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Just or bust? Energy justice and the impacts of siting solar pyrolysis biochar production facilities

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ABSTRACT

Biochar has seen an explosion of research over the past decade as an environmentally sustainable material for enhancing agricultural yields, treating wastewater, and sequestering atmospheric carbon. In contrast, there is a lack of research into the social and economic sustainability of biochar. To address this gap, we propose environmental justice (EJ) indicators as a proxy for social and economic considerations when siting biochar production facilities. Specifically, we develop a siting index for a biochar pyrolysis facility using low-cost, carbon-neutral solar energy. This siting index provides a framework for analyzing potential facility locations based on both technical and environmental and energy justice considerations. Results indicate that EJ analyses may influence the planning processes for industrial facility siting and that incorporating EJ into siting decisions would represent a commitment to environmental sustainability as well as the social and economic conditions of communities.

1. Introduction

The production, modification, and evaluation of biochar – the solid carbonaceous product resulting from heating biomass in an oxygen free environment (pyrolysis) or other thermochemical processing of biomass [1] – has seen an explosion of research over the past decade. Biochar (Table 1) is being advanced as a sustainable material for enhancing agricultural yields, treating wastewater, and sequestering carbon from the atmosphere – all necessary to meet the needs of the world's growing population. For instance, land and water availability, including clean water needs [2] and future scenarios which involve farming on contaminated land or irrigating agricultural fields with reclaimed wastewater [3], are important considerations for ensuring food security and sustaining an estimated global population of nearly 9.8 billion by 2050 [4]. The Intergovernmental Panel on Climate Change has reported that global arable land area is projected to increase through 2050, but that there is high uncertainty in estimates of how productive the land will be due to lower nutrient quality of the soils [5]. Since 2010, research has increasingly evaluated biochar as a sustainable substance that may aid in meeting many of these critical needs. However, much of this research identifies biochar as a sustainable solution based solely on its potential for carbon sequestration, waste reuse, and other environmental factors, without considering the social or economic impacts of biochar production and use. This article addresses this gap and proposes application of a quantitative environmental justice framework to biochar facility siting.

To illustrate the increasing research focus on biochar in meeting these many critical needs, we conducted a literature search of the Web of Science database in June 2019 which resulted in 9445 publications addressing the topic of *biochar* from the beginning of 2010 through the date of the search (June 14, 2019). Narrowing that search to also include *sustainable* or *sustainability* as topics yielded 709 and 253 results, respectively, representing 7.51% and 2.68% of the biochar literature. The number of publications meeting these search criteria has risen yearly (Fig. 1).

Despite the many definitions of sustainability, each hinges considerably on acknowledging the need for protecting resources while meeting the needs of people now and into the future. Under the 1969

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Table 1
Definitions of selected terms in this study, and related terms.

Term	Definition	References
Biochar	Solid carbonaceous product of thermochemical processing of biomass, typically through pyrolysis (high temperature, low-oxygen conditions)	[1]
Biomass	Organic material derived from recently-living plants which can be burned directly or converted to a liquid or gas; may be "purpose-grown" or derived from wastes	[1,6]
Bioenergy	Renewable energy which is derived from biomass	[7]
Bio-oil	Product of condensation of vapor phase, high-molecular weight products of biomass pyrolysis	[1]
Biofuels	Biomass-derived transportation fuels	[8]

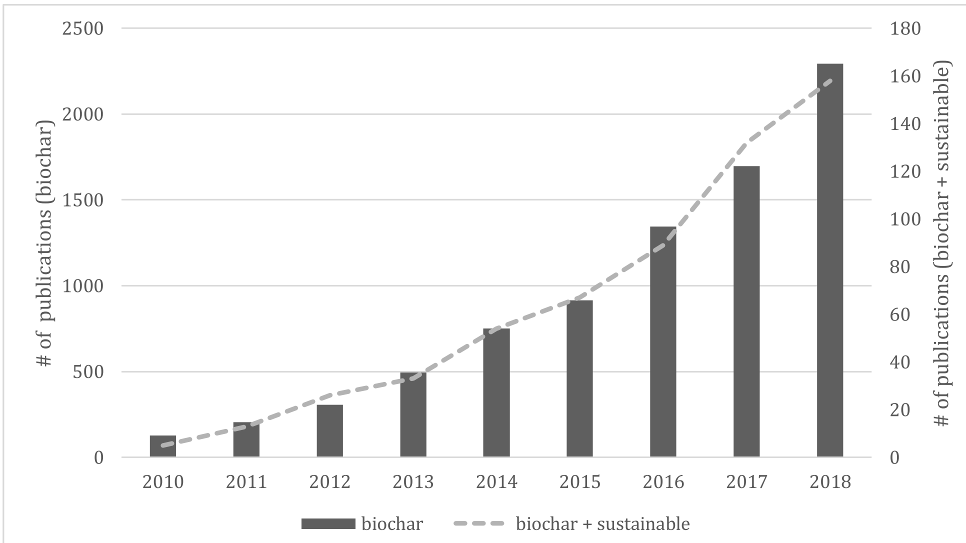

Fig. 1. Publications (2010–2018) with *biochar* (bars) and *biochar + sustainable* (dashed line) as topics (Web of Science database accessed 6/14/19).

National Environmental Policy Act (NEPA), sustainability is defined as a way "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" [9]. The Brundtland Commission Report, *Our Common Future*, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [10]. Sustainability also has an ethical and moral component [11]. Connecting the three sustainability pillars – society, economy, and environment – to one another ensures that environmental achievements do not come at the expense of societal needs or economic development.

A holistic approach to evaluating the sustainability of biochar requires a commitment to something beyond merely the idea of sustainability; it requires some level of quantification. Failure to link environmental solutions to the societal and economic well-being of the communities in which they are located makes new technologies vulnerable to "greenwashing", where the sustainability of a technology is only a surficial veneer [12] underpinned by negative social, economic, and/or environmental impacts. As indicated by the literature on sustainable development, sustainability requires a project to balance economic, environmental, and equitable considerations of development "over the present and future time scales" [13]. New renewable energy projects and the broader transition towards renewable energy can harden and compound issues of distributive and procedural inequity. Thus, prior to asserting that a new resource or technology is "sustainable," it is necessary to consider the impacts of unequal environmental pollution and degradation on marginalized communities ("environmental justice") [14], issues related to access to clean and affordable energy ("energy justice") [15], consideration of the social and economic impacts of environmental policies ("just environmentalism") [16], and discussion of the procedural and structural mechanisms through which marginalized communities are involved and engaged in siting decisions [17].

With this in mind, to further elucidate the perspective from which biochar researchers are asserting the sustainability of biochar, the literature was searched for additional terms related to the definitions of sustainability. When *sustainable* and *sustainability* were replaced with single terms such as *society, economy*, or their variants, the results comprised less than 4% of the total biochar literature for the time period of interest; finding two or more variants (e.g., *society* and *economy*) in a single paper was less common (Fig. 2). These results indicate that current declarations of the sustainability of biochar may be superficial and that an analysis of social and economic impacts is needed. This analysis may be accomplished by an examination of environmental justice aspects of biochar production.

1.1. Environmental justice, sustainability, and energy justice

Development and operation of energy facilities – whether renewable or otherwise – can have significant social, environmental, and economic impacts on the communities in which they are located. These impacts include both the negative externalities of development and the social and economic development benefits that access to sustainable technologies can help provide. Sustainability demands that energy facility siting take into consideration both *environmental justice* – "fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" [18] – and *energy justice* – which has been defined as "a global energy system that fairly disseminates both the costs and benefits of energy services and one that has representative and impartial energy decision making" [19]. Energy justice applies the principles of justice to the entire life cycle of energy, from production to distribution and use,

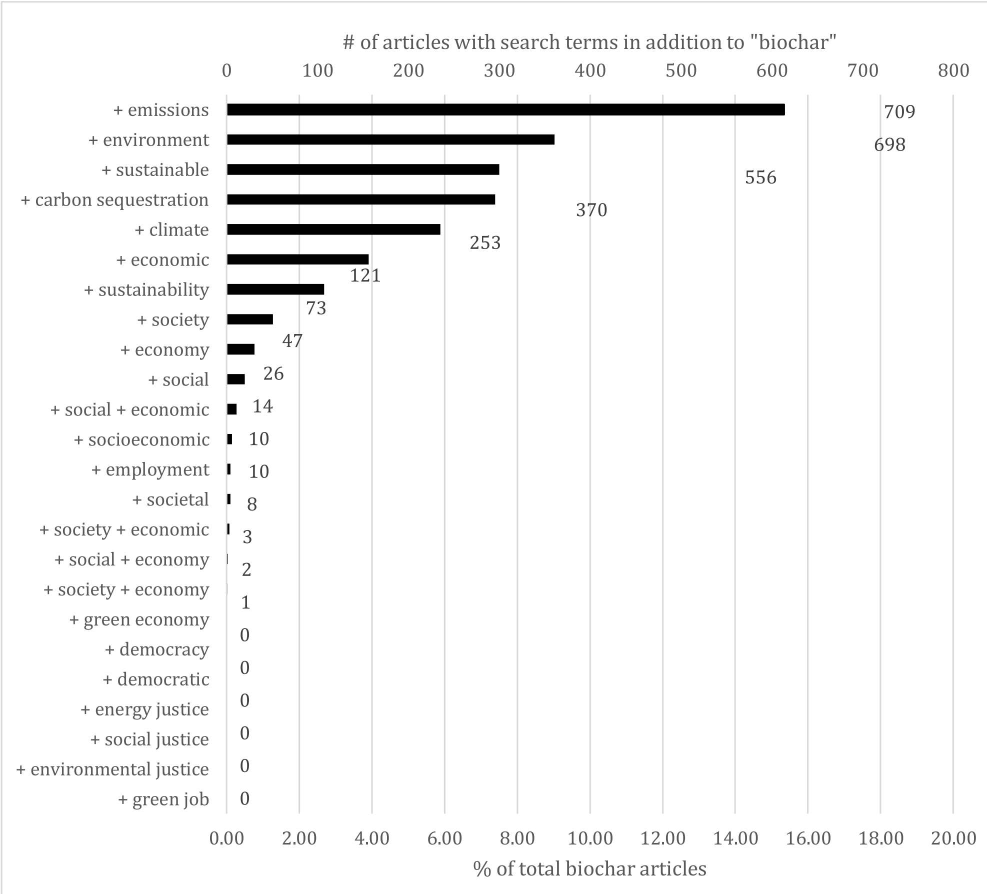

Fig. 2. Co-occurrence of search term topics with *biochar* in Web of Science database. Includes data from 2010 through the date of the search (6/14/19).

and a key part of addressing energy injustice is identifying the population affected [20]. Energy justice may be viewed as a distinct issue within environmental justice [21] or vice versa: it is necessary to assure that global energy justice considerations do not result in localized environmental justice concerns and further that the benefits of global energy transitions provide localized benefits in the form of affordable access to reliable energy. These frameworks clearly link the three pillars of sustainability by connecting a community's environmental circumstances to its social and economic condition.

Although biochar is widely touted as a sustainable resource, current research does not consider the energy or environmental justice impacts of siting biochar facilities within communities. Instead, this research focuses almost exclusively on the carbon reduction or carbon negative potential of biochar. Yet, an intersectional approach to understanding climate change as expanding beyond the sole issue of emissions is advantageous and consistent with sustainability principles [22]. There are three axes to energy justice: climate justice, environmental justice, and energy democracy [23]. The juxtaposition of the intense focus on biochar as a sustainable material against the lack of research into environmental justice indicates that biochar researchers have been asserting the sustainability of biochar based principally on environmental benefits, rather than holistic considerations of procedural and distributive justice. An analysis of the 9445 papers on biochar published from 2010 through the date of the search further supports the environmental focus of sustainability claims: biochar papers include the topics *emissions, environment*, and *carbon sequestration* more frequently than any socioeconomic topics (Fig. 2). In stark contrast, no results in the biochar literature for that time period included the topics *environmental justice, energy justice,* or *social justice* (Fig. 2).

Actively considering a wide range of potential impacts of the biochar life cycle will help to ensure that its environmental benefits are not overshadowed by avoidable negative socioeconomic impacts. The importance of this issue is further underscored as some conservation groups have advocated for biomass facilities to be excluded from renewable energy subsidies based on environmental justice concerns [24]. Biomass, wind, and solar developments have spurred environmental and energy justice controversies. These controversies arise as a result of environmental, economic, and democratic critiques. For instance, solar, biomass, and wind developments result in impacts to land use and community health, and produce externalities related to transportation, waste disposal, and particulate pollutants [24,25]. In addition to these direct environmental impacts, these technologies may increase the cost of household energy as a result of higher costs of generation or support for social programs within the utility rate structure, and thus have a regressive impact [26]. Further, policies solely focused on decarbonization fail to address structural inequities embedded in the current energy system [17].

In contrast, other scholars have advocated for proactive siting of small-scale distributive or renewable generation facilities in environmental justice communities to improve environmental conditions and create economic opportunities [27]. An evaluation of the social and economic impacts of large-scale biochar production is necessary to have a true understanding of the sustainability of this promising material, as there exists an “inextricable” linkage between environmental conditions and socioeconomic equality [28].

This paper bridges environmental and energy justice concepts by applying environmental justice tools for siting of a solar-powered facility for production of biochar, a product with multiple environmentally-beneficial applications. This work also supports the need to understand more about potentially vulnerable groups affected by energy production [29,30].

1.2. Purpose of an evaluative framework

To address the socioeconomic impacts of biochar production, the authors have developed a framework that illustrates a method by which environmental justice considerations – as a representation of social and economic impact of biochar production – can be evaluated. Of note, our analysis considers biochar production using low-cost, carbon-neutral solar energy. This issue is particularly important to investigate, as many authors [31–34] have noted the policy and economic barriers preventing large scale biochar production and usage. Further, "the environmental justice problems posed by green energy sources are in many ways the same problems posed by traditional energy sources" [25]. Therefore, this paper focuses on social and economic issues – with an environmental justice focus – surrounding siting of solar energy pyrolysis facilities for the production of biochar from corn stover.

Upon demonstration of the scalability of pyrolytic biochar production using solar energy and selection of a target market for the product, the application of environmental justice considerations is an essential starting point for assessment of the social and economic consequences of the technology (siting and operation) and the resulting material. Our analysis focused on the social and economic impacts of this green industry at a local scale – rather than at a national scale – due to a greater potential for local impacts to influence opinions of the industry [35]. In addition, renewable energy projects are met with higher public acceptance in communities if companies are required to identify community benefits of their operation [36]. An analysis which considers local community conditions will allow a determination of whether improved environmental quality through biochar use is also linked to improved societal and economic conditions. Our evaluation is limited in scope to a specific industry (biochar) using a particular production method (concentrated solar power) and feedstock (corn stover); however, this narrow scope is necessary for an initial exploration of the utility of a sustainable siting framework. This type of evaluative framework may allow active mitigation of potentially adverse effects, a higher degree of certainty in biochar as a "sustainable" material, and better informed policies to foster the widespread adoption of biochar as an agricultural amendment, a wastewater treatment material, and a method of carbon sequestration.

1.3. Biochar production and applications

1.3.1. Applications of biochar

Analysis of the demand for biochar involves many variables, which depend on the type of biochar application and the effectiveness of biochar originating from various feedstocks for those different applications. Distinct markets exist in agriculture, wastewater treatment, and in biochar utility as a carbon sequestration agent. The applicability of biochar for those different uses is a function of the respective feedstock, pyrolysis conditions, the resultant physical, chemical and structural properties of the biochar, and the effects of those properties in the media in which it is applied [37,38]. Although bio-oil and syngas are also formed as valuable products during pyrolysis, this section focuses on potential applications of biochar.

1.3.1.1. Agriculture. Agriculture presents a potential opportunity for the use of agricultural waste as a beneficial product [39]. Evidence suggests that the benefits of biochar as an agricultural soil amendment may even last beyond one growing season [40]. Amendment of soil with biochar produced from readily available waste cocoa shells resulted in a positive, yet highly variable, impact on maize production in rural Indonesia [41], as well as a net social benefit measure (based on the health, climate, and economic benefits of biochar amendment) of US $173 per household per year. While this savings is likely highly specific to that study, the authors also tap into broad issues facing sustainability when they emphasize that future research must focus on improving the efficiency and reducing the environmental impact of biochar production.

In an investigation of necessary factors for successful development of biochar production systems for agricultural use in Norway, continuous biochar production located close to the feedstock and end use of the biochar product contributed to the development of a functional biochar system [42]. Reliance on distributed biochar production, particularly in an era of farm diversification, would, however, negatively affect development of a wider-scale system of biochar production and application.

A decrease in cost per unit of energy production with increasing facility size for conversion of forestry biomass in Oregon also supports centralized biomass conversion [43]; the authors cite a large availability of feedstock and a stationary, grid-connected facility as optimal. Additional costs and logistics associated with transportation of feedstock and product must also be considered in a centralized production approach.

1.3.1.2. Wastewater treatment. The use of biochar for treating organics and inorganics in water and wastewaters has been evaluated by several authors [2,31,33,44–46]. Its successful application has been found to be specific to the feedstock, the pyrolysis conditions, and the contaminant to be treated. While biochar is an effective treatment method for a range of organics (dyes, phenolics, polyaromatic hydrocarbons) and inorganics (cationic and anionic), a thorough economic evaluation is needed to evaluate and optimize the use of biochar on a large scale [33]. Favorable economics could further the use of biochar – alone or with modification [45] – to treat contaminants such as metals [44,46] and antibiotics [31]. Biochar may also be an effective method to remove ammonium nitrogen from liquid wastes originating from animal agriculture [2], providing protection for water resources impacted by nutrient pollution.

1.3.1.3. Carbon sequestration. Nearly a decade of research has been done to investigate the utility of biochar as a carbon sequestration agent. Not only can biochar perform direct sequestration of CO_2 [47,48], it can also result in decreases in N_2O emissions from nitrogen fertilizer applications [49]. Biochar can go beyond a carbon-neutral technology, as it has the potential to remove carbon dioxide from the atmosphere [50]. Instead of burning biochar produced from bioenergy crops as a fuel, its use as a soil amendment for carbon sequestration, among its other benefits, further advances the potential of biochar as a carbon-negative technology [51]. The utility and economics of biochar as a CO_2 sequestration agent are dependent on the price of carbon emissions, the existence of carbon taxes, and the emissions trading framework in place [32,49]. Despite the wide, "uneven" range of estimates for biochar stability in soils [52], developing a quantifiable way to measure the environmental, social, and economic benefits of biochar is necessary prior to a large-scale implementation of biochar. This analysis should include regional employment opportunities, local air pollution concerns, efficiency of the pyrolysis conversion process, and the impacts of feedstock production [32].

While we have a deep appreciation for the suitability of biochar for use in many applications, the scope of this paper is necessarily limited to an examination of a portion of the biochar life cycle – solar pyrolysis production of biochar from corn stover – in order to focus on social and economic issues, in particular, environmental and energy justice.

1.3.2. Solar biochar production

This paper focuses on evaluating solar biochar production from the supply side, including feedstock and solar availability. A framework for evaluating the sustainability of pyrolytic biochar production using solar energy is necessary as a precursor to any overall evaluation of both the supply (production) and demand (use) sides of the process.

Solar processing of waste materials is a technology at “a very early technology readiness level” [53]. However, several studies have used modeling and experimental verification of the use of solar energy for processing carbonaceous materials into biochar, bio-oil, and pyrolytic gas. The extent of the solar pyrolysis reaction has been modeled and verified with experimental measurements of carbonaceous feedstock conversion [54]. In addition, a Scheffler parabolic solar dish is capable of providing necessary energy for pyrolysis of a non-edible Jatropha seed [55]. Solar flux corresponding to an average direct normal insolation (DNI) of 2.5–3 kWh/m^2/day produced maximum biochar yield of 51%, bio-oil yield of 20%, and pyrolytic gas yield of 29%. Other solar reactors, including parabolic dish reactor (PDR) and parabolic trough collector (PTC) concentrated solar power (CSP) systems, are capable of solar pyrolysis of biomass [56]. In addition to CSP, a linear Fresnel reflector (LFR) system has been modeled as a method of converting a generic cellulose-, hemicellulose-, and lignin-containing biomass to char, volatile tars, and gasses [56]. Batch pyrolysis of chicken litter using a solar dish concentrator was used to produce biochar with characteristics similar to traditional pyrolysis processes, successfully demonstrating the application of solar pyrolysis to produce a valuable product from a waste material [53].

1.3.3. Emissions from biomass pyrolysis

Despite the use of emission-free solar energy, some emissions would be expected from the pyrolysis process. While appropriate treatment technologies could reduce levels of these pollutants, assessment of the sustainability of biochar production requires awareness of these potential environmental burdens, and we present them here as further indication of the need for environmental justice considerations in facility siting decisions. Sulfur oxides (SOx) and nitrogen oxides (NOx), both criteria pollutants with human health impacts, are expected from biomass pyrolysis, though the concentrations of these pollutants are dependent on the composition of the biomass [57]. Particulate matter, another criteria pollutant, is produced through the formation of ash during pyrolysis [57–59]. In addition, biomass gasification can produce concentrations of ammonia and hydrogen sulfide which are “not negligible” [60].

Another potential concern is related to emissions associated with the transportation of the biomass to the pyrolysis facility [59]. The use of diesel vehicles would result in additional emissions of criteria pollutants as well as emissions of volatile organic compounds. Similarly, bottom ash produced through pyrolysis [57] would require transportation for disposal or further beneficial use. Although transportation-related emissions are indirectly associated with the solar pyrolysis facility, they may be of significant concern to neighboring communities during the facility siting process, alongside more general community concerns about increased truck traffic.

2. Methodology

A favorable geographic location for the use of solar technology for biochar production will have, at a minimum, adequate feedstock which is readily available, requiring minimal transportation and producing fewer associated emissions. In addition, production facilities will require adequate solar input. Among sites that meet these two baseline characteristics, industries may choose to site in states with renewable energy incentives and supporting policies. Therefore, the remainder of this paper will focus on (1) regions where these three conditions may co-exist and (2) the population demographics and socioeconomic status of those communities using environmental justice indicators as a proxy.

2.1. Feedstock and solar availability

To address the baseline facility siting requirement of adequate corn stover feedstock, the authors used data from the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) [61], specifically NASS's corn county maps. Additional data was derived from the US Department of Energy (DOE) Alternative Fuels Data Center (AFDC) [62]. Much of this information came from the BioFuels Atlas. Information for preliminary screening of solar availability was derived from the US Department of Energy National Renewable Energy Laboratory (NREL) [63] Concentrating Solar Power 1998–2009 maps.

Corn grain production (in bushels) from 2000 to 2010 was analyzed from the USDA NASS dataset. Sixteen states were identified as consistent top corn producers year-to-year in that timeframe based on agricultural survey and census data: Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, Wisconsin, South Dakota, Kansas, Missouri, Michigan, Texas, Kentucky, Colorado, North Dakota, and Pennsylvania.

To address the second baseline siting criteria of solar input, the NREL solar map was used as a preliminary screening tool to identify a subset of these states (portions of Nebraska, Kansas, Texas, and Colorado) which are favorable from a solar perspective (>5 kWh/m^2/day). To further identify favorable areas for siting solar biochar production from corn stover, corn production by county in each of those four states for a more recent time period (2015–2017) was determined and the top producing counties in each state were identified.

To cross-reference production data to availability of corn stover, the DOE AFDC data was queried to determine whether high corn-producing counties also had high levels of corn stover production. Of the states and counties identified in the USDA data, 13 counties produced over 100,000 t/year of corn stover.

Based on preliminary screening of the NREL map, several additional states (California, Oregon, Idaho, Nevada, Arizona, Utah, Wyoming, New Mexico, and Oklahoma) were favorable from a solar perspective. Independent of corn or corn stover production, a state was considered “favorable” if a portion of the state received an annual average DNI of greater than 6 kWh/m^2/day. Based on the AFDC data, two counties in those states also produced over 50,000 t of corn stover/year.

A review of the NASS and AFDC data and preliminary screening of the NREL solar map resulted in ten locations with potential to meet the two minimum criteria of adequate feedstock and solar input. Average monthly solar insolation (H_c) was calculated based on a flat plate surface facing south at each location, using a clear sky model and the CP&R method [64] for these ten locations. Since H_c represents the amount of solar irradiation which is available for harvesting and because local conditions affect the actual solar irradiation at a given location, the H_c calculations were compared to measurements from the nearest NREL Measurement and Instrumentation Data Center (MIDC) station [65]. In some cases, the nearest MIDC station was in another county or another state. Despite this, every effort was made to select a comparable station in the same multi-year physical solar model (PSM) DNI range. For one study location, no MIDC sites met this criteria, so a monitoring location from the Atmospheric Radiation Measurement (ARM) program was selected for comparison. The average of 25 DNI results available through the National Solar Radiation Database (NSRDB) Data Viewer was used as a comparison to calculated H_c values.

2.2. State incentives for renewable energy

An additional factor influencing facility siting may be the availability of incentives for renewable energy and, more generally, a state's overall attitude toward renewable energy. Selection of sites in several states allows for comparison of energy efficiency and renewable energy (EERE) incentives in multiple states. Available state and federal incentives were identified using the North Carolina Clean Energy Technology Center's Database of State Incentives for Renewables & Efficiency (DSIRE) [66].

2.3. Environmental justice analysis

To gain a better understanding of population demographics, socioeconomic characteristics, and existing environmental burdens in communities where solar CSP biochar production may be favorable based on the above technical and policy data, the authors queried the US Environmental Protection Agency's (US EPA) Environmental Justice Screening and Mapping Tool (EJSCREEN) [67]. EJSCREEN is a publicly accessible, peer-reviewed screening tool developed by US EPA [68] initially as a method of complying with Executive Order 12,898, *Federal Actions To Address Environmental Justice in Minority Populations and Low-Income Populations* [69]. Since its initial development, EJSCREEN has been made available to the public to allow communities and other stakeholders to consider environmental justice in their decision-making [70]. This tool is intended for use in the pre-decisional phase of processes, like policy development by federal agencies, to identify areas which may warrant further analysis; specifically it is used by US EPA to implement aspects of permitting, enforcement, and geographically-based programs [71]. In addition to federal agencies, EJSCREEN has been used by municipalities [72] and community groups [73,74]. It has also been suggested as a tool for use in planning and siting scenarios [75–78].

EJSCREEN combines demographic and socioeconomic data and environmental conditions to produce an environmental justice (EJ) Index. The EJ Index is the product of an environmental indicator value, the difference between demographic/socioeconomic and environmental indicators in a geographic area (e.g., Census block group) and national averages for those indicators, and the population residing in that geographic area [68]:

$$EJ = EI\ (DI_B - DI_U) \times P$$

where EJ, EI, DI_B, DI_U, and P are defined as the environmental justice index, environmental indicator, demographic index for the block group, demographic index for the United States, and population count for group, respectively.

Table 2
Top corn producing states (2000–2010) and top corn producing counties (2015–2017) in those states. Data from USDA National Agricultural Statistics Service (NASS), US DOE National Renewable Energy Laboratory (NREL), and US DOE Alternative Fuels Data Center (AFDC).

Top corn producing states (2000–2010)	Counties in top 5 for corn production (2015–2017)
Nebraska*	**York**†, Hamilton†, Antelope†, Buffalo†, Phelps†, **Dawson**†, Custer†, Platte†
Kansas*	Sherman, Haskell, Sheridan, Brown, Gray, **Stevens**†, Doniphan, Nemaha, Thomas, Marshall, **Meade**§
Texas*	Sherman, **Dallam**†, **Castro**†, Moore, Hansford, Hale,
Colorado*	**Yuma**†, Kit Carson, Phillips, **Weld**†, Washington, Baca, Logan
Iowa	
Illinois	
Minnesota	
Indiana	
Ohio	
Wisconsin	
South Dakota	
Missouri	
Michigan	
Kentucky	
North Dakota	
Pennsylvania	

* Indicates favorable (>5 kWh/m^2/day) solar availability in some portions of the state (NREL).
† Indicates high (>100,000 t/year) corn stover production (AFDC).
Bold indicates county selected for environmental justice analysis using EJSCREEN.
§ Meade County, Kansas, was in the top 10 corn producing counties in this timeframe and was selected for inclusion based on corn stover production.

EJSCREEN includes information on six demographic and socioeconomic variables in a given geographic area: percent low-income; percent minority; percent with less than high school education; percent linguistically isolated; percent of population under age 5; and percent of population over age 64. Demographic and socioeconomic data in EJSCREEN is populated from the US Census Bureau's American Community Survey 5-Year Summary File. EJSCREEN treats demographic and socioeconomic data as "very general indicators" of susceptibility to environmental exposures [68]. Potential environmental exposures are characterized using 11 environmental indicators including: proximity to National Priorities List (NPL, or "Superfund") sites; summertime ambient ozone levels; annual average small particulate matter (PM 2.5) levels; percent pre-1960 housing units (as an indicator of lead paint presence); and pollutant loadings from wastewater discharges. The geographic areas in EJSCREEN may be as small as a Census block group or as large as a 9-mile buffer (or, circle) around a specific point [68].

The 80th percentile has been suggested [68] as an initial level at which a user of EJSCREEN may want to obtain more detailed information and does not necessarily indicate that a geographic area is an environmental justice community. The authors used 80th percentile values as an initial screening value to indicate that indicators in a geographic area may require further evaluation during the early phase of facility siting analyses. The EJSCREEN tool was queried for standard reports, based on a 9-mile buffer from a point in the center of each county analyzed (the largest geographic area available).

The US EPA's EJSCREEN technical documentation is clear that EJSCREEN is subject to uncertainty, as the underlying data contain uncertainties, and emphasizes that EJSCREEN analyses should be supplemented with additional data on the community. We are confident that our use of the EJSCREEN reports is in the manner intended. Environmental and energy justice are complex issues which require a "multifaceted" approach [30]. Multiple bases – including social and environmental concerns – exist for opposition to renewable energy infrastructure [79]. The environmental justice indicators used in this framework reduce complex issues to a few simplistic data points; however, energy campaigns in the United States have been influenced by environmental justice [29]. Therefore, the authors use EJSCREEN indicators as part of a siting framework, recognizing it as an early action in the series of steps necessary for sustainable siting decisions.

3. Results

3.1. Corn and corn stover availability

Through analysis of USDA NASS data and the US DOE NREL map, four states were determined to have both consistently high corn production and adequate solar radiation: Nebraska, Texas, Kansas, and Colorado. Eight of the highest-producing counties in those states which also had high levels (>100,000 t/year) of corn stover production, based on US DOE AFDC data, were selected for further analysis: Dawson and York Counties, Nebraska; Stevens and Meade Counties, Kansas; Castro and Dallam Counties, Texas; and Yuma and Weld Counties, Colorado (Table 2).

Of the states most favorable for solar – independent of corn production – two counties in those states were identified to have moderately high (>50,000 t/year) levels of corn stover production: San Joaquin County, California; and Texas County, Oklahoma (Table 3).

3.2. Solar analysis

The center of each county was selected for both the solar calculations and environmental justice analyses. Across the ten counties

Table 3
Solar availability and corn stover production. Data from NREL and AFDC.

Favorable* solar states	Counties with >50,000 t/year corn stover production
California	**San Joaquin**
Oklahoma	**Texas**
Colorado	**Yuma, Weld**
Idaho	
Nevada	
Arizona	
Utah	
Wyoming	
New Mexico	
Oregon	

* Independent of corn or corn stover production, "favorable" indicates solar availability > 6 kWh/m^2/day in a portion of a state.

Bold indicates county selected for environmental justice analysis using EJSCREEN.

studied, the locations' H_c values averaged 5.49 ± 1.11 kWh/m^2/day. In nine of ten locations, the calculated H_c was over 5 kWh/m^2/day for eight of 12 months of the year (Fig. 3). When compared to the MIDC and ARM data, the H_c values were, in all 10 locations, an underestimate of measured DNI (Table 4). Some discrepancy between calculated and measured values is to be expected based on local surface conditions. The purpose of the solar data analysis is simply to ensure adequate solar energy input for the solar biochar production process; both the calculated and measured data support the adequacy of solar input.

3.3. Solar incentives

The DSIRE database showed a range of state and federal financial incentives and regulatory policies which support EERE. While it is beyond the scope of this paper to analyze the policies and incentives in detail, the authors use the data from the DSIRE database as an indicator of the degree of favorability of each state toward renewable energy technologies. Results from the DSIRE database are summarized in Table 5.

Analysis of the total financial incentives and regulatory policies available in the six states in this study shows that California not only has the most available incentives, but also the greatest percentage of all available EERE-favorable incentives and policies at the state level (85.4%). Texas also has a significant number of EERE-favorable policies and incentives available (154) as well as a significant portion (81.8%) of total EERE-favorable incentives/policies at the state level; Colorado is close behind (78%). Oklahoma, Kansas, and Nebraska had fewer overall EERE-incentives and policies, as well as lower percentages of state policies and incentives among those totals. At this time, not all state EERE-favorable incentives may be available to biochar production. For example, the California Global Warming Solutions Act currently provides credits only for displacement of fossil fuels, not carbon storage [80].

3.5. Environmental justice

Table 6 provides a summary of results from each EJSCREEN standard report for the ten geographic areas analyzed. EJSCREEN reports indicate that four of the ten locations have at least one EJ Index at or above the 80th percentile nationwide.

For example, Dawson County, Nebraska, has a 16% linguistically isolated population, compared to the national average of 5%, placing it in the 90th percentile nationwide. Outreach to the community on siting a facility in this area should take language needs into consideration. San Joaquin County has levels of small (2.5 μm) particulate matter (PM 2.5) in the 96th percentile nationwide; facility planners must consider early in siting discussions any process or transportation emissions which may contribute to PM 2.5 emissions or formation in this area. EJSCREEN also identifies other socioeconomic pressures on communities including education and poverty.

4. Discussion

The literature states that continuously-operating, centralized biochar production facilities located close to sources of feedstock are preferable from an economic and technical perspective [34,35]. Analysis of US corn production and corn stover data, led the authors to focus on areas in Nebraska, Kansas, Texas, and Colorado. In order to consider other locations with lesser corn production, but favorable solar radiation, locations in Oklahoma and California were also included in this study.

An analysis of state incentives may influence solar biochar production facilities to locate in states like California and Texas, which have a long history of successful Renewable Energy Portfolio Standards (RPS). Despite many variations in RPS mandates, program management, and definitions of qualifying renewable production, these programs, adopted by state legislatures, indicate a strong state commitment to development of electricity production from renewable sources [81].

Although renewable energy projects are often touted as job creators

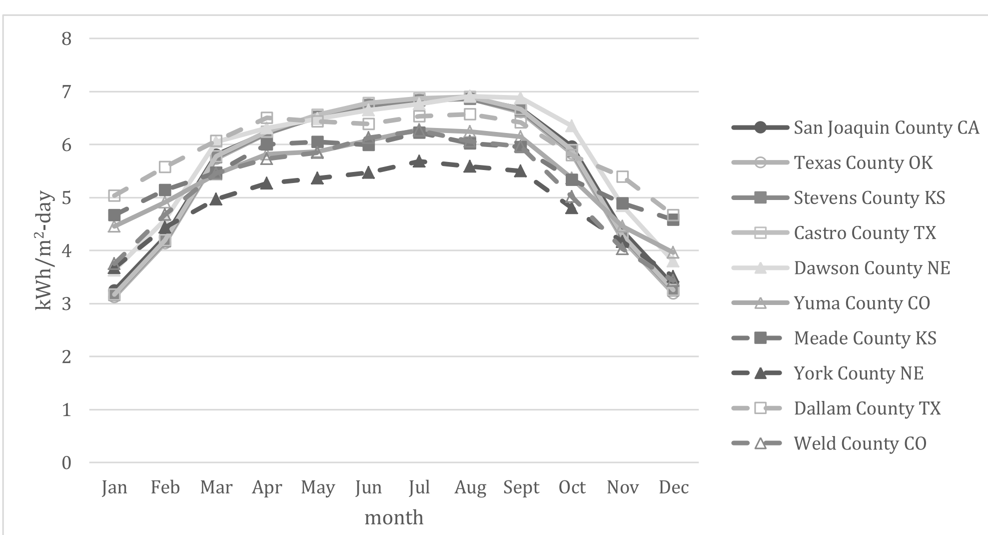

Fig. 3. Monthly average insolation (H_c) in locations selected for study.

Table 4
Comparison of H_c calculated at each study location to MIDC and ARM DNI data.

Study location	H_c (kWh/m^2/d)	Average measured DNI (kWh/m^2/d) *Monitoring station and location*	Percent difference between calculated H_c and measured DNI
San Joaquin County (CA)	5.57 ± 1.38	6.40 ± 0.07 *MIDC site code 385,512,125 Sacramento Municipal Utility District (Anatolia)*	14.9
Texas County (OK)	5.50 ± 1.44	6.64 ± 0.07 *MIDC site code 380,510,365 SS2 SOLRMAP Sun Spot Two - Swink (RSR)*	20.7
Stevens County (KS)	5.53 ± 1.42	6.64 ± 0.07 *MIDC site code 380,510,365 SS2 SOLRMAP Sun Spot Two - Swink (RSR)*	20.2
Meade County (KS)	5.53 ± 0.59	6.64 ± 0.07 *MIDC site code 380,510,365 SS2 SOLRMAP Sun Spot Two - Swink (RSR)*	20.1
Castro County (TX)	5.55 ± 1.43	6.64 ± 0.07 *MIDC site code 380,510,365 SS2 SOLRMAP Sun Spot Two – Swink (RSR)*	19.6
Dallam County (TX)	5.95 ± 0.65	6.64 ± 0.07 *MIDC site code 380,510,365 SS2 SOLRMAP Sun Spot Two – Swink (RSR)*	11.6
Dawson County (NE)	5.77 ± 1.22	5.92 ± 0.04 *ARM site EF1 Larned KS*	2.6
York County (NE)	4.87 ± 0.76	5.92 ± 0.04 *ARM site EF1 Larned KS*	21.6
Yuma County (CO)	5.42 ± 0.80	6.17 ± 0.02 *MIDC site code 397,510,465 Solar Technology Acceleration Center (SolarTAC)*	13.8
Weld County (CO)	5.20 ± 1.00	6.17 ± 0.02 *MIDC site code 397,510,465 Solar Technology Acceleration Center (SolarTAC)*	18.7

[82–84], there are critics from an economic perspective [85,86] as well as questions about siting suitability based on societal preferences [87,88]. While the economics of government-subsidized renewable energy are beyond the scope of this work, potential environmental justice concerns with siting and operation of renewable energy facilities should be determined in the pre-planning phase of projects. EJSCREEN allows project developers to review selected community characteristics and existing environmental burdens on the community in order to determine how the operational aspects of renewable energy production may exert an additional impact on a community.

Of note, but not included in the evaluation framework presented here are the environmental, social, and economic impacts of the components and operation of the CSP system itself. Although the evaluative framework in this paper does not include a life cycle assessment (LCA) of the solar production unit itself, there exists a body of research [84,89,90] which points to the economic, social, and environmental sustainability of CSP systems. The CSP literature shows lower GHG emissions [90] and higher job creation [84] when compared to fossil-based production systems, as well as a favorable pay-back period for CSP systems [89]. Together, these findings support the notion of biochar production using solar energy derived from a CSP system as an environmentally, economically, and socially sustainable production technology.

4.1. Facility siting and environmental justice

For a new industrial facility to truly be considered sustainable, it must – at a minimum – not exacerbate the social, economic, or environmental burdens which exist in a community. During the early phases of facility siting assessments, EJSCREEN provides a tool for project proponents to assess whether a community may be disproportionally impacted by the siting of a large industrial facility. The results of an EJSCREEN report can be combined with the technical factors necessary for a solar biochar production facility to be feasible, allowing project proponents to evaluate objective community and environmental data in concert with data on feedstock availability, solar availability, and financial or regulatory incentives.

4.2. Evaluative framework: solar biochar siting index

A quantifiable evaluative framework for siting of solar pyrolysis biochar production facilities must be developed in order to truly advance this technology as sustainable and perform data-driven siting analyses. A standardized approach which addresses social, economic, and environmental attributes of a community will lend additional support to biochar as a sustainable technology. As a framework, the authors propose the following as a method of calculating a solar biochar siting index (B), a measure of determining the favorability of a site for solar biochar production:

$$B = aS + bF + cI - dE + eJ$$

where:

B = solar biochar siting index
S = solar irradiance
F = feedstock availability
I = state EERE incentives
E = existing environmental burden
J = job creation potential
a, b, c, d, e = weighting factors (sum of weighting factors = 1)

Table 5
Summary of state and federal renewable and efficiency incentives/policies. Data from DSIRE database (accessed 6/18/18).

State	Total incentives	Financial incentives			Regulatory policies			% of total incentives that are state incentives
		Total	State	Federal	Total	State	Federal	
Nebraska	46	37	13	24	9	5	4	39.1%
Kansas	40	27	3	24	13	9	4	30%
Texas	154	112	88	24	42	38	4	81.8%
California	192	140	116	24	52	48	4	85.4%
Oklahoma	60	48	24	24	12	8	4	53.3%
Colorado	127	102	78	24	25	21	4	78%

Table 6
Summary of EJSCREEN reports.

Study county (state)	EJSCREEN EJ Indexes[*] at/over the 80th percentile nationwide										
	PM 2.5	Ozone	NATA[**] diesel PM	NATA air toxics cancer risk	NATA respiratory hazard index	Traffic proximity and volume	Lead paint indicator	Superfund proximity	RMP proximity	Hazardous waste proximity	Wastewater discharge indicator
San Joaquin (CA)	X	X	X	X	X	X	X	X	X		X
Texas (OK)		X							X		X
Stevens (KS)											
Meade (KS)											
Castro (TX)	X	X					X		X		
Dallam (TX)											
Dawson (NE)		X	X				X		X		X
York (NE)											
Yuma (CO)											
Weld (CO)											

[*] For definition of EJSCREEN terms, see: https://www.epa.gov/ejscreen/glossary-ejscreen-terms.
[**] National Air Toxics Assessment.

This approach allows a company to consider and assign importance (weights) to the critical technical requirements of solar biochar production (S, F), as well as the available financial and policy incentives (I) in their siting decisions. In addition, a company can also assign weights to factors including existing environmental burden (E); as a negative term in the equation, it decreases the value of the siting index (B). Finally, a weight can be assigned to the job creation potential (J) of a project based on the nature and duration of the jobs (short-term construction, long term operation and maintenance, etc.). The data necessary for calculating this siting index is readily available from sources including EJSCREEN, the American Community Survey, the U.S. Bureau of Labor Statistics, and other governmental sources; analyzing the data as a matter of practice will enhance the credibility of biochar as a sustainable material.

4.3. Siting analysis using the solar biochar siting index

Using the solar biochar siting index described above, the authors were able to objectively screen ten potential locations for siting of a solar pyrolysis biochar production facility. The solar irradiance term (S) was set to represent the average H_c for the site, as a fraction of 7.5 kWh/m^2/d (Table 3), the maximum DNI value indicated on NREL solar maps. The feedstock availability term (F) was set as a fraction of the highest corn stover production of the ten sites in this analysis. The state EERE incentives term (I) was set based on the fraction of EERE incentives offered by the state (Table 5, last column). The existing environmental burden term (E) was set to represent the fraction of EJSCREEN EJ Indexes at or over the 80th percentile nationally (Table 6).

For this analysis, the weighting factors were set to give equal weights to solar irradiance and feedstock availability (0.35) and equal weights to the three other terms in the equation (0.1). Finally, the job creation term (J) was kept constant in the ten locations in this analysis, as the notional facility was assumed to bring the same job creation potential to each location (i.e., the term *eJ* was set to 0.1). In reality, J could vary – even for analysis of the same facility in different locations – based on the supporting industries (for example, transportation) which would be needed in different locations.

An ideal location would allow a project proponent to take advantage of abundant feedstock, adequate solar input, and available EERE incentives, and not adversely impact communities with disproportionate environmental burdens. Using the framework described above for a preliminary siting assessment of the ten study locations, the most-preferred location for a hypothetical solar pyrolysis facility for conversion of corn stover to biochar would be Yuma County, with the highest biochar siting index, B (Table 7, second-to-last row), and the least preferred location would be San Joaquin County. These results are driven primarily by the technical consideration of feedstock availability, but they also reflect significant potential environmental justice concerns in San Joaquin County (Table 6). The most and least favorable locations are the same even if environmental justice considerations are excluded from the biochar siting index, and the weight associated with the EJ Index variable is reassigned to the technical considerations (i.e., it is split equally between solar and feedstock availability; see Table 7 footnotes).

However, there are some notable changes evident in the relative ranking of sites based on the siting index with and without the environmental justice term in the biochar siting index equation. Most notably, Castro County and Texas County become less favorable overall when environmental justice indicators are included in the siting index, as each county has several EJ Indexes at/over the 80th percentile (Table 6). Inclusion of environmental justice in the biochar siting index also results in a wider distribution of site index values, providing additional distinction between sites which may appear to be similar based on technical considerations and state incentives alone. For example, feedstock availability drives the top four counties toward higher siting index values; the gap between the fourth and fifth counties is wider when EJ is included in the siting index, reinforcing that the top locations could be favorable, even when the socioeconomic proxy of environmental justice based on EJSCREEN reports is considered.

Project proponents making intra-state siting decisions may find utility in inclusion of environmental justice index values. These results show that when environmental justice is not considered, the biochar siting indices of the two study counties in Nebraska (York and Dawson) differ by 0.01; with EJSCREEN data included, the gap between these sites is greater (0.05). Incorporating environmental justice in the biochar siting index is particularly noteworthy for the Texas counties in this study: without considering environmental justice, the biochar siting indices of the two counties differ by 0.07; with environmental justice as part of the siting index, Dallam County is slightly more favorable (0.1 difference), however three sites outside of Texas become more favorable than Castro County.

5. Conclusion

When consulted early in siting or policy discussions, EJSCREEN has the potential to bring to light community characteristics which could be adversely impacted by additional industry and may help to set the stage for meaningful public engagement on environmental, societal, and economic issues. While EJSCREEN is not an environmental risk assessment tool and it cannot provide all data of interest on a community, it is valuable in preliminary assessments and could be critical in reducing barriers to widespread adoption of biochar. The existence of a

Table 7
Sample siting analysis using the solar biochar siting index framework.

Variable*	San Joaquin (CA)	Texas (OK)	Stevens (KS)	Meade (KS)	Castro (TX)	Dallam (TX)	Dawson (NE)	York (NE)	Yuma (CO)	Weld (CO)
S: *Solar DNI as fraction of 7.5 kWh/m^2/d*	0.74	0.73	0.74	0.74	0.74	0.79	0.77	0.65	0.72	0.69
F: *Feedstock availability as fraction of highest site*	0.21	0.4	0.42	0.45	0.36	0.48	0.87	1	0.96	0.37
I: *Fraction of EERE incentives at state level*	0.85	0.53	0.3	0.3	0.82	0.82	0.39	0.39	0.78	0.78
E: *Fraction of EJSCREEN EJ Indexes at/over 80th percentile*	0.91	0.27	0	0	0.36	0	0.45	0	0	0
B: Solar biochar siting index**	0.43	0.52	0.54	0.55	0.53	0.63	0.67	0.72	0.77	0.55
Solar biochar siting index *without* EJSCREEN EJ Indexes***	0.57	0.61	0.59	0.61	0.62	0.69	0.79	0.8	0.85	0.60

* The job creation term (J) was kept constant in the six locations in this analysis (i.e., the term *eJ* was set to 0.1).
** $B = aS + bF + cI - dE + eJ$ (weights: $a = 0.35$; $b = 0.35$; $c = 0.1$; $d = 0.1$; e*).
*** $B = aS + bF + cI + eJ$ (weights: $a = 0.4$; $b = 0.4$; $c = 0.1$; e*).

framework – even with adjustments to the weighting and definition of the terms outlined above – is a step forward in ensuring that there is an early consideration of environmental justice issues in siting of solar pyrolysis biochar production facilities. Where potential environmental justice concerns are identified, and siting proceeds despite those concerns, project proponents are better poised to mitigate the impacts of the project on the community.

This approach can help to ensure that biochar production facilities are not offsetting potential positive effects in a community with negative environmental, health, or other consequences. A similar index-based approach which includes objective screening for environmental justice measures could be extended to other "green" and traditional industries, often billed to communities as economic engines and job creators. The proactive consideration of community characteristics and needs at a local scale would be a strong complement to factors which influence technical feasibility of a process such as solar biochar production, as aggregated in a biochar siting index.

The authors highlight the need for continued collaboration between engineering, social sciences, and basic and applied sciences to understand and address environmental and energy justice. While we cannot make a final determination or quantification of the social and economic impacts of solar biochar production from corn stover, this study nonetheless makes a significant step forward in the literature by beginning a meaningful dialogue about those impacts with environmental and energy justice at the forefront of policy and planning discussions. For this promising material to be truly sustainable, standardizing this type of approach in the biochar industry would be a clear demonstration of a commitment to elevating all three pillars of sustainability – social, economic, and environmental – in concert.

Declaration of Competing Interest

The authors declare no conflicts.

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