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Title: Biochar's Cost Constraints are Overcome in Small-Scale Farming in Tropical Soils in Lower-Income Countries

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Abstract: Biochar has been lauded for its potential to mitigate climate change, increase crop yields and reverse land degradation in tropical agricultural systems. Despite its benefits, confusion persists about whether the use of biochar is financially feasible as a soil ameliorant. A comprehensive review of previous studies of biochar's financial feasibility was performed (33 relevant publications). Financial performance appraisal (US$ Mg^{-1} biochar) and greenhouse gas abatement cost estimates (US$ Mg^{-1} CO_2e) were used to gauge the financial feasibility of the biochar scenarios within each publication. Ordinary Least Squares Multiple Linear Regression was used to evaluate the predictive capacity of scenario financial feasibility as dependent on variables including national income levels,

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climatic conditions, pyrolysis technology scales and pyrolysis capabilities. Analysis revealed that scenarios where biochar was applied targeting yield increases in high-value crops in tropical locations with low incomes and biochar-focused small-scale production, were overall significant predictors of biochar scenario financial feasibility. We find that the average abatement cost of biochar applied in 'lower-income countries' is -US$58 Mg^{-1} CO_2e (financially feasible) compared with +US$93 Mg^{-1} CO_2e in 'higher-income countries' (not financially feasible). Climate policies of lower-income countries in tropical climates should consider biochar as an input for small-scale climate smart agriculture to address land degradation in tropical agricultural systems. Based on recent evidence it is suggested that biochar fertilizers, a value-added biochar product, could present a commercially feasible pathway for biochar value-chain development in higher-income countries.

1. Introduction

Biochar is the carbonaceous residue resulting from pyrolysis that is applied to soil (Sohi, Krull, Lopez-Capel, & Bol, 2010). Biochar has been observed to enhance crop yields (Jeffrey, Verheijen, van der Velde, & Bastos, 2011), reduce soil-related greenhouse gas emissions (Cayuela et al., 2014; Jeffery, Verheijen, Kammann, & Abalos, 2016) and improve crop productivity and soil function particularly in weathered and acidic soils in humid climates (Crane-Droesch, Abiven, Jeffrey, & Torn, 2013).

The loss of soil organic matter is a major driver of soil and land degradation in tropical agricultural systems (Ayuke et al., 2011). The long-term chemical stability of biochar is resistant to weathering, making it amenable to tropical conditions (Lehmann, Gaunt, & Rondon, 2006). Meta-analyses of field trials have indicated that positive results are more likely for biochar applications in soils in the humid tropics with low pH, soil carbon and cation exchange capacity (Jeffery et al., 2017). This is also shown in the results of recent long-term field trials in tropical soils where multiple years of yield gains in cereal crops have been observed (Cornelissen et al., 2018; Pandit et al., 2018). Average biochar yields effect in temperate soils exhibit no yield effect, though there is significant variance in temperate soil field trial results (Jeffery et al., 2017).

Biochar's chemically recalcitrant quality gives it a capacity to sequester carbon and play a role in climate change mitigation (McGlashan, Shah, Caldecott, & Workman, 2012). Estimates made by Lehmann et al. (2006) suggested that biochar had the technical potential to sequester 5.5 – 9.5 Pg C y^{-1} globally by 2100 where projected energy demand was supplied through pyrolysis systems. Woolf, Amonette, Street-Perrott, Lehmann, and Joseph (2010) estimates a lower sustainable maximum technical potential of 1.8 Pg C y^{-1} where pyrolysis is only deployed in circumstances where it does not adversely affect food security, natural habitat or soil conservation.

Early studies of biochar's costs and benefits have concluded that biochar is unlikely to be financially feasible in consideration of agronomic performance alone due to the costs of production greatly exceeding benefits (Bach, Wilske, & Breuer, 2016). 'Financially feasible' refers to any biochar use scenario(s) that results in a positive net present value as deduced from a cost benefit analysis (Boardman, Greenberg, Vining, & Weimer, 2017), including revenues associated with coproduction unless otherwise specified. 'Coproduction' refers to pyrolysis units with the capacity to generate outputs other than biochar such as liquids (bio-oil, biodiesel, pyroligneous acid), gases (syngas) or energy (bioenergy). 'Agronomic effects', 'agronomic benefits' or 'agronomic performance' as used in this paper refers to biochar's influence on crop yield gain, fertilizer cost savings through improved application efficiency and agricultural lime cost savings through liming-effect benefits and does not include revenues associated with coproduction.

These early studies published prior to 2013 focused on higher-income countries; temperate climates, capital intensive large-scale centralized pyrolysis units and cereal crops. Several publications covering higher-income countries assumed that no yield gain value was being created by the biochar product (Brown, Wright, & Brown, 2011; Bushell, 2018; Field, Keske, Birch, Defoort, & Cotrufo, 2013; Granatstein et al., 2009; Kulyk, 2012; Roberts, Gloy, Joseph, Scott, & Lehmann, 2010; Shackley, Hammond, Gaunt, & Ibarrola, 2011) with value being derived from coproducts or alternative revenue streams such as bioenergy and biofuel (Roberts et al., 2010), carbon pricing (Kulyk, 2012) or avoided waste disposal fees (Shackley et al., 2011). Some authors have suggested that biochar financial feasibility, and hence abatement cost, should be benchmarked against Bioenergy Carbon Capture and Storage cost for any feasibility analysis to be practically meaningful (Fidel et al., 2017), yet this benchmark itself is highly questionable with regards to social acceptance, technical viability and financial feasibility (Fridahl & Lehtveer, 2018).

Studies published after 2013 demonstrated financially feasible results in cases considering biochar scenarios that were located in tropical climates and in lower-income countries (Fru, Angwafo, Ajebesone, Precillia, & Ngome, 2018; Joseph, Anh, Clare, & Shackley, 2015; Mekuria et al., 2013; Mohammadi et al., 2017; Pandit et al., 2018) reflecting meta-analyses that indicated that biochar's crop yield effects are substantially greater in tropical soils relative to temperate soils (Crane-Droesch et al., 2013; Jeffery et al., 2017). These scenarios appraised decentralized small-scale pyrolysis units, with a daily feedstock throughput capacity between 0 and 2 Mg.

More recently banded biochar applications (Blackwell, Krull, Butler, Herbert, & Solaiman, 2010; Shackley, Clare, Joseph, McCarl, & Schmidt, 2015) and biochar fertilizers (Zheng et al., 2017) have demonstrated high biochar yield spreads (percentage crop yield growth per hectare per metric ton of biochar), and alternative biochar uses, such as for use as cattle feed have also exhibited cases of financial feasibility (Joseph, Pow, et al., 2015).

Previous studies have examined the factors that most influence biochar profitability. Shackley et al. (2015) argued that the capacity of biochar to increase revenues (e.g. by increasing yields and crop quality) and reduce farming costs (e.g. reduce requirements for other costlier inputs such as fertilizer and agricultural lime) were the most important determinants of biochar's financial feasibility. Biochar products that demonstrate these capacities over multiple years perform better financially, as do pyrolysis technologies that include the production and sale of coproducts such as bio-oil and syngas (Shackley et al., 2015). Biochar can also be sold at a negligible price when it is a byproduct of pyrolysis processes whose profitability can rely on energy production, liquid fuel production, waste management or nutrient recycling (Maroušek, Vochozka, Plachý, & Žák, 2017; Robb & Joseph, 2019).

Biochar has the capacity to play an important role in the sustainable intensification (SI) of agriculture. SI is an intervention in traditional agricultural systems where financial value and production outputs are increased while positive environmental outcomes are maintained or enhanced (Pretty, 2018). SI is central to the UN Sustainable Development Goals (UN, 2017). For the benefits of SI concepts to be more widely realized, Pretty et al. (2018) argue that SI interventions like biochar must also be financially feasible. But despite many studies, confusion persists over whether biochar can be financially feasible. Is it correct to say, as Bach et al. (2016) do, that the vast majority of biochar applications to low value crops will never be financially feasible if only yield gains are considered? In this paper we address this question in performing a review of previous studies to systematically identify the factors that influence the financial feasibility of biochar.

2. Methods

2.1 Systematic Review

A systematic review of papers was performed following the methodology of Pickering and Byrne (2014). The review was finalized on the 30th of October 2018, with papers published after this time not considered. First, various online databases including Google Scholar, Scopus, the Web of Science and Crossref were searched using keyword combinations of 'biochar' and 'cost benefit analysis', 'economic' and 'life cycle analysis'. After considering whether the publications assessed the financial feasibility of biochar where applied to soil, 33 results were found to be relevant (Aller et al., 2018; Blackwell et al., 2010; Brown et al., 2011; Bushell, 2018; Clare et al., 2015; Dickinson et al., 2015; Field et al., 2013; Fru et al., 2018; Galinato, Yoder, & Granatstein, 2011; Granatstein et al., 2009; Harsono et al., 2013; Joseph, Anh, et al., 2015; Kulyk, 2012; Kumar et al., 2018; Kung, McCarl, & Cao, 2013; Li et al., 2015; McCarl, Peacocke, Chrisman, Kung, & Sands, 2009; Mekuria et al., 2013; Mohammadi et al., 2017; Pandit et al., 2018; Radlein & Bouchard, 2009; Robb & Dargusch, 2018; Roberts et al., 2010; Shackley et al., 2012; Shackley et al., 2015; Shackley et al., 2011; Sparrevik, Lindhjem, Andria, Fet, & Cornelissen, 2014; Steiner et al., 2018; Widiastuti, 2016; Widowati & Asnah, 2014; Wrobel-Tobiszewska, Boersma, Sargison, Adams, & Jarick, 2015; Zheng et al., 2017), consisting of 26 papers in peer reviewed journals, two grey literature reports, three book chapters and two postgraduate theses. These included publications such as Shackley et al. (2011) that did not consider any agronomic benefits in their biochar application scenarios, but considered avoided waste disposal fees and coproduction revenues (biofuels, bioenergy).

Revenue stream data that was collected from each publication consisted of increased crop yields and revenues associated with coproduction including sales of biofuel or bioenergy. Cost savings included fertilizer savings, agricultural lime savings, transport cost savings and avoided waste disposal fees. Revenues from carbon pricing or similar environmental schemes were deducted to enable comparison across scenarios. Carbon pricing was subsequently applied to test for sensitivity.

Distinct scenarios within publications were included where the following criteria were met:

(i) the biochar product valuation incorporates application to soil (and was not combusted for energy, for example),

(ii) there were multiple crops considered;

(iii) there were multiple technology scenarios considered (e.g. fast / slow pyrolysis, as in Kung et al. (2013));

(iv) there were multiple feedstocks considered (e.g. Shackley et al. (2011));

(v) there were multiple locations considered (e.g. Dickinson et al. (2015)).

We did not include distinct scenarios where:

(i) there were multiple carbon prices;

(ii) there were multiple application rates (e.g. Pandit et al. (2018)), in this circumstance, the application rate with the highest financial feasibility was selected, assuming the user would not pursue a less profitable option);

(iii) there were different local climatic scenarios such as low or high rainfall, or there are different scenarios considering persistence of agronomic effects, in which case a mean value was calculated (e.g. Blackwell et al. (2010)).

Some publications indicated biochar market prices via surveys (Galgani, van der Voet, & Korevaar, 2014; Ji, Cheng, Nayak, & Pan, 2018; Ng et al., 2017; You, Tong, Armin-Hoiland, Tong, & Wang, 2017; Zhang et al., 2017) or adopted market consumer prices without sources (Liu, Liu, Yousaf, & Abbas, 2018). These publications did not consider how biochar may have provided value to the user. For that reason, those papers were not included in our analysis. In some cases where the biochar financial feasibility assessment includes both assumed market prices and justified revenue streams such as fertilizer saving, the justified portion has been included, as in Harsono et al. (2013) and Wrobel-Tobiszewska et al. (2015). Other publications required additional assumptions to enable calculation of indicators, such as Steiner et al. (2018), which considers lettuce farming in Ghana.

2.2 Financial Feasibility Indicators

Within each scenario we calculated three simple indicators of biochar project value creation, (1) net biochar value (US\$ Mg^{-1}), (2) net agronomic biochar value (US\$ Mg^{-1}) and (3) abatement cost (AC) (US\$ Mg^{-1} CO_2e). Net biochar value (V) is the net present value of the project divided amongst the tonnage of biochar produced over the project lifetime. This metric considers the total value of the project, including both biochar agronomic value and revenues from coproducts (bio-oil, bioenergy, syngas).

$$V = \frac{\sum_0^T \frac{R_t}{(1+i)^t} - \sum_0^T \frac{C_t}{(1+i)^t}}{Q} \qquad (1)$$

Here 'Q' is defined as the metric tons of biochar produced over the project's lifetime (Mg), 'R_t' are all the revenues associated with the project at time 't', excluding revenues from carbon taxes, 'C_t' are all the costs associated with the project (operating costs, fixed costs, financial costs). Where feedstock is associated with an avoided cost (e.g. gate fees) this is treated as a negative cost. 'T' is the project life in years, where $0 \leq t \leq T$.

A second indicator, V_{bc}, is the net agronomic value of biochar (US$ Mg^{-1}), where only revenues associated with the biochar product (e.g. crop yield gain, fertilizer saving, agricultural lime displacement) are considered. This gives an indication of the financial value of the biochar from the user's perspective.

$$V_{BC} = \frac{\sum_0^T \frac{R_{bc,t}}{(1+i)^t} - \sum_0^T \frac{C_{bc,t}}{(1+i)^t}}{Q} \quad (2)$$

$R_{bc,t}$ are all the revenues associated with biochar agronomic value in a given year 't', where $R_{bc,t}$ is always less than or equal to R_t..

Cash flows were discounted at the rate applied in each publication, assuming that the rate adopted by each author is appropriate in each given circumstance (Table S1). In the majority of studies, the details of cash flows were not provided, and so a discount rate sensitivity analysis could not be performed, and discount rates could not be changed. However, as discussed in the results, the average of discount rates for scenarios that were not financially feasible was lower (7.27%) than the average for financially feasible scenarios (8.26%). No statistically significantly difference was found between means (p=0.104) and so there is no evidence to suggest that financial feasibility was due to more favorable (lower) discount rates.

Where V_{bc} was equal to V, the project had no coproducts such as bioenergy or biofuel and is a biochar focused project. Where valuations were performed in different currencies, cash flows have been converted to US dollars at the time of the assessment, unless a specific exchange rate was stated. Where 'V' or 'V_{bc}' was greater than zero, each metric ton of biochar created financial value for the user, and we defined and referred to such scenarios as being financially feasible. Where 'V' or 'V_{bc}' is equal to zero, the project is at breakeven point from the user's perspective. Breakeven point (BEP) in this paper is defined as being the sum of all discounted costs including costs of feedstock, production, transport and application.

2.3 Abatement Cost

The third indicator is the abatement cost (AC). AC measures the average financial cost of reducing one unit of pollution (namely one metric ton of greenhouse gas) in a given scenario.

$$\mathrm{AC} = -\frac{V}{C} \quad (3)$$

Carbon abatement 'C' was calculated by contrasting the footprint of the baseline activity with the footprint of the biochar scenario. In following the ISO14040 (2006) guidelines, activities within the boundaries of the calculation consisted of biomass collection, pyrolysis and biochar soil application, excluding upstream land use change and downstream crop processing. The baseline was either mineralization through natural biomass decomposition or emissions from biomass burning as specified in each scenario. Where scenarios calculated reduced soil greenhouse gas emissions or avoided nitrification from saved fertilizer, this was included, otherwise it was assumed that these emissions were zero. The majority of abatement was achieved through the sequestration of organic carbon contained in the biochar itself, calculated as biochar organic carbon content 'C' remaining after 100 years multiplied by the ratio between carbon dioxide and carbon. Where the biochar decomposition rate was not considered by the authors, physical persistence of carbon was assumed to decay in accordance with the two pool model outlined in the meta-analysis of biochars by Wang, Xiong, and Kuzyakov (2016). Emissions abatement associated with coproducts displacing fossil fuels (biofuels, bioenergy) were included. Treatment of each scenario is outlined in supplementary materials (Table S2).

2.4 Scenario variables

Six variables were considered as determinants of biochar financial feasibility. These were pyrolysis feedstock throughput scale, pyrolysis coproduction capability, climate, income levels, consideration of crop yield effect and crop value.

Scenarios were separated into quartiles of pyrolysis feedstock throughput scale as 'small' (0 to 2 Mg per day), 'medium small' (2 to 44 Mg per day), 'medium large' (44 to 192 Mg per day) and 'large' (192 to 2000 Mg per day).

'Yield spread' or 'biochar yield spread' was defined as the crop yield growth (% ha^{-1}) attributable to a single metric ton of biochar. For example, a biochar that improves crop yields by 10% with a 3 Mg ha^{-1} application has a biochar yield spread of 3.33%.

'Lower-income' and 'higher-income' countries were defined according to the World Bank classification of income level (Fantom & Serajuddin, 2016). This classification assigns economies into four income groups by Gross National Income per capita. As of July 2018, these thresholds are high (> US$12,055), upper-middle (US$3,896-12,055), lower-middle (US$996 – US$3895) and low (< US$995). In this paper, 'lower-income' refers to the two lower classes, whereas 'higher-income' refers to the two higher classes.

2.5 Ordinary Least Squares linear regression

Ordinary Linear Squares linear regression (OLS) of these variables was performed to evaluate the predictive capacity of determinants for both total biochar financial feasibility (V) and biochar agronomic net value (V_{bc}).

$$y = b_0 + b_1 x_1 \, x_2 + b_2 x_3 + b_3 x_4 + b_4 x_5 \qquad (4)$$

Where 'y' is a the dependent variable (V or V_{bc}), 'b_0' is an intercept; 'b_1', 'b_2', 'b_3' and 'b_4' are model parameters resulting from regression; 'x_1' is an indicator variable of climate (0 = temperate, 1 = subtropical & tropical), 'x_2'is an indicator variable of Income (0 = high / medium high, 1 = medium low / low), 'x_3' is an indicator variable of yield focus (0 = yield exclusion, 1 = yield inclusion), 'x_4' is a continuous variable of technology scale (Mg per day of feedstock throughput), 'x_5' is an indicator variable of co-production capability (1 = co-production, 0 = biochar focused).

Due to the high correlation (81%) between climate (tropical / temperate latitudes) and income levels (GNI per capita), a new indicator variable was created from both the climate and the income level to avoid multicollinearity. The product of these variables ('x_1x_2') created an indicator variable of both climate and income level (1 = Medium Low / Low income and Subtropical & Tropical climate, 0 = High / Medium High or Temperate climate).

A Variance Influence Factor (VIF) was calculated following this to check for multicollinearity. All variables were tested for normality using the Kolmogorov-Smirnov test.

3. Results

Twenty-seven of 70 scenarios were financially feasible in terms of biochar net value (V > 0). Nineteen of the twenty-three feasible scenarios were feasible due to biochar agronomic net value (V_{bc}>0). Biochar scenarios were on average across all scenarios not financially feasible (US-$181.4 Mg^{-1}), implying an average abatement cost (AC) of US$73 Mg^{-1} CO_2e. Average biochar agronomic value creation, including crop yield gains, nutrient saving and liming, was US$144 Mg^{-1} (Table 1).

Table 1. Summary results of systematic review. Ranges (±) are one standard error. Bc – Biochar. AC – Abatement cost.

The average breakeven point was US$433 Mg^{-1}, close to the general biochar cost of US$400 Mg^{-1} suggested by Bach et al. (2016). Average feedstock and transport costs were US$31 Mg^{-1} and US$47 Mg^{-1} respectively. Median daily feedstock throughput was 44 Mg day^{-1}, ranging from 1 kg day^{-1} for biochar cook-stoves in Vietnam (Joseph, Anh, et al., 2015) to 2,000 Mg day^{-1} for a large-scale biochar and bioenergy coproduction plant in the USA (Brown et al., 2011).

Discount rates were on average 7.6 ± 2.3%, with financially feasible scenarios exhibiting a higher average rate (8.26%) than infeasible scenarios (7.27%), with no statistically significant difference between the means ($p = 0.104$).

Of the ten scenarios where coproduction was a determining factor of biochar feasibility, six were from Shackley et al. (2011) where an avoided waste disposal fee as well as bioenergy coproduction made the projects financially feasible (agronomic benefits were not considered). Granatstein et al. (2009) and Shackley et al. (2015) relied on bio-oil coproduction to attain scenario profitability. The financially feasible scenarios that rely on yield gains were found in Fru et al. (2018), Joseph, Anh, et al. (2015), Kumar et al. (2018), Li et al. (2015), Mekuria et al. (2013), Mohammadi et al. (2017), Pandit et al. (2018), two scenarios from Robb and Dargusch (2018), Shackley et al. (2012), Sparrevik et al. (2014), Steiner et al. (2018), Widiastuti (2016), Widowati and Asnah (2014) and Zheng et al. (2017).

There were several commonalities amongst the 19 scenarios where biochar financial feasibility depended on agronomic effects. Sixteen of the 19 scenarios were located in low or lower-middle income countries, with the exception of Li et al. (2015), Zheng et al. (2017) and Kumar et al. (2018). All such scenarios were in tropical (14) or subtropical (4) locations with the exception of Zheng et al. (2017). Four scenarios considered coproduction technologies, namely cook-stoves (Joseph, Anh, et al., 2015; Mohammadi et al., 2017) and a Rice Husk Gasifier (Shackley et al., 2012). When the scenarios were aggregated based on these common points, several scenario characteristics emerged as being indicative of financial feasibility (Table 2)

Table 2. Review characteristic averages in order of lowest cost abatement

The confluence of these determinants of biochar value was confirmed through correlation between key variables outlined in Table 3. For example, where a biochar project has been evaluated in a tropical climate as an indicator variable, this was correlated with lower-income levels in the country of application (82.3%), incorporation of agronomic yield effect in valuation (73.2%), and a tendency to target higher value crops for biochar application (39.3%). Similarly, there was a negative correlation between pyrolysis technology scale and tropical climate (-34.1%).

OLS regression (Fig. 1) resulted in a predictive model that fitted data better than a model with no independent variables significant to $p < 1\%$ (V: F = 5.41, p =3.28e-04; V_{bc}: F = 8.44, p = 3.55e-06), however none of the independent variables were themselves significant predictors (Table 4, Table S3, Table S4). The OLS regression accurately determined whether scenarios were or were not financially feasible in 78.57% of cases in predicting V, and 88.57% of scenarios predicting $V_{bc..}$ Kolmogorov-Smirnov tests of variables indicated normality and the variance influence factor was not suggestive of significant multicollinearity.

Table 3. Correlation between scenario variables. Climate (0 = Te – Temperate , 1 = S – Subtropical, Tr – Tropical), Yield ('Y' - yield inclusion, 'NY' - no yield inclusion. Y = 1, NY = 0), Crop Value ('No Crop' - no crop is considered in the valuation, 'Cereal' - a cereal crop is the target, 'Other' – a higher value crop is the target. 0 = No Crop / Cereal, 1 = Other) and Technology Scale (the daily maximum feedstock throughput capacity in metric tons). Income (Gross National Income per capita as defined in Fantom and Serajuddin (2016), as 'H' - High, 'MH' - Medium High, 'ML' - Medium Low, and 'L' – Low. 0 = H / MH, 1 = ML/ L)

Typically, financially feasible biochar scenarios included those that had small-scale labor-intensive models of biochar focused production in tropical latitudes with lower-income levels. However, Table 3 also indicated that coproduction capacity and technology scale had weak correlative relationships to overall value, suggesting that larger-scale centralized pyrolysis units may be financially feasible if utilized in lower-income countries, conditional on feedstock availability and access to relevant energy infrastructure. This is reflected in the OLS regression, where both technology scale and coproduction had the lowest predictive significance as components of the model (Table 4).

Table 4. Coefficients and P-values of OLS regression variables

Figure 1. Predicted and Actual biochar scenario values using OLS Linear Regression model. LHS is the fitted model for 'V', RHS is the fitted model for 'V_{bc}'. Both predictive models were significant ($p<1\%$), but none of the independent variables were found to be statistically significant as components of the model (Table 4).

Similarly, a significant correlation to biochar's value to the user was the value of the target crop, which indicated opportunities for biochar applied in pursuit of agronomic benefit in higher value crops in higher-income countries. Kumar et al. (2018) exemplifies such an opportunity as it considered a high-income country (Israel) and a high value crop (sweet pepper). The performance of this biochar was modest (1.35% yield spread), yet the high value of the sweet pepper augmented financial feasibility.

Zheng et al. (2017) was the exceptional case in several respects. The study considered a biochar fertilizer produced from wheat straw, applied at a low rate of 0.45 Mg ha^{-1}, substituting a slow release fertilizer. It was the only financially feasible case considering yield gain alone that was in a temperate climate with a higher-income level. It targeted wheat, a low-value cereal, and had a centralized pyrolysis unit (a vertical kiln with a 2 Mg per day feedstock throughput). Despite these characteristics that would appear to be impediments, biochar net agronomic value was found to be US$651 Mg^{-1}. This was a result of high crop yield effects relative to the low biochar application rate, achieving a biochar yield spread of 23.8%. This result and other similar studies (Farrar et al., 2019; Qian et al., 2014; Qiao, Fu, Zheng, Li, & Pan, 2014; Yao et al., 2015) indicate that biochar fertilizers may prove a profitable pathway for application of biochar in broadacre cereal agriculture in higher-income countries (Joseph et al., 2013).

3.1 Temperate or tropical climate

Tropical conditions were associated with average biochar net values that exceeded the averages from subtropical and temperate climates (Fig. 2, Table 2) ($p < 0.05$). Yield spreads in tropical scenarios were found to be 2.71% on average, which was greater than the average of temperate yield spreads of 0.73% ($p < 0.05$).

Figure 2. **(A)** Boxplot of Biochar Net Agronomic Value (V_{bc}) by climatic condition of scenario location, and **(B)** a boxplot of biochar yield spreads assumed in tropical / temperate scenarios (percentage crop yield increase per hectare per metric ton of biochar).

This result is consistent with a recent meta-analysis by Jeffery et al. (2017) which reported that tropical soils exhibited an average 25% yield gain with a median 15 Mg ha^{-1} application, equivalent to a yield spread of 1.66% Mg^{-1} biochar, while temperate soils in general appeared to have no response to biochar on average. A similar result was observed in Crane-Droesch et al. (2013).

An example of this is the contrast between McCarl et al. (2009); a study from the US, and Sparrevik et al. (2014); a study from Indonesia. In Sparrevik et al. (2014), all value was derived from maize yield gain, and net biochar value (V) was US$173 Mg^{-1}. The pyrolysis unit (Adam retort) was capable of processing 670 kg of feedstock per day, and the feedstock (Cocoa shell) was free, yet farmers had to collect and centralize the biomass.

In the fast pyrolysis scenario from McCarl et al. (2009), value from biochar yield gain was US$13 Mg^{-1}, value from coproduction was US$667 Mg^{-1} and total value of revenues was US$680 Mg^{-1}. The coproduction (bioenergy) facility processed 192 Mg of feedstock per day, and the cost per metric ton of feedstock was US$59. In aggregate, costs totaled US$999 Mg^{-1} (BEP) and hence net biochar value (V) was an unprofitable -US$319 Mg^{-1}. The temperate / tropical dichotomy was also demonstrated in Dickinson et al. (2015), where in a Sub Saharan Africa scenario both production costs were lower and agronomic revenues more than twice the North Western Europe scenario.

3.2 Lower-income and higher-income

As previously outlined, the World Bank classifies relative income levels of countries and regions by GNI per capita (Fantom & Serajuddin, 2016). In classifying the scenarios amongst the four categories of income, and then further aggregating into higher-income and lower-income, we found that 50 scenarios were performed in higher-income countries, and 20 scenarios in lower-income countries. As to be expected, the contrast between lower-income and higher-income countries was substantial. In higher-income countries, average feedstock costs of US$45 Mg^{-1} and transport costs of US$62 Mg^{-1} were greater by an order of magnitude in contrast to low-income countries, and much higher average feedstock throughput in excess of 304 Mg per day. In the two low-income scenarios (Dickinson et al., 2015; Pandit et al., 2018) average feedstock throughput was 70kg day^{-1}, with average feedstock and transport costs near zero.

Figure 3. **(A)** Boxplot of biochar net value (V). 'Higher GNI' constituting countries with high and medium-high GNI per capita, 'Lower GNI' constituting countries with low and medium-low GNI per capita. **(B)** Boxplot of biochar net value (V) by pyrolysis technology scale. Pyrolysis scale quartiles are defined by daily feedstock throughput as 'S' - small (0.8kg to 2 Mg), 'MS' - medium small (2 to 44 Mg), 'ML' medium large (44 to 192 Mg) and 'L' - large (192 to 2000 Mg). **(C)** Boxplot of biochar net value (V) by technology capability (with or without coproduction capability). **(D)** Boxplot of biochar net value (V) by crop yield inclusion or exclusion (no yield) in valuation. **(E)** Boxplot of biochar net value (V) by value of crop, and by crop yield inclusion / exclusion (other) in valuation. 'No crop' are scenarios where no target crop has been specified, 'Cereals' are cereal crops, 'Non-cereal crops' are scenarios that target higher value crops.

The average net value creation (V) was substantially higher in low-income and low-middle income countries (Fig. 3A). This was likely a result of the low breakeven point of biochar projects in lower and lower-middle income bracket countries. However, this was also in part due to the tendency of valuations in higher-income countries to exclude revenues associated with yield gain.

Biochar yield gain revenues would also be expected to be higher in lower-income countries, as these scenarios (Indonesia, Vietnam, Nepal, Sub-Saharan Africa) are mostly in tropical and subtropical regions, where biochar's performance is generally higher than that of temperate latitudes (Jeffery et al., 2017). Tropical and subtropical lower-income countries such as Indonesia and Vietnam appear to exhibit a confluence of favorable conditions for biochar application for agronomic benefit.

3.3 Scale of pyrolysis

Small-scale pyrolysis technologies had an average cost advantage over medium and large-scale facilities (fig. 3B). The average net biochar value (V) for the smallest quartile of scenarios was US$141 Mg^{-1} implying a negative AC of -US$63 Mg^{-1} CO_2e whereas the largest quartile resulted in an average net biochar value of -US$282 Mg^{-1}, implying a high AC of US$102 Mg^{-1} CO_2e. Examples of the smaller-scale technologies used in financially feasible scenarios included biochar cook stoves (Joseph, Anh, et al., 2015; Mohammadi et al., 2017), Top Lit Updraft kilns (Fru et al., 2018), Japan Open Retorts (Steiner et al., 2018), Adam Retorts (Sparrevik et al., 2014) and Flame Curtain Kilns (Pandit et al., 2018). These all had a daily feedstock throughput capacity of less than a metric ton, with most below 100kg. The breakeven point for these kilns ranged between US$16 Mg^{-1} (Mekuria et al., 2013) and US$196 Mg^{-1} (Pandit et al., 2018).

Middling-scale technology quartiles exhibited the highest average BEP, indicating that larger-scale centralized units may have a competitive edge on medium-scale units due to economies of scale. Yet there may be other impediments to this centralized model, such as the insufficient cash reserves of small-scale farmers preventing purchase of biochar from a centralized source or prohibitive transport costs from the pyrolysis facility to the target crop. The advantage of the small-scale model is that it is generally a closed system, where farmers produce and use their own biochar.

3.4 Technology focus

On average, scenarios where pyrolysis technology was dedicated to biochar production were more profitable than scenarios where pyrolysis technology had co-production capability (fig. 3C). Such coproduction facilities were often focused on bioenergy or biofuels as the main source of revenue, with biochar being a secondary product. The breakeven point for biochar-focused pyrolysis technologies was less than half that of the average for coproduction scenarios (Table 2).

Despite this general result, small-scale coproduction technologies have been shown to be financially feasible (Joseph, Anh, et al., 2015; Mohammadi et al., 2017; Shackley et al., 2012). In Shackley et al. (2012) rice husk biochar was a waste stream of gasification for electricity, and was sold at a negligible price to nearby farmers. This opportunistic approach depended on high electricity prices to make the gasification system profitable. Joseph, Anh, et al. (2015) and Mohammadi et al. (2017) both assessed the returns from biochar cook stoves, a technology that allows for domestic cooking requirements along with a biochar coproduct, which had the added benefit of minimizing the requirement for additional labor. This may be particularly important for small-scale farmers where decreased labor availability may prove a constraint.

3.5 Yield inclusion or exclusion

Where crop yield gain was included in financial analysis, a US$384 Mg^{-1} premium was added to average net biochar value (V) (fig. 3D). Scenarios that incorporated yield gain were financially feasible on average (US $49 Mg^{-1}). Scenarios that excluded consideration of yield gain were far less financially feasible on average (US-$334 Mg^{-1}). The average revenue from scenarios where biochar yield effect was excluded was US$9 Mg^{-1}, far less than the average revenue of US$286 Mg^{-1} where yield was included.

Robb and Dargusch (2018) considered biochar financial feasibility from a nutrient saving perspective (yield exclusion) and crop yield perspective (yield inclusion), and concluded in four different cropping scenarios that the financial of biochar applied for increased yield purposes far exceeded the financial value created from savings of avoided fertilizer.

Roberts et al. (2010) considered nutrient saving in four different, but not yield effects, arguing that the soil in question (US corn belt) was already highly fertile, and as such unlikely to exhibit yield gain from biochar application. The study calculated agronomic revenues between US$41–79 Mg^{-1} with a breakeven price between US$163-332 Mg^{-1} making the scenarios financially infeasible. Similarly, Field et al. (2013) excluded yield gains and calculated agronomic revenues of US$2 Mg^{-1} from nutrient saving and liming effect, and calculated a breakeven price of US$270 Mg^{-1} making the scenario highly financially infeasible.

Yield inclusion was found to be correlated with tropical climatic conditions (73%) and lower-income levels (65%). No causal relationship could be ascribed to yield inclusion or exclusion as a predictor of overall financial feasibility, thought the overall model was found to be significant (Table 3).

Scenarios that were financially feasible ($V > 0$) were found to have an average biochar yield spread of 3.18%, which was much higher than scenarios that were not financially feasible ($V < 0$) with an average biochar yield spread of 0.62%. All else being equal, it is the case that financial feasibility is improved with higher biochar yield effects.

3.6 Crop selection

Crop value improves biochar financial feasibility where biochar application causes yield improvement. On average, biochar applications in low-value cereal crops are not financially feasible (US-$45 Mg^{-1}), while biochar applications in higher-value crops (non-cereal crops) are financially feasible (US$157 Mg^{-1}, Table 2, Fig. 3E). This was well exemplified in Robb and Dargusch (2018), which assumed uniform biochar performance (2% biochar yield spread) across crops of Australian wheat, cotton and sugarcane. Application in Australian wheat resulted in discounted revenues of

US$81 Mg^{-1} and net value (V) of US-$220 Mg^{-1} whereas biochar applied in a higher value crop of Australian sugarcane resulted in US$370 Mg^{-1} in discounted revenues, with a net value (V) of US$134 Mg^{-1}.

It remains the case that where biochar can be shown to improve crop yields, targeting higher value crops augments scenario financial feasibility. This assumes produce is sold to market and is not used for subsistence purposes.

3.7 Carbon pricing

Average carbon prices from five different carbon trading schemes from 2018 were applied to test the sensitivity of scenario financial feasibility (WBG, 2018). Biochar average financial feasibility (V) exceeds zero where the carbon price (per metric ton CO_2-e) exceeded US$55 (Fig. 4). Of the 70 scenarios, a US$2 carbon price of the Guangdong ETS pilot increased the number of viable scenarios from 27 to 28. A US$16 carbon price achieved under the European Union ETS increased the number of viable scenarios from 27 to 31. A US$25 price (UK carbon price floor) increased the number of viable scenarios from 27 to 34. A US$55 price (French carbon tax) increased the number of viable scenarios from 27 to 38. A US$77 price (Finland carbon tax) increased the number of viable scenarios from 27 to 44.

Figure 4. Influence of different carbon prices on average biochar financial feasibility (V). Error bars represent one standard error.

Under conditions of very high carbon prices above US$55 (French carbon tax) such as those found in a small number of Western European countries, approximately half of the scenarios were financially feasible. Only four scenarios that were previously not financially feasible became financially feasible under a moderate level carbon pricing policy of US$16 (EU ETS). While previous studies have concluded that biochar requires high carbon prices to reach financial feasibility (Kulyk, 2012; McCarl et al., 2009), we have demonstrated that this impediment is specific to the conditions of these studies and cannot be generalized. It is not generally the case that biochar project financial feasibility will depend on high carbon prices, but it is generally the case that scenario financial feasibility will be insensitive to carbon pricing policy without exceptionally high prices. Biochar projects cannot rely on carbon pricing schemes for financial feasibility and should instead target circumstances in which biochar creates agronomic and other forms of financial value for users.

3.8 Review limitations

The major limitation of this review is the inability to ascribe causality due to correlation between variables, otherwise known as the fundamental problem of causal inference (Holland, 1986). For example, average financial feasibility is higher for biochar-focused technologies as opposed to coproduction capable technologies. Yet biochar-focused / co-production capability itself was not a significant predictor of financial feasibility within the overall model. The correlation between production capability and other variables such as income levels may be a property of the dataset taken from the review and may be coincidental. It may also be the case that there is some confounding observed or unobserved variable linking technological scale and coproduction capability with another variable, such as low income levels limiting the capacity to acquire coproduction technology (Athey & Imbens, 2017). As found in the OLS analysis, the overall model inclusive of all variables is a significant predictor of financial feasibility, yet no individual variable is a statistically significant predictor.

Climate change is expected to have regional effects of increased temperature and decreased soil moisture (Smith, 2012). As well as climate change mitigation through carbon sequestration (Wang et al. 2016), biochar may also play a role in climate change adaptation through improvement of soil health (Waters et al., 2011). Low applications of biochar have been shown to increase soil moisture, indicating that biochar may mitigate water shortages on drought-prone soils as a result of climate change (Koide et al., 2015). Aged biochars have been shown to enhance soil properties (Liang et al., 2006) and accumulate soil organic carbon (Weng et al., 2017). Due to variability of potential future climate change impacts and the lack of knowledge of long-term biochar effects across a range of circumstances, these potential benefits of biochar's use for climate adaptation were not considered in this review.

This review sought to examine financial feasibility studies of biochar where applied to soil. The review scope excluded a publication considering biochar's use as an animal feed, detailed in Joseph, Pow, et al. (2015). In this scenario, a hardwood biochar is fed to beef cows at a rate of 0.33 kg per cow per day. Through avoiding costs of feed, this scenario results in revenues of US\$1,691 Mg^{-1} and a biochar net value (V) of \$1,553 Mg^{-1}. Both the revenues and net value derived in this scenario are in exceedance of any other scenario considered in this review. This scenario did not quantify the effects of biochar on potential animal weight gain that have been observed in preliminary research (Leng, Preston, & Inthapanya, 2012) which would deliver further financial benefits. A recent industry report (Robb & Joseph, 2019) evaluated biochar as a cattle feed and found that improved cattle health and weight gain delivered greater financial benefit to the user than the feed cost displacement scenario in Joseph, Pow, et al. (2015).

Biochar's use as an animal feed, as a medium for water use efficiency and in environmental remediation may be of greater financial value relative to biochar's use as a soil amendment. This is reflected in a 2018 US Biochar industry survey which indicated that emerging markets include stormwater management; water retention in turf, landscaping and urban tree plantings; biochar soil blends for horticulture; remediation of mine tailings and as a replacement for activated carbon in industrial uses (Groot, Pepke, Fernholz, Henderson, & Howe, 2018). Given the literature's overwhelming focus on biochar's use as a soil amendment, it is almost certainly the case that the literature does not reflect all benefits biochar users are experiencing in practice.

4. Conclusion

This review sought to address the predominant view in the biochar-related literature that biochar, whilst highly beneficial for positive agronomic and environmental outcomes, was generally not financially feasible. Of the 70 scenarios reviewed, 19 biochar applications were financially feasible in consideration of crop yield gain. These 19 scenarios shared numerous characteristics, namely they were mostly to be found in lower-income countries (16 of 19), focusing on crop yield improvement (19 of 19) in higher-value crops (10 of 19) or cereal crops (9 of 19) as the only source of project value (16 of 19), using small decentralized pyrolysis technology (16 of 19) in tropical latitudes (17 of 19).

OLS multiple linear regression of scenarios drawn from the reviewed literature indicated that these characteristics overall were significant predictors of biochar net value (V) and biochar net agronomic value (V_{bc}). Scenarios with small-scale biochar focused technology in lower-income nations located in tropical climates focusing on yield gain in high value crops were predictive of scenario financially feasibility. Scenarios of large-scale biochar projects with coproduction capacity in higher-income nations in temperate climates focusing on revenue streams other than from crop yield increases are predictive of scenarios that are not financially feasible.

Despite the significance of the overall result, no individual variable was a statistically significant predictor. For example, tropical soils and low-income countries were highly correlated, making their individual causal role unclear. It is well established that low income countries have lower biochar production costs and crop yields in tropical soils benefit the most from biochar on average (Jeffery et al., 2017). It is also trivially the case that targeting higher value crops will increase biochar valuation, where the crop harvest is sold to market and not used for subsistence purposes (Robb & Dargusch, 2018). Coproduction capability and Technology Scale both had the weakest overall predictive significance within the OLS regression (Table 4), and pyrolysis technology scale had the lowest correlation with other variables, suggesting that larger scale pyrolysis technology scenarios with coproduction capability may be financially feasible propositions in lower-income countries.

Previous studies (Kulyk, 2012; McCarl et al., 2009) have concluded that biochar projects will not be financially feasible without high carbon prices such as those found in a handful of Western European countries. This review highlights numerous biochar scenarios which are financially feasible without carbon pricing. Given that global carbon markets are unlikely to be developed to the extent where infeasible scenarios are made feasible by carbon pricing (Joseph, Anh, et al., 2015), biochar projects should seek alternative forms of financial value creation rather than relying on carbon markets.

Some studies have reached generalized conclusions about the general lack of feasibility of biochar and have concluded that biochar abatement cost is high (Bach et al., 2016; Maroušek et al., 2017; McGlashan et al., 2012). These studies overlook alternative contexts such as tropical low-income countries. They also overlook biochar's uses as an animal feed, as a water saving medium and recent innovations such as biochar fertilizers which have been shown to create significant net financial value (Groot et al., 2018; Joseph, Pow, et al., 2015; Robb & Joseph, 2019; Zheng et al., 2017). This review has shown that previous conclusions of biochar's general lack of financial feasibility assume circumstances that are overall predictors of scenarios that are not financially feasible and cannot be generalized.

Shifting cultivation is practiced by up to 500 million people throughout the global tropics (FAO, 1985), covering 30% of all arable land (Brady, 1996). As much as 0.2 Pg C yr^{-1} could be sequestered using biochar in shifting cultivation systems throughout the world (Lehmann et al., 2006), in regions where rural poverty (Sanchez, 2002) and land degradation (Ayuke et al., 2011) are often pressing concerns. Small-scale farmers in these areas pursue a diverse range of livelihoods (Cramb et al., 2009) and biochar may be applied to augment yields in cash crops.

Estimates of biochar's potential as a negative emissions technology typically report prohibitive abatement costs when financial feasibility is assessed in high-income countries such as US$135 $Mg^{-1} CO_2e$ by McGlashan et al. (2012). Our review of the literature observed similar estimates for average abatement costs in temperate latitudes (US$119 Mg^{-1} CO_2e) and higher-income countries (US$93 Mg^{-1} CO_2e), however, our examination of the literature shows that biochar applications in lower-income countries in the humid tropics can generally be financially feasible from the small-scale farmer's perspective, with an average abatement cost of US-$63 Mg^{-1} CO_2e and US-$71 Mg^{-1} CO_2e respectively. Climate policies of lower-income countries in tropical latitudes should consider biochar as an input for small-scale climate smart agriculture to address land degradation in tropical agricultural systems.

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References

Aller, D., Archontoulis, S., Zhang, W., Sawadgo, W., Laird, D., & Moore, K. (2018). Long term biochar effects on corn yield, soil quality and profitability in the US Midwest. *Field Crops Research, 227*, 30-40.

Athey, S., & Imbens, G. (2017). The state of applied econometrics: Causality and policy evaluation. *Journal of Economic Perspectives, 31*(2), 3-32. doi:10.1257/jep.31.2.3

Ayuke, F., Brussaard, L., Vanlauwe, B., Six, J., Lelei, D., Kibunja, C., & Pulleman, M. (2011). Soil fertility management: impacts on soil macrofauna, soil aggregation and soil organic matter allocation. *Applied Soil Ecology, 48*(1), 53-62. doi:10.1016/j.apsoil.2011.02.001

Bach, M., Wilske, B., & Breuer, L. (2016). Current economic obstacles to biochar use in agriculture and climate change mitigation. *Carbon Management, 7*(3-4), 183-190. doi:10.1080/17583004.2016.1213608

Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2010). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. *Soil Research, 48*(7), 531-545. doi:10.1071/SR10014

Boardman, A., Greenberg, D., Vining, A., & Weimer, D. (2017). *Cost-benefit analysis: concepts and practice*: Cambridge University Press.

Brady, N. (1996). Alternatives to slash-and-burn: a global imperative. *Agriculture, Ecosystems & Environment, 58*(1), 3-11. doi:10.1016/0167-8809(96)00650-0

Brown, T., Wright, M., & Brown, R. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining, 5*, 54-48. doi:10.1002/bbb.254

Bushell, A. (2018). *A Pricing Model and Environmental Impact Analysis for manure-based biochar as a soil amendment.* (Master of Environmental Management), Duke University,

Cayuela, M., van Zwieten, L., Singh, B., Jeffery, S., Roig, A., & Sánchez-Monedero, M. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment, 191*, 5-16. doi:10.1016/j.agee.2013.10.009

Clare, A., Shackley, S., Joseph, S., Hammond, J., Pan, G., & Bloom, A. (2015). Competing uses for China's straw: the economic and carbon abatement potential of biochar. *Gcb Bioenergy, 7*(6), 1272-1282. doi:10.1111/gcbb.12220

Cornelissen, G., Nurida, N., Hale, S., Martinsen, V., Silvani, L., & Mulder, J. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Science of The Total Environment, 634*, 561-568. doi:10.1016/j.scitotenv.2018.03.380

Cramb, R., Colfer, C., Dressler, W., Laungaramsri, P., Le, Q., Mulyoutami, E., . . . Wadley, R. (2009). Swidden Transformations and Rural Livelihoods in Southeast Asia. *Human Ecology, 37*(3), 323-346. doi:10.1007/s10745-009-9241-6

Crane-Droesch, A., Abiven, S., Jeffrey, S., & Torn, M. (2013). Heterogeneous global crop yield response to biochar: a meta-regression analysis. *Environmental Research Letters, 8*(4), 1-8. doi:10.1088/1748-9326/8/4/044049

Dickinson, D., Balduccio, L., Buysse, J., Ronsse, F., Van Huylenbroeck, G., & Prins, W. (2015). Cost-benefit analysis of using biochar to improve cereals agriculture. *Global Change Biology Bioenergy, 7*, 850-864. doi:10.1111/gcbb.12180

Fantom, N., & Serajuddin, U. (2016). *The World Bank's Classification of Countries by Income*. Retrieved from https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-7528

FAO. (1985). *Tropical Forestry Action Plan*. Retrieved from Rome, Italy:

Farrar, M., Wallace, H., Xu, C., Nguyen, T., Tavakkoli, E., Joseph, S., & Bai, S. (2019). Short-term effects of organo-mineral enriched biochar fertiliser on ginger yield and nutrient cycling. *Journal of Soils and Sediments, 19*(2), 668-682.

Fidel, R., Archontoulis, S., Babcock, B., Brown, R., Dokoohaki, H., Hayes, D., . . . Wright, M. (2017). Commentary on 'Current economic obstacles to biochar use in agriculture and climate change mitigation'regarding uncertainty, context-specificity and alternative value sources. *Carbon Management, 8*(2), 215-217. doi:10.1080/17583004.2017.1306408

Field, J., Keske, C., Birch, G., Defoort, M., & Cotrufo, M. (2013). Distributed biochar and bioenergy coproduction: a regionally specific case study of environmental benefits and economic impacts. *Gcb Bioenergy, 5*, 177 - 191. doi:10.1111/gcbb.12032

Fridahl, M., & Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. *Energy Research & Social Science, 42*, 155-165.

Fru, B., Angwafo, T., Ajebesone, N., Precillia, T., & Ngome, M. (2018). Effect of Biochar Issued from Crop Wastes on the Yield of Variety 8034 Cassava in the Humid-Forest Agroecological Zone, Cameroon. *International Journal of Horticulture, Agriculture and Food Science, 2*(1), 13-27. doi:10.22161/ijreh.2.1.1

Galgani, P., van der Voet, E., & Korevaar, G. (2014). Composting, anaerobic digestion and biochar production in Ghana. Environmental–economic assessment in the context of voluntary carbon markets. *Waste management, 34*(12), 2454-2465. doi:10.1016/j.wasman.2014.07.027

Galinato, S., Yoder, J., & Granatstein, D. (2011). The economic value of biochar in crop production and carbon sequestration. *Energy Policy, 39*, 6344-6350. doi:10.1016/j.enpol.2011.07.035

Granatstein, D., Kruger, C., Collins, H., Galinato, S., Garcia-Perez, M., & Yoder, J. (2009). *Use of biochar from the pyrolysis of waste organic material as a soil amendment. Final project report*. Retrieved from Wenatchee, WA:

Groot, H., Pepke, E., Fernholz, K., Henderson, C., & Howe, J. (2018). *Survey and analysis of the US Biochar industry*. Retrieved from www.dovetailinc.org/report_pdfs/2018/DovetailBiochar118.pdf

Harsono, S., Grundman, P., Hang Lau, L., Hansen, A., Salleh, M., Meyer-Aurich, A., . . . Ghazi, T. (2013). Energy balances, greenhouse gas emissions and economics of biochar production from palm oil empty fruit bunches. *Resources, Conservation and Recycling, 77*, 108–115. doi:10.1016/j.resconrec.2013.04.005

Holland, P. (1986). Statistics and causal inference. *Journal of the American statistical Association, 81*(396), 945-960.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A., van Groenigen, J., Hungate, B., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters, 12*(5), 1-6. doi:10.1088/1748-9326/aa67bd

Jeffery, S., Verheijen, F., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry, 101*, 251-258. doi:10.1016/j.soilbio.2016.07.021

Jeffrey, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta–analysis. *Agriculture, Ecosystems and Environment, 144*, 175-187.

Ji, C., Cheng, K., Nayak, D., & Pan, G. (2018). Environmental and economic assessment of crop residue competitive utilization for biochar, briquette fuel and combined heat and power generation. *Journal of Cleaner Production, 192*, 916-923. doi:10.1016/j.jclepro.2018.05.026

Joseph, S., Anh, M., Clare, A., & Shackley, S. (2015). Socio-economic feasibility, implementation and evaluation of small-scale biochar projects. In J. S. Lehmann J (Ed.), *Biochar for Environmental Management: Science and Technology* (2nd ed., pp. 853-879). London: Earthscan.

Joseph, S., Graber, E., Chia, C., Munroe, P., Donne, S., Thomas, T., . . . Pan, G.-X. (2013). Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components. *Carbon Management, 4*(3), 323-343. doi:10.4155/cmt.13.23

Joseph, S., Pow, D., Dawson, K., Mitchell, D., Rawal, A., Hook, J., . . . Solaiman, Z. (2015). Feeding biochar to cows: An innovative solution for improving soil fertility and farm productivity. *Pedosphere, 25*(5), 666-679. doi:10.1016/S1002-0160(15)30047-3

Koide, R., Nguyen, B., Skinner, R., Dell, C., Peoples, M., Adler, P., & Drohan, P. (2015). Biochar amendment of soil improves resilience to climate change. *Gcb Bioenergy, 7*(5), 1084-1091. doi:10.1111/gcbb.12191

Kulyk, N. (2012). Cost-benefit analysis of the biochar application in the US cereal crop cultivation.

Kumar, A., Elad, Y., Tsechansky, L., Abrol, V., Lew, B., Offenbach, R., & Graber, E. (2018). Biochar potential in intensive cultivation of Capsicum annuum L.(sweet pepper): crop yield and plant protection. *Journal of the Science of Food and Agriculture, 98*(2), 495-503. doi:10.1002/jsfa.8486

Kung, C., McCarl, B., & Cao, X. (2013). Economics of pyrolysis-based energy production and biochar utilization: A case study in Taiwan. *Energy Policy, 60*, 317-323. doi:10.1016/j.enpol.2013.05.029

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Change, 11*, 403-427. doi:10.1007/s11027-005-9006-5

Leng, R., Preston, T., & Inthapanya, S. (2012). Biochar reduces enteric methane and improves growth and feed conversion in local “Yellow” cattle fed cassava root chips and fresh cassava foliage. *Livestock Research for Rural Development, 24*(11).

Li, B., Fan, C., Zhang, H., Chen, Z., Sun, L., & Xiong, Z. (2015). Combined effects of nitrogen fertilization and biochar on the net global warming potential, greenhouse gas intensity and net ecosystem economic budget in intensive vegetable agriculture in southeastern China. *Atmospheric Environment, 100*, 10-19.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'neill, B., . . . Petersen, J. (2006). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal, 70*(5), 1719-1730.

Liu, R., Liu, G., Yousaf, B., & Abbas, Q. (2018). Operating conditions-induced changes in product yield and characteristics during thermal-conversion of peanut shell to biochar in relation to economic analysis. *Journal of Cleaner Production, 193*, 479-490. doi:10.1016/j.jclepro.2018.05.034

Maroušek, J., Vochozka, M., Plachý, J., & Žák, J. (2017). Glory and misery of biochar. *Clean Technologies and Environmental Policy, 19*(2), 311-317. doi:10.1007/s10098-016-1284-y

McCarl, B., Peacocke, C., Chrisman, R., Kung, C., & Sands, R. (2009). Economics of biochar production, utilization and greenhouse gas offsets. In J. S. Lehmann J (Ed.), *Biochar for Environmental Management: Science and Technology* (pp. 341–358). London: Earthscan.

McGlashan, N., Shah, N., Caldecott, B., & Workman, M. (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection, 90*(6), 501-510. doi:10.1016/j.psep.2012.10.004
Mekuria, W., Getnet, K., Noble, A., Hoanh, C., McCartney, M., & Langan, S. (2013). Economic valuation of organic and clay-based soil amendments in small-scale agriculture in Lao PDR. *Field Crops Research, 149*, 379-389. doi:10.1016/j.fcr.2013.05.026
Mohammadi, A., Cowie, A., Cacho, O., Kristiansen, P., Anh Mai, T., & Joseph, S. (2017). Biochar addition in rice farming systems: Economic and energy benefits. *Energy, 140*, 415-425. doi:10.1016/j.energy.2017.08.116
Ng, W., You, S., Ling, R., Gin, K., Dai, Y., & Wang, C. (2017). Co-gasification of woody biomass and chicken manure: Syngas production, biochar reutilization, and cost-benefit analysis. *Energy, 139*, 732-742. doi:10.1016/j.energy.2017.07.165
Pandit, N., Mulder, J., Hale, S., Zimmerman, A., Pandit, B., & Cornelissen, G. (2018). Multi-year double cropping biochar field trials in Nepal: Finding the optimal biochar dose through agronomic trials and cost-benefit analysis. *Science of The Total Environment, 637*, 1333-1341. doi:10.1016/j.scitotenv.2018.05.107
Pickering, C., & Byrne, J. (2014). The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *Higher Education Research & Development, 33*(3), 534-548. doi:10.1080/07294360.2013.841651
Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science, 362*(6417), eaav0294. doi:10.1126/science.aav0294
Pretty, J., Benton, T., Bharucha, Z., Dicks, L., Flora, C., Godfray, H., . . . Morris, C. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability, 1*(8), 441. doi:10.1038/s41893-018-0114-0
Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., . . . Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. *Carbon Management, 5*(2), 145-154. doi:10.1016/j.rser.2014.10.074
Qiao, Z., Fu, J., Zheng, J., Li, L., & Pan, G. (2014). Effects of different biochar fertilizer on growth, quality and agronomic N use efficiency of green pepper. *Chin. J Soil Sci*, 174-179.
Radlein, D., & Bouchard, T. (2009). A preliminary look at the economics of a new biomass conversion process by Dynamotive. *Dynamotive Report*.
Robb, S., & Dargusch, P. (2018). A financial analysis and life-cycle carbon emissions assessment of oil palm waste biochar exports from Indonesia for use in Australian broad-acre agriculture. *Carbon Management, 9*(2), 105-114. doi:10.1080/17583004.2018.1435958
Robb, S., & Joseph, S. (2019). *A Report on the Value of Biochar and Wood Vinegar: Practical Experience of Users in Australia and New Zealand*. Retrieved from Australian New Zealand Biochar Initiative: www.anzbi.org/wp-content/uploads/2019/06/ANZBI-2019- -A-Report-on-the-Value-of-Biochar-and-Wood-Vinegar-v-1.1.pdf
Roberts, K., Gloy, B., Joseph, S., Scott, N., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science and Technology, 44*, 827–833. doi:10.1021/es902266
Sanchez, P. (2002). Ecology. Soil fertility and hunger in Africa. *Science, 295*(5562), 2019-2020. doi:10.1126/science.1065256
Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., & Haszeldine, S. (2012). Sustainable gasification–biochar systems? A case-study of rice-husk gasification in Cambodia, Part II:

Field trial results, carbon abatement, economic assessment and conclusions. *Energy Policy, 41*, 618-623. doi:10.1016/j.enpol.2011.11.023
Shackley, S., Clare, A., Joseph, S., McCarl, B., & Schmidt, H. (2015). Economic Evaluation of Biochar Systems. In J. Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management: science and technology* (Vol. 2, pp. 821-822). London: Earthscan.
Shackley, S., Hammond, J., Gaunt, J., & Ibarrola, R. (2011). The feasibility and costs of biochar deployment in the UK. *Carbon Management, 2011*, 335-356. doi:10.4155/CMT.11.22
Smith, P. (2012). Soils and climate change. *Current opinion in environmental sustainability, 4*(5), 539-544. doi:10.1016/j.cosust.2012.06.005
Sohi, S., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. In L. Donald (Ed.), *Advances in Agronomy* (pp. 47-82). Burlington: Academic Press.
Sparrevik, M., Lindhjem, H., Andria, V., Fet, A., & Cornelissen, G. (2014). Environmental and socioeconomic impacts of utilizing waste for biochar in rural areas in Indonesia–a systems perspective. *Environmental science & technology, 48*(9), 4664-4671. doi:10.1021/es405190q
Steiner, C., Bellwood-Howard, I., Häring, V., Tonkudor, K., Addai, F., Atiah, K., . . . Buerkert, A. (2018). Participatory trials of on-farm biochar production and use in Tamale, Ghana. *Agronomy for Sustainable Development, 38*(1), 12. doi:10.1007/s13593-017-0486-y
UN. (2017). Sustainable Development Goals. Retrieved from https://www.un.org/sustainabledevelopment/
Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. *Gcb Bioenergy, 8*(3), 512-523. doi:10.1111/gcbb.12266
Waters, D., Van Zwieten, L., Singh, B., Downie, A., Cowie, A., & Lehmann, J. (2011). Biochar in soil for climate change mitigation and adaptation. In *Soil Health and Climate Change* (pp. 345-368): Springer.
WBG. (2018). *State and Trends of Carbon Pricing 2018* (1464812187). Retrieved from Washington DC:
Weng, Z., Van Zwieten, L., Singh, B., Tavakkoli, E., Joseph, S., Macdonald, L., . . . Morris, S. (2017). Biochar built soil carbon over a decade by stabilizing rhizodeposits. *Nature Climate Change, 7*(5), 371. doi:10.1038/NCLIMATE3276
Widiastuti, M. (2016). Analysis Benefit Cost Ratio of Biochar in Agriculture Land to Increase Income Household in Merauke Regency. *Jurnal Penelitian Sosial dan Ekonomi Kehutanan, 13*(2), 135-143.
Widowati, W., & Asnah, A. (2014). Biochar can enhance potassium fertilization efficiency and economic feasibility of maize cultivation. *Journal of Agricultural Science, 6*(2), 24-32.
Woolf, D., Amonette, J., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications, 1053*, 1-9.
Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., & Jarick, S. (2015). An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass and Bioenergy, 81*, 177-182. doi:10.1016/j.biombioe.2015.06.015
Yao, C., Joseph, S., Lianqing, L., Genxing, P., Yun, L., Munroe, P., . . . Thomas, T. (2015). Developing more effective enhanced biochar fertilisers for improvement of pepper yield and quality. *Pedosphere, 25*(5), 703-712. doi:10.1016/S1002-0160(15)30051-5
You, S., Tong, H., Armin-Hoiland, J., Tong, Y., & Wang, C. (2017). Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of Indonesia. *Applied Energy, 208*, 495-510. doi:10.1016/j.apenergy.2017.10.001

Zhang, T., Liang, F., Hu, W., Yang, X., Xiang, H., Wang, G., . . . Liu, Z. (2017). Economic analysis of a hypothetical bamboo-biochar plant in Zhejiang province, China. *Waste Management & Research, 35*(12), 1220-1225. doi:10.1177/0734242X17736945

Zheng, J., Han, J., Liu, Z., Xia, W., Zhang, X., Li, L., . . . Zheng, J. (2017). Biochar compound fertilizer increases nitrogen productivity and economic benefits but decreases carbon emission of maize production. *Agriculture, Ecosystems & Environment, 241*, 70-78. doi:10.1016/j.agee.2017.02.034

Table 1. Summary results of systematic review. Ranges (±) are one standard error. Bc – Biochar. AC – Abatement cost.

	Financially feasible scenarios	**Average financial feasibility** (US$ Mg^{-1} Bc)	**Average Abatement** (CO_2e Mg^{-1} Bc)	**Average AC** (US$ Mg^{-1} CO_2e)	**Average cost** (US$ Mg^{-1} Bc)
V	27 of 70	-148 ± 405	-2.68 ± 1.37	54± 209	433 ± 409
V_{bc}	19 of 70	-330 ± 485			

Table 2. Review characteristic averages in order of lowest cost abatement

Characteristic	Sub-Characteristic	AC US$ Mg^{-1} CO_2e	V US$ Mg^{-1} Bc	V_{bc} US$ Mg^{-1} Bc	Scenarios (70 in total)	Revenue US$ Mg^{-1} Bc	BEP US$ Mg^{-1}	Technology Scale Mg FS day^{-1}	FS cost US$ Mg^{-1} FS	Transport US$ Mg^{-1} Bc
Climate	Tropical	-71	146	145	17	315	170	4	2	4
Technology scale	Small-scale	-63	141	141	18	316	175	1	1	7
Crop value	Higher-value crop	-59	157	157	13	324	167	4	6	13
GNI	Lower	-58	143	143	20	309	167	3	2	11
Yield inclusion	Yield included	-17	49	-9	34	344	295	145	16	33
Climate	Subtropical	-16	69	-70	9	329	399	60.26	33	24
Technology focus	Biochar	-14	33	7	29	310	277	134	6	43
Crop value	Cereal agriculture	15	-45	-145	26	298	343	210	26	37
Technology scale	Medium large-scale	61	-200	-481	18	359	558	97	51	35
GNI	Higher	93	-264	-462	50	275	540	304	45	62
Technology focus	Coproduction	95	-276	-499	41	267	543	277	45	49
Technology scale	Large-scale	102	-282	-482	17	206	489	778	45	109
Technology scale	Medium small-scale	110	-265	-350	17	253	519	17	28	31
Climate	Temperate	119	-306	-502	44	40	542	333	43	69
Yield inclusion	Yield excluded	135	-334	-554	36	229	563	287	44	58
Crop value	No crop	148	-362	-597	31	258	620	314	45	69

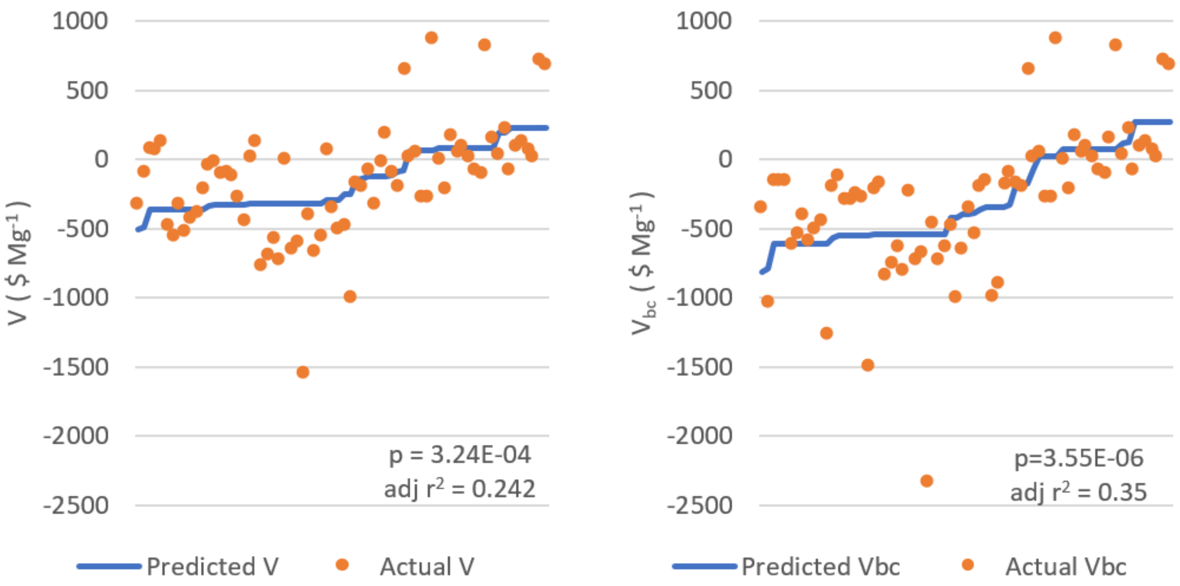
AC – Abatement Cost. GNI - Gross National Income per capita as defined by the World Bank(Fantom & Serajuddin, 2016) - This classification assigns economies into four income groups by Gross National Income per capita. As of July 2018, these thresholds are high (> US$12,055), upper-middle (US$3,896-12,055), lower-middle (US$996 – US$3895) and low (< US$995). In this paper, 'lower-income' refers to the two lower classes, whereas 'higher-income' refers to the two higher classes. FS – Feedstock. 'Higher value crop' are non-cereals. 'No Crop' indicates that no revenues from biochar crop yield improvements were considered in the scenarios. BEP – Breakeven Point

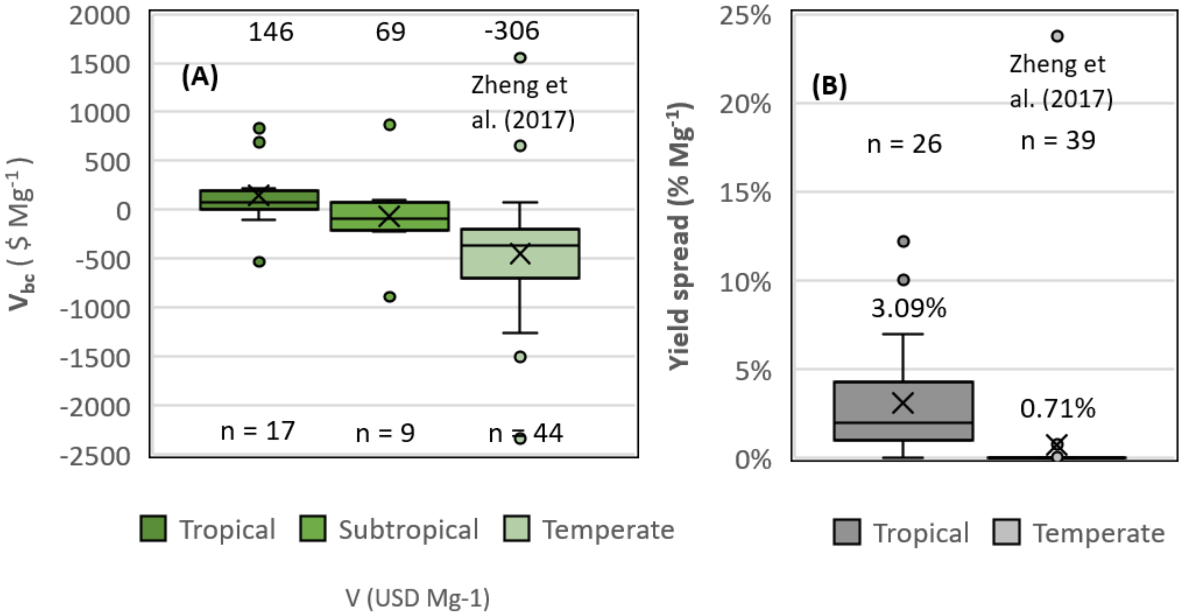
Table 3. Correlation between scenario variables. Climate (0 = Te – Temperate , 1 = S – Subtropical, Tr – Tropical), Yield ('Y' - yield inclusion, 'NY' - no yield inclusion. Y = 1, NY = 0), Crop Value ('No Crop' - no crop is considered in the valuation, 'Cereal' - a cereal crop is the target, 'Other' – a higher value crop is the target. 0 = No Crop / Cereal, 1 = Other) and Technology Scale (the daily maximum feedstock throughput capacity in metric tons). Income (Gross National Income per capita as defined in Fantom and Serajuddin (2016), as 'H' - High, 'MH' - Medium High, 'ML' - Medium Low, and 'L' – Low. 0 = H / MH, 1 = ML/ L)

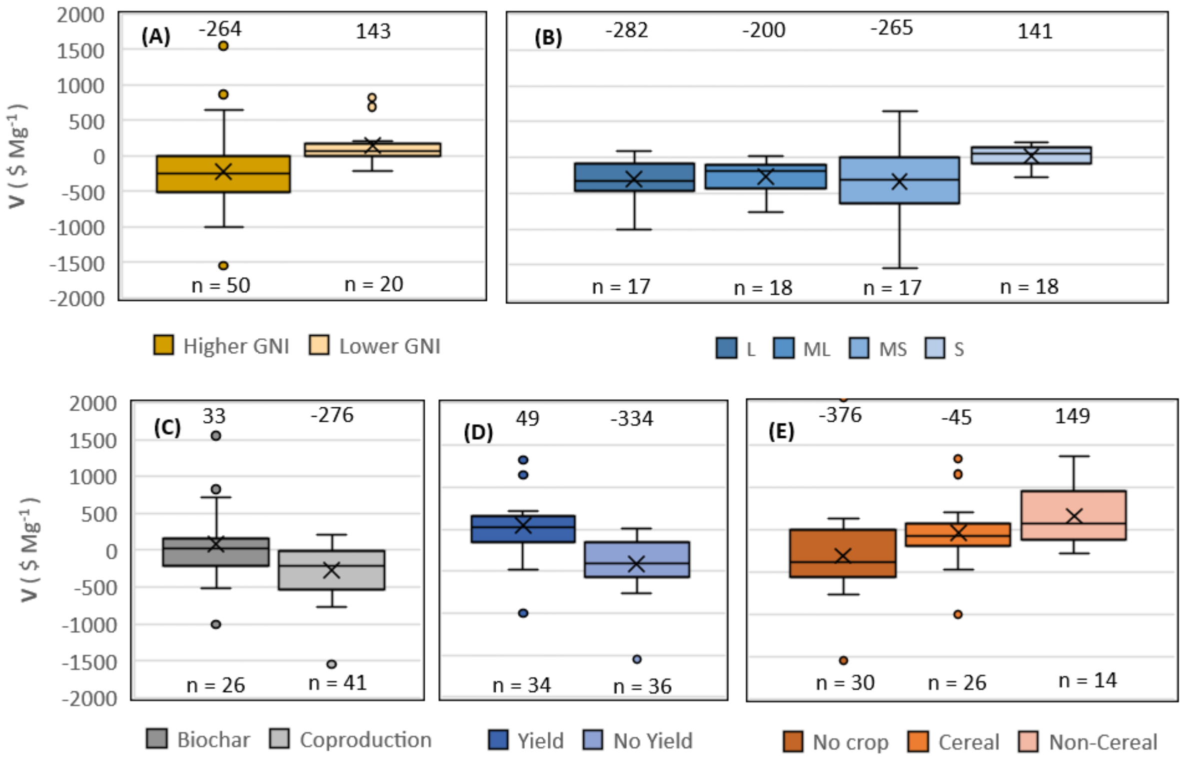
	Climate	**Income**	**Yield**	**Crop Value**	**Coproduction**	**Technology Scale**
Climate	1					
Income	0.823	1				
Yield	0.732	0.651	1			
Crop Value	0.355	0.395	0.443	1		
Coproduction	-0.554	-0.559	-0.633	-0.450	1	
Technology Scale	-0.341	-0.310	-0.161	-0.244	0.160	1
V_{bc}	0.539	0.533	0.531	0.427	-0.487	-0.280
V	0.512	0.458	0.477	0.369	-0.379	-0.242

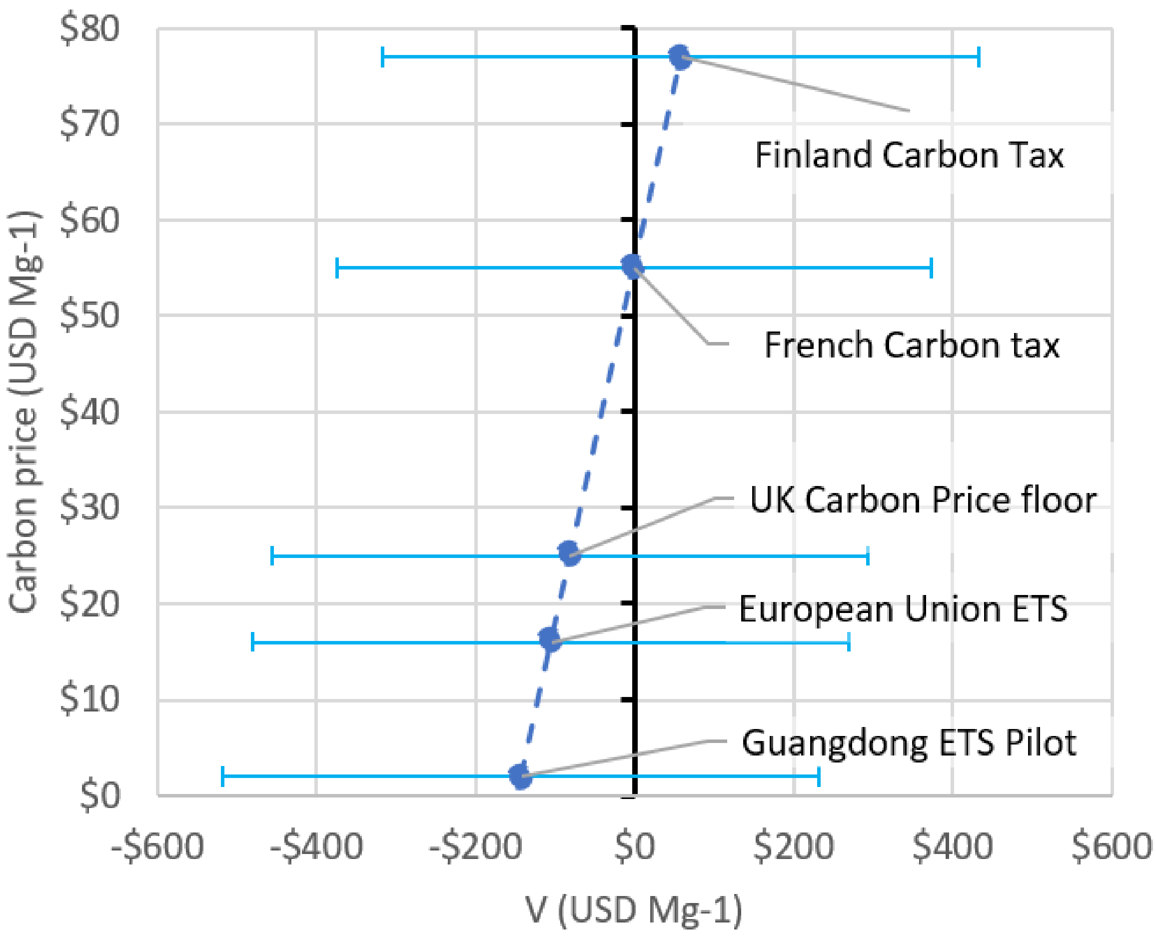
Table 4. Coefficients and P-values of OLS regression variables

Dependent variable	*Independent variables*	*Coefficients*	*P-value*
	Intercept	-287.31	2.40E-02
	Climate*GNI	162.61	2.21E-01
V	Yield	206.94	1.02E-01
	Cereal	143.46	2.49E-01
	Coproduction	-26.84	8.19E-01
	Tech. Scale	-0.09	3.57E-01
	Intercept	-387.88	1.04E-02
	Climate*GNI	247.02	1.17E-01
V_{bc}	Yield	216.89	1.46E-01
	Cereal	198.09	1.79E-01
	Coproduction	-148.59	2.86E-01
	Tech. Scale	-0.14	2.58E-01




(A)
146
69
-306
Zheng et al. (2017)
n = 17
n = 9
n = 44
Vbc ($ Mg-1)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
Tropical
Subtropical
Temperate
V (USD Mg-1)
(B)
Zheng et al. (2017)
n = 26
n = 39
3.09%
0.71%
Yield spread (% Mg-1)
25%
20%
15%
10%
5%
0%
Tropical
Temperate


(A)
-264
143
n = 50
n = 20
V ($ Mg-1)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
Higher GNI
Lower GNI
(B)
-282
-200
-265
141
n = 17
n = 18
n = 17
n = 18
L
ML
MS
S
(C)
33
-276
n = 26
n = 41
Biochar
Coproduction
(D)
49
-334
n = 34
n = 36
Yield
No Yield
(E)
-376
-45
149
n = 30
n = 26
n = 14
No crop
Cereal
Non-Cereal


Carbon price (USD Mg-1)
$80
$70
$60
$50
$40
$30
$20
$10
$0
-$600
-$400
-$200
$0
$200
$400
$600
V (USD Mg-1)
Finland Carbon Tax
French Carbon tax
UK Carbon Price floor
European Union ETS
Guangdong ETS Pilot