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Does biochar improve all soil ecosystem services?

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OPINION

Does biochar improve all soil ecosystem services?

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Abstract

Biochar is considered to sequester C and deliver other soil ecosystem services, but an overview that synthesizes the current knowledge of biochar implications on all essential soil ecosystem services is difficult to find in the ample biochar literature. Most previous research and review articles on this topic focused on a single ecosystem service and did not integrate all essential soil ecosystem services. This overview paper (1) synthesizes the impacts of biochar on water and wind erosion, C sequestration, soil water, nutrient leaching, soil fertility, crop yields, and other soil ecosystem services based on published literature and (2) highlights remaining research areas. Literature indicates that, in addition to sequestering C, biochar can reduce N_2O emissions, nitrate leaching, and runoff; increase soil microbial biomass, plant available water, and crop yields (particularly in tropical regions), and CO_2 emissions; and have small or no effects on water and wind erosion. Biochar benefits can be in this order: C sequestration > N_2O emissions > Nitrate leaching > Available water > Soil biology > Soil fertility > Crop yields > Runoff. However, literature also indicates that biochar does not always improve all ecosystem services. Its benefits depend on biochar feedstock, pyrolysis temperature, application rate, biochar properties, soil properties, climate, and other factors. For example, biochar can enhance crop yields more in degraded and low fertility soils than in highly fertile and fine-textured soils. Long-term (>3 years) field-scale studies under different soil types, management conditions, and climates are needed for a determination of optimum levels of application, comprehensive life-cycle analysis, and assessment of agronomic and environmental tradeoffs. Overall, biochar can improve most soil ecosystem services, but the extent of such improvement is highly dependent on biochar properties and soil and climatic conditions.

KEYWORDS
biochar, carbon sequestration, crop yields, ecosystem services, erosion, fertility, greenhouse gases, leaching, soil biology, soil water

1 | INTRODUCTION

Restoring and enhancing soil ecosystem services of agricultural lands are increasingly critical in the face of climatic fluctuations including droughts, intense rainstorms, flooding, and heat waves, among others (Feng et al., 2016; Routschek et al., 2014). Such vital soil services include provisioning (i.e., food, fiber, and feed production), regulating (i.e., climate fluctuations), supporting (i.e., cycling of C, water, and nutrients), and others (MEA, 2005). Soil C loss due to intensive cultivation is one of the main causes for the declining soil ecosystem services in agricultural systems (Power, 2010; Powlson et al., 2011). Adding C-enriched amendments such as biochar can be a potential strategy to help restore the soil C

lost and thus soil ecosystem services (Lehmann et al., 2006; Smith, 2016).

The potential benefits of biochar have attracted tremendous interest in biochar research in recent years. A literature search in Web of Science shows an exponential increase in the number of publications on biochar in the last 10 years (2010–2020). For example, <200 articles about biochar were published before 2010, but about 13,000 articles including both research articles and reviews have been published between 2010 and mid-2020. However, such publications often focus on a single ecosystem service of biochar such as C sequestration (Brassard et al., 2016; Lal, 2015), soil fertility (Ding et al., 2016), crop production (Biederman & Harpole, 2013), and soil biota (Lehmann et al., 2011). A paper that synthesizes biochar impacts on all essential ecosystem services is rather difficult to find within the biochar literature.

Furthermore, individual publications appear to report some conflicting results about biochar impacts. Some consider that biochar can be a strategy to address current agricultural and environmental concerns, but others show some skepticism (Mukherjee & Lal, 2014; Schlesinger & Amundson, 2019). For example, while biochar can promote C sequestration, it appears to have contrasting or mixed effects on crop yields

(El-Naggar et al., 2019; Jeffery et al., 2011). This suggests that biochar application may not improve all ecosystem services at once. A synthesis paper can help with discerning which ecosystem services are or are not impacted by biochar application. Thus, the objectives of this review are to: (1) synthesize the impacts of biochar on water and wind erosion, C sequestration, soil water, nutrient leaching, soil fertility, crop yields, and other soil ecosystem services; and (2) highlight remaining research areas. Note that the goal of this paper is not to discuss in depth each individual ecosystem service but rather provide an integrated overview of the implications of biochar use on leading soil ecosystem services.

2 | CARBON SEQUESTRATION

Because biochar has a high C concentration (25%–95% C), its addition to soil can rapidly increase soil C (Blanco-Canqui et al., 2020; Lehmann et al., 2006; Liu et al., 2016; Table 1). The extent to which biochar will increase C concentration in the soil depends, however, on biochar feedstock, application rate, pyrolysis temperature, and soil properties. Moreover, it is not well understood how soil properties affect biochar C stability and sequestration (Table 2; Figure 1).

TABLE 1 Summary of impacts of biochar application on soil ecosystem services. Question marks indicate unclear impact. Short check mark indicates some biochar impact, while long check mark indicates clear or consistent impact. Note that data on some soil ecosystem services are few

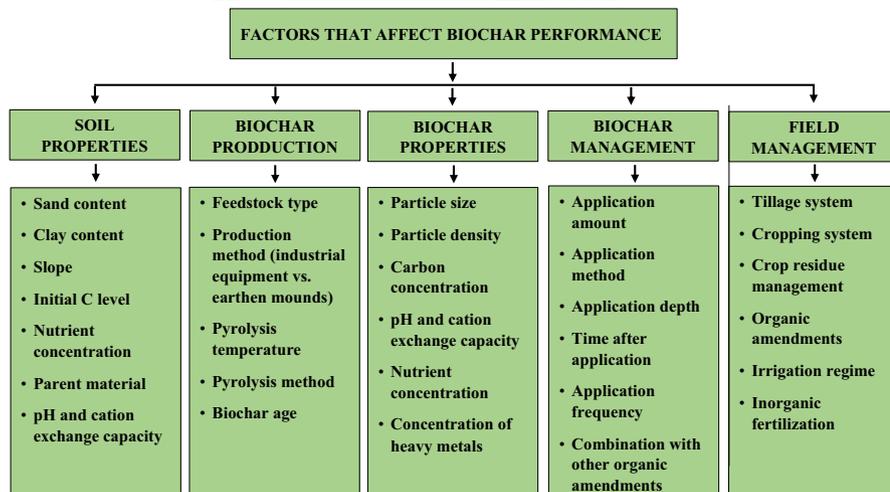| Ecosystem service	Parameter	Biochar impact	Impact description
Carbon sequestration	Sol C	✓	Increases
Greenhouse gas fluxes	CO_2	✓	Often increases
	CH_4	?	Inconsistent effect
	N_2O	✓	Reduces
Soil biology	Microbial biomass	✓	Increases
	Soil fauna	?	Unclear
Water erosion	Runoff	✓	Often reduces
	Sediment loss	?	Mixed or no effect
	Nutrient loss	?	Mixed or no effect
Wind erosion	Soil loss	?	Mixed or no effect
Nutrient leaching	Nitrates	✓	Reduces
Available water	Available water	✓	Increases
Soil fertility	Nutrients	✓	Improves nutrient use efficiency
	Acidity	✓	Reduces
Crop yields	Degraded or low fertility soils	✓	Increases
	High fertility soils	?	Mixed or no effect
	Temperate regions	?	Mixed or no effect
	Tropical regions	✓	Increases

Biochar produced from animal manure and solid waste feedstocks often has lower C concentration than that from crop residues and woody biomass as the latter feedstocks have higher lignin and cellulose content (El-Naggar et al., 2019; Tomczyk et al., 2020). Also, soil C concentration increases with the amount of biochar application and pyrolysis temperature (i.e., 350°C vs. 700°C; Table 2). An increase in pyrolysis temperature reduces the concentration of labile C but increases the concentration of stable C (Tomczyk et al., 2020). Application of biochar can be particularly effective at increasing C levels in degraded or low C soils (El-Naggar et al., 2019).

Biochar may not only increase soil C concentration through direct C addition but also indirectly through a negative priming effect. Biochar can have negative, positive, or no priming effect, depending on biochar and soil characteristics as reviewed by Maestrini et al. (2015). Biochar has a positive priming effect if it stimulates activity of microorganisms to decompose organic matter by providing additional substrate and habitat, whereas it can have a negative priming effect if it adsorbs labile C and protects C from microbial decomposition, thereby contributing to some stabilization of C inside biochar micropores. Biochar with a negative priming effect may reduce mineralization of native soil organic matter and fresh crop residues, potentially increasing C concentration in the soil more than the amount of C added with biochar (Ding et al., 2018). The positive or negative priming effects of biochar can have significant implications for C sequestration as they influence the amount of C that can accumulate in the soil in the long term. While most biochar studies reporting negative priming effects are short term and from laboratory settings (Maestrini et al., 2015), the few emerging field studies indicate significant priming effects of biochar. A field study on a US Midwestern silty clay loam soil found that woody biochar applied at 9.3 Mg ha^{-1} (63% C) to no-till corn and dedicated bioenergy crops increased soil C stock twice (14 Mg soil C ha^{-1}) the amount of C added with biochar (7 Mg biochar C ha^{-1}) compared to no biochar application after 6 years (Blanco-Canqui et al., 2020). Another field study reported that biochar had a positive priming when applied at 30 Mg ha^{-1} to a wheat–corn rotation but negative when applied at 60 and 90 Mg ha^{-1} after 8 years (Sun et al., 2020). It is important to note that biochar could increase mineralization of organic matter (i.e., CO_2 emissions) but also increases the accumulation of C. Thus, in general, biochar could be less about C preservation but more about accumulating C as well as promoting soil C formation.

Several questions still exist, however, regarding the potential of biochar for long-term soil C sequestration. Some estimate that, even under a widespread application to croplands, the potential of biochar for net C sequestration is

TABLE 2 Summary of response of each ecosystem service to biochar feedstock, application rate, and pyrolysis temperature as well as soil characteristics (Blanco-Canqui, 2017; Borchard et al., 2019; Edeh et al., 2020; El-Naggar et al., 2019; Jeffery et al., 2017; Razzaghi et al., 2020; Tomczyk et al., 2020; Ye et al., 2020; Zhang et al., 2020). High means high response and Low means low response. Questions marks indicate that the response is unclear due to either limited data or complex interactions among factors

Ecosystem service response	Feedstock		Application rate		Pyrolysis temperature		Soil texture		Soil pH	
	Wood and crop residues	Manure	Low	High	Low	High	Coarse	Fine	Acidic	Basic
Carbon sequestration	High	Low	Low	High	Low	High	?	?	?	?
Emissions of CO_2	Low	High	Low	High	High	Low	High	Low	No effect?	No effect?
Emissions of N_2O	Low	High	High	Low	No effect?	No effect?	High	Low	High?	Low?
Biological activity	Low	High	?	?	High	Low	High	Low	High	Low
Water erosion	?	?	?	?	?	?	?	?	?	?
Wind erosion	?	?	?	?	?	?	?	?	?	?
Nitrate leaching	High	Low	Low	High	Low	High	High	Low	High	Low
Available water	High?	Low?	Low?	High?	Low?	High?	High	Low	?	?
Soil fertility	Low	High	Low	High?	High	Low	High	Low	High	Low
Crop yields	Low	High	High?	Low?	High?	Low?	High	Low	High	Low

limited (Schlesinger & Amundson, 2019; Smith, 2016). The conversion efficiency of biomass into biochar can be low because 50%–70% of biomass C is lost as CO_2 during pyrolysis (Schlesinger & Amundson, 2019; Schmidt et al., 2019) although one may argue that this loss of C is smaller than the loss of C from biomass if the biomass would have been left on the fields after harvest (Lehmann et al., 2006). A related question is: How stable is biochar C in the soil? A meta-analysis by Ameloot et al. (2013) reported that biochar C decomposition decreases with an increase in pyrolysis temperature, biochar C concentration, and time. Thus, biochar properties along with soil properties potentially determine the stability of biochar C in the soil. More robust life-cycle analysis as well as long-term field studies across different soil textural classes, initial C levels, biochar type, management scenarios, and climate are needed to fully evaluate the mechanisms and extent to which biochar can sequester C in the soil and mitigate climate change.

3 | GREENHOUSE GAS EMISSIONS

Biochar application generally increases CO_2, has mixed effects on CH_4, and reduces N_2O emissions from soil (Table 1). Previous reviews indicate that biochar application increases CO_2 emissions by 16%–28% (He et al., 2017; Sagrilo et al., 2015; Song et al., 2016; Zhang et al., 2020), whereas it reduces N_2O emissions by 16%–54% (Borchard et al., 2019; Brassard et al., 2016; Cayuela et al., 2014; He et al., 2017, Kammann et al., 2017; Song et al., 2016; Zhang et al., 2020). Literature shows that biochar effects on N_2O emissions can be more consistent than that on CO_2 and CH_4 emissions. For example, biochar does not generally affect CH_4 emissions in upland systems, but it could reduce CH_4 emissions in paddy (i.e., rice) systems (Liu et al., 2016). The reduction in CH_4 emissions can be due to biochar-induced improvement in soil acidity, aeration, and CH_4 uptake (Brassard et al., 2016; Jeffery et al., 2016; Li et al., 2018).

The exact mechanisms by which biochar alters CO_2 and reduces N_2O emissions are not fully understood, but it could increase CO_2 emissions by releasing labile C and increasing microbial activity (Li et al., 2018). The release of labile C could decrease with time after application. Similarly, biochar can reduce N_2O emissions by (1) adsorbing ammonium and nitrates and immobilizing N due to its high specific surface area and porosity, which reduces N availability for N_2O emissions; (2) reducing soil compaction, acidity, and denitrification, and enhancing structural properties (i.e., aeration) and microbial biomass (Blanco-Canqui, 2017; Cayuela et al., 2014).

Biochar impacts on gas emissions depend on biochar feedstock, application rate, pyrolysis temperature, soil properties, and other factors (Figure 1). First, soil CO_2 and N_2O emissions are often lower from plant-derived biochar with high lignin content and high C/N ratio (i.e., wood, crop residues) than from low lignin content and low C/N ratio biochar (i.e., animal manure; Brassard et al. 2016; Liu et al., 2016). Second, in general, as the amount of biochar application rate increases, CO_2 emissions increase, whereas N_2O emissions decrease (Borchard et al., 2019; Brassard et al., 2016; Cayuela et al., 2014; He et al., 2017;Liu et al., 2016; Sagrilo et al., 2015; Song et al., 2016). Third, an increase in pyrolysis temperature reduces CO_2 emissions (He et al., 2017; Liu et al., 2016; Sagrilo et al., 2015; Song et al., 2016) but does not generally appear to affect N_2O emissions (Brassard et al., 2016; Cayuela et al., 2014; He et al., 2017; Song et al., 2016). Fourth, biochar application could interact with soil texture as it commonly increases emissions of CO_2 and N_2O in coarse-textured soils (i.e., sandy, sandy loam, loam) compared to medium- (i.e., loam, silt loam), and fine-textured (i.e., silt clay loam, clayey) soils (Borchard et al., 2019; Cayuela et al., 2014; He et al., 2017; Liu et al., 2016; Sagrilo et al., 2015). Fifth, CO_2 emissions appear to be unaffected by soil pH, but N_2O emissions can be higher from acidic than from alkaline soils (Table 2).

However, it is still unclear how soil pH influences biochar effects on soil gas emissions.

Biochar-induced increase in CO_2 emissions could decrease with time after application as the release of labile C decreases, whereas the reduction effect in N_2O emissions with biochar can decrease with time as the biochar potential for adsorbing nitrates decreases (He et al., 2017; Song et al., 2016). Yet, how biochar application affects CO_2, CH_4, and N_2O emissions in the long term as biochar ages is unclear. Most studies are short term and from laboratory conditions. Laboratory experiments tend to yield higher reduction in N_2O emissions with biochar than field experiments, which may be due to larger amounts of biochar applied in laboratory experiments, reduced variability, and limited or no biochar interactions with crops (He et al., 2017).

4 | SOIL BIOLOGY

Soil microorganisms directly influence soil ecosystem services through C cycling, nutrient transformations, soil aggregation, and other dynamic processes. Studies comprehensively assessing biochar impacts on soil biology are, however, few. A review by Lehmann et al. (2011) concluded that biochar application can increase soil microbial biomass in most cases. Furthermore, a review of 46 studies by Liu et al. (2018) concluded that biochar can increase microbial biomass N by 12%. Biochar could also promote mycorrhizal fungi growth, which contributes to nutrient cycling, nutrient uptake, and soil aggregation (Lone et al., 2015; Yu et al., 2019). It can particularly improve biological activity in degraded soils by improving their physical and chemical properties (Yu et al., 2019). However, it should be noted that biochar application may adversely affect soil biological properties if biochar contains toxic compounds (Cayuela et al., 2014).

Some of the mechanisms by which biochar application can improve soil biological properties include (Ameloot et al., 2013; Gul et al., 2015; Lehmann et al., 2011):

- Provision of labile C and nutrients,
- Nutrient retention by reducing losses (i.e., runoff, leaching, N_2O emissions),
- Provision of microhabitats within its porous structure,
- Adsorption of microbes,
- Increased water retention and availability,
- Reduction in soil acidity,
- Flocculation with soil aggregates,
- Adsorption of toxic elements and compounds,
- Chemical bonding,
- Direct interspecies electron transfer, and
- Other effects.

Biochar properties including pore size, specific surface area, and pH, among others, can determine the extent to which biochar influences soil biology. First, biochar particles can shelter microbes within their pores, but colonization of pores by microbes is limited if pores are too small (Gul et al., 2015). Second, biochar particles with high specific surface area and high cation exchange capacity can attract and adsorb more microorganisms than biochar with low surface area and ion exchange capacity. Third, high pH biochar can reduce soil acidity and thus enhance microbial processes in acid soils.

Biochar properties, in turn, depend on biochar feedstock and pyrolysis temperature. First, nutrient-rich or low-lignocellulosic feedstock such as manure appear to improve biological activity more rapidly than wood biochar (Table 2), but the latter can also enhance microbial processes when aged or composted with nutrient-rich organic materials (Gul et al., 2015). Second, biochar produced at low temperatures may have more labile nutrients or easily degradable organic matter for microorganisms than high temperature biochar (Ameloot et al., 2013; Brassard et al., 2016). One of the mechanisms by which biochar can increase soil microbial activity can be through direct interspecies electron transfer (DIET). Chen et al. (2014) discussed that biochar is electrically conductive and enhances DIET in co-cultures of bacteria (*Geobacter metallireducens* and *Geobacter sulfurreducens*).

Current understanding of why and how biochar improves soil biological properties including stimulation of DIET is still limited. Some consider that the "charosphere," which refers to the soil surrounding the biochar, can provide more labile C or nutrients to microorganisms than biochar (Quilliam et al., 2013). Also, effects of biochar on microbial community structure, soil fauna (i.e., earthworms, nematodes), enzymes activities, and their interactions with biochar are not well understood (Biederman & Harpole, 2013; Lehmann et al., 2011; Liu et al., 2018). It is also unclear how biochar will affect soil biological properties with time once the initial flush of labile C or nutrients is exploited and only more stable or non-easily degradable C remains. Overall, biochar generally improves microbial abundance although field-scale studies quantifying changes in soil biology after biochar addition are scant.

5 | WATER EROSION

Extreme weather events under fluctuating climates (i.e., localized rainstorms of high intensity) can increase risks of water erosion, particularly in sloping agricultural landscapes (Routschek et al., 2014). These extreme events are predicted to occur more frequently (Feng et al., 2016; Tomasek et al., 2017). For example, intensity rain events (>5 cm day^{-1}) in the US Corn Belt with potential to increase water erosion have increased by 82% compared to the 1961–1990 baseline (Saunders et al., 2012). The increased water erosion may not

only increase risks of pollution of downstream water sources but also reduce soil productivity, leading to an overall decline in ecosystem services. The question is: Can biochar be used to reduce accelerated water erosion?

Field studies on biochar and water erosion are few. The majority of studies were conducted under disturbed soils packed in small trays of soil (Blanco-Canqui, 2019). Biochar application generally reduces runoff but has mixed effects on soil loss (Blanco-Canqui, 2019; Li et al., 2017; Peng et al., 2019; Table 1). The reduction in runoff can be due to biochar-induced reduction in soil bulk density, which increases soil porosity and thus water infiltration (Blanco-Canqui, 2017). The reduced runoff with biochar can have positive implications for reducing export of dissolved C and nutrients in runoff (Peng et al., 2019), but the mixed biochar effects on soil loss suggest that biochar may not reduce losses of sediment-associated nutrients.

Data are few to assess how the different factors affect biochar impacts on water erosion. One, low C/N (i.e., manure) biochar or biochar combined with other organic amendments (i.e., compost or manure) appears to be more effective at reducing water erosion than high C/N biochar alone (Lee et al., 2018) as labile organic materials in low C/N biochar may enhance soil aggregation and reduce soil erodibility (Blanco-Canqui, 2017). Indeed, the biochar-induced organic C accumulation in the soil can promote soil aggregation, thereby reducing soil erosion. Two, amount of biochar applied and pyrolysis temperature do not seem to affect biochar effectiveness (Table 2). Three, biochar appears to reduce soil loss more in coarse-textured (Bashagaluke et al., 2019) than in medium- or fine-textured soils (Li et al., 2017; Peng et al., 2016) possibly due to biochar-enhanced aggregation in the coarse-textured soils (Blanco-Canqui, 2017). Also, the high specific surface area and high porosity of biochar particles can protect soil organic matter and provide habitat to soil microorganisms responsible for soil aggregation (Lehman et al., 2011). Four, biochar can be more effective at reducing soil loss in fields with slopes <10% (Li et al., 2017).

Biochar can also be susceptible to water erosion. Biochar particles exposed to the surface can be preferentially transported in runoff due to the lower bulk density and higher hydrophobicity than soil particles (Lee et al., 2018; Peng et al., 2019). Indeed, the method of biochar application can affect the biochar losses in runoff. For example, surface-applied biochar can be more easily lost in runoff relative to biochar incorporated into the soil (Sadeghi et al., 2016). Thus, incorporation of biochar through one-time tillage can be a strategy to minimize biochar erosion. Furthermore, time after application could alter biochar impacts on soil loss as biochar ages in the soil, but long-term (>3 years) field studies to assess this are lacking. In sum, the few field studies suggest that biochar can reduce runoff but have inconsistent effects on soil loss.

More field-scale studies are needed to better understand if biochar can deliver another ecosystem service, which is water erosion control and reduction in water pollution.

6 | WIND EROSION

Increasing drought periods and heat waves under fluctuating climatic conditions can increase both frequency of windstorms and the susceptibility of the soil to wind erosion (Duniway et al., 2019). This is particularly true in arid and semiarid regions. Droughts, such as the one in 2012 that was the fifth most severe drought encompassing over 50% of the United States, are an example of increasing concern (NOAA, 2012). Can biochar be used to reduce risks of soil erosion by wind? Data to answer this question are still limited. Actual measurements of soil loss (i.e., dust) following biochar application are very few. One of the studies that measured wind erosion using tunnels reported that palm biochar reduced soil particle transport by 40% in week 1, 21% in week 10, and 8% in week 20, suggesting that effectiveness of biochar for reducing wind erosion can rapidly decrease with time after application (Feizi et al., 2019). The same study found that biochar was one of the least effective strategies to reduce wind erosion.

Some studies measured soil dry aggregate distribution and stability after biochar application, which are indicators of soil's resistance to wind erosion. The larger and more stable the soil dry aggregates, the lower the susceptibility of the soil to wind erosion. A review of biochar effects on dry aggregate stability across eight soils reported that biochar increased dry aggregate stability in three but had no effect in five soils although most studies measured dry aggregate stability in short-term experiments (<1 year; Blanco-Canqui, 2017). The few data indicate that biochar application has limited or no effect on reducing wind erosion, but similar to water erosion, more long-term (>3 years) field data are needed to understand the benefits of biochar for controlling wind erosion for different soil types in arid and semiarid regions. The significant positive effects of biochar on wet aggregate stability but the small or no positive effects on dry aggregate stability suggest that the biochar-induced C buildup in the soil probably contributes more to reduced water erosion potential than to reduced wind erosion.

Furthermore, biochar particles are susceptible to wind erosion and can release air pollutants (i.e., particulate matter). Method of application, particle size, surface area, and moisture content will determine the susceptibility of biochar to losses. Incorporating biochar into the soil, moistening biochar prior to application, and pelletizing biochar are some of the strategies that can control dust and reduce release of particulate matter (Blackwell et al., 2010; Maienza et al., 2017). Overall, biochar appears to have limited effects on reducing

wind erosion, but it can be lost during application if not properly managed.

7 | NUTRIENT LEACHING

Fluctuating climatic patterns with intense rainstorms and flooding are also increasing concerns of leaching of nutrients from croplands. For example, in the US Midwest, leaching of nitrates from croplands, primarily from corn and soybean systems, is considered to significantly contribute to nutrient loads to Mississippi River and water pollution in the Gulf of Mexico (Kladivko et al., 2014; USGS, 2016). Particularly, leaching of nitrates can be a problem in sandy soils with high hydraulic conductivity, raising concerns associated with not only reduced N use efficiency but also human health risks. The question is: Can biochar be used to reduce nitrate leaching?

According to three reviews (Blanco-Canqui, 2019; Borchard et al., 2019; Liu et al., 2018), biochar application generally reduces nitrate leaching (Table 1). Biochar application can reduce nitrate leaching by imparting different physicochemical properties to soil although the exact mechanisms are still unclear. Because biochar particles have higher surface charge density, specific surface area, porosity, ion exchange capacity, and water retention capacity than inorganic soil particles, they can increase the potential of the soil to adsorb, entrap, and stabilize organic molecules and N compounds (Sanford et al., 2019; Tian et al., 2018). Biochar often increases nitrate residence time or nitrate concentration in the root zone by confining nitrates within its pores and altering nitrification, denitrification, and other processes of N cycle. It can also promote ammonium adsorption through the increased soil cation exchange capacity as well as microbial biomass activity. Some studies reported that biochar can add functional groups with positive charges, which can increase the anion exchange capacity of the soil to enhance nitrate adsorption (Sanford et al., 2019). While impacts of biochar on soil anion exchange capacity after biochar application have been little studied, some studies reported that the stability of the biochar anion exchange capacity can change with time as biochar decomposes. Lawrinenko et al. (2016) reported that the anion exchange capacity of alfalfa, corn stover, and cellulose biochar decreased as biochar aged but such decrease was lower in biochar pyrolyzed at high (700°C) than at low (500°C) temperatures.

The reduction in nitrate leaching with biochar can have significant implications for the management of N and water pollution, but factors affecting biochar effectiveness should be considered to reduce overgeneralization of the positive effects of biochar (Figure 2). High C/N or lignocellulosic-rich biochar can reduce nitrate leaching more than low C/N biochar. Also, biochar potential to reduce nitrate leaching generally increases as the amount of biochar applied increases (Table 2). However, it is important to note that, in some cases, biochar may not reduce nitrate leaching even when applied at high rates (Nguyen et al., 2019; Teutscherova et al., 2018). This can be due partly to low adsorptive ability and low C concentration of some biochars (Gao et al., 2020). Reviews suggest that an increase in pyrolysis temperature of biochar can increase its effectiveness to reduce nitrate leaching (Borchard et al., 2019) but not always (Liu et al., 2018) although field data from studies conducted under biochar pyrolyzed at different temperatures (Bu et al., 2019; Sanford et al., 2019) are scarce to fully discern how pyrolysis temperature affects nutrient leaching.
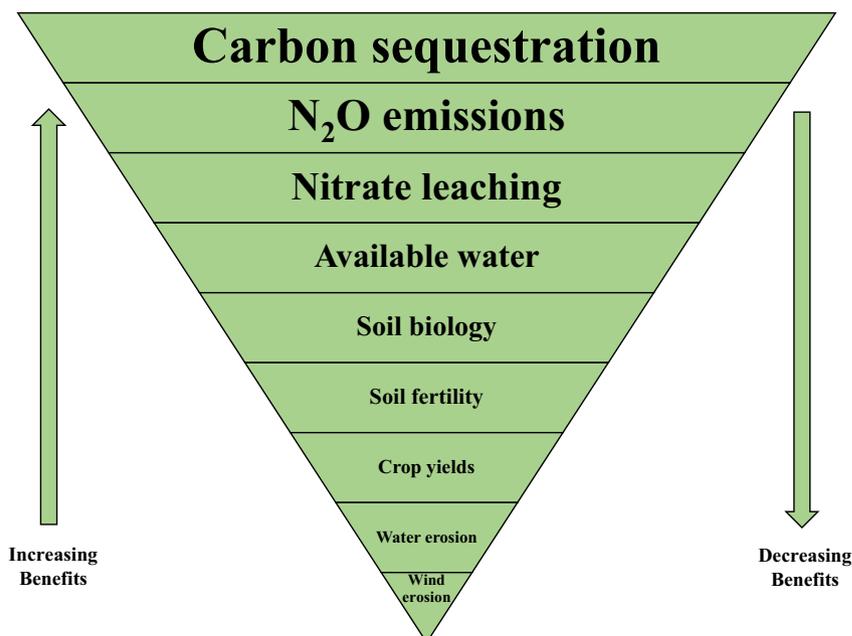
FIGURE 2 Differential biochar impact on soil ecosystem services in an ascending or descending order. Note that the largest font size indicates highest impact whereas the smallest font size indicates lowest impact

Carbon sequestration

N$_2$O emissions

Nitrate leaching

Available water

Soil biology

Soil fertility

Crop yields

Water erosion

Wind erosion

Increasing Benefits

Decreasing Benefits

Soil texture and soil pH may also affect biochar impacts on nitrate leaching. Biochar can particularly reduce nitrate leaching in coarse-textured, low C, and acidic soils (Table 2).

The few field studies, which monitored nitrate leaching at different points in time after application, reported that biochar effectiveness for reducing nitrate leaching could decrease within months after application (Beusch et al., 2019; Tian et al., 2018). This potential decrease of biochar ability to reduce leaching with time may adversely affect the N use efficiency. Much focus has been on the effects of biochar on nitrate leaching. Yet, leaching of ammonium, P, and C also deserves consideration. A review found that biochar can have inconsistent effects on reducing leaching of ammonium, P, and C (Blanco-Canqui, 2019), suggesting that biochar application may be more effective for reducing leaching of nitrates than other nutrients. Overall, biochar reduces nitrate leaching in most cases but can have variable effects on reducing leaching of other nutrients.

8 | SOIL WATER

Enhancing the ability of the soil to capture and retain water under dry conditions (i.e., droughts) and to drain water under wet conditions (i.e., intense rainstorms, flooding) is increasingly important to manage agroecosystems under fluctuating climates. For example, intense rainstorms are lasting longer and impacting larger areas than before (Feng et al., 2016). The question is: Can biochar be used to manage soil water relations? Reviews on this topic suggest that biochar application can contribute to soil water management and conservation (Blanco-Canqui, 2017; Edeh et al., 2020; Razzaghi et al., 2020).

First, biochar application can improve the ability of the soil to conduct water under saturated conditions and thus improve drainage, particularly in fine-textured or flood-prone soils. A review by Blanco-Canqui (2017) reported that biochar application can double saturated hydraulic conductivity in fine-textured soils. Another review reported that biochar application increases saturated hydraulic conductivity by 36% in medium- and 28% in fine-textured soils (Edeh et al., 2020). While field studies are few, biochar can also increase water infiltration in clayey soils (Prober et al., 2014). Thus, in cases where biochar increases saturated hydraulic conductivity and water infiltration, biochar can improve drainage in soils.

Second, biochar application can also conserve soil water, which can be particularly beneficial in water-limited regions (Table 1). Reviews indicate that biochar application generally increases the ability of the soil to adsorb and retain plant available water (Blanco-Canqui, 2017; Edeh et al., 2020; Razzaghi et al., 2020). The amount of water retained in the soil is, however, highly dependent on soil texture (Table 2).

Biochar increased available water by 38% in coarse-textured soils, 19% in medium-textured soils, and 16% in fine-textured soils (Blanco-Canqui, 2017; Edeh et al., 2020; Razzaghi et al., 2020). This indicates that the increase in available water can be about twice higher in coarse-textured than in medium- and fine-textured soils.

In addition to soil texture, other factors including feedstock, application rate, and biochar properties may affect biochar impacts on available water (Table 2; Figure 1). Wood or high temperature biochar could retain water more than manure or low temperature biochar (Table 2), but field data are limited to corroborate this. Wood biochar pyrolyzed at high temperatures can have higher specific surface area and higher C concentration and thus higher ability to adsorb and retain water than biochar pyrolyzed at low temperatures. Biochar application rate can also affect water retention, but the extent depends on soil texture. A review by Edeh et al. (2020) concluded that between 30 and 70 Mg ha^{-1} of biochar are needed to increase available water in sandy soils but <30 Mg ha^{-1} of biochar in clayey soils. Also, an increase in biochar C concentration can lead to greater water retention. Based on the reviews by Edeh et al. (2020) and Razzaghi et al. (2020), an increase in biochar C concentration significantly increases available water. Additional factors including biochar particle size, specific surface area, and porosity potentially affect water retention. Indeed, available water could increase with a decrease in biochar particle size and increase in specific surface area and porosity (Edeh et al., 2020).

Some suggested that biochar application can be a strategy to improve resilience of agricultural systems against droughts (Edeh et al., 2020), but the extent to which this improvement can reduce the amount of precipitation or irrigation water and contribute to soil resilience and adaptation to drought conditions is unclear, particularly in temperate regions (Atkinson, 2018; Phillips et al., 2020). Furthermore, it is unclear if the increase in available water results in a consistent increase in crop yields as discussed later. Overall, addition of biochar can improve drainage in fine-textured soils and increase available water particularly in coarse-textured soils, but its potential to improve soil resilience against droughts or flooding needs further assessment using long-term field studies.

9 | SOIL FERTILITY

Biochar can improve soil fertility, particularly in low C, sandy, and acidic soils (Ding et al., 2016; El-Naggar et al., 2019; Liu et al., 2018; Purakayastha et al., 2019. However, soil fertility benefits of biochar could diminish with time (Mia et al., 2017) unless split or repeated applications of biochar are used, which warrant further investigation. Some of the mechanisms by which biochar can improve soil fertility include nutrient provision, enhancement nutrient availability,

reduction in N leaching, reduction in N_2O emissions, among others.

First, biochar can be a source of some essential nutrients including P, K, Ca, Mg, and others, depending on biochar feedstock, application rate, and pyrolysis temperature (Table 2). Nutrient-rich or low C/N biochar (i.e., manure) provides greater amount of nutrients (i.e., N) than high C/N biochars. Also, an increase in biochar pyrolysis temperature increases volatilization of C, N, and S in the form of CO_2, NO_2, and SO_2, thereby reducing the labile concentration of C, N, and S, but it can increase concentrations of P and basic cations (Ca, K, and Mg; and the biochar potential to adsorb nutrients (El-Naggar et al., 2019). Second, biochar reduces nitrate leaching and thus improves N retention and N use efficiency (Blanco-Canqui, 2019; Borchard et al., 2019). The reduction in nutrient leaching may not only improve N use efficiency but also improve the quality of downstream water sources. The intrinsic physicochemical properties of biochar (i.e., surface area, charge density (electrostatic attraction forces), porosity, C concentration) will affect its potential to sorb and retain nutrients (Figure 1).

Third, biochar can reduce N losses to the atmosphere as discussed earlier. The reduced N_2O emissions with biochar, similar to reduced N leaching, can contribute to higher N use efficiency. However, biochar effects on NH_3 volatilization appear to less consistent than those on N_2O emissions. A meta-analysis of published studies found that biochar can increase NH_3 volatilization by 11%, especially in low pH (<5), low C ($\leq$10 g C kg^{-1}), and clayey soils (Liu et al., 2018). Overall, biochar can reduce N_2O emissions but may or may not increase NH_3 volatilization.

Fourth, biochar can enhance soil fertility by increasing biological N fixation in legumes. A meta-analysis of studies reported that biochar can increase biological N fixation by 63% in legumes (Liu et al., 2018). It also showed that N fixation can be especially high in soils with pH <5 and <80 Mg ha^{-1} of biochar application. Addition of nutrients (i.e., P, K, Mo, B), increase in pH, stimulation of microorganisms (i.e., rhizobium), and increase in root nodulation following biochar application can explain the enhanced N fixation from the atmosphere (Mia et al., 2014; Rondon et al., 2007). Long-term studies assessing the extent of N fixation and the optimum levels of biochar application are, however, lacking.

Fifth, biochar can improve the overall ability of the soil to retain and supply nutrients by improving soil properties. For example, biochar often increases soil specific surface area, porosity, cation exchange capacity, pH, water holding capacity, and microbial abundance (Tian et al., 2018). Increased specific surface area, porosity, and cation exchange capacity directly enhance the ability of the soil to adsorb and store nutrients, while increased water retention reduces the amount of water available to transport and leach nutrients. Also, the increase in soil pH through the liming effect of alkaline biochar

can reduce Al toxicity, promoting soil organic matter mineralization and nutrient availability (i.e., available P). Biochar is often used as liming amendment in low pH soils to reduce sorption of nutrients by Fe and Al compounds (Tian et al., 2018).

10 | CROP YIELDS

Application of biochar can increase crop yields in most cases. Reviews found the increase in crop yields can range from 10% to 38% (Agegnehu et al., 2017; Crane-Droesch et al., 2013; Jeffery et al., 2017; Liu et al., 2013; Palansooriya et al., 2019; Purakayastha et al., 2019; Ye et al., 2020). Note that the yield increases reported in the reviews are averages. Biochar may not increase yield in all cases (Jeffery et al., 2017). Indeed, in some cases, crop yields may decrease following biochar application. A review by Spokas et al. (2012) noted that biochar application can increase crop yields in 50%, have no effect in 30%, and reduce them in 20% of cases. The impact of biochar on crop yields is highly soil, biochar, and management specific (Table 1; Figure 1). Some of the soil and climatic conditions affecting biochar impacts are discussed below.

First, biochar could increase crop yields in tropical soils but have small or no effects in temperate soils. A review by Jeffery et al. (2017) found that biochar can increase crop yields in tropical regions by about 25% but not in temperate regions. Biochar appears to increase crop yields in tropical soils through a liming effect and nutrient input as these soils often have lower organic matter and lower pH compared with less weathered soils in temperate environments. Additionally, rainfed agriculture with limited fertilizer input may benefit more from biochar than irrigated systems receiving high rates of fertilization. A review by Ye et al. (2020) concluded that, on average, biochar increased crop yields more in nonfertilized than in fertilized soils. In productive fields or temperate regions, biochar can provide various services (i.e., C sequestration, reduced N leaching) but increase in crop yield may not be one of them.

Second, biochar effects on crop yields are highly dependent on initial soil conditions. Degraded or problem soils can benefit from biochar more than highly productive or fertile soils. Specifically, biochar can increase crop yields in sandy, acidic, and low organic matter soils but, in clayey, near neutral pH, and high organic matter soils, biochar can have small effects, no effects, or even decrease yields (Yu et al., 2019). However, it is important to note that even highly productive agricultural lands (i.e., temperate regions) have patches of degraded or problem soils (i.e., sandy, acidic, low C), which could thus benefit from biochar application. For example, adding biochar to a soil with low adsorption properties such as sand can improve the ability of the soil to retain water and nutrient

properties, thereby improving yields. If the goal is to enhance crop yields, then targeting problem soils or low productive fields with biochar can be a strategy.

Third, biochar application does not always increase crop yields even in some tropical environments. Nutrient concentration of biochar directly affects crop response. Nutrient-rich biochar such as those derived from animal manure can increase crop yields more than biochar derived from wood and crop residues (Table 2). Thus, crop yield response to biochar application may be in this order of feedstock: Manure > Crop residue > Wood. Biochar feedstock can have contrasting effects on ecosystem services. For example, manure biochar can increase yields but may have limited potential for reducing nutrient leaching, while the reverse is true for wood biochar. Selection of feedstock will depend on the goal for biochar use.

Fourth, how much biochar should we apply to boost crop yields? Some reviews observed no significant relationship between biochar application rates and crop yields (Biederman & Harpole, 2013), but others have found that high application rates (>40 Mg ha^{-1}) may reduce crop yields (Liu et al., 2013; Table 1). The optimum application rate can be 5 Mg ha^{-1} (Ye et al., 2020), 20 Mg ha^{-1} (Liu et al., 2013), and 10–40 Mg ha^{-1} (Liu et al., 2018). This wide range suggests that the minimum amount of biochar needed to increase crop yields varies with site-specific and biochar characteristics. It also suggests that the right amount of biochar should be established for each representative soil or field to reduce application costs and increase economic feasibility of biochar use.

Fifth, biochar may need nutrient enhancement to improve soil fertility and crop yields. Composting, co-composting, and mixing biochar with animal manure, poultry manure, crop residues, compost, inorganic fertilization, and other materials can be strategies to enhance biochar potential to improve soil fertility (El-Naggar et al., 2019). Optimizing the pyrolysis temperatures and applying aged biochar can be additional options (Mia et al., 2017). These enhancement methods can benefit especially nutrient-low biochars (i.e., wood).

Sixth, how long will the biochar benefits last? Most biochar studies on crop yields are short term (<3 years) and some were conducted in greenhouse experiments for <1 year. How biochar affects crop yields in the long term (>3 years) is unclear due to limited literature. The few available data suggest that crop yield response to biochar with time may depend on N fertilization. In a review, Ye et al. (2020) found that, in non-fertilized soils, biochar increased crop yield only in the first 2 years; but, in fertilized soils, biochar increased yields only in the third year after application. The early impact of biochar on crop yields may be due to nutrient input and liming effect, while the late impact can be due to biochar oxidation, which can lead to improvement in nutrient retention

(Spokas et al., 2012). Repeated or annual applications can be an option to maintain the liming and fertilization effects of biochar. Overall, benefits of biochar for increasing yields persist for at least 1 or 2 years, but long-term field studies are unavailable to fully discern the longevity of biochar benefits.

Seventh, biochar and crop yield studies focused more on horticultural crops (i.e., vegetables, fruit) than on agronomic or field crops (i.e., grains). Also, more studies are from small- than large-scale farms. Biochar often increases yields in horticultural crops and in small-scale farms as crops grown in pots appear to more positively respond to biochar than field crops. Also, biochar can increase yields of legumes, vegetables, and grasses more than corn, wheat, and rice. How biochar will affect crop yields when applied to watershed- or large-scale agricultural or commercial farms is unclear. Dokoohaki et al. (2019) estimated that, in the United States, the economic benefits of applying biochar to main agronomic crops could be in this order: corn > soybeans > wheat with the highest economic benefit for corn in the southeastern United States and soybeans in the eastern United States. Most studies, particularly from tropical regions, reporting increases in crop yields with biochar are from biochar produced at small scales (i.e., soil pits, earthen mounds, metal, or brick kilns) and not at large scales using industrial equipment. The high cost and limited availability of biochar presently limit the biochar use under large-scale farming. Enhancing biochar (i.e., composting, mixing, coating) or applying frequently can further increase the cost and complexity of application at large scales. Unless increases in crop yields or other ecosystem services (i.e., leaching control, C sequestration) are greater than the cost of biochar, the economic viability of biochar use could be limited.

11 | MOVING FORWARD

Literature is replete with studies on biochar and its impacts on soils, crop production, and environment, but there are still questions regarding the potential of biochar to improve such soil ecosystem services. Some of the knowledge gaps that need attention include:

1. The majority of published studies on biochar are from laboratory (i.e., soil columns) or greenhouse (i.e., pots) experiments. Performance of biochar in small pots or columns can differ from field conditions with variable soil and environmental conditions. Indeed, some laboratory biochar experiments did not have growing plants, which overlooks biochar–soil–root interactions. Field studies using watersheds or large-scale farms under different soil types, management scenarios, and climates are needed to conclusively ascertain the impacts of biochar on soil ecosystem services.

2. Most of the existing field studies are short term (<3 years). Long-term (>3 years) studies are needed to better understand how biochar affects soil ecosystem services with time after application. Soil response to biochar can be slow as biochar particles can require significant amount of time to interact with the soil and impart changes. For example, soil physical properties are often slow to change and thus their changes can be measurable only in the long term.

3. Most of the studies, particularly those conducted in the laboratory or greenhouse, have applied large amounts (>30 Mg ha^{-1}) of biochar and found some beneficial impacts. However, application of large amounts of biochar to croplands is neither practical nor economical. Thus, a need exists to determine the minimum application rate of biochar to obtain the desired benefits under different soil types, crops, and climates.

4. Emerging research suggests that biochar combined with other organic amendments (i.e., animal manure, poultry manure, compost) can be more effective at improving crop production and other ecosystem services than biochar alone. Thus, field research is needed to determine the right type and amount of combination (i.e., ratio) for field-scale application recommendations.

5. Applying the same amount of biochar across the whole field increases the amount and cost of biochar. Thus, banding or placing biochar in crop rows along with fertilizers or other amendments can be an option to enhance both biochar–soil–root contact and biochar effectiveness. Additional field research on such methods of biochar application or placement is needed under different soil types, cropping systems, and climates.

6. Emerging literature suggests that biochar application can have more beneficial effects on degraded or problem soils than on highly fertile or productive lands, but how problem soils respond to biochar application in the long term needs further investigation.

7. Biochar performance can depend on the feedstock and pyrolysis temperature but such conclusion is mostly based on laboratory studies. Long-term field studies with different biochar feedstocks and different pyrolysis temperatures are needed.

8. Most studies are from one-time application of biochar. Research is needed to assess if annual or split application of biochar could be better than one-time application to maintain biochar benefits.

9. Uncertainty regarding biochar C dynamics and stability in the soil continues. Long-term studies are needed to assess biochar C residence time for different biochar feedstock types, soil characteristics, biochar pyrolysis temperatures, and climates.

10. Long-term field data are needed as input for ecosystem service models to scale up the site-specific biochar performance to regional scales and make recommendations.

11. Biochar is neither available in large quantities nor it is economical to be used in commercial agriculture. Development of strategies to produce biochar at local and regional scales is needed to expand the use of biochar globally.

12 | CONCLUSIONS

This synthesis indicates that applying biochar to agricultural lands has potential to improve soil ecosystem services. In general, biochar can sequester C, reduce N$_2$O emissions, and nitrate leaching and improve soil biology, soil fertility, plant available water, and crop yields (mainly in tropical regions) but can increase CO$_2$ emissions and have small or no effect on water erosion and wind erosion (Table 1; Figure 2). However, the ability of biochar to improve the cited ecosystem services strongly depends on biochar feedstock (wood vs. manure), production characteristics (i.e., equipment, pyrolysis temperature), and biochar properties (particle size, C concentration, porosity), among others. A multitude of biochar types exists and not all of them have the same properties. Moreover, soil characteristics (sand content and C level), site-specific management (agronomic crop, horticultural crop, biochar application method), and climate can affect biochar performance (Figure 1). For example, biochar does not enhance crop yields in all climates nor soils. It can enhance crop yields more in tropical than in temperate regions. Similarly, it often boosts yields in low-nutrient, low C, acidic, and sandy soil but not generally in highly fertile and fine-textured soils with neutral pH and high C levels.

Biochar use will depend on the goal. For instance, in temperate regions or highly productive soils, the goal of biochar use could be to improve nutrient use efficiency by reducing nitrate leaching and N$_2$O emissions and sequestering C but not to increase crop yields. Also, the desired ecosystem service goal will dictate the selection of biochar type. For instance, biochar with high concentration of stable C (i.e., wood) can be the right type for C sequestration, while biochar with high concentration of N and other essential nutrients (i.e., animal manure) for soil fertility and crop yield improvement. Similarly, biochar with high adsorptive capacity can be the top choice for the reduction in nutrient leaching and remediation of contaminated soils. Balancing feedstock type and pyrolysis temperature, which are key factors influencing biochar performance, is needed to attain the desired ecosystem service from biochar on a site-specific basis.

Long-term (>3 years) watershed or field-scale biochar studies at regional scales are needed to fully discern the

effects of biochar on soil ecosystem services and to perform comprehensive life-cycle analysis, establish threshold levels of biochar application, identify biochar combinations (i.e., co-composting, activating), and assess potential tradeoffs between agronomic and environmental benefits. Such long-term biochar studies should be accompanied by periodic and detailed soil sampling to better understand how biochar impacts soil ecosystem services with time after application. Overall, biochar can improve most essential soil ecosystem services but the extent of biochar benefits depends on soil and biochar characteristics as well as climatic conditions.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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