Global land-use and carbon emission implications from biochar application to cropland in the United States

Jerome Dumortier, Hamze Dokoochaki, Amani Elobeid, Dermot J. Hayes, David Laird, and

Fernando E. Miguez

February 19, 2020

Abstract

Biochar has the potential to increase crop yields when applied to agricultural land. We integrate agronomic and economic simulation models to determine the expected yield increase from biochar applications in the United States. We calculate the location-specific willingness to pay of U.S. farmers to apply biochar to their cropland if biochar increases yields over 20 years. In addition to the potential benefit of higher revenue for farmers, biochar applications also have policy implications if biochar production is combined with bio-fuel production or used to reduce greenhouse gas emissions from indirect land-use change. Thus, the results are then combined with an agricultural outlook model to determine the effects on global land-use change and net carbon emissions. Our results indicate that biochar application is most profitable for croplands in the Southeast U.S. due to the combination of high yield increases and availability of biomass to produce biochar. An increase in U.S. yields above trend by 1% for corn, soybeans, and wheat would decrease net total global emissions by 25-87 Tg of CO₂-equivalent.

1 Introduction

Avoiding irreversible climate change requires a major reduction in anthropogenic greenhouse gas (GHG) emissions (IPCC, 2013). Agriculture and forestry (including both direct and indirect land-

%Yield Increase from Biochar

Low and High Commodity Prices

Agricultural Trade Model Scenario:
1% higher yields of U.S. maize, soybean, and wheat

Land-Use Change and Carbon Emissions

Global Cropland Area: -0.06%
Global GHG Reduction: 25-87 Tg CO₂-eq

use effects) are responsible for approximately 25% of global anthropogenic GHG emissions (IPCC, 2014). Two possible mitigation options applicable to agriculture and forestry are (1) avoiding cropland expansion into pastures and forests and (2) increasing the amount of carbon sequestered in soils and standing vegetation. Applying biochar to agricultural soils is one means of addressing both options. Biochar additions can increase crop yields above the long-term trend and thus, reduce the amount of land necessary for a given production quantity while at the same time increase soil carbon sequestration (Galinato et al., 2011; Kauffman et al., 2014; Dang et al., 2015). Biochar has been identified as a supply-side mitigation option with a high technical mitigation potential, i.e., more than 10 Mg CO₂-equivalent (CO₂-e) ha⁻¹ year⁻¹ (IPCC, 2014).

Biochar is produced in combination with bio-oil and producer gas through the pyrolysis of cellulosic biomass from residues (e.g., agricultural or forestry) and dedicated bioenergy crops (e.g., switchgrass or miscanthus). Bio-oil can be stabilized (for example by adding ethanol) and sold as fuel oil or refined to produce fermentable sugars, bio-asphalt, liquid transportation fuels, and other products (Yoder et al., 2011; Kauffman et al., 2014). Biochar has several positive characteristics if used as a soil amendment such as improving soil water retention, enhancing the provision of nutrients, reducing soil bulk density, and potentially increasing crop yields (Galinato et al., 2011; Kauffman et al., 2014; Dang et al., 2015). It is also used as a filter for liquid biowaste to bio-chemically as well as physically sorb nutrients before being applied to agricultural land (Maroušek et al., 2018). Producer gas has little economic value but can be used as an energy source during the pyrolysis process or to produce H₂ gas needed for refining bio-oil (Yoder et al., 2011).

Treating agricultural soils with biochar is of interest for three reasons: First, higher yields can potentially reduce the agricultural land required for crop production and hence, can decrease carbon emissions from avoided land-use change. We show that a higher crop yields in the U.S. does indeed reduce global land requirements. Second, it can improve the profitability of farming and enhance rural welfare depending on the expected yield increase and the prices of crops and biochar. Third, the combined production of biochar and bio-oil, which can be upgraded into liquid transportation fuels, can lead to carbon-negative energy production (Li et al., 2017). Carbon-negative energy production is achieved by attributing carbon credits for soil biochar applications

and avoided land-use change due to increased yields on treated cropland. Research has estimated that the required yield increase for carbon-neutral grain ethanol production is 5.98% for application of fast pyrolysis corn stover biochar (Kauffman et al., 2014). Although carbon-negative biofuel production is associated with major technological, economic, and agronomic uncertainties.

Biochar prices depend on the location of the production sites which results in uncertainty (Belmonte et al., 2018). Calculating the willingness-to-pay (WTP) for biochar instead has the advantage that it offers a benchmark to which a prevailing biomass price can be compared to. Cheap biochar can be produced from fermentation residues at European farms that operate biogas stations for electricity production. Its quality is homogeneous during the whole year and pyrolysis is highly efficient since it is accelerated by waste heat from biogas combustion (Maroušek, 2014; Opatokun et al., 2016).

There are currently no national financial incentives to reduce carbon emissions or to increase carbon sequestration in the U.S. and thus, potential yield improvements are the only economic incentive for farmers to apply biochar at this time. We quantify the expected yield and return increase as well as the supply of biochar feedstock (i.e., corn stover, switchgrass, and forest logging residues) in the United States. We then combine the results with a global agricultural outlook model to calculate the effects of increased crop yields in the U.S. on global land-use and emissions as well as the potential carbon credit payment to farmers. Carbon credits would lower the cost to farmers for biochar application. In general, biochar application results in plethora of other financial effects that are beyond the scope of this paper. For example, it reduces soil resistance to tillage which results in significant savings on diesel consumption (Maroušek et al., 2017). Biochar also serves as substitute for lower quality charcoals which could be sold for energy purposes (Lu and Hanandeh, 2019). Thus, there is a trade off for farmers to apply biochar to soils and improve soil quality in the long-run as opposed to selling it as a substitute for charcoal and obtain immediate benefits (Mardoyan and Braun, 2014; Vochozka et al., 2016).

The contribution of our analysis to the biochar literature is two-fold: First, we calculate the WTP per ton of biochar using location-specific expected yield increase data under low and high commodity prices. Previous literature assessed biochar-induced yield increases, potential for car-

bon sequestration, and increase in financial returns at the regional level whereas our study covers the contiguous United States. We identify the locations by calculating the WTP, which are likely to apply biochar given its price. Second, we demonstrate that a biochar-induced crop yield increase in the U.S. of 1% leads to a reduction in global cropland. This demonstrates an important indirect effect of biochar as a GHG mitigation technology. For example, Brewer et al. (2016) review studies based on the carbon sequestration potential and the reduction in GHG emissions after biochar application that are directly attributable to the plot of land receiving biochar. We extend this type of analysis to the indirect effects involving trade. To determine this indirect effect, the use of a global agricultural outlook model is required because the effect of commodity yield increases on crop area is determined by the magnitude of two opposing effects. First, the higher yield increases crop area because farmers benefit from the additional yield (and thus, higher financial returns) and expand crop area. Second, the negative relationship between price and quantity demanded limits the ability of this land expansion. Increasing yield and area leads to more supply which in turn decreases commodity prices. Thus, farmers have an incentive to decrease crop area. A global agricultural outlook model which solves for market-clearing conditions (e.g., where supply equals demand) taking into account both effects. Here we show that increasing yield in the United States also leads to more production and thus, lower commodity prices globally. This results in a reduction of global land used for crop production and lower GHG emissions (Kauffman et al., 2014). Although there is currently no national carbon price and/or credit system, global agricultural land-use and GHG emissions are reduced due to a yield increase triggered by biochar application in the United States.

In this article, we hypothesize that biochar can be produced in sufficient quantities from agricultural residues and switchgrass to have a significant impact on crop yields in the United States. In addition, the subsequent biochar application to U.S. agricultural soil reduces indirect emissions from global land-use change. Direct effects of biochar applications on soil carbon sequestration are not considered here, but have been previously considered (Roberts et al., 2009; Peters et al., 2015; Patel et al., 2016).

2 Materials and Methods

In order to calculate the impact of biochar-induced yield increases on global land-use change and GHG emissions, we proceed as follows. First, we determine suitable areas for biochar application in the U.S. by calculating farmers' crop and location-specific WTP in \$ Mg⁻¹. Second, we address the issue of biomass supply in order to produce biochar at the county-level in the United States. And third, we use a global agricultural outlook model to determine if the yield increase in the U.S. results in a decrease of global agricultural area and GHG emissions.

2.1 Expected Yield Increase

Complex interactions between crops, soil characteristics, and climate have resulted in significant variations in the estimates of yield responses to biochar applications (Biederman and Harpole, 2013). Crane-Droesch et al. (2013) have conducted a meta-analysis using a database of 40 published studies to determine the effect of biochar applications on crop productivity. Our analysis is based on the work by Dokoohaki et al. (2019) who added an additional 63 studies that were published after 2013 to the existing database by Crane-Droesch et al. (2013). From all studies, soil characteristics (i.e., soil organic carbon, sand, silt, clay content, cation-exchange capacity, and soil pH value) and biochar characteristics (e.g., carbon content, nitrogen level, ash content, pH value, and pyrolysis temperature) were extracted. Soil nutrient levels such as nitrogen were not used because total nutrient content is a weak indicator for nutrient availability (Crane-Droesch et al., 2013). In a next step, a Bayesian network model was used to determine the effects of biochar

Table 1: Chemical properties of biochar used for this analysis. For all the types of biochar, the pyrolysis temperature was 500°C.

Feedstock	pH	C (%)	N (%)	Ash (%)	C:N
Corn Stover (fast pyrolysis)	8.4	52.4	0.46	37.0	134.4
Corn Stover (slow pyrolysis)	9.9	69.8	1.25	9.1	65.4
Switchgrass (slow pyrolysis)	9.9	71.0	0.88	15.2	94.1
Forestry residues (slow pyrolysis)	7.0	77.6	0.53	7.0	169.2

application on the yield response ratio h , i.e., $h = \ln(y_b/y_c)$ where y_b and y_c are the yield with and without biochar application, respectively (Figure 1). The response ratio can then be transformed into a percentage change increase by calculating $m_k = (\exp(h_k) - 1) \cdot 100$ with m_k and h_k being the response ratio and percent yield increase for pixel k , respectively. Significant soil-related predictors of the response ratio are clay content, pH-value, cation-exchange capacity, and organic carbon content. Biochar characteristics that have a negative effect on the response ratio are carbon, nitrogen, and the highest pyrolysis temperature. The yield response is statistically invariant to the nitrogen application rate, biochar ash content, and biochar pH value. There is also no significant relationship between the biochar feedstock and the crop type. For additional details, we refer the reader to the original paper by Dokoochaki et al. (2019).

We use one fast pyrolysis and three slow pyrolysis biochar feedstocks from the Bayesian network model: (1) corn stover (fast pyrolysis), (2) corn stover (slow pyrolysis), (3) switchgrass (slow pyrolysis), and (4) forest residues (slow pyrolysis) (Table 1). The biochar yield from biomass conversion is assumed to be 0.32, 0.28, 0.31, and 0.28 for corn stover (fast and slow pyrolysis), switchgrass, and forestry residues biochar, respectively based on a pyrolysis temperature of 500°C (Yoder et al., 2011). The Bayesian network model predicts location-specific yield responses across the U.S. for the six crops (i.e., groundnut, corn, rice, sorghum, soybeans, and wheat) by combining data from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) and location-specific soil properties from the Gridded Soil Survey Geographic (gSSURGO) database (USDA, 2016).

2.2 Net Present Value Analysis

To calculate the value of biochar for a farmer, we calculate the expected financial return from applying biochar to the soil and compare it with the financial return without biochar. The expected financial return with and without biochar application over 20 years is discounted to present time to obtain the net present value (NPV). Note that we assume biochar application only once in the first year but the benefits in terms of yield increase remain in effect over 20 years. The WTP per ton of biochar can be calculated from the difference between the NPV with and without biochar

Figure 1: Graphical representation of the Bayesian Network model with the variables influencing the response ratio. Gray circles indicate biochar properties, blue circles indicate soil properties and orange circles management options.

application. Crops included in the NPV analysis are corn, peanuts, rice, sorghum, soybeans, and wheat. The Bayesian network model calculates the yield increase for a given location based on the soil characteristics which are assumed to be identical for all six crops.

In a first step, we obtain county-level yield data from the USDA NASS for the six crops for the period 1996 to 2017. For each crop and county, we fit a linear trend model that includes only time

Table 2: Lowest and highest commodity prices (2017 \$ t⁻¹) observed between 1996 and 2017.
Source: USDA NASS Quickstats

Commodity	Corn	Peanuts	Rice	Sorghum	Soybeans	Wheat
low	96.85	427.80	109.16	79.30	225.29	134.42
high	280.34	800.26	363.04	233.27	549.20	335.50

as the independent variable. Assuming linear growth in yields, i.e., a constant increase in Mg ha⁻¹ year⁻¹ and a decreasing growth rate over time, is consistent with current observations (Grassini et al., 2013). Based on the linear model, we project the yield over the next 20 years. Because we do not observe yields at the sub-county level for the entire U.S., we assume the same base yield by crop throughout the county.

In a second step, we calculate the minimum and maximum prices for each of the six commodities that were observed between 1996 and 2017 (Table 2). These lowest and highest crop prices provide lower and upper bounds for our NPV estimates. We assume a discount rate of $r = 5\%$ and constant commodity prices over the projection period. Thus, the NPV without biochar application for commodity i in county j can be calculated as follows

$$NPV_{ij}^{no-biochar} = \sum_{t=1}^{20} \frac{p_i \cdot y_{ijt}}{(1+r)^t}$$

where p_i represents the constant commodity price and y_{ijt} is the expected yield in time t . As in Kauffman et al. (2014), we assume that the biochar application shifts the yield by a constant percentage over the projection period. Given the expected yield increase m_k where k represents a particular pixel from the GIS data set and assuming a biochar application rate of 5 Mg ha⁻¹ in the first year, we can calculate the WTP for grid cell k as follows: $WTP_k = (m_k \cdot NPV_{ij}^{no-biochar})/5$.

2.3 Biochar Feedstock Availability

In order to produce biochar, corn stover, switchgrass, and forest residues need to be supplied to the pyrolysis facility. The amount of biochar that is available for cropland depends on the harvest

169 decision of farmers with respect to corn stover and switchgrass. We use an economic simulation
170 model for U.S. agriculture that calculates the crop allocation at the county level for corn, soybeans,
171 wheat, and switchgrass as well as the harvest decision for corn stover by farmers. The model
172 has been used previously to determine the location specific availability of agricultural residue and
173 bioenergy crop (i.e., switchgrass and miscanthus) biomass (Dumortier, 2016; Dumortier et al.,
174 2017). A detailed description of the model is covered in the referenced literature and hence, we
175 limit ourselves to the basic outline of the model. The model does not include peanuts, sorghum,
176 and rice which represent less than 5% of crop area of the six crops covered in our model in 2017.

177 Commodity prices are endogenous to the model and are determined by aggregate supply and
178 demand. To incentivize the production of biomass, a price per metric dry ton is imposed. Given
179 the price for biomass, farmers decide how much area is allocated to corn, soybeans, wheat, and
180 switchgrass. Corn stover is treated as a fifth crop in our analysis. That is, corn harvested from
181 “regular” and from corn stover acreage satisfies the demand for corn from food, feed, and exports.
182 Without any biomass price, area is only allocated to corn, soybeans, and wheat. The model is
183 also able to calculate the effects on commodity prices from a change in land allocation in the U.S.
184 as well as from higher yields. To assess our estimates at the county level, we also compare our
185 estimates of biomass supply with estimates from the 2016 Billion-Ton study (U.S. DOE, 2016).
186 The forest supply is treated separately from cropland (Dumortier, 2013). We assess the supply of
187 logging residues not whole tree biomass. The residues considered are upland and lowland forest
188 logging residues.

189 **2.4 Global Carbon Implications**

190 Although the paper analyzes the effects of biochar application on the financial returns to farmers,
191 the important aspect of yield increases is the potential to reduce land conversion and thus, GHG
192 emissions. To determine which effect dominates, we use an agricultural commodity model, i.e.,
193 the CARD/FAPRI Model, to determine international land-use effects. The CARD/FAPRI Model
194 projects global agricultural production over a period of 10-15 years by modeling major crops and
195 livestock categories. The partial equilibrium model clears the international and domestic markets

for agricultural commodities by clearing the market, i.e., supply equaling demand for all commodities. We quantify the effects of the yield increase on global crop production and land-use allocation using a baseline and a yield increase scenario. In particular, we assess the carbon balance changes on a global scale from increasing U.S. yields of corn, soybeans, and wheat by 1% above the trend yield. This yield increase is assumed to have been triggered by applying biochar to the U.S. crop area of the three aforementioned crops. The scenario run results in important insights with respect to model calibration and expected land-use change. The CARD/FAPRI Model has been used in previous policy analysis about biofuel policy (Searchinger et al., 2008; Dumortier et al., 2011; Elobeid et al., 2012; Carriquiry et al., 2019), trade policy (Elobeid and Tokgoz, 2008), and GHG policy (Dumortier et al., 2012).

The CARD/FAPRI Model covers barley, maize, cotton, oats, palm kernel, groundnut, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugarcane, sunflower, and wheat in 58 countries and regions. Large agricultural producers such as Argentina, Brazil, China, Russia, and the U.S. are modeled at the country scale whereas smaller countries are grouped together by region, e.g., Other Asia or Other Africa. Due to its importance in terms of agricultural production and biomass/soil carbon content, Brazil is subdivided into six regions to better capture land-use dynamics. These better capture differences in agricultural productivity, production cost, and biomass/soil carbon content (Carriquiry et al., 2019). What sets the Brazil model apart from the rest of the countries and regions in the CARD/FAPRI model is that it explicitly calculates pasture as a function of crop and livestock returns. Pasture in the countries and regions other than Brazil is modeled ad-hoc as a function of the livestock herd size with a fixed stocking rate. The effect of biochar-induced yield increase is dampened by the fact that crop prices decline and thus, input cost of livestock products. This leads to an expansion of herd size and pasture into potentially native vegetation.

Figure 2: Median yield increase and expected willingness-to-pay (WTP \$ Mg⁻¹) under low and high commodity prices for four biochar feedstocks.

Figure 3: Median WTP \$ Mg⁻¹ for slow pyrolysis corn stover biochar. The spatial distribution and values for the other feedstocks (i.e., fast pyrolysis biochar from corn stover and slow pyrolysis biochar from switchgrass and wood) are similar.

3 Results and Discussion

3.1 Expected Yield Increase

The basis for our analysis of biochar-induced yield improvements in the U.S. is an agronomic model providing soil- and location-specific estimates of expected yield increase from applying biochar from corn stover (fast and slow pyrolysis), switchgrass (slow pyrolysis), and forestry residues (slow pyrolysis) to soils in the contiguous U.S. (Dokoohaki et al., 2019). Spatial variations in median expected yield increases across the U.S. range from 2.5% (biochar from switchgrass) in North Dakota to 12.7% in New Jersey (Figure 2). The median predicted yield increase is generally lowest for biochar derived from switchgrass and highest for forestry residue biochar. Overall the largest biochar-induced yield increases were in the U.S. Southeast and the Northeast which are also regions that have limited cropland and low quality soils. Large corn, soybeans, and wheat producing states such as Iowa, Kansas, Illinois, and Indiana have simulated yield increases ranging from 3.8% to 6.0%.

3.2 Willingness-To-Pay for Biochar

The expected yield increase obtained from the agronomic model is translated into farmers' WTP for biochar (in \$ Mg⁻¹). The WTP is the per metric ton of biochar difference between the NPV from crop production with and without biochar application. We calculate the expected additional revenue due to biochar-induced higher yields over 20 years under low and high commodity prices for six crops, i.e., corn, peanuts, rice, sorghum, soybeans, and wheat (Figure 2). States that rank high in terms of expected yield increase may have lower crop yields resulting in a lower WTP for biochar because the additional yield — although high in terms of percent increase — does not translate into much additional revenue. For example, North Carolina and South Carolina have large percentage yield increases but are outperformed by Alabama, Georgia, and Florida in terms of WTP.

In general, the highest WTP is observed in states along the Eastern seaboard (Figure 3). Also, eastern Mississippi and northeastern Louisiana have large areas in which farmers have a high WTP for biochar. Although farmers in Alabama, Georgia, and Florida would have a high WTP for biochar according to Figure 2, the total area on which biochar would be applied is very small because those states only have small areas of the six crops that are covered in this analysis.

To better determine the percentage of crop area covered at various WTP values, we performed a kernel density estimation as well as calculating a cumulative distribution function (Figure 4). The kernel density estimation of the WTP for all six crops shows that for biochar prices of \$238-\$265 Mg⁻¹, 5% of crop area would be covered under low commodity prices. Under high commodity prices, biochar prices of \$665-\$747 Mg⁻¹ would result in the same coverage. The lower bound of the price range for a given commodity price level is biochar obtained from switchgrass and the upper bound is for biochar produced from forest residues. To obtain a cropland coverage of 25%, biochar prices need to decrease to \$146-\$169 Mg⁻¹ and \$395-\$453 Mg⁻¹ under the low and high commodity price scenarios, respectively. Those numbers illustrate the importance of commodity prices which introduces 2.7-fold differences between the upper and lower bound for WTP for a given crop yield and biochar feedstock. Note that our WTP measure is based only on the expected yield increase over a 20 year period and does not take into account any change in management

Figure 4: Kernel density estimation of willingness-to-pay (2017 \$ Mg⁻¹) for low and high commodity prices.

practice. Under the assumption that the costs associated with applying biochar to the field and any change in management practice are relatively comparable across the study area (e.g., national, state, and county), our results still indicate areas that are more likely to apply biochar. In that case, the WTP has to be corrected to take the additional cost of implementation into account which will likely decrease the WTP (assuming that other inputs are not reduced).

Figure 5: Percent of crop area for corn, peanuts, rice, sorghum, soybeans, and wheat treatable under low and high biomass production cost and various biomass prices. If switchgrass is included in the calculations besides either fast or slow pyrolysis corn stover, the percentage of area treatable includes switchgrass and corn stover as biomass resources. Otherwise, only corn stover is included.

3.3 Biomass Supply

We quantify the maximum annual area coverable with biochar knowing that not all cropland receives biochar due to low profitability. The 2017 total area of the six crops evaluated in this study was 88.63 million hectares and we assume an application rate of 5 Mg ha⁻¹. Corn stover, switchgrass, and forestry residue are used as biochar feedstock. Currently, only biochar from forestry residue is produced on a commercial scale and thus, a biomass price needs to be present to incentivize farmers to supply biomass for biochar production. We use an economic simulation model (Dumortier, 2016; Dumortier et al., 2017) to assess the regional supply of corn stover and switchgrass and the 2016 Billion-Ton Study (BTS) to quantify the supply of forestry residue (U.S. DOE, 2016). The 2016 BTS and the older 2011 BTS (U.S. DOE, 2011) evaluate the availability of

biomass for bioenergy production from agricultural residues, forests, energy crops, and waste re-sources. Because of high transportation cost, biochar production and its application to cropland will in its initial technological diffusion stage most likely be a highly localized market which makes the location of feedstock supply and biochar demand an important aspect.

There is significant uncertainty around biomass production from corn stover and switchgrass in the United States. To capture the wide range of parameter values, we differentiate our scenarios along four dimensions: (1) biomass production cost (high/low), (2) biomass price, (3) adoption of switchgrass, and (4) tillage (Figure 5). The 2011 BTS provides sustainable corn stover removal rates under reduced- and no-tillage but we also use revised removal rates from the 2016 BTS.

Under high biomass production cost and a biomass price of \$55 Mg⁻¹, little biomass is available and the maximum coverage is 0.4% of cropland using the revised removal coefficients from the 2016 BTS. At the price of 55 \$ Mg⁻¹ and low biomass production cost, an annual coverage of 12% can be achieved assuming that farmers remove corn stover at a rate consistent with the 2011 BTS no-tillage removal coefficients. The biomass price increasing to \$110 Mg⁻¹ results in a large variation of the coverage ranging from 1.7 (1.91%) to 28.0 (31.7%) million hectares. The production of biomass is very sensitive with respect to the biomass production cost and the assumed removal coefficients. Figure 5 indicates that there are significant variations in the amount of biochar available to treat crop area at an application rate of 5 Mg ha⁻¹. The most favorable outcome in terms of total annual area coverable by biochar is under the regime of supplying biomass from both, corn stover and switchgrass, under low biomass production cost and a high biomass price.

As opposed to corn stover and switchgrass, the supply of forestry residue is not very sensitive to the price of biomass (U.S. DOE, 2016). We focus on lowland and upland forestry residue in the year 2025 at the state level. The supply of forestry residue is very inelastic with regard to biomass price and scenario (e.g., housing and energy demand) (U.S. DOE, 2016). Forestry residue are mostly available in the Southeast and Northeast as well as Minnesota, Wisconsin, and Michigan. Forestry residue are also available in the Pacific Northwest, although transportation cost to the closest cropland will probably eliminate any benefit from applying forestry residue biochar to agricultural soils in the Pacific Northwest. The area that can be covered with biochar produced

from forestry residue ranges from 0.41-0.42 million hectares per year depending on the biomass price ranging from \$33-\$110 per dry ton. Given the total area of the six crops, forestry residue area able to cover only 0.48% of crop area per year. This suggests that forestry residues alone would only be able to cover a small area likely concentrated in the U.S. Southeast.

3.4 Greenhouse Gas Emissions

In the previous sections, we focused on additional revenue for U.S. farmers resulting from applying biochar to soils. To evaluate the effect of higher commodity yields in the U.S. on global GHG emissions, we use the CARD/FAPRI agricultural outlook model to quantify the land-use effects of 1% higher yields for corn, soybeans, and wheat in the United States. As aforementioned, the CARD/FAPRI Model has been used in previous analysis on land-use change and GHG calculations (Dumortier et al., 2012; Carriquiry et al., 2019). The GHG component of the CARD/FAPRI Model also includes changes in pasture due to changes in the livestock sector.

With the higher yields, the global land use is estimated to be only 0.06% lower compared to the baseline. The difference in area is approximately 0.47 million hectares. There are significant declines in crop area in Brazil (0.30%), Russia (0.16%), and Mexico (0.12%) whereas the reduction in the U.S. is only 0.06%. The reduction in Brazil is important due to the large areas that are situated in carbon rich environments. In Russia, there is a significant decrease in area for oats (-0.11%) and wheat (-0.26%). Wheat accounts for over 58% of agricultural area modeled for Russia in the CARD/FAPRI Model.

The GHG emissions in the CARD/FAPRI Model are calculated for minimum, mean, and maximum carbon coefficients. The reductions in emissions range from 25.09 to 68.56 Tg of CO₂-e. The emission savings are slightly higher, i.e., 30.16 to 86.88 Tg of CO₂-e, if only cropland is considered. The higher yields results in a decrease in commodity prices and an expansion of the livestock sector which subsequently increases the amount of pasture used and hence, carbon emissions. To quantify how those emission savings translate into carbon payment for farmers in the U.S., we proceed as follows: Assuming that farmer's with the highest WTP are the first to apply biochar, we calculate the minimum crop area necessary to achieve a yield increase by 1% at the national level.

Depending on the biochar feedstock and commodity prices, this area ranges from 9.27 to 10.53 million hectares. If we assume that the carbon payments — from the reduction in emissions — would be distributed equally to farmers irrespective of their individual yield increase, then for every one dollar increase in carbon price (measured in CO₂-e), farmers would receive between \$2.40 and \$9.40 ha⁻¹. For example, assuming a low carbon price of \$10 Mg⁻¹ CO₂-e farmers would receive between \$24 and \$94 ha⁻¹. Hence, carbon credit scheme could significantly increase the WTP for biochar.

Our analysis is limited to biochar production in the U.S. but can be extended to other countries and regions as well. For example, Ji et al. (2018) find that biochar is the utilization of agricultural residues which yields higher profits and higher GHG reductions compared to briquette fuel and combined heat and power (CHP) systems. Calculating the potential yield increase in global agricultural soils based on the method presented in Dokoochaki et al. (2019) is beyond the scope of this paper but research suggests high yield increases in tropical soils. For example, Agegnehu et al. (2016) finds that organic amendments using biochar, compost, or a mixture of both can increase yields by 10%-29% in tropical Ferrasols. Similar findings of yield responsiveness to biochar in tropical soils is reported by Lychuk et al. (2015) and Jeffery et al. (2017). Based on soil pH, biochar feedstock type, and location, Jeffery et al. (2017) reports no yield response in temperate latitudes (i.e., above the 35th degree parallel) but 25% average yield increases in the tropics. This is generally consistent with our findings which shows the highest yield increase in Southeast U.S. states which are below the 35th degree parallel.

Relevant to the research presented in this paper is the work of Woolf et al. (2010). They find that biochar has the potential to avoid up to 1.8 Pg of CO₂-e annually. Those avoided emissions include avoided soil emissions from biomass decay, biochar as a soil amendment and subsequent carbon sequestration, as well as bioenergy production and avoided fossil fuel emissions. Their model does not include avoided emissions from land-use as presented in this paper. Although our current results represent 4.8% of the emissions reduction found by Woolf et al. (2010), this is only based on the indirect effects of avoided land-use change from a 1% increase in maize, soybeans, and wheat yield in the United States. As mentioned before, yield increases in the U.S. as well as other

countries (especially in the tropics) can be substantial and could potentially add significantly higher avoided GHG emissions. To curb GHG emissions globally over the next decades, a multitude of technologies is necessary and biochar is one of them. Previous research has shown that small changes in yields play a significant role in avoiding biomass and soil carbon emissions on a global scale Hertel et al. (2010); Dumortier et al. (2011). Adoption of biochar as a mitigation option needs to incorporate those avoided land-use emissions which are presented in this analysis to accurately assess emissions reductions.

Lehmann et al. (2006) estimates the global potential of converting biomass carbon to biomass biochar. The slow pyrolysis process is more efficient at retaining carbon (estimated to be 50% of the initial carbon input) than slashing-and-burning it (3%) or leaving it for decomposition (maximum of 20%). Replacing slash-and-burn and using agricultural and forest residues could sequester carbon at a rate of 1.36 Pg CO₂-e yr⁻¹. This number does not include the effects of higher yields on a global scale as analyzed in this paper. Oliveira et al. (2017) provides a review about the environmental benefits of biochar on a global scale and cites a potential for storing carbon in biochar could result of emissions prevention of 0.1-0.3 Pg CO₂-e yr⁻¹. Given current availability of agricultural residues, Windeatt et al. (2014) estimates that 0.55 Pg CO₂-e yr⁻¹ can be sequestered in global soils long term. Those numbers do not include the 0.87 Pg CO₂-e yr⁻¹ we find from a 1% yield increase for maize, soybeans, and wheat in the United States.

Our results can inform and supplement analysis that assess the sustainability of biochar systems. This is particularly important if biochar application occurs within the context of bioenergy production (Rosen, 2018). Life-cycle analysis (LCA) of biochar is beyond the scope of this paper but previous research is plentiful (Roberts et al., 2009; Peters et al., 2015; Patel et al., 2016). Using biochar as either a substitute for coal in a power plant or as a soil amendment has been analyzed by Lu and Hanandeh (2019). They assess the life cycle emissions from bio-oil and biochar production. Their scenario produces (1) bio-oil from woody biomass to substitute heavy fuel oil in an industrial boiler and (2) biochar to be spread on corn fields. Their results in the highest reduction in GHG emissions but with moderate effects on other environmental parameters. Pröll and Zerobin (2019) investigate biomass combined heat and power (CHP) with various carbon capture

approaches. They find that CHP with carbon capture and storage outperforms CHP with biochar as carbon negative emission technology. They attribute this result to the unreleased energy in the biochar case. However, their analysis does not include the use of biochar in soils for the various benefits mentioned above. Munoz et al. (2017) find that the climate change mitigation aspect of biochar is the most important among other aspects such as human toxicity, freshwater eutrophication, and fossil fuel depletion. Results indicate a reduction in GHG emissions of 2.74 Mg CO₂-e Mg⁻¹ of biochar from forest residues applied to soils.

Maroušek et al. (2017) highlights potential economic and policy barriers as well. As of April 2015, the biochar price was approximately \$250 Mg⁻¹ which meets farmers' WTP of approximately 10%-50% of U.S. cropland according to our analysis. Besides the economic aspects, the authors also mention the policy framework which does not allow biochar to be applied in certain regions of the world (e.g., European Union) due to uncertainty about the long-run effects of biochar in the soil and the irreversibility of its application.

4 Conclusion and Future Prospects

There are a variety of climate change mitigation technologies and biochar can potentially contribute to dampen the effect of land-use change and increase carbon sequestration in the soil while enhancing the financial returns from crop production for farmers. In addition, biochar increases soil nutrient and water holding capacity. Predicting the adoption of biochar by farmers is challenging because its profitability depends on the soil characteristics, crop and biochar prices, and availability of biochar itself. For our biochar analysis, we focus on the expected yield increase of corn, peanuts, rice, sorghum, soybeans, and wheat. The three feedstocks considered for biochar production are corn stover, switchgrass, and wood biomass. We quantify the additional financial returns from biochar application due to higher yields which represents a tangible benefit for farmers. Currently, biochar is not applied to U.S. soils at a large scale and we hypothesize that its initial application will be from sources close to the fields where it is applied. Biochar application in the Corn Belt is less likely than in the U.S. Southeast and Northeast of the United States. Although corn stover is abundant in the Midwest, the expected yield increase and the resulting financial re-

turn are not as high as in the U.S. Southeast. The regions of the U.S. in which farmers have a high WTP for biochar coincides with area that have an abundance of woody biomass, i.e., the Southeast and Northeast. Thus, those areas are characterized by a “spatial match” where farmers have a high WTP in addition to sufficient resources. We show that carbon payments for avoided land-use change can significantly reduce the cost of biochar application. Future research should also focus on the transportation logistics of biochar from the biomass source to the field where it is applied. This article offers insights into the economic aspects of biochar application and more research is necessary to evaluate all aspects of its application. Our analysis shows that U.S. biochar production and application can lead to a reduction of emissions from indirect land-use change. We hypothesis that those results are not unique to U.S. biochar but would lead to similar results globally of land sparing.

Given the methods and results of our analysis, there is need for additional research. First, the modelling of yield response to biochar application using the Bayesian network model – on which our analysis is based – needs to be expanded from the U.S. to other major agricultural producers. Especially countries which have large areas of cropland in the tropics such as Brazil and southern parts of China. Previous research presents evidence that biochar applied to cropland in the tropics results in significant yield increases. Thus, an expansion of the Bayesian Network model could lead to a better understanding of the locations that provide the highest benefit in terms of expected yield increase and financial returns. This can help to increase the effectiveness and efficiency of biochar application and policy aimed at its promotion. The extension of the model is independent of the indirect land-use change effects because it promotes soil health, higher yields, and financial benefits to farmers. Second, the supply of biochar feedstock such as crop residues and/or energy crops needs to be evaluated in countries other than the United States. There has been plentiful research on biofuel feedstock supply but the location of a bioenergy production facility can be chosen whereas the optimal location of biochar application is fixed assuming that it is largely soil and climate dependent. Transportation costs may play a role in developing a large-scale biochar industry. The advantage of biochar application to cropland is its longevity, i.e., that remains in the soil for decades. And third, biochar production in conjunction with bioenergy

production and its associated lifecycle emissions need to be evaluated. Biochar application has direct benefits in terms of soil health and higher yields but as demonstrated in this analysis, can have important indirect effects in terms of avoided land-use and avoided GHG emissions. We hypothesize that those effects could potentially be very large because even small increases in yields reduce the need for more cropland. Third, future research needs to look at the context in which biochar is produced. As mentioned before, there are various energy-producing pathways which result in biochar production and an evaluation in terms of sustainability (including production, transportation, and use) is required to ensure long-term environmental and economic viability as a climate change mitigation tool.

5 Acknowledgement

This project was supported by the Global Climate and Energy Project, by Stanford sub-award agreement No. 60413992-112883-A.

References

- Agegnehu, G., Bass, A. M., Nelson, P. N., Bird, M. I., 2016. Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment* 543, 295–306.
- Belmonte, B. A., Benjamin, M. F. D., Tan, R. R., 2018. Bi-objective optimization of biochar-based carbon management networks. *Journal of Cleaner Production* 188, 911–920.
- Biederman, L. A., Harpole, W. S., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *Global Change Biology Bioenergy* 5 (2), 202–214.
- Brewer, C. E., Schmidt-Rohr, K., Satrio, J. A., Brown, R. C., 2016. Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. *Journal of Environmental Management* 181, 484–497.

- Carriquiry, M., Elobeid, A., Dumortier, J., Goodrich, R., 2019. Incorporating sub-national brazilian agricultural production and land-use into u.s. biofuel policy evaluation. *Applied Economic Perspectives and Policy* forthcoming (0), 0.
- Crane-Droesch, A., Abiven, S., Jeffery, S., Torn, M. S., 2013. Heterogeneous global crop yield response to biochar: a meta-regression analysis. *Environmental Research Letters* 8 (4), 044049.
- Dang, Q., Wright, M. M., Brown, R. C., 2015. Ultra-Low Carbon Emissions from Coal-Fired Power Plants through Bio-Oil Co-Firing and Biochar Sequestration. *Environmental Science and Technology* 49, 14688–14695.
- Dokoohaki, H., Miguez, F. E., Laird, D., Dumortier, J., 2019. Where should we apply biochar? *Environmental Research Letters* 14 (044005), 1–9.
- Dumortier, J., 2013. Co-firing in coal power plants and its impact on biomass feedstock availability. *Energy Policy* 60, 396–405.
- Dumortier, J., 2016. Impact of agronomic uncertainty in biomass production and endogenous commodity prices on cellulosic biofuel feedstock composition. *Global Change Biology Bioenergy* 8 (1), 35–50.
- Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J. F., Martin, P. A., Mulik, K., 2012. The effects of potential changes in United States beef production on global grazing systems and greenhouse gas emissions. *Environmental Research Letters* 7 (2), 024023.
- Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J. F., Tokgoz, S., 2011. Sensitivity of carbon emission estimates from indirect land-use change. *Applied Economic Perspectives and Policy* 33 (3), 428–448.
- Dumortier, J., Kauffman, N., Hayes, D. J., 2017. Production and spatial distribution of switchgrass and miscanthus in the United States under uncertainty and sunk cost. *Energy Economics* 67, 300–314.

- Elobeid, A., Carriquiry, M., Fabiosa, J. F., 2012. Socioeconomic and environmental impacts of biofuels: Evidence from developing nations. Cambridge University Press, Ch. Implications of global ethanol expansion on Brazilian regional land use, pp. 171–190.
- Elobeid, A., Tokgoz, S., 2008. Removing Distortions in the U.S. Ethanol Market: What Does It Imply for the United States and Brazil? . American Journal of Agricultural Economics 90 (4), 918–932.
- Galinato, S. P., Yoder, J. K., Granatstein, D., 2011. The economic value of biochar in crop production and carbon sequestration. Energy Policy 39, 6344–6350.
- Grassini, P., Eskridge, K. M., Cassman, K. G., 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications 4 (2918).
- Hertel, T. W., Golub, A. A., Jones, A. D., O'Hare, M., Plevin, R. J., Kammen, D. M., 2010. Effects of u.s. maize ethanol on global land use and greenhouse gas emissions: Estimating market-mediated responses. BioScience 60, 223–231.
- IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., van Groenigen, J. W., Hungate, B. A., Verheijen, F., 2017. Biochar boosts tropical but not temperate crop yields. Environmental Research Letters 12 (5), 1–6.
- 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.

514 Kauffman, N., Dumortier, J., Hayes, D. J., Brown, R. C., Laird, D. A., 2014. Producing en-
515 ergy while sequestering carbon? the relationship between biochar and agricultural productivity.
516 Biomass and Bioenergy 63, 167–176.

517 Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - A
518 review. Mitigation and Adaptation Strategies for Global Change 11, 403–427.

519 Li, W., Dang, Q., Brown, R. C., Laird, D., Wright, M. M., 2017. The impacts of biomass proper-
520 ties on pyrolysis yields, economic and environmental performance of the pyrolysis-bioenergy-
521 biochar platform to carbon negative energy. Bioresource Technology 241, 959–968.

522 Lu, H. R., Hanandeh, A. E., 2019. Life cycle perspective of bio-oil and biochar production from
523 hardwood biomass; what is the optimum mix and what to do with it? Journal of Cleaner Pro-
524 duction 212, 173–189.

525 Lychuk, T. E., Izaurralde, R. C., Hill, R. L., McGill, W. B., Williams, J. R., 2015. Biochar as a
526 global change adaptation: predicting biochar impacts on crop productivity and soil quality for
527 a tropical soil with the Environmental Policy Integrated Climate (EPIC) model. Mitigation and
528 Adaptation Strategies for Global Change 20 (8), 1437–1458.

529 Mardoyan, A., Braun, P., 2014. Analysis of czech subsidies for solid biofuels. International Journal
530 of Green Energy 12 (4), 405–408.

531 Maroušek, J., 2014. Significant breakthrough in biochar cost reduction. Clean Technologies and
532 Environmental Policy 16 (8), 1821–1825.

533 Maroušek, J., Kolář, L., Vochozka, M., Stehel, V., Maroušková, A., 2018. Biochar reduces nitrate
534 level in red beet. Environmental Science and Pollution Research 25 (18), 18200–18203.

535 Maroušek, J., Vochozka, M., Žák, J. P. J., 2017. Glory and misery of biochar. Clean Technologies
536 and Environmental Policy 19 (2), 311–317.

537 Munoz, E., Curaqueo, G., Cea, M., Vera, L., Navia, R., 2017. Environmental hotspots in the life
538 cycle of a biochar-soil system. Journal of Cleaner Production 158 (1-7).

- Oliveira, F. R., Patel, A. K., Jaisi, D. P., Adhikari, S., Lu, H., Khanala, S. K., 2017. Environmental application of biochar: Current status and perspectives. *Bioresource Technology* 246, 110–122.
- Opatokun, S. A., Kan, T., Shoaibi, A. A., Srinivasakannan, C., Strezov, V., 2016. Characterization of food waste and its digestate as feedstock for thermochemical processing. *Energy & Fuels* 30 (3), 1589–1597.
- Patel, M., Zhang, X., Kumar, A., 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renewable and Sustainable Energy Reviews* 53, 1486–1499.
- Peters, J. F., Iribarren, D., Dufour, J., 2015. Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment. *Environmental Science and Technology* 49 (8), 5195–5202.
- Pröll, T., Zerobin, F., 2019. Biomass-based negative emission technology options with combined heat and power generation. *Mitigation and Adaptation Strategies for Global Change*, 1–18.
- Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., Lehmann, J., 2009. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science and Technology* 44, 827–833.
- Rosen, M. A., 2018. Environmental sustainability tools in the biofuel industry. *Biofuel Research Journal* 17, 751–752.
- Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of u.s. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319 (5867), 1238–1240.
- U.S. DOE, 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN, U.S. Department of Energy.

- U.S. DOE, 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN, U.S. Department of Energy.
- USDA, 2016. USDA National Agricultural Statistics Service Cropland Data Layer. Available at <https://nassgeodata.gmu.edu/CropScape/> accessed 11 June 2018.
- Vochozka, M., Váchal, A. M. J., Straková, J., 2016. Biochar pricing hampers biochar farming. *Clean Technologies and Environmental Policy* 18 (4), 1225–1231.
- Windeatt, J. H., B.Ross, A., Williams, P. T., Forster, P. M., Nahil, M. A., Singh, S., 2014. Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment. *Journal of Environmental Management* 146, 189–197.
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1 (56), 1–9.
- Yoder, J., Galinato, S., Granatstein, D., Garcia-Pérez, M., 2011. Economic tradeoff between biochar and bio-oil production via pyrolysis. *Biomass and Bioenergy* 35, 1851–1862.

Highlights

- Yield increases of 2.5%-12.7% above baseline from biochar application to cropland
- Crop prices are main determinant for willingness-to-pay for biochar
- Biochar adoption likely in the Southeast and Northeast due to high willingness-to-pay
- Reduction in global crop area due to biochar-induced higher crop yields in the U.S.
- Potential for significant carbon credits for avoided indirect land-use change