Current economic obstacles to biochar use in agriculture and climate change mitigation

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ABSTRACT

Biochar may become a key instrument at the nexus of managed carbon flows, including value added potential in soil amelioration, climate protection, energy supply and organic waste management. This article reflects the potential use of biochar in agriculture from the perspective of the farming economy. Biochar soil amendment in crop production is regarded as a win—win situation, both for assumed increases in cropping yields and carbon sequestration in soil organic matter. However, an extensive review on biochar effect on crop yield has not yet been able to provide compelling arguments to foster more widespread biochar use in cropping systems. Furthermore, the half-lives of biochars are frequently shorter than commonly suggested, and other financial incentives, such as including biochar in carbon credit systems, are not in place to compensate for the extra cost of applying biochar. As a result, we conclude with a somewhat skeptical view for a widespread use of biochar in agriculture in the near future.

KEYWORDS

biochar; crop yield; stability; abatement costs; rentability

Introduction

About 11% of the global land surface is used for agricultural crop production, and agriculture operations cause 13% of human-based global greenhouse gas (GHG) emissions [101]. An increasing number of scientists advocate the use of biochar in farming systems to contribute to resolving two high-priority global problems: securing agricultural food production for a growing population by sustainably amending soils, and simultaneously mitigating climate change and reducing the carbon footprint of mankind [1—3]. However, farmers’ decisions to apply biochar to their fields will primarily depend on agronomic benefits and/or other economic returns. Results from dozens of field trials of biochar soil amendment range from strongly positive to distinctly negative impacts on crop yield [3—11]. The large variability in yield effect can be explained by several factors, such as the extremely broad variety of biochar products in terms of carbonization process parameters, feedstock and optional blends (with compost, manure or digestate) as well as their interactions with particular soil and weather conditions, the particular crop or the use of fertilizers (when added to managed farmland). Nevertheless, the resulting uncertainty creates a major obstacle for any worldwide use of biochar envisioned in agriculture.

Two decades of biochar research have continued to produce large numbers of publications annually and, as a result, it is difficult to keep up with the profusion of emerging topics in the world of biochar [12]. This opinion piece will be limited to highlighting a few issues that still seem to be critical to overcome economic and political constraints for the spread of agricultural biochar use in the near future [13]: first, the highly variable yield effect of biochar soil amendment and the economic viability of its use in agriculture; second, the limited stability of C in fresh-produced biochars incorporated in soils; and third, the lack of economic efficiency when using biochars for carbon sequestration compared to other carbon dioxide (CO₂) abatement technologies.

This paper refrains from considering any other forms of biochar uses [14], that may evolve into a possible source of revenue for farmers in the future. Instead, we present a compilation of the yield effects of biochar application in field studies, a review of the stability of biochar products in soil incubation experiments, and a rough calculation illustrating the farmer’s perspective on the economic benefit of biochar soil amendment. Potential services and benefits, which may convince policy stakeholders and farmers in the future, are summarized in the final section.

Yield effects of biochar soil amendments

To achieve carbon sequestration effects of a noticeable order of magnitude, farmers have to benefit from biochar application, and as long as there is no other incentive, the increase in harvest yield has to at least be larger than the total cost of applying biochar. A rise in crop yield in the range of 38–45%, such as reported by Lehman and Joseph [15], appears to over-
emphasize peak values, and does not correspond to the general situation as per our calculation. The surprising number of literature reviews in recent years [3–11] which have quantified the yield effects of biochar application to soil lends evidence about the high relevance of this issue. These reviews differ mainly in the time period covered and in the broadness or selectivity of the publications covered, and present somewhat contradictory conclusions on the impact of biochar amendment on biomass productivity.

To develop a database for economic calculations (next section), we checked all publications listed by the abovementioned reviews as well as a few additional articles (up to February 2016). It was not our goal to perform a detailed meta-analysis of the data with respect to factors, processes, potentials, limitations, global aspects, etc. of biochar soil amendment, which has been done comprehensively by several of the previously mentioned reviews. We were mainly interested in figures regarding absolute change in harvested biomass (in Mg ha$^{-1}$) due to biochar treatment. Therefore, we only included data from field experiments, because only crop yield under natural growing conditions (weather, pest infestation, etc.) is meaningful for an evaluation of the yield effect of biochar in cropping systems. According to Jeffery et al. [8], in fact yield response in pot studies on average is 3 times higher than in field trials. Furthermore, it is hard to convert yield data from pot studies and/or greenhouse trials into yield per hectare. With regard to results of field experiments, the database expands the data collections of, for example, Crane-Droesch et al. [6], Jeffery et al. [8], Dickinson et al. [7], or Liu et al. [9] as it considers a broader range of biochar types and agricultural crops.

In total, from 48 publications we extracted 507 yield differences, that is data pairs with versus without biochar treatment in field trials with agricultural crops (Supplemental Table S1, including references). To our knowledge this is the most comprehensive database on biochar yield effects in field studies. The biochar-free control variants consist of unfertilized, mineral fertilized or organic fertilized (compost, manure, digestate) plots. From the 507 data points, 211 yield changes are from 1-year field trials, while 296 results originate from 2–5-year trials; in all of them, biochar was only added during the first year of cultivation. The total data set can be subdivided into 291 positive results (yield increase), 190 negative results (yield decrease) and 26 results without change. Only 133 (corresponding to 26.2%) of the yield differences were statistically significant according to the original publication. The median of the relative yield change is 2.8% for the overall data collection and 7.5% for maize (n = 168), 1.3% for cereals not including maize (n = 135), 3.7% for rice (n = 81) and 2.8% for other crops (n = 123) (Figure 1; Table S2). The medians of the absolute yield changes are 0.34, 0.04, 0.1 and 0.29 Mg ha$^{-1}$ for maize, cereals, rice and other crops, respectively.

In general, these yield improvements are somewhat smaller than those reported in the aforementioned reviews. From Liu et al. [9], the yield response in field studies can be estimated to approximately 8%. Woolf et al. [3] calculate a relative biomass increase of 2.8% per Mg biochar-C ha$^{-1}$ added for cereals in field experiments, which would be equivalent to a 28% yield increase for a recommended application rate of 15 Mg ha$^{-1}$ biochar (with a 67% C content). Jeffery et al. [8] specify mean changes in crop productivity of 5.0, 4.7 and 3.9% for maize, wheat and rice, respectively. Crane-Droesch et al. [6] report an overall average crop yield increase of approximately 10% in the first year for 3 Mg ha$^{-1}$ biochar addition, which did not decline significantly in the following seasons. The compilation of Mukherjee and Lal [10] focused on experiments with a negative yield response on biochar. Note that the averaged yield impacts of the aforementioned reviews are only partly comparable to each other and to our results (Figure 1; Table S2) due to diverging data populations. All of the data underline the large variability of crop response to adding biochar to the soil. Based on current understanding, it is therefore difficult to predict which change in yield (direction and magnitude) can be expected by applying any particular type of biochar to a specific crop under given soil—climate conditions. Overall, the review supports the statement by Jeffery et al. [16] that the merits of biochar are portrayed over-enthusiastically by some authors, where results are not robustly substantiated by experimental data. We therefore emphasize the need for the unprejudiced collection and interpretation of database information.

**Economic viability of biochar use in crop production**

From a farmer’s perspective, profitability is central to the decision of whether biochar soil amendment can be part of the cropping system. The profit surplus due to yield increase induced by biochar application must at least compensate for the costs, which consist of the purchase (or, alternatively, the cost of own production), transportation and incorporation of a certain quantity of biochar. To assess the revenue associated with biochar application, from the 507 data of our literature review, we selected the 428 results for marketable crops. The crop yield difference (in Mg ha$^{-1}$) was priced according to the market price of the respective commodity (2014/2015 US crop farm prices; see Table S3); for multi-annual trials, the revenues of the individual years were averaged over the 2–5-year period of the respective study. Next, the revenue was correlated to the amount of biochar added in the particular field trial, giving a total of 272 figures on the specific revenue per one Mg of biochar applied.
used feedstock and transportation distances for feedstock as well as for the biochar produced; operational farm costs in the region of USD 5—10 Mg⁻¹ of biochar incurred by transportation and application to the field must be accounted for as well. Given these figures on revenues and prices, the crucial factor for a cost–benefit analysis is obviously the assumption on the permanence of the yield increase by a biochar. If we assume a (very optimistic) annual revenue surplus of USD 20 Mg⁻¹ from using a cheap char costing USD 200 Mg⁻¹, then this yield increase has to be effective over a period of at least 10 years to realize a profit for the farmer (discounting of the investment in biochar amendment is not accounted for). A calculation with more realistic assumptions of USD 4 Mg⁻¹ revenue surplus and a price of USD 400 Mg⁻¹ biochar demonstrates that the vast majority of biochar applications to crops will never be economical if only the yield gain is paid off.

This evaluation of biochar profitability is in line with the results generated by numerous other publications. None of the following economic assessments resulted in a profit for the farmer if only the agronomic value of biochar amendment to soil was considered. For Chinese agriculture, Clare et al. [20] calculated that commercially produced biochar is uneconomic as a farming input, and briquetting for heat energy is the most cost-effective carbon abatement strategy for straw. Blackwell et al. [21] derived break-even costs for applying biochar of AUD 100–140 (USD 75–105) per hectare for Western Australia, based on an assumption of an initial 10% yield increase declining linearly to nil over 12 years. For biochar from a pinewood feedstock in Colorado, Field et al. [22] concluded that the locally available feedstock is generally too expensive for the system’s profitability, and using charcoal as biochar outperforms its use for cooking when GHG mitigation is priced above USD 50 Mg⁻¹ CO₂eq. In a study by Roberts et al. [23], the transportation distance for feedstock further constrains the profitability of biochar pyrolysis systems. Galinato et al. [24] calculated that the farmer’s break-even price of biochar would have to be lower than USD 9.19 Mg⁻¹ for winter wheat production in Washington State, USA. Singh et al. [25] found that biochar is agronomically unaffordable based on application rates of 5—20 Mg ha⁻¹ and low expected benefits in crop yield. For Northwestern Europe, Dickinson et al. [7] deduced that cereal farmers could never expect a net gain from a biochar investment, even when the timespan of profits is extended infinitely. Liu et al. [9] also maintain that the high cost of biochar would not be offset by the potential economic gain based on average yield improvement and current prices.

However, only in some of the assessments is the longevity of yield effect – that is, the limited stability of biochars in soil – considered. The current estimates on biochar cost-effectiveness are constrained by the

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**Figure 1.** Boxplot of relative yield changes of four crop types due to biochar soil application in field trials; number of data in parentheses (see Tables S1 and S2).

The median of the overall data collection amounts to a revenue surplus of USD 1.57 Mg⁻¹ biochar with a 25–75% quantile ranging from USD—1.77 to 10.74 Mg⁻¹ biochar (Figure 2; Table S4). For the four crop types of maize, cereals (not including maize), rice and other crops, the revenue medians of USD 9.76, 2.99, 0.50 and 10.80 Mg⁻¹ biochar, respectively, differ slightly, while for the multi-year trials only an averaged annual revenue of USD 0.82 Mg⁻¹ biochar was calculated. The spread of revenues for maize and for the multi-year results form a relatively narrow band, while the profitability of biochar amendments in the production of cereals, rice and other crops shows much greater variation.

Production costs and market prices, respectively, for commercial biochars span from USD 272 Mg⁻¹ up to more than USD 5000 Mg⁻¹ with a bulk in the region between USD 350 and 500 Mg⁻¹ [17–19]. Costs depend mainly on the type of production process,
fact that almost two thirds of the 428 data points reviewed were based on 1-year trials or refer to the first year of multiple-year studies. Only minor data have been published from longer lasting experiments, with the longest time series set at 5 years. The results reflecting more than 1 year indicate that the observed yield effects (positive as well as negative) tend to continue for several years, but on average at a very low level of yield effect. Biochar effectiveness may last for or slowly decline over a currently unknown number of years. This restricts our conclusions, and it will probably take several more years to obtain sufficient results from long-term studies to offset repeated annual revenues against one-time expenses for biochar application. To this end, it has to be mentioned that our evaluation did not consider the case of farm-owned biochar production. There can be advantages for individual farm-scale businesses, such as combined heat and energy supply via biomass gasification [26]. But this represents a considerable initial capital investment, which is probably beyond the scope of many farmers.

Stability of biochar in soils

The economic estimations of the previous section demonstrate that the stability of biochar in soil is a key factor not only for an evaluation of the long-term carbon sequestration potential [3,27], but also for the longevity of biochar effects on yields. Several studies report a biochar stability in the region of hundreds to thousands of years or more for pyrolysis biochar and charcoal [e.g. 3,28,29]. However, these figures are mainly derived from the age or the decay rate analysis of black pyrogenic carbon and charcoal fragments in soils left over from the burning of above-ground biomass. The results are undoubtedly valid for the residual black carbon, as the most stable fraction of soil organic matter. However, it is not generally possible to draw conclusions from these types of studies on the stability of freshly produced biochar, because the amount of carbon initially incorporated into the soil is not known and thus the carbon loss over time cannot be calculated.

To get an overview of the stability of today’s biochar products, we carried out a literature review and compiled a total of 161 values on half-life ($t_{1/2}$) and/or mean residence time (MRT). Data resulted from the analysis of 69 pyrolytic and 25 hydrothermally carbonized chars, taken from 27 studies on the mineralization of fresh biochars in incubation experiments (Table S5). Data is presented as biochar half-lives, as this would be the likely basis to calculate carbon credits. The majority of results in the data ensemble involve pyrolytic biochars; from the 104 half-life values from incubation in soil, the median is 20.6 years, and a 5–95% interval of $t_{1/2}$ ranges between 3.0 and 547 years. These findings show that an assumption of biochar half-lives always lasting a magnitude of hundreds of years seems to be somewhat optimistic and is not supported by soil incubation measurements of freshly pyrolyzed chars. For the 25 analyzed hydrothermally carbonized chars (HTC), calculations indicate a $t_{1/2}$ median of only 2.9 years and a 5–95% interval from 0.5 to 18.1 years (40 observations; Figure 3; Table S6). Thus, the mineralization rates of many HTC chars are not much less than those of their feedstock [30,31].

It is outside the scope of the present publication to perform a detailed meta-analysis on the factors on which biochar stability depends, such as feedstock, carbon content, carbonization parameters, incubation experimental setup, etc. We only want to mention that there are some problems in principle with degradation studies on newly produced biochars, including the following three: Studies can usually monitor the mineralization only for a very short time relative to the magnitude of $t_{1/2}$. For example, the median and the longest incubation periods of the reviewed studies were 0.6 and 8.5 years, respectively. While this timespan would demand patience on the part of the biochar producer (who wants to discover characteristics of his product), the initially higher mineralization of labile fractions within a biochar can dominate the degradation data and introduce a bias toward shorter $t_{1/2}$ [32]. Different decay or mineralization models can result in significantly different $t_{1/2}$ values [30]. The majority of studies fitted a double-exponential decay function on their data on CO$_2$ loss over time, corresponding to a more labile and a more stable fraction of carbon in the biochar, but single-exponential function and approaches with time-depended decay rate have also been applied [33]. Up to now, only a few results on any correlation between biochar properties (e.g. O: C and H:C atomic ratios, highest treatment temperature [29,34–36], and half-life from soil incubation experiments) have been presented [30,34,37]. The
predictability of $t_{1/2}$ based on physico-chemical biochar properties is not sufficient.

The rating of biochar half-life is closely linked to the evaluation of its overall sequestration potential for a biochar strategy and its profitability in crop production. The C sequestration value of biochar is estimated as a carbon stability factor in CO$_2$-equivalent terms, according to the following equation [27]:

$$\text{CO}_2 - \text{Csequestered} = 1 - \exp\{t_{1/2} \cdot \ln(0.5)/\text{TH}\}$$

where $t_{1/2}$ (in years) is the half-life of biochar in soil, and TH is the analytical time horizon for evaluating the GHG offset potential, commonly set to 100 years. According to Figure 3, if a $t_{1/2}$ of 20 years approximates the median half-life for pyrolysis biochars, then the 100-year carbon sequestration value accounts for only 13% of the amount of C in fresh pyrolysis biochar. Thus, from 1 Mg C in newly produced biochar with a $t_{1/2}$ of 20 years, only 0.13 Mg C can be accounted for as long-term sequestered carbon quantity on average. This relatively small fraction of stable carbon has to be put into perspective when assessing the CO$_2$ sequestration potential of (freshly produced) biochar and its economic value for CO$_2$ offset credits. The bottom line remains that pyrolysis biochar, but not HTC char, has a certain potential to increase agricultural SOC contents. However, greater effort is required to achieve credible test procedures, preferably combining measurements and models which are generally accepted to certify the $t_{1/2}$ of today’s biochar products.

**The economic viability of biochar as a carbon abatement strategy**

Given the situation of the lack of profitability for the user, it is possible to envision increasing calls for subsidies for biochar application in agriculture to establish biochar as a substantial part of a national or global climate mitigation policy. A biochar strategy as an option for enhanced C sequestration has to compete with various other techniques available to reduce net CO$_2$ emissions. Obviously, economic efficiency demands promotion of those technologies that involve the lowest cost per Mg of carbon dioxide reduction. Pratt and Moran [38] introduced a very high assumption of 50% yield gain to calculate positive cost-effectiveness for biochar projects for their study for Asia. We, however, used a cradle-to-grave economic assessment by McCarl et al. [18] to compare the CO$_2$ abatement costs of biochar with the costs of other GHG offset technologies. McCarl et al. [18] calculated a net margin of USD $-45$ and $-70$ Mg$^{-1}$ biochar along the production chains of fast and slow pyrolysis biochars, respectively. Based on an assumed permanent net sequestration of 50% of biochar carbon, the assessment results in abatement costs between USD 221 and 345 Mg$^{-1}$ CO$_2$ for biochar C. However, using a much lower C sequestration potential of only 13% over a 100-year analytical time horizon for calculations, as outlined in the previous section, would increase these costs by a factor of almost 4.

The CO$_2$ abatement costs of currently available technologies [39,40] clearly show that the combined heat and power cycle in power generation and modern thermal insulation of buildings can be the most cost-effective strategies (Figure 4). A biochar strategy takes a rather mediocre position among the options to reduce society-wide net CO$_2$ emissions. In view of the political search for strategies to reduce national carbon footprints and mitigate climate change, economists will reason that the abatement costs of a subsidized biochar strategy must not be higher than those of the most cost-efficient CO$_2$ reduction strategies (e.g. combined heat and power or thermal insulation of buildings). The current value of carbon credits was about USD 8.75 Mg$^{-1}$ CO$_2$ on average in 2015 (equivalent to about USD 2.40 Mg$^{-1}$ C) on the European Energy Exchange. This price for CO$_2$ withheld from the atmosphere cannot contribute significantly to better economic conditions for biochar use, provided biochar would be included in the trading scheme. Furthermore, placing biochar in the carbon credit trading scheme would require revisiting the effective storage of CO$_2$-C in soils, as biochar half-life would be the critical parameter determining its value.

**Conclusion**

Crop yield change due to soil amendment with biochar is a complex process that depends on many factors, such as biochar type and application rate, mineral and/or organic fertilizing, soil type, weather conditions, crop management, etc. A full cost-benefit analysis for a specific crop based on a valid prediction of yield response is required before biochar application can be recommended on a larger scale [10]. From the farmer’s point of view, the present results from field trials do not allow reliable estimates of the effects on individual crop yields or even crop rotations. The results are highly variable and no general approach is available to
The profitability of biochar application in cropping systems may be enhanced if further aspects can be monetized in the future. Carbon credits for biochar use in agriculture have been an almost omnipresent argument within the biochar research community. However, the carbon credit price has to be many times higher than its current level to make biochar economically attractive to farmers. It is possible that the reduction of nitrous oxide (N₂O) emissions from soils due to biochar amendment will be additionally priced in the future; however, if that is to occur, biochar’s N₂O mitigation capacity must be studied in cropping systems under field conditions, e.g. based on the review by Cayuela et al. [42]. Some other effects of biochar are mentioned frequently, which are interlinked but often presented as worthwhile as such. This would include such aspects as, for instance, the stabilization of soil organic matter, enhanced soil water retention capacity and increased cation exchange capacity. Nevertheless, these factors are of interest to scientists rather than to farmers if they do not translate into significantly increased plant growth and harvest yield.

However, previous sections outlined why we presently prefer to promote options other than a biochar strategy. It seems that the assessment of biochar half-life in particular has to be pushed to a higher confidence level before policymakers may be tempted to consider biochar for national strategies. Altogether, some major obstacles to biochar use have not changed since the assessment of Shackley et al. [43]: biochar does not have any generally recognized value for carbon storage in agriculture, and the competition for biomass resource use increasingly restricts the availability of feedstock. On top of that, in many European countries it continues to be illegal to spread (commercial) biochar products on farmland.

Novel areas for biochar application will probably gain more relevance in the future, for example as additives for manure or digestate to lower ammoniac volatilization, to reduce odour or to minimize nitrate leaching after spreading. At present, we consider that biochar use in agriculture is judged mainly from an economic point of view, which will decide the fate of biochar use and technical development in the next few years. In light of this, uncertain effects on crop yield will not spur widespread interest among farmers to apply biochar. Our analysis suggests some of the reasons why biochar is unlikely to play a major role in climate mitigation policy in the near future. With respect to the limited mass potential in carbon sequestration from the sides of both biomass resources and the use of reasonable amounts of biochar application to agricultural fields, biochar can present itself as only one of many options in a bundled strategy for carbon emission reduction [44,45].

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Executive summary

Background

- Historical records of anthropogenic charred biomass in soils has triggered recent biochar research;
- Biochar research aims predominantly at amending soils, increasing soil organic carbon stocks, and reducing climate-relevant net emissions;
- Scientists envision farmers worldwide applying biochar to their fields, increasing agronomic productivity and simultaneously contributing to climate change mitigation.

Biochar stability and yield effects:

- Results from numerous field trials show effects ranging from positive to negative on harvest yield;
- Only a few studies provide multi-annual data and there is even less proof for the longevity of effects on soil quality and crop yield;
- Various incubation experiments found a much shorter half-life of biochar C in soil than that presumed from historical charcoal records.

Biochar profitability in crop production:

- Increases in revenues from harvest do not offset the costs of biochar application in the vast majority of cases;
- Assumption of the longevity of a (positive) biochar yield effect is crucial for cost—benefit analysis;
- Credits for carbon sequestration must be multiple times higher than current prices to compensate for biochar costs.
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