possible explanation, or to leave results, without explanation, to be interpreted as the cause of a certain ineffable magic. As is noted in many places throughout the literature, scientists can advance the state of biochar knowledge into

the next and future stage (Stage III) with increased reporting of physicochemical properties and standardized characterization methods [190,193], as well as from further mechanistic investigation into results prior to their publication.

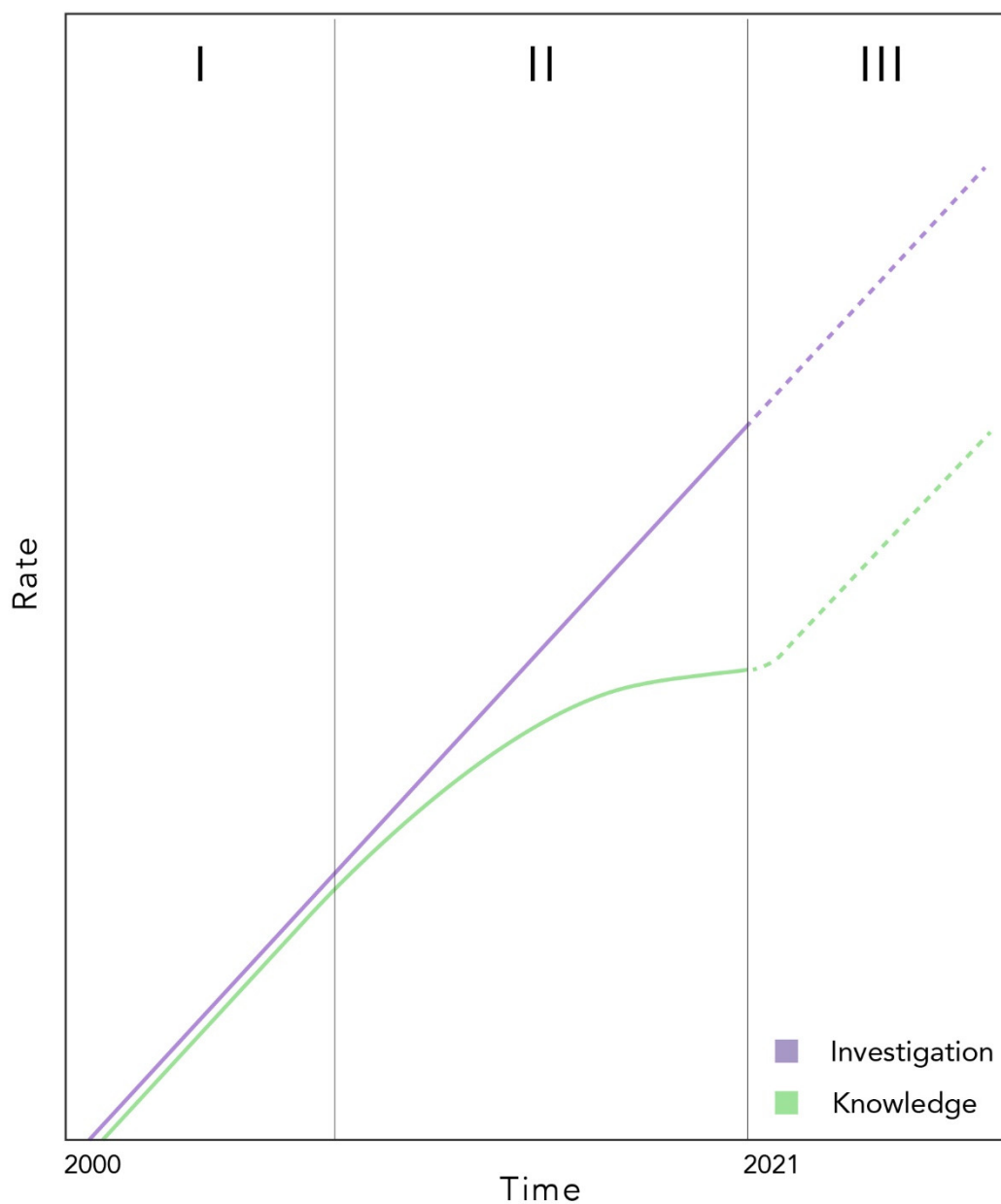


Figure 4. Conceptual diagram of the rate of biochar investigation vs. the rate of biochar knowledge accrual. In earlier stages of biochar research (Stage I), publications and knowledge were accrued at nearly the same rate. Currently (Stage II), research outpaces knowledge, with an increase in publications not necessarily leading to a concomitant increase in new, novel, or mechanistic understanding. In the future (Stage III), the scientific community can advance knowledge with every publication by working together creatively to produce deeper, more mechanistic results which optimize the environmental, ecological, and agricultural benefits of biochar.

Fortunately, there are an increasing number of meta-analyses which link specific results with particular biochar properties [12,25,45,53,84]. However, few of these link biochar properties with production variables [17], and even fewer with variables beyond feedstock and production temperature. Soil and agricultural scientists are not broadly equipped with the knowledge base and skill set to reliably determine how best to control variables such as chamber residence time and atmospheric pressure, levels of oxidation, or carrier gas flow rate, for the consistent development of specific properties. Biochar research may be propelled into Stage III through increased collaboration between soil scientists and those in the material, industrial, and bioenergy sciences, as well as with commercial biochar producers. These collaborations could result in a more comprehensive understanding of how to produce and utilize biochars for the consistent delivery of specific benefits.

The number of variables involved in the production and use of biochar for agronomic outcomes presents obvious challenges to ensuring benefits to any one particular system. Additionally, the challenge in creating highly similar biochars is prohibitive for other scientists to repeat studies or test those biochars in other climates, soils, and land management use. There is also the challenge of a dearth of long-term field-scale experiments. One literature review concluded that, of nearly 800 studies evaluated, approximately 25% were conducted in the field [10]. Of those field studies, more than 50% were in plots less than 20 m² and under investigation for one year or less. Authors also concluded that the majority of studies were conducted using small-batch laboratory-produced biochars, rather than those available at commercial-scale. This practice further prevents replicability in biochar research. These findings highlight the limitations in biochar research, which pose challenges to extrapolating results to production-scale agriculture. Indeed, it has been observed that laboratory results do not necessarily scale, as in Jones et al. (2012), where the short-term effects of biochar on soil properties, GHG emissions, and plant growth reported from laboratory studies were not observed in a three-year field trial using the same soil and biochar [25]. Fortunately, there have been a number of large-scale field trials spanning three or more planting seasons published in recent years [11,20,21,28,30,33,51,54,194–196]. However, inconsistencies in results from these and earlier studies emphasize the need for additional location-specific, biochar-specific, long-term, field-scale research, which link results with mechanistic investigations from the laboratory.

While there appears to be more consensus over biochar's ability to deliver climate change mitigation benefits, here too the state of knowledge suffers from a lack of observations beyond the lab. A recent report concluded that biochar may sequester over 1 Pg CO₂e yr⁻¹, but with high variability in estimates [197]. Authors note that the addition of biochar to soil has not been well demonstrated beyond research settings, and therefore, the trade-offs, cost, and feasibility of large-scale implementation are poorly understood. While the public interest in adding biochars to soil is palpable, the present provides a crucial opportunity for scientists to more critically examine how to optimize the potential of this terrestrial C sink. The legacy of Terra Preta de Indio—those storied carbon-rich soils of the Amazon—may have launched biochar research on an agricultural, soils-focused trajectory. However, it is not too late to diversify its uses if the data indicate that there are other strategies which may deliver more consistent benefits or reduced drawbacks. A large-scale analysis of regional biomass availability, technical capacity, and environmental and economic need may aid in the development of a quantitative biochar decision tree that supports users in optimizing benefits for local purposes. Conceptual decision trees for optimizing biochar benefits for both producers and users are provided in Figure 5.

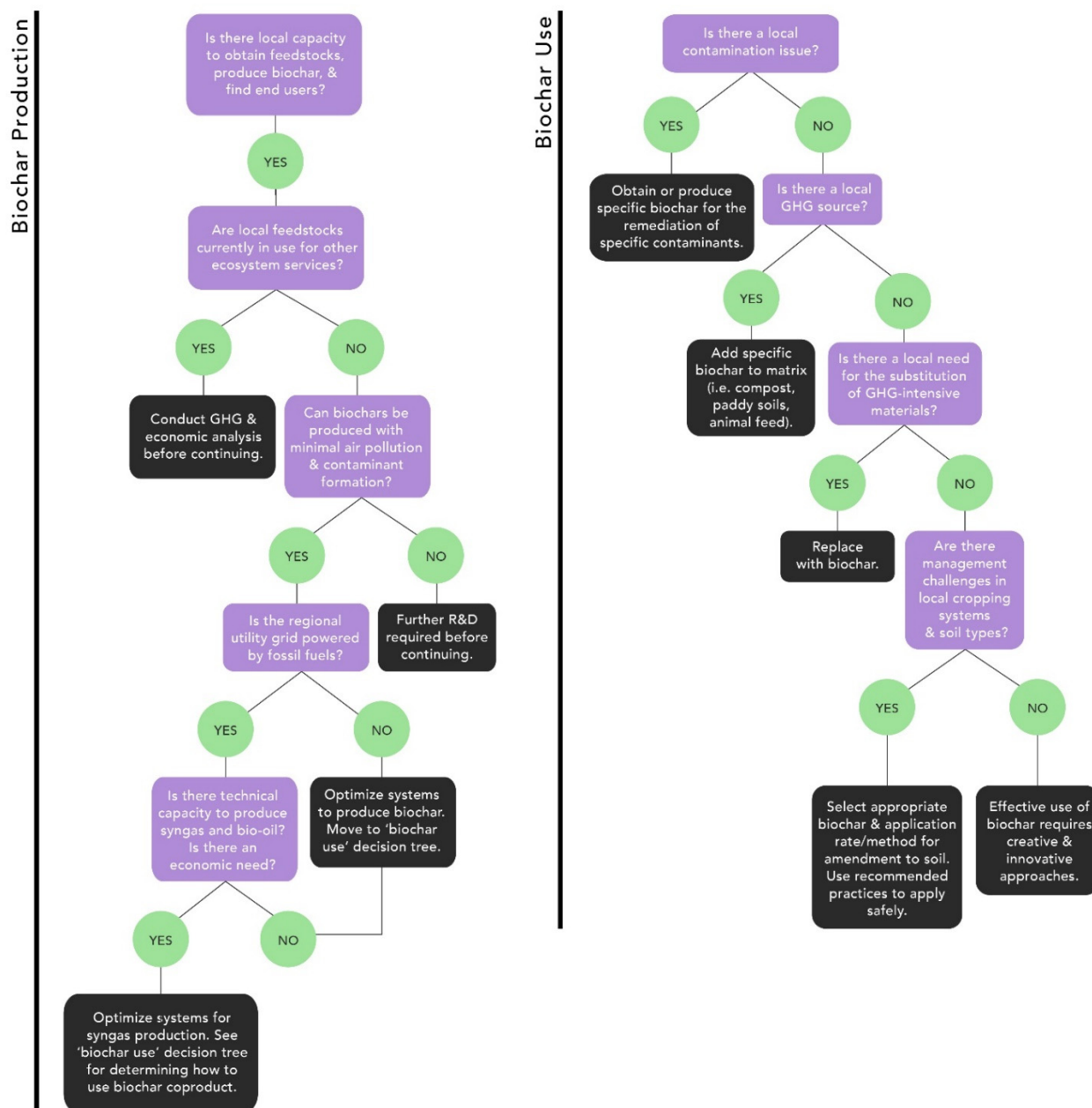


Figure 5. Conceptual decision trees for the sustainable production (left) and use (right) of biochar, which may aid in optimizing environmental and economic benefits.

4. How Can We Best Move Forward?

Scientists have a critical role in ensuring that the current boom in biochar research produces information for its safe and effective use, which optimizes benefits for humans and the environment. We propose that by working together as a scientific community, the following strategies can assist in this goal, and in doing so, increase the rate of knowledge accrual to match the rate of investigation.

1. Results and conclusions from biochar studies should be limited to the specific conditions in which results were observed. Biochar has great potential to deliver numerous agricultural and environmental benefits. However, it has many variables and will perform differently in different conditions. While the enthusiasm of the day is useful for driving research, generating awareness, and leveraging funding, scientists should be

careful to manage expectations and avoid generalizing their data to indicate that results extrapolate to other biochars or conditions.

2. Researchers should strive towards standardized biochar characterization methods and increased reporting of biochar production parameters and physical and chemical properties. In order to increase the efficacy of biochar for specific applications, it is necessary that researchers and biochar producers have access to comprehensive biochar production and characterization data. This is necessary for replicability of research, to guide decisions for biochar selection based on intended use, and to assist in tailoring biochars for specific purposes.

3. Biochar must be studied in real-world conditions to evaluate its long-term effects on soil productivity and health. There is a pressing need for long-term field-scale research utilizing commercially available biochars with high consistency in composition. As in all scientific fields, the pressure to produce results within a single grant cycle or graduate student tenure is an obvious challenge. However, our current reduced rate of knowledge gain will persist if we do not push experimental designs towards real world conditions. Only then can we better understand the benefits, drawbacks, tradeoffs, and costs associated with the production and use of biochar.

4. Results from biochar studies should always be explained on a physical, chemical, or biological basis. While field-scale research is critical, it is not sufficient for scientists to present results without further investigation into their mechanistic underpinnings. In order to advance the state of knowledge about biochar, results must be supported by mechanistic experimentation or explanations supported by other evidence.

5. Soil scientists cannot ensure the sustainable and effective production and use of biochar alone. In the research arena, there should be increased collaboration with industrial and material scientists in order to link biochar production parameters with specific characteristics. Groups of collaborators could work with large-scale biochar companies to produce biochars that are tailored for specific outcomes within certain soil and climate parameters. In the policy arena, scientists can guide the safe and effective use of biochar by working with governments to develop policies that require a specific O/C ratio for maximum C sequestration benefits. Policies should also be developed which require biochars to conform to safety standards. Finally, policy could assist in outreach and education efforts, so that biochars amended to working lands are applied in ways which safeguard human and environmental health.

6. Scientists, entrepreneurs, and other stakeholders should use creativity in discovering novel and beneficial uses for biochar. While research has demonstrated that biochar can improve soil health and agricultural production under specific conditions, its use in climate change mitigation, remediation, and product substitution may provide greater environmental benefits, with fewer potential unintended consequences. We must “think outside the soil” to advance biochar research towards new frontiers.

7. Biochar investigation should prioritize maximizing its numerous potential benefits. The technologies which convert waste biomass to biochar, bioenergy, and pyrolytic acid, have great potential to operate within “closed loop” systems if optimized properly. Locally sourced feedstocks can be converted to a range of coproducts, which can then be used locally for ecological, environmental, or agricultural outcomes. In temperate climates with fertile soils, biochar may be less useful as an agricultural soil amendment, and more beneficial in the remediation of contaminated sites, in storm or wastewater management, as a substitution for mining GHG-intensive materials, or modified to retain nutrients in compost production. If produced and employed thoughtfully, biochar has a high probability of serving as a climate mitigation tool. The key is to extract as many possible benefits from biochar production systems for multiple and variable uses.

While current efforts have largely focused on the potential of biochar to increase agricultural production and soil health, biochar research need not focus on soil alone. Biochars are a category of materials that can provide numerous benefits, and should be employed in a manner where they best address global sustainability constraints including, but not limited to, climate change, soil and water contamination, and productivity in

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