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Biochar and forest restoration: a review and meta-analysis of tree growth responses

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Abstract "Biochar", or charcoal intended for use as a soil amendment, has received great attention in recent years as a means of enhancing carbon sequestration and soil properties in agricultural systems. Here we address the potential for biochar use in the context of forest restoration, reviewing relevant experimental studies on biochar use in forest ecosystems, the properties of chars generated from wood waste material, and available data on tree growth responses to biochar. To our knowledge the earliest mention of char use as a soil amendment is actually specifically in the context of forest restoration (in the 1820s in Scotland). Wood waste biochars have an unusual set of properties that suggest their applicability in a forest restoration context: namely, high recalcitrance promoting long-lasting effects, retention of cations, anions, and water, in the soil, sorptive properties that can reduce bioavailability of a wide range of toxic materials, and relative ease of production from locally available feedstocks. A meta-analysis of recent studies on biochar responses of woody plants indicates a potential for large tree growth responses to biochar additions, with a mean 41 % increase in biomass. Responses are especially pronounced at early growth stages, and appear to be higher in boreal and tropical than in temperate systems, and in angiosperms than conifers; however, there is high variability, and field studies are few. The properties of biochars also vary greatly depending on feedstock and pyrolysis conditions; while this complicates their use, it provides a means to design biochars for specific restoration situations and objectives. We conclude that there is great promise for biochar to play an important role in a wide variety of forest restoration efforts, specifically as a replacement product for other forms of organic matter and liming agents.

Keywords Biochar · Charcoal · Feedstock · Forest restoration · Pyrolysis · Soil carbon

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Introduction

"Biochar" is a term recently coined as a label for charcoal intended for use as a soil amendment, generally derived from organic waste feedstocks such as sawmill or crop residues. Biochar has received substantial attention as a means to enhance carbon sequestration in managed ecosystems (Lehmann and Joseph 2009; Woolf et al. 2010); it has as well been hailed as a central component of carbon-neutral or even carbon-negative energy systems that could over time reduce atmospheric CO_2 concentrations (Lehmann 2007a, b). Since fire constitutes the most important agent of natural forest disturbance globally, additions of biochar to forest soils may also be viewed as a means to better "emulate" natural disturbance processes (Thomas 2013). The chemical and physical properties of chars vary greatly depending on feedstock, pyrolysis conditions, and weathering; for example, char pH can vary from ~6 to 11 (Enders et al. 2012). Due to this variability it is generally more correct to refer to "biochars" than "biochar"; also only some chars are intended or designed for use as a soil amendment, and so it useful to distinguish between biochars and the broader category of "chars". Chars themselves are a subset of the much broader "black carbon continuum" that includes soot, graphitic carbon, high-carbon ashes, and coal (Spokas 2010).

The overwhelming focus of studies examining biochar effects on soil processes and plant growth has been agricultural systems (Jeffery et al. 2011; Biederman and Harpole 2013; Liu et al. 2013). Positive growth responses generally are found, particularly on coarse-textured and/or acidic soils, but negative effects also occur (Spokas et al. 2012). As might be expected given highly variable physio-chemical properties, studies have found pronounced differences in plant growth responses among different chars (e.g., Rajkovich et al. 2012; Pluchon et al. 2014). The pooled average biomass increase of agricultural crops in response to biochar additions, as derived from recent meta-analyses, is ~10–30 % (Jeffery et al. Biederman and Harpole 2013; Crane-Droesch et al. 2013; Liu et al. 2013). There is some evidence that growth and physiological responses to chars in the soil vary substantially among plant taxa, with, for example, higher growth responses generally seen in legume than non-legume crops (Liu et al. 2013).

Relatively few studies have examined char effects on trees and other woody vegetation, although there has been a recent rapid growth in this literature. A 2013 review (Stavi 2013) noted that nearly all experiments on forest systems had examined responses to wildfire-produced charcoal or ash, rather than industrially produced biochar per se. Positive effects of chars on tree growth have been documented in boreal and sub-boreal forest systems (Wardle et al. 1998; Makoto et al. 2010; Robertson et al. 2012; Pluchon et al. 2014), with much more limited data available on temperate and tropical trees (e.g., Scharenbroch et al. 2013; Sovu et al. 2012; Fagbenro et al. 2013). With few exceptions, the duration of experimental studies on tree responses has been short, with most studies examining seedling responses only.

Several mechanisms may account for enhanced plant growth in response to char additions to soil. Important possible mechanisms include effects of soluble nutrients contained in fresh char, sorption of growth-inhibitory substances such as phenolics (Wardle et al. 1998) or salts (Thomas et al. 2013), increased soil water retention, and increased soil pH (Atkinson et al. 2010). Fresh chars are commonly high in soluble K, P and certain cations (e.g., Sackett et al. 2014). Pluchon et al. (2014) have recently reported a correlation between P availability in chars generated from boreal species and seedling growth responses. Increased P availability is thought to play an important role in long-persistent positive effects on plant growth in char-rich "terra preta" soils of the Amazon basin (Glaser et al. 2001). Weathering alters char properties (Joseph et al. 2010), and there is evidence that positive agronomic effects of chars can increase over multiple rotations (Major et al. 2010). In addition, low molecular weight molecules, including a variety of polyaromatic hydrocarbons, are commonly sorbed during pyrolysis and gradually leached following char addition to soils, with possible species-specific toxic effects on a variety of organisms (Bastos et al. 2014; Marks et al. 2014; Kołtowski and Oleszczuk 2015), including plants (N. V. Gale unpublished data). It is possible that gradual leaching or microbial degradation of such compounds could also influence patterns of response over the first few years following biochar additions to soil.

Biochar has a number of properties of particular interest from the perspective of forest restoration. First, their recalcitrance implies that biochars added in the context of a restoration project will not rapidly decompose. In contrast, rapid losses of other forms of organic matter may decrease their effectiveness, increase required addition rates, and/or result in requirements for multiple additions. Second, biochars act to retain plant nutrients—both cations and anions—as well as water in the soil. This is particularly important in highly degraded, coarse-textured substrates frequent in the context of forest restoration. Third, the sorptive properties of biochar are likely to result in decreased bioavailability of a wide range of materials that are either generally toxic or adverse to plant growth at high concentrations, including metals, salts, poly-aromatic hydrocarbons, and residual herbicides. The wide range of materials that may be sorbed and the potential for long-term sorption are both unusual benefits. Fourth, biochar may be relatively easily and economically generated from locally available feedstocks, and so offers important potential advantages in terms of both economics and logistics.

In the present paper we start by more fully developing these arguments regarding the potential of biochar for forest restoration. We draw mainly on recent work on the mechanisms of biochar effects on soil properties and plant growth processes, but also note a remarkably long history of applied use of biochar for forest restoration going back to at least the 1820s. We then present a meta-analysis of existing data on growth responses of woody plants to biochar additions, examining variability in responses among biomes, between conifers and angiosperm trees, and with respect to experiment duration and type.

Historical perspectives

The concept of using charcoal as a tool for forest restoration is not new; indeed, intentional use of chars to enhance growth of woody vegetation likely dates to prehistory. It is widely known that activities of pre-Columbian inhabitants of the Amazon basin led to the widespread incorporation of chars in this region, resulting in extensive human-modified soils (anthrosols) termed "terra preta" in Brazil (Glaser et al. 2001). Radiocarbon dating and archeological evidence suggest a peak of terra preta formation at roughly 1000 AD, with dates of formation ranging from ~500 BC to 1640 AD (Heckenberger et al. 2003; Neves et al. 2003). While terra preta soils are widely distributed in Amazonia, their overall frequency and spatial distribution is still highly uncertain (Glaser and Birk 2012). It is likewise unclear whether terra preta soils were actually created intentionally. Contemporary indigenous groups in Amazonia commonly use middens—that generally include incorporation of chars—for home garden purposes, and it has been argued that terra preta soils could have originated from the similar use patterns by pre-Columbian peoples (Hecht 2003; Schmidt and Heckenberger 2009). It should be noted that there is some evidence for anthropogenic dark earths in areas outside of Amazonia as well, including parts of

Mesoamerica (Graham 2006), Africa (Blackmore et al. 1990; Fairhead and Leach 2009), and possibly Borneo (Sheil et al. 2012).

While the term biochar is of very recent vintage, the scientific study of chars in relation to soil processes and plant growth has a long history. Wilson (2013) has recently drawn attention to an important body of historical scientific literature on char as a soil amendment dating to the 1850s. The most prominent early scientific use of char as a plant growth medium were experiments by Justus Von Liebig, who used the recalcitrance of char to demonstrate uptake of carbon from the atmosphere by plants. Von Liebig also noted that great capacity of char to sorb ammonia, and commented in passing on positive effects of char on plant growth. This effect was evidently well recognized at the time in horticultural circles. Wilson (2013) cites an anonymous source in 1847 as stating: "The use of charcoal as a fertilizer is generally well known. Its expense, however, often precludes its use" (Anonymous 1847).

We have fortuitously located two earlier scientific sources that comment on the use of char as a fertilizer, specifically in the context of forest restoration. Patrick Matthew (1831) summarizes and elaborates on a char-based fertilization method used in preparation for tree planting on deforested peaty soils in the Scottish highlands described earlier by Robert Monteath (1824). As the key passage appears not to have been previously noted in the modern biochar literature, we quote it in full:

> A small pile, about six in number, is then burnt upon the intended site of each tree, if necessary, aided in the combustion by furze or other fuel; taking care, by proper regulation of the quantity of fuel, or otherwise, to prevent the combustion from proceeding too far, and the ashes from becoming white and light, as in this case a considerable part of their virtues is dissipated. (Matthew 1831, p. 142–143)

The passage is remarkable in several respects. First, it points to the utilization of chars for forest restoration purposes well before their use in horticulture in Central Europe in the 1850s. Second, it demonstrates an understanding of the important distinction between char and fully combusted wood ash in terms of effects on soil properties and tree growth. Third, it constitutes another overlooked scientific contribution of the iconoclastic forester Patrick Matthew, who (in the same 1831 volume "On Naval Timber and Arboriculture") elaborates a well-developed theory of the "natural process of selection" some 29 years before the publication of Charles Darwin's "Origin of Species" (Zon 1913; Sutton 2014).

Mechanisms for positive effects on restoration objectives

Arguments for the utility of biochar in the context of forest restoration begin with the same property that is the key to biochar's role in carbon sequestration: recalcitrance. Addition of topsoil, or of organic matter in the form of various types of compost or biosolids is a widespread and often critically important practice in environmental restoration projects on heavily disturbed or contaminated sites (Wong 2003). In sites where subsoil or unmodified parent material is the primary growth medium, organic matter is generally necessary both a source of plant nutrients and to provide sufficient cation exchange capacity to prevent rapid loss of mobile mineral nutrients. The carbon half-life of many organic materials in common use as soil amendments is <1 year (e.g., Bernal et al. 1998, Bolan et al. 2012), though recalcitrant fractions commonly do have considerably longer half-lives. Biochar is certainly much longer lived. Modeling studies have commonly employed a carbon half-life of 100–200 years, though this is undoubtedly conservative. Estimates of the actual carbon half-life of biochars are extremely variable, with an upper range of ~10,000–100,000 years (Spokas 2010).

There is strong evidence for positive effects of biochar additions on forest soil nutrient status in the short term. In addition, most biochars have very low N content, though often much higher levels of P, K and Ca (e.g., Sackett et al. 2014). Higher retention of N (and S) can, however, occur during pyrolysis of woody chars due to formation of heterocyclic N (Kloss et al. 2012). In many cases additions of compost or other materials with relatively high N are likely to be necessary for maintaining nutrient balance. A handful of agronomic studies have found evidence for synergistic effects of biochar-compost mixtures on soil nutrient availability (Schulz and Glaser 2012; Liu et al. 2013), and plant responses (Schulz and Glaser 2012). Work along these lines has only very recently examined responses in the context of contaminated soils (Beesley et al. 2014).

In many forest restoration situations soil contaminants will be of concern. The sorptive properties of biochars are commonly responsible for biochar's capacity to mitigate the impacts of plant stress by reducing exposure of plants to stress agents (Yu et al. 2009; Beesley et al. 2010, 2011; Buss et al. 2011). Studies have documented reduced bioavailability of heavy metals and sulfates in the presence of biochar incorporated in contaminated soils (Beesley et al. 2010; Borchard et al. 2012). One study has also documented strong hysteresis in sorption, approaching a state of irreversible sorption, of Cu(II) ions in certain biochars (Borcard et al. 2012). Natural charcoals have been found to be important sink locations for metal ions and other contaminants in ecological systems more generally. A study examining charcoal in wetland sediments in an area impacted by mine wastes found 40-fold higher levels of metal contaminants in charcoal compared with source soils (Baker et al. 2011). These results suggest that biochar applications have the potential to both limit short-term leaching of metal ions and other contaminants, and to effectively sequester a variety of contaminants over very long time periods.

The viability of biochar for forest restoration is contingent on the assumption that trees will generally show positive growth responses to biochar additions, specifically at early stages of development under soil conditions similar to those found in a restoration context. In the present paper we address this assumption by means of a meta-analysis of experimental studies on tree responses to biochar additions, most published within the last 2–3 years.

Meta-analysis methods

We searched peer-reviewed literature published through Oct. 2014 to locate studies presenting growth responses of trees to biochar additions: we conducted searchers using Google Scholar (scholar.google.com) and Web of Science (thomasonreuters.com) databases using the search terms "biochar", "char", "charcoal", and "black carbon", and in addition consulted recent meta-analyses and reviews (in particular Spokas et al. 2012, Biederman and Harpole 2013; Liu et al. 2013; Stavi 2013). We included all studies based on woody plant species that presented mean responses for aboveground biomass, or for both height and stem diameter. We only considered studies specifically examining responses to chars, and not wood ash, except cases of high-carbon wood ash with organic matter >30 %. Where data were only available in graphical format, figures were scanned and digitized. We located a total of 17 studies examining responses of 36 woody plant species (Table 1).

Table 1 Studies included in meta-analysis of woody plant growth responses to biochar additions

Region	Country	Type	Duration (d)	Feedstock	Temp. (°C)	Dosage	N_{spp}	N_{comp}	Reference
Tropical	Indonesia	pot	84	NA	NA	5–15 %	1	12	Budi and Setyaningsih (2013)
Tropical	Zambia	pot	93	NA	NA	NA	7	7	Chidumayo (1994)
Temperate	Tasmania	field	821	Wood (*Acacia*)	550	47 t/ha	1	8	Eyles et al. (2013)
Tropical	Nigeria	pot	84	Wood	~350	5–20 t/ha	1	12	Fagbenro et al. (2013)
Tropical	Singapore	pot	180	NA	NA	25 %	2	6	Ghosh et al. (2015)
Temperate	USA	pot	49	Wood (*Quercus*)	500[a]	25 %	1	6	Headlee et al. (2014)
Boreal	Finland	pot	63	Wood (*Picea/Pinus*)	NA[a]	15–60 %	1	16	Heiskanen et al. (2013)
Temperate	Japan	pot	120	Mixed	NA	20 %	1	9	Makoto et al. (2010)
Temperate	USA	pot	56	Wood	NA[a]	25–50 t/ha	1	4	McElligott (2011)
Temperate	Spain	field	584	Wood	NA[b]	5–14 t/ha	1	30	Omil et al. (2013)
Boreal	Sweden	pot	70	Wood (various)	450	30 t/ha	4	216	Pluchon et al. (2014)
Boreal	Australia	pot	180	Wood (*Eucalyptus*)	700	37–74 t/ha	1	4	Reverchon et al. (2014)
Boreal	Canada	pot	102	Wood (*Pinus*)	410	4–7 t/ha	2	5	Robertson et al. (2012)
Temperate	USA	pot	548	Wood (*Pinus*)	550–600	25 t/ha	2	8	Scharenbroch et al. (2013)
Tropical	Indonesia	pot	167	NA	NA	10–20 %	2	41	Siregar (2007)
Tropical	Laos	field	1460	Rice hulls	NA	4 t/ha	8	24	Sovu et al. (2012)
Boreal	Sweden	pot	57	Wood (*Empetrum*)	450	20 t/ha	2	12	Wardle et al. (1998)

Duration is the longest growth period for studies with multiple measurements; genus of woody feedstock used for production of biochar is given where available. N_{spp} is the total number of species in study, and N_{comp} is the number of comparisons between biochar-amended treatments and untreated controls

[a] Fast pyrolysis process used

[b] High-carbon wood ash

Growth responses were quantified as either aboveground or total biomass where these data were directly presented. In cases where stem diameter (d) and height (h) measures only were reported, we utilized d^2h as a proxy measure for biomass. Following the precedent of recent meta-analyses of crop responses (Biederman and Harpole 2013; Liu et al. 2013), we utilized the log-transformed biomass response ratio as an effect size metric: RR = ln(B/C), where RR is the response ratio metric, B is mean biomass of biochar-treated trees, and C is mean biomass in control trees without biochar additions. In studies presenting data on responses to multiple biochar treatments (i.e., different dosages, biochar sources, or soil conditions) we treated each treatment type as a separate meta-analytic observation. We employed a paired non-parametric Wilcoxon test to detect positive responses, considering tests significant at $P < 0.05$. Non-paired Wilcoxon test were used to compare responses between groups. Analyses were conducted in the statistical software R version 3.1.0 (R Core Team 2012).

Results

Publications included in the meta-analysis indicate a consistent and strong overall pattern of positive growth responses to biochar additions among woody plants (Figs. 1, 2). The mean response ratio metric for the entire data set was 0.347 ± 0.046 ($P < 0.001$), corresponding to a 41 % increase in biomass in response to biochar additions. For all

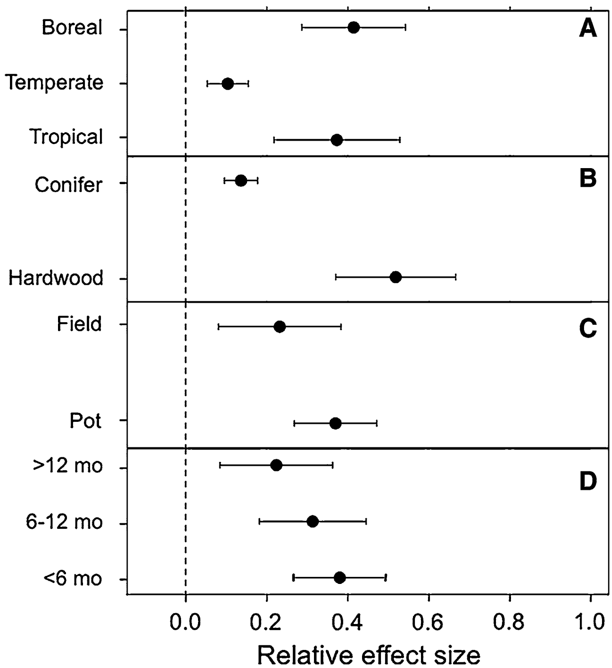

Fig. 1 Relative effect size (mean ± 95 % CI) for biochar effects on tree biomass, with experimental results classified by (*a*) biome, (*b*) major taxonomic group (conifer vs. hardwood trees), (*c*) experiment type, and (*d*) duration of experiment. All responses shown are statistically significant (paired Wilcoxon test with $P < 0.05$)

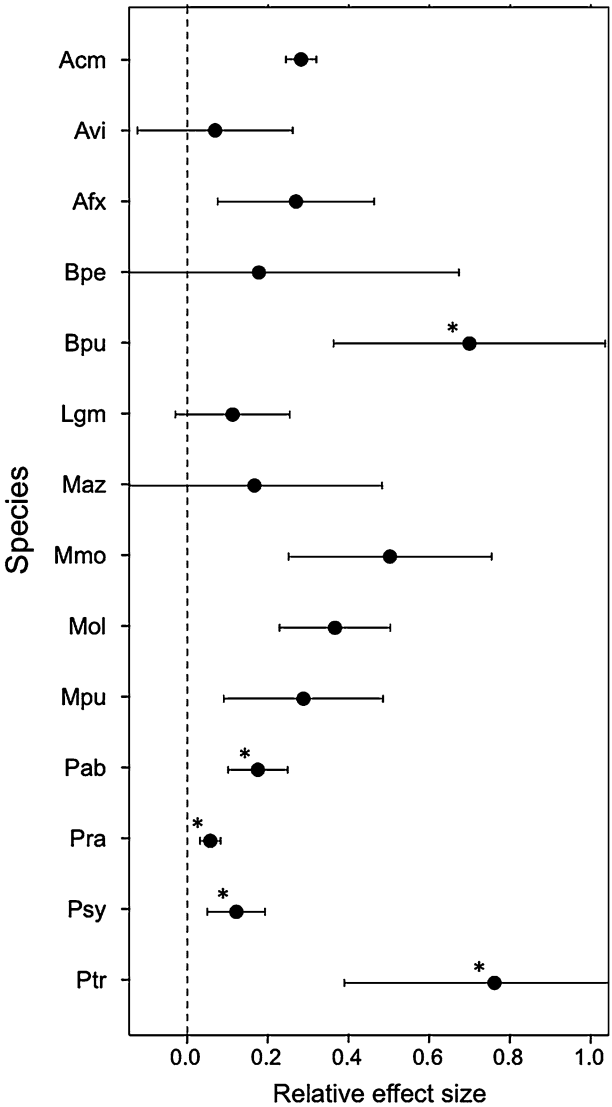

Fig. 2 Relative effect size (mean ± 95 % CI) for biochar effects on tree biomass for tree species represented by at least 3 trials in the meta-analysis data set. Significant biochar responses (paired Wilcoxon test with $P < 0.05$) are indicated *asterisk*. Abbreviations for species names are as follows: Acm *Acacia mangium*, Avi *Alnus viridis*, Afx *Afzelia xylocarpa*, Bpe *Betula pendula*, Bpu *Betula pubescens*, Lgm *Larix gmelinii*, Maz *Melia azedarach*, Mmo *Michelia montana*, Mol *Moringa oleifera*, Mpu *Malus pumila*, Pab *Picea abies*, Pra *Pinus radiata*, Psy *Pinus sylvestris*, Ptr *Populus tremula*

subgroups compared (Fig. 1), response ratio metrics likewise were significantly greater than zero (at $P < 0.05$). Responses of both tropical and boreal trees were larger than those observed for temperate tree species ($P < 0.01$ in both cases), but tropical and boreal responses were similar (Fig. 1a). Responses of hardwoods (angiosperms) were on average considerably greater than those of conifers ($P < 0.001$: Fig. 1b). In terms of study type, there were not detectable differences in response between pot trials (including greenhouse and growth chamber studies as well as shadehouse and similar studies with growth containers) and field trials with trees planted in native soils ($P > 0.05$: Fig. 1c). There were not detectable differences in responses relative to duration of study ($P > 0.05$: Fig. 1d); however, there was a trend toward shorter-term studies showing larger responses, and the pairwise comparison between medium-term studies (6–12 months) and long-term studies (>12 months) was marginally significant ($P = 0.098$).

Considering tree species with a relatively large number of trials represented in the data set ($N \geq 3$), there was very high apparent variation in responses among species (Fig. 2). Response ratio metrics were positive in all cases, but varied from $\sim$0.05 to 0.75. Species-specific responses were significant (by the conservative Wilcoxon test used) in 5 of 14 cases (Fig. 2).

Discussion

Prior meta-analyses for plant responses to char have essentially only examined data on agronomic crops (Jeffery et al. 2011; Biederman and Harpole 2013; Crane-Droesch et al. 2013; Liu et al. 2013). Our results strongly support the contention that trees in general show strong positive growth responses to biochar in a range of ecological systems and soil conditions. Indeed, the mean response ratio metric (response ratio metric of 0.347 ± 0.046, or a 41 % increase in biomass) is considerably higher than that found in prior meta-analyses of crop responses: response ratio metrics of $\sim$0.27 for aboveground biomass and $\sim$0.18 for yield as reported by Biederman and Harpole 2013, and mean increases of 11–14 % in yield reported by Jeffery et al. 2011 and Liu et al. 2013.

Although very encouraging, caution is required in interpreting and extrapolating these results. First, most results are from short-term pot experiments: 75 % of results included in analyses were for tree seedlings grown <6 months. Second, some of the very high growth responses observed, particularly for boreal tree species (e.g., Pluchon et al. 2014), may reflect unusual soil interactions in which strongly growth-inhibitory phenolics are sorbed by added chars (Wardle et al. 1998). Third, although we did not detect an obvious publication bias in graphical analyses of results, it is somewhat likely that there is under-reporting of neutral and negative results in the still-emerging literature on tree growth responses to biochar. Fourth, meta-analyses in general are best suited for cases in which treatments are highly standardized and repeatable (Gurevitch et al. 2001), and this cannot be said for biochar studies at present, due to the fact that biochars are inherently variable in properties. Many of the studies examined did not report the feedstock or pyrolysis temperature of char used (Table 1), posing serious problems for replicability of the particular studies, and comparability across studies. There is no real substitute for larger comparative studies conducted with well-characterized chars and soil conditions.

Both pot and field trials showed strong evidence of biomass growth responses, with no obvious difference in response, suggesting that pot trials may be broadly related to responses in the field, at least for early tree growth (Fig. 1c). The strongest responses appear to be found in short trials, with a weak pattern of declining response with increasing trial length. This could be due to physical changes in char through time, including uptake of soluble nutrients directly associated with fresh chars. However, another likely mechanism is that of inherent changes in growth responses arises from the leveling off of plant growth curves (e.g., Thomas et al. 1999): response ratios are likely to be maximized near the inflection point of plant growth curves, which in trees tend to fall very early in growth. The pattern of declining effects with time contrasts with that found for annual crops, where there is some evidence for increasing benefits of biochar over multiple cropping seasons (Major et al. 2010; Crane-Droesch et al. 2013).

The results also suggest important systematic differences in biochar response patterns in relation to tree phylogeny, among ecological systems, and among species. Among biomes there appears to be a general pattern of high response to boreal and tropical trees, with much lower responses in temperate trees. High responses to char additions observed in tropical species are consistent with a pervasive pattern of strong P limitation in tropical forests (Vitousek 1984), in conjunction with both high soluble P in chars and a capacity for chars to retain phosphate ions by sorption. P limitation effects seem much less likely to explain high responses in boreal tree species; however, Pluchon et al. (2014), found a relationship between P levels in char and seedling growth responses, suggesting P limitation in boreal forest. Along these lines, strong P limitation has been documented in some northern temperate forests where it is though to be related to high levels of anthropogenic N deposition (Gradowski and Thomas 2006, 2008). In addition, sorption of phenolics certainly contributes to high responses observed in some boreal studies (Wardle et al. 1998). We speculate that the low average response observed in temperate forests may thus result from N limitation in combination with low soil phenolics or other growth-inhibitory substances.

The analyses presented also suggest a pattern of higher biochar responses in hardwoods (angiosperms) than in conifers (Fig. 1b). In general evergreen conifers show relatively resource-conservative growth strategies relative to angiosperms, being generally adapted to environments with low productivity, in particular low temperatures and nutrient availability (Coomes et al. 2005; Lusk 2011). Associated traits include lower rates of nutrient uptake and adaptation to acid soils, which may explain the relatively low average biochar responses observed for conifers. However, the apparent systematic difference between conifers and angiosperms masks great interspecific differences, particularly apparent among angiosperms (Fig. 2). Such differences in plant response could potentially result in large effects of char additions on community composition and biodiversity of ecosystems. This is an important area for future research of particular relevance with respect to forest restoration.

Chars used in studies of tree responses have varied widely, and in many cases there is little information available in prior studies on char characteristics, feedstocks used, and properties (Table 1). It is widely recognized that pyrolysis conditions, in particular peak temperature and duration of pyrolysis, have profound effects on resulting chars (Enders et al. 2012), with, for example, pH, EC, and ash content increasing with pyrolysis temperature (Brewer et al. 2011; Kloss et al. 2012; Ronsse et al. 2013). Surface area generally increases with pyrolysis temperatures up to 500 °C, due to volatilization of compounds (Kloss et al. 2012); however surface area appears to commonly decrease at temperatures >600 °C (Ronsse et al. 2013). Wood biochars are generally the most aromatic and recalcitrant of biochars, and have the lowest ash content but also relatively low pH (Enders et al. 2012; Kloss et al. 2012). Wood is generally comprised of ~45 % cellulose, 25–30 % hemicellulose, and 20–25 % lignin (McKendry 2002; Yang et al. 2007); however, woods show remarkably high variation in these constituents, with distinct differences among groups. Notably, hemicellulose content is very low in most conifers, while lignin content is high (Pettersen 1984). Thus, different woods will result in chars with substantially different properties. It has even been suggested that the differences in properties of chars derived from different tree species may result in an ecological “afterlife” through differential effects of chars on seedling establishment and growth (Pluchon et al. 2014). Such ecological "afterlife effects" could contribute to positive feedbacks in post-disturbance regeneration: e.g., angiosperm biochar promoting angiosperm regeneration.

Biochar and natural disturbance emulation

An important general argument for the use of biochars in restoration is that natural disturbances often involve char deposition, and that colonizing species can be expected to be adapted to chars. Natural chars occur in many if not most soils in forests and other ecosystems (Krull et al. 2008; Jauss et al. 2015). In non-forest systems chars are increasingly recognized as playing a critical role in soil nutrient dynamics as well as constituting a long-term C stock (Spokas 2010). For example, recent results suggest that nearly *all* the cation exchange capacity of Mollisols, some of the world's most productive agricultural soils, may be attributable to pyrogenic carbon (Mao et al. 2012). There is remarkably little information available on the distribution of natural chars, their properties, and their potential role in soil processes and forest productivity, particularly in forest ecosystems with relatively long natural fire return intervals. In many forested regions fire suppression has drastically reduced char inputs to forest soils in the last 100 years. Conversion of biomass into charcoal from wildfire occurs across a gradient of temperatures, pyrolysis time, and oxygen environments, and often from numerous feedstocks: the result is certain to be incredibly diverse chars, though data on natural char properties of forest soils are limited (Kuhlbusch et al. 1996; Czimczik et al. 2002).

Like industrially produced biochars, natural charcoals generally have high surface areas, ion exchange capacities, and liming capacity, properties that have the potential to enhance forest productivity. In temperate and boreal forests with little soil turnover charcoal is a fire legacy that is commonly recalcitrant at the organic-mineral soil interface (Hart and Luckai 2013). Mineral element solutes from freshly produced charcoal stimulate soil fauna and plant species classified as ecological pioneers following fire (DeLuca et al. 2006; Wardle et al. 1998). High surface areas and porosity allow for sorption of inhibiting soil compounds (e.g., phenolics) (Wardle et al. 1998), and have been hypothesized to provide habitat and refugia for soil fauna (Zackrisson et al. 1996). High porosity, combined with variable surface charge helps improve water retention on fine and coarsely textured soils (Busscher et al. 2003). Negative surface charges from oxidation increases cation exchange capacity, increasing nutrient retention and availability of important limiting elements like Ca and Mg (Laird et al. 2010; Brais et al. 2000). Perhaps the most important role of charcoal in systems with fire is its liming capacity: natural chars are deposited together with ash (primarily $CaCO_3$) and the sorption of protons in the soil solution from negatively charged sites on charcoals can basify soils by several orders of magnitudes (Hart and Luckai 2013). Although chars are essential for sorption of nutrients, the "model" of natural wildfire points to the potential importance of combining biochar with ash in forest restoration, or of directly utilizing "high-ash" biochar.

Prospects for biochar in forest restoration

What might biochar specifically replace in forest restoration practice? First and foremost, biochar may replace other forms of organic matter, having the advantages of recalcitrance, high cation exchange capacity, capacity to reduce leaching of anions, and potential for sorption of toxic substances and salts. In an agricultural context, biochar is almost always added as an additional amendment to soils with appreciable organic matter, and it is common for biochar-compost mixtures to be used (Blackwell and Riethmuller 2009). One issue arising is that biochars generally have very low N content and through sorption of ammonium may so strongly sorb available N that it makes it less available, an effect expected to be offset by additions of fertilizers or composts with high N content. There are thus compelling reasons to expect that biochar use in forest restoration practice would be as a component of a mixture of soil amendments. There is also a strong case for biochar as a product substitute for lime. Dolomitic lime rapidly decomposes chemically and is a major source of agricultural CO_2 emissions (West and McBride 2005). Thus substitution of char for lime would effectively have a two-fold effect on carbon emissions, by sequestering waste material C that would have been emitted, and by offsetting C emissions from lime. However, data suggest that the pH and liming capacity of wood-derived chars are generally lower than other chars (Ronsse et al. 2013), pointing to the importance of specifically designed chars or possibly use of high-ash biochars in cases where liming effects are of particular importance.

In agronomic systems, there is increasing recognition that biochar applications generally require biochars with specific properties to ameliorate specific soil conditions (e.g., Novak et al. 2009), and that large-scale differences in soil properties suggest a specific "niche" for biochar use in poorer soils with low CEC and soil C. These considerations are perhaps even more likely to be the case with biochars applied in the context of forest restoration. Wood biochars will likely be the most easily accessible in forest restoration projects, and to some extent engineered chars could potentially be 'designed' by choosing appropriate feedstocks; however, modification of pyrolysis temperature or system may also be important. Biochar use in practice is likely to be best targeted toward poor soils with low organic C, and perhaps specifically contaminated soils.

In conclusion, there is strong evidence for positive effects of biochar additions on growth of woody plants, with observed responses that appear to be generally larger than those observed in agricultural crops. However, there appears to be high heterogeneity in responses among tree species and ecological systems, and it is not possible to unambiguously distinguish this heterogeneity from differences in soils and chars used given existing data. Given the high heterogeneity in properties of chars and soils, it is critical that future studies provide more comprehensive details on properties of chars used, and the recent promulgation of characterization guidelines should assist in this regard (IBI 2014). Full realization of the potential for biochar use in forest restoration will necessitate a better understanding of heterogeneous responses to allow an informed matching of specific chars to specific restoration objectives.

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