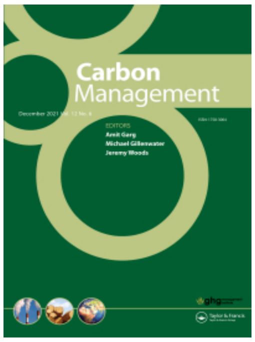

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Economic feasibility of biochar for carbon stock enhancement in Finnish agricultural soils

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ABSTRACT

Biochar is a promising climate mitigation measure that can safely capture and store atmospheric carbon dioxide in soil for many years. We conduct an economic analysis to assess the economic feasibility of increasing Finnish mineral agricultural soil carbon stock with biochar in an increasingly dry and warm climate scenario. The Monte Carlo simulations showed that it is challenging to achieve economic feasibility with current carbon prices and biochar costs. To make biochar application economically feasible with a carbon subsidy at the level of the European Union Emissions Trading System (EU ETS) carbon price of 88 EUR/t CO_2eq, the cost of biochar material would need to be reduced to less than one-third of its current average price. Alternatively, economic viability could be achieved if the subsidy paid to the farmers was between two to nine times larger than the EU ETS carbon price for the current range of biochar market prices. Lastly, the feasibility can be achieved by simultaneous doubling of the carbon price and halving average biochar cost. Currently, the biochar market is thin and a decrease in biochar cost level is needed to make biochar competitive with other climate change mitigation measures.

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KEYWORDS
Biochar; carbon dioxide removal; boreal; agricultural soil; carbon sink

Introduction

Efforts to mitigate climate change include both reducing greenhouse gas emissions and enhancing carbon sinks. Most European Union (EU) member states have notable challenges in meeting carbon sink targets for land use, land use change and forestry (LULUCF) sector [1]. A prominent option is the enhancement of soil carbon stocks [2]. The current global carbon stock in soils is estimated to be between 1,500 to 2,500 billion tons of carbon [2,3] which is likely only 50–66% of the soil potential capacity [4]. Soil carbon management is considered as one of the most promising methods for climate mitigation and it offers additional benefits [2,5]. Soil carbon management simultaneously improves soil quality which has the potential to increase food production. Therefore, it can help to meet the food demand of the growing human population predicted to reach 9.7 billion by 2050 [6]. Soil health is central to Sustainable Development Goals 2 for Zero Hunger, 13 for Climate Action and 15 for Life on Earth [7].

Soil carbon stock can be increased by preventing the release of accumulated carbon from the soil or applying additional organic carbon such as biochar [4,5,8]. Biochar is a carbon substance produced by burning biomass in a high-temperature and low-oxygen environment [9]. The process, called pyrolysis, produces a material with carbon content between 35% and 88% [10–12]. It is highly resistant to decomposition when applied to soil [5] and up to 82% of biochar carbon remains in the soil after 100 years [10].

Biochar has been used in agriculture for centuries, except in Western industrialised countries, to improve soil quality [7]. As a climate mitigation option, biochar is more expensive than other carbon farming measures like conservation agriculture which includes no- or reduced tillage, crop rotations and cover crops [5]. However, biochar offers more reliable long-term carbon storage. Carbon accrued via conservation agriculture is exposed to a high risk of reversal with changes in soil management or complete land use conversion [4] and

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thus requires long-term commitment to prescribed management regimes [13].Furthermore, monitoring, reporting, and verification of soil organic carbon content is complex [14] and it is more straightforward to measure the carbon input from biochar. For this reason, there are a few methodologies used to issue both biochar carbon credits [15–17] and soil carbon credits but the latter are much more involved and certify credits for short-term [13,18].

Global climate mitigation potential with biochar is estimated at 130 billion tons of carbon dioxide equivalent (CO_2eq) over a century [13,19]. In Europe, the theoretical potential is estimated to be 70–290 million tons of CO_2eq annually [20]. Additional aid in climate change mitigation is achieved from avoided methane and nitrous oxide gases that would occur if the organic residue was left untreated to decay instead [19]. In contrast, current European biochar production is small. Around 130 thousand tons of CO_2eq are produced annually and the projection for biochar production is 2.3 million tons of CO_2eq per year by 2030 with current levels of investment [21].

Biochar is one of the carbon dioxide removal (CDR) technologies which are likely to be used by most countries in their pursuits to reach national climate goals [22,23]. Developed nations in particular are expected to simultaneously reduce emissions and invest in CDR technologies to lower the costs of the technologies over time [24]. Still, national climate strategies more frequently include the plans to use the cheaper nature-based CDRs such as conservation agriculture and forestry, instead of investing in new technologies [22]. Only Canada, Japan and Denmark explicitly mention biochar CDR in their climate strategies [22]. Canada refers to biochar as a CDR that may be used but does not have a target on the quantity of emissions that would be removed with the method [22]. The strategy perceives biochar as a long-term carbon removal and storage solution that is more developed than other CDRs [25]. Japan has allocated government funding to a number of climate-related initiatives throughout Southeast Asia including programs that support the advancement of biochar [26]. Furthermore, their plans include R&D into biochars that both improve agricultural yields, and store carbon in soils [27]. Denmark is the only country that has quantified the reliance on biochar CDR in climate policy to two million tons CO_2eq annually by 2030 [28]. However, the plans for how biochar will be obtained and used are not yet developed at the time of writing [29]. Therefore, only a few developed countries include biochar in their climate strategies, and even in those instances, plans for its use remain vague and largely underdeveloped.

In addition to local economic considerations, the economic feasibility of enhancing soil carbon stock with biochar depends on local ecological factors. These tend to be similar across cold climate countries. Firstly, the feedstock available for biochar production is comparable in cold climates as the local flora such as pine and spruce is similar [30]. The choice of feedstock determines both the concentration of carbon in biochar and the estimated decomposition rates [11]. Secondly, biochar's agricultural benefits to soil quality and crop yields tend to be smaller in cold climates than in warmer climates [30,31]. Since cold climate countries produce similar cereals [32], biochar crop yield effects may be comparable. Additionally, the application of stable biochar carbon may be more beneficial in cold climate soils. Soil carbon management measures such as conservation agriculture can offer long-term carbon storage if the carbon atoms are able to form associations with the mineral particles of the soil [34]. Soils in Northern Europe are generally more carbon-saturated than those with warm climates as the colder temperatures lead to lower decomposition rates [33]. When the soil is already saturated, mineral particle surfaces are not able to make more associations thereby leaving the carbon exposed to reversal.

This paper examines Finland as a case study. The study uses experimental field data from Southern Finland. In Finland, the mineral-associated carbon pool capacity limit is nearly reached [34] making biochar potentially a uniquely suitable measure. Furthermore, the Finnish LULUCF sector has been a historically consistent carbon sink in the past, but it turned into a source of greenhouse gas emissions in 2018 [35,36]. Thus, biochar, as a more stable form of carbon, can contribute to turning the Finnish LULUCF sector from a source of emissions to a sink.

The literature on the economics of biochar use for increasing soil carbon stock in agricultural soil is scarce. There is one soil science study that considers biochar's economic attractiveness to farmers in cold climates with a field experiment to evaluate various agricultural benefits [37]. However, they did not consider the monetary benefit that a farmer could receive from increasing the soil carbon stock. Economic research on biochar focuses on its production cost estimation [38], profitability of biochar production [39,40], and technical biochar capacity [20,41–44]. Our study is the first to assess the level of economic incentive needed to make carbon sequestration with biochar economically feasible for a farmer.

The aim of this paper is to study the economic feasibility of using biochar to enhance carbon stock in Finnish agricultural mineral soils. We first study economic feasibility with current carbon prices and biochar cost and, second, explore the combinations of carbon prices and biochar costs for which biochar application is economically viable. The economic analysis considers the benefits and costs of biochar application compared to a no-biochar-application case. The crop yields are simulated in an increasingly warm climate scenario with decreasing summer precipitation to reflect a situation where biochar would have the highest potential to increase crop productivity compared to the no-biochar-application case. A systematic literature review was conducted to explore the scope of agricultural biochar benefits. We used Monte Carlo simulations to estimate future crop yields under changing climate conditions and to project biochar costs. Sensitivity analysis was carried out to assess the results' dependence on parameter value choices.

Model and data

Model description

The economic analysis consisted of computing an expected Net Present Value (NPV) (Equation 1) accounting for the costs and benefits that the farmer would incur if biochar was applied to a field under the chosen policy scheme on a hectare level. We considered a scheme in which the society pays the landowner for the carbon stock increase in the first year when biochar is applied in the form of a carbon subsidy, and the landowner pays for the biochar-related emissions annually thereafter, while at the same time realising agricultural biochar benefits in the form of increased yields and reduced fertilizer costs. A positive NPV is an indicator that biochar application is profitable to the farmer. In such a case the society could expect that the farmer would go ahead with the biochar project with a given carbon subsidy level.

The Equation 1 describes the NPV. At the beginning of the planning horizon, $t = 0$, the society subsidises the farmer for the soil carbon stock increase with biochar (BC, ton, dry weight) at the carbon price P_C (EUR/ton CO_2eq). Carbon concentration in biochar is described by α. Biochar carbon is converted into CO_2 units by using the ratio of atomic weight of C to CO_2 molecule (β). The farmer pays for the biochar at the cost P_{BC} (EUR/ton) and incurs a variable spreading cost, S (EUR/ton/ha), and a fixed tillage cost, G (EUR/ha).

$$E[NPV] = \alpha \cdot \beta \cdot BC \cdot P_C - BC \cdot (P_{BC} + S) - G + \sum_{t=1}^{T} \left[(\Delta Y_t \cdot P_{crop} - \beta \cdot L_t \cdot P_C + \Delta F_t) \cdot (1 + r)^{-t} \right] \quad (1)$$

Over time, $t = 1, 2, \ldots, T$ where T is planning horizon, the farmer capitalizes the difference in the crop yields with biochar and without biochar, (in tons, at time). The difference in crop yields is multiplied by a barley crop price, P_{crop}, (EUR/ton). Biochar gradually decomposes causing emissions, L_t (tons of C) multiplied by β. The farmer incurs a respective emissions penalty at each time period, t, at a carbon price, P_C (EUR/ton CO_2eq). ΔF_t (EUR/year) indicates annual fertilizer savings occurring due to the properties of biochar. All cashflows are discounted at a constant interest rate r.

We used the Intergovernmental Panel on Climate Change (IPCC) model to describe biochar stock dynamics over the planning horizon [11]. The model provides carbon stock development in 100-year increments where BC is biochar application quantity (tons), α is carbon content in biochar, and R_{perm} is the fraction of carbon remaining in the soil after 100 years (Equation 2).

$$\Delta CStock = BC \cdot \alpha \cdot R_{perm} \quad (2)$$

We obtain annual carbon stock change by linearly interpolating 100-year increments with the spline interpolation method where $t = 1, 2, \ldots, 100$ (Figure A.1, supplementary material). Consequently, annual biochar-related emissions were estimated from the annual changes in the stock (Equation 3).

$$L_t = CStock_{t-1} - CStock_t \quad (3)$$

First, we used Monte Carlo simulations (10,000 runs) to obtain the NPV distribution with the base case parameters (Table 1). Biochar costs and barley yields are treated as stochastic variables. The Monte Carlo simulation is commonly used to deal with variables that pose uncertainty and is a common approach in economic biochar studies [20,38–42]. Second, we studied for which biochar cost and carbon price combinations the policy scheme results in the NPV breakeven which indicates the farmer's economic motivation to apply

Table 1. Base case parameter values and values used in the sensitivity analysis.

Parameter name	Base case values	Description & Sources	Sensitivity analysis	Description & Sources
Carbon content in Spruce biochar 450 °C, *α* (%)	88	[12,71,78]	–	–
Permanence factor in biochar stock dynamics, R_{perm} (%)	80	[11]	69, 91	[11]
Biochar application quantity, ***BC*** (tons/ha)	33	Maximum in empirical studies, Table A.2, supplementary material	1, 7	Table A.2, supplementary material
Carbon price, P_C (EUR/ton CO_2eq)	88	EU ETS October 2023 [56]	250, 535	Biochar carbon credits range from 90-535 [55]
Crop price, P_{crop} (EUR/ton)	253	[79]	150, 350	[79]
Biochar cost, P_{BC} (EUR/ton)	Right skewed normal distribution	Figure 1(b), Table A.6, supplementary material [38]	–	–
Interest rate, ***r*** (%)	3	–	0, 1, 12	–
Planning horizon, *T* (years)	100	[15,16,65,80]	1,000	–
Biochar application cost, ***S*** (EUR/ton/ha)	3.27	[51], Table A.5, supplementary material	–	–
Tillage cost, ***G*** (EUR/ha)	34.32	[51,53]	–	–
Fertilizer quantity (kg/ha)	80	[12]	–	–
Fertilizer price (EUR/kg)	0.63	[12,49]	–	–
Fertilizer saving (%/ton of biochar)	2.18	Table A.4, supplementary material. The effect decreases together with decreasing biochar carbon stock	–	–
Biochar impact on crop yields (tons/ha)	Crop yields reduce with time according to climate change	[46], Figure 1(a)	Crop yields are not affected by climate change	[46], Figure 1(a)
Biochar crop yield impact, (%/ton of biochar)	0.41	Table A.3, supplementary material The effect decreases together with decreasing biochar carbon stock	No yield impact	–

biochar to the fields. Lastly, sensitivity analysis was conducted to study the robustness of the result against the most uncertain parameters (Table 1).

Case study parameters and model specifications

The model was run with parameters that describe Finnish agricultural conditions. The agricultural biochar effects were found via a systematic literature review. Scopus and EBSCO databases were checked for experimental cereal crop field studies in Finland which report biochar impacts on crop yields or agricultural soil. The search was done with a query ((Finland OR Finnish OR boreal) AND biochar). Out of 93 resulting articles, 22 were duplicates and 9 studies satisfied the selection criteria (Table A.2, supplementary material).

Past literature did not provide sufficient data on long-term biochar stock dynamics as the number of experimental plots is limited and the longest timespan of the field experiments is 8 years (Table A.2, supplementary material). Thus, we relied on the IPCC model for biochar carbon stock dynamics in agricultural soil (Equation 2) [11].

We consider barley in the analysis as it is the most common crop in Finland covering 39% of crop cultivation area [32]. Barley is a common crop in other cold climate countries; it covers 29% of Swedish crop cultivation area, nearly 100% in Iceland [32], and 19% in Canada [45]. Barley yields in the Monte Carlo simulations were based on probability distribution functions (PDFs) produced by Rötter, Höhn [46]. They specifically study barley yields in Finland under different climate scenarios. We choose one climate change scenario, IPSL-CM4, for the analysis. The climate scenario has increasing temperatures, decreasing summer precipitation, and increased early drought after sowing. The climate scenario choice helps in establishing the theoretical biggest positive impact of biochar on crop yield in Finnish conditions. Crop yields between 2000 and 2100 are described by linearly interpolated PDFs (Figure 1(a); Table A.1, supplementary material). The years after 2100 are all assumed to follow the 2071-2100 PDF. For sensitivity analysis of results without the climate change scenario, we simulate barley yields with the PDF for the crop yields between 1970 and 2011.

Biochar's ability to improve crop yields, ΔY_t, is based on an understanding that biochar aids crop resilience in droughts via its ability to improve soil's water-holding capacity [20,47,48]. Finnish field studies found that, on average, a ton of biochar carbon is associated with 0.85% water holding capacity improvement (Table A.3, supplementary material). Assuming that water availability explains 55% of

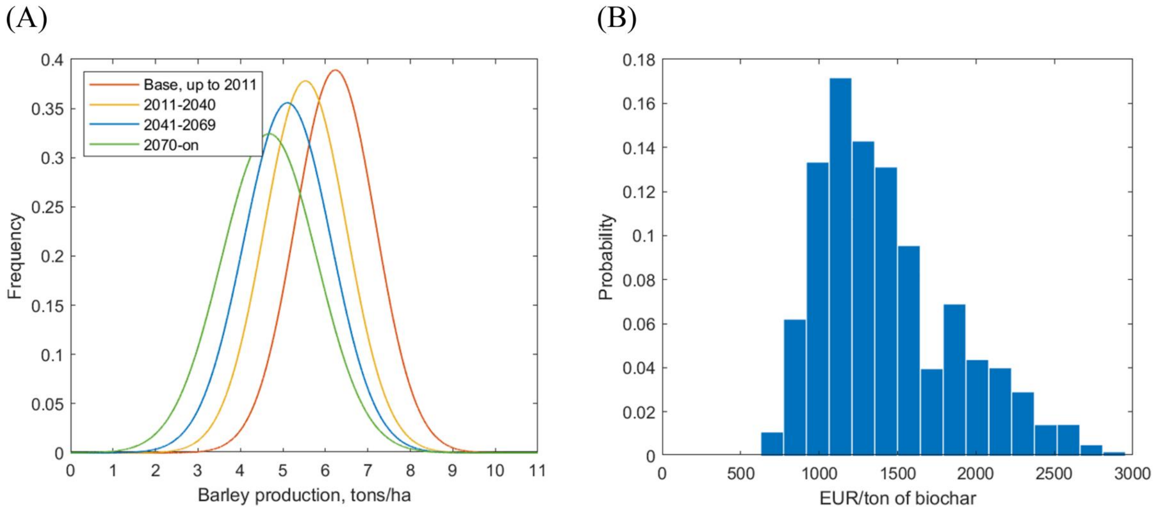

Figure 1. Probability distributions for stochastic variables: barley yields and biochar material cost. (A) Crop yields distributions based on Rötter, Höhn [46] in no climate change scenario (up to 2011) and with increasingly dry and warm climate scenario (2011–2070 and beyond). (B) Biochar material cost distribution based on Nematian, Keske [38] and observed market biochar prices.

crop yields [46], each ton of biochar applied is assumed to correspond to 0.41% crop yield improvement (Table 1). We assume that the effect reduces according to the decrease in biochar stock over time.

The annual fertilizer cashflow, ΔF_t, in Equation 1 is the net value between fertilizer quantity used on the field in the scenarios with biochar and without biochar. The difference is achieved from biochar's ability to improve plants' nitrogen use efficiency (NUE) [12]. NUE expresses how much more efficiently plants use available nitrogen per kg of fertilizer applied [12], therefore, a lesser quantity can be applied. The literature review showed that on average NUE is improved by 2.18% per each ton of biochar (Table A.4, supplementary material). A typical N fertilizer application rate in field experiments is 80 kg/ha [12] and a fertilizer price is 0.63 EUR/kg [49]. The fertilizer savings are scaled according to biochar application quantity. As with the barley yield effect, the fertilizer saving effect decreases with the reduction of biochar carbon stock at each time period.

Biochar cost distribution is right-skewed normal with a mean 1,440 EUR/ton, skewness parameter 0.82, and SD 424 (Figure 1(b)). The biochar cost distribution is based on the biochar production cost distribution by Nematian, Keske [38] and adjusted to the range of biochar prices found in the global biochar market 765-2,661 EUR/ton (Table A.6, supplementary material). We assume that biochar can be bought from any country without shipping cost. Similar biochar cost ranges were used in other economic biochar studies [39,50].

The biochar application consists of two stages: spreading and tilling. A sand spreader [48] or liming machinery [51] can be used to spread biochar. The available tillage methods are rotary power harrow [48] or moldboard [52]. The variable spreading cost based on labour, fuel and maintenance costs is assumed to be 3.27 EUR/ton/ha [51] (Table A.5, supplementary material). Valtiala, Niskanen [53] estimated the fixed cost for tillage based on fuel and labour cost factors in Finland to be 34.32 EUR/ha. The marginal decrease in tillage cost is small with increasing hectares [53], therefore, it is not considered in this study.

Results

Figure 2(a) shows the simulated NPV distribution for biochar application in Finnish mineral agricultural soils. The probability for a positive NPV is negligible, thus, the farmer does not have enough economic incentive to apply biochar to the agricultural fields for the baseline level of carbon subsidy. The simulated NPV distribution has the shape of a normal left-skewed distribution, and all its values are negative. The distribution has a negative mean (−31,414 EUR/ha) and a large spread (SD 14,112) that is caused by the wide spread in biochar costs (Figure 1(b)). At the mean, the initial cashflow (−37,853 EUR) is much larger than the sum of the rest of the discounted cashflows (6,439 EUR) (Figure 2(b)). As biochar's effects on crop yield improvement and fertilizer savings diminish along with the decreasing biochar carbon stock in the soil, the annual cash flows also decline over the planning horizon. Discounting reduces the weight of annual cashflows occurring further in the future. The observed discontinuities in the annual

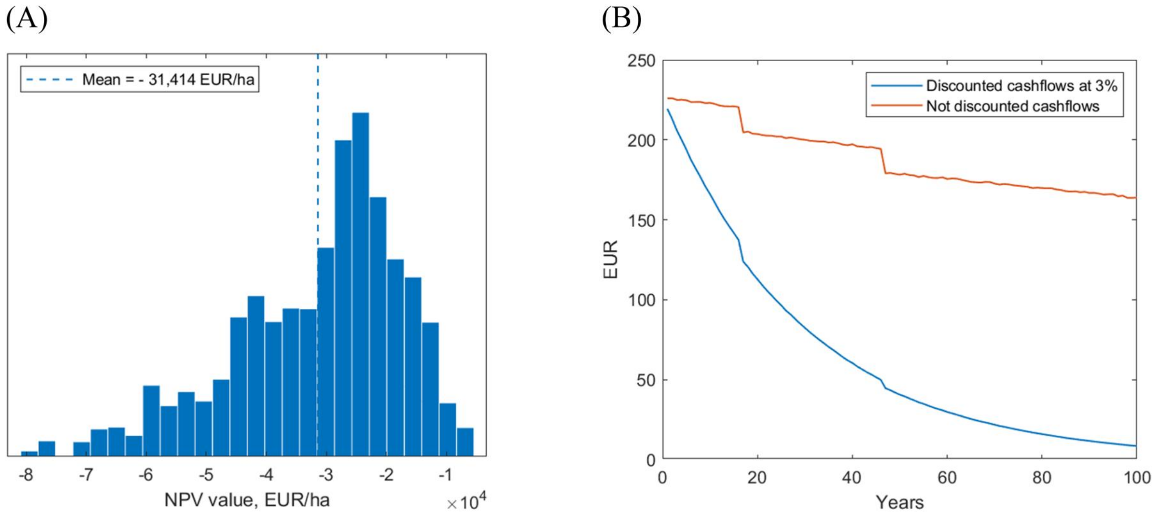

Figure 2. Results with the baseline parameters. (A) Net present value distribution of 33 tons/ha biochar application to mineral agricultural soil and other base case parameter values, and (B) the flow of discounted and non-discounted annual cashflows over time excluding the first year.

cashflow curve occur due to the barley yields that are simulated over three separate PDFs representing three time periods (Figure 1(a)).

It is of interest to a policy maker to find the level of carbon subsidy that would incentivize the farmer to apply biochar to the fields. Figure 3(a) shows for which combinations of carbon subsidy and biochar cost levels the mean NPV is at the breakeven (diagonal line), for which pairs it is positive (the green area), and for which pairs it is negative (the red area). A positive NPV is a prerequisite for the biochar application to be carried out. For the baseline carbon subsidy level, the biochar cost needs to be at most 487 EUR/ton for the biochar application to be economically feasible. The required biochar cost is one-third of the current average biochar cost and falls outside the range of the current biochar cost distribution (Figure 1(b)). On the other hand, the minimum biochar cost in the biochar cost distribution (765 EUR/ton) requires the carbon subsidy to be at least 183 EUR/ton CO_2eq. This is almost equivalent to doubling the carbon price (176 EUR/ton CO_2eq) and simultaneously halving mean biochar cost (720 EUR/ton). The maximum biochar cost (2,661 EUR/ton)requires the carbon subsidy to be at least 812 EUR/ton CO_2eq. For the current mean biochar cost (1,440 EUR/ton), the carbon subsidy needs to be at least 407 EUR/ton CO_2eq to make biochar application profitable. Thus, the carbon subsidy should be between two to nine times larger than the EU ETS carbon price (October 2024) to breakeven depending on the available biochar price.

A comprehensive sensitivity analysis was conducted to study the results' dependency on the parameter values. Figure 3(b) shows changes in

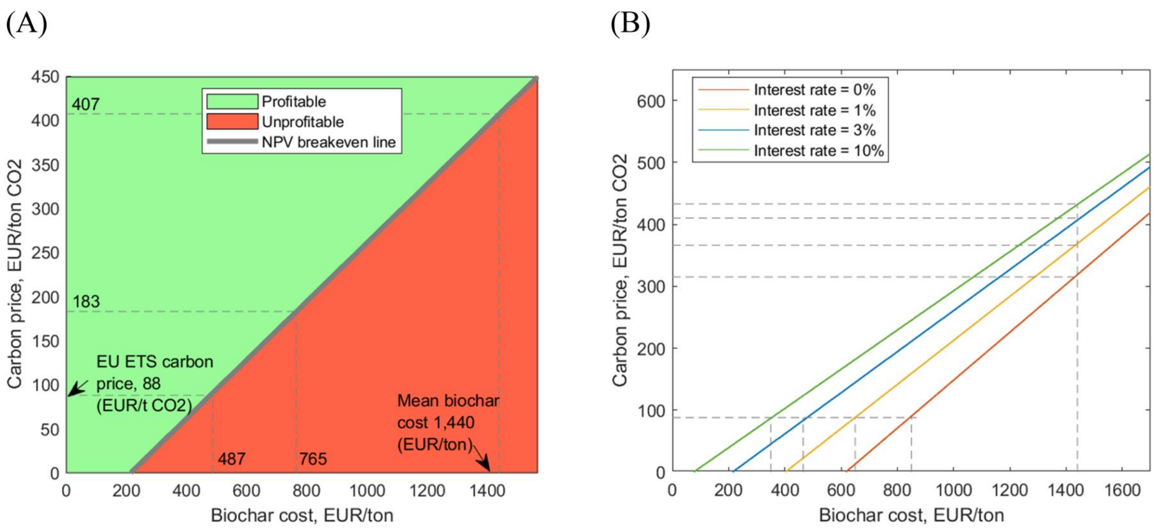

Figure 3. Breakeven curves showing combinations of carbon price and biochar cost where total costs are equal to total revenues. The carbon price and biochar cost pairs above the breakeven curve lead to a positive net present value. The net present value is negative below the breakeven curves. (A) Breakeven curve with the base case parameters. (B) Sensitivity analysis for the rate of interest.

the breakeven curves' slopes with different interest rates. Lower interest rates result in a relatively higher weight of future cashflows making biochar application economic feasibility more likely. The lower the discount rate, the more the planner values the benefits occurring in the future. On the other hand, the higher the interest rate, the lower the biochar cost must be for the chosen level of carbon subsidy. This is because the cashflows occurring in the future are positive, albeit small, contrary to the first negative and large cashflow. Similarly, carbon subsidies can be lower with lower interest rates to breakeven for the chosen level of biochar cost.

The NPV distribution results are most sensitive to the levels of interest rate (Figure 4(a)), planning horizon length (Figure 4(b)), biochar application quantity (Figure 4(c)), and carbon price (Figure 4(d)). Firstly, if the planning horizon is extended until 1,000 years (approximating infinite time horizon), the NPV median becomes positive at interest rates below 0.37% even with current levels for carbon subsidy and biochar cost (Figure 3(b)). However, this result is highly dependent on the planner's belief on how long the value of gradually decreasing biochar carbon stock persists. We have assumed that the carbon price remains the same over time, but in reality it may first be higher, and later on, if the climate crises are solved, it would gradually approach zero. Secondly, increasing carbon subsidy shifts the NPV cumulative distribution functions (CDFs) positively (Figure 4(d)). The NPV mean and median are positive given the highest recorded biochar carbon credit price in the voluntary carbon market (535 EUR/ton CO_2eq, Table 1). Thirdly, decreasing biochar application quantity per ha makes the NPV medians clearly less negative, but they remain negative (Figure 4(c)). Nonetheless, the spreads of NPV distributions reduce with decreasing biochar application quantity which means that lower biochar quantities reduce results uncertainty.

We assessed the sensitivity of the results to the most uncertain model parameters, namely, the crop yield effect of biochar (Figure A.2a, supplementary

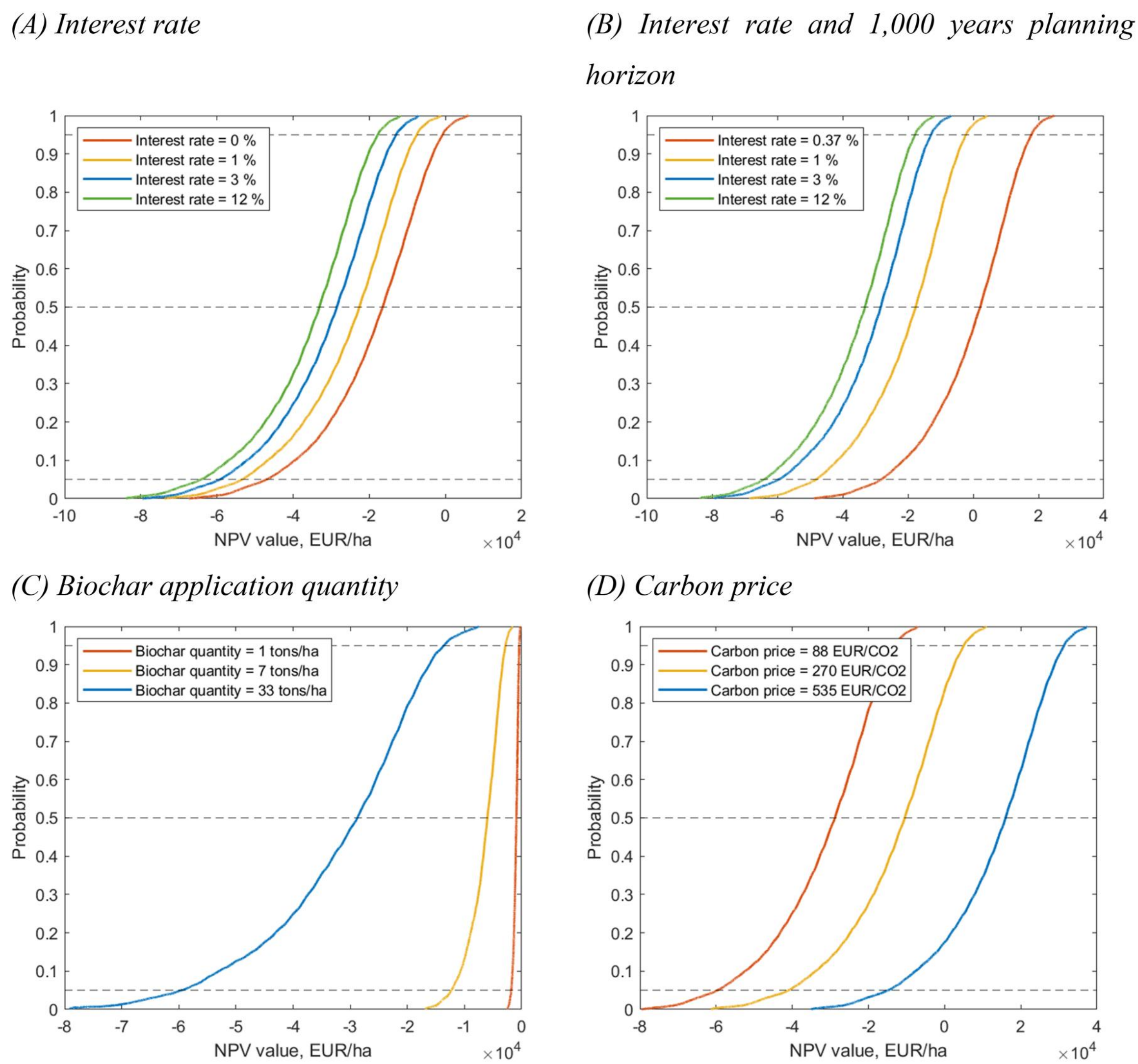

Figure 4. Net present value cumulative distribution functions (CDFs) sensitivity analysis.

material, Table 1), the effect of climate change on baseline barley yields (Figure A.2b, supplementary material), and biochar carbon stock dynamics (Figure A.2d, supplementary material). A comparison of NPV distributions with and without biochar's effect on crop yield shows that crop yield improvement from biochar is not important for NPV in our case study on boreal agricultural soils. Furthermore, decreases in crop yields due to climate change, and crop price levels have a minor impact on the NPV (Figure A.2c, supplementary material). Similarly, IPCC biochar stock model parameters were altered (Table 1), which did not have much impact on the NPV results (Figure A.2d, supplementary material) even with the extended time horizon (Figure A.2e, supplementary material).

Discussion

Result interpretations

In this paper, we studied the economic feasibility of biochar for carbon stock enhancement in Finnish mineral agricultural soils. The results show that carbon stock increase with biochar may be economically feasible, but meeting the required conditions is challenging. We find four situations in which biochar application is economically justified by adjusting certain parameter values and keeping everything else constant. Firstly, if the carbon subsidy is fixed to the EU ETS price (October 2023), then biochar application is possible if the biochar material cost is at least 3 times smaller than the current average biochar cost. Secondly, given the range of current biochar cost levels, soil carbon stock increase from biochar is achievable if the society would be willing to pay a carbon subsidy two to nine times bigger than the EU ETS carbon price. Thirdly, simultaneous doubling in carbon price and halving biochar average cost all else equal makes biochar application feasible. Lastly, the NPV median is non-negative if the interest rate is below 0.4% and the planning horizon is set to 1,000 years. Such policymaker would give significant consideration to the well-being of future generations.

Our results, regarding the required level for carbon subsidy, cannot be directly contextualized as currently there is no carbon farming policy in the EU for any agricultural measures [54] and farmers are passive participants in the biochar carbon credit voluntary market [15,16]. However, biochar carbon credit price in the voluntary carbon market can serve as a reference for how society might value the climate mitigation service that a farmer delivers by applying biochar to soil. The observed biochar carbon credit prices in the voluntary carbon market which are between 90 and 535 EUR/ton CO_2eq with an average of ∼200 EUR/ton CO_2eq [55] fall in the range of required carbon subsidy levels we find in our results. For comparison, a carbon subsidy of 407 EUR/ton CO_2eq, makes biochar application feasible with a current average biochar cost. The subsidy levels are high partly due to the local colder climate conditions: the farmers are not able to recover much of biochar cost from agricultural biochar benefits. Biochar credits are the cheapest among other carbon removal credits; the average price of direct air capture and carbon storage (DACCS) carbon credit is 656 EUR/ton CO_2eq and bio-oil is 485 EUR/ton CO_2eq [56]. Still, the credit prices include the credit registry margin and the carbon dioxide 100 years permanence [15,16] which is not included in the subsidy. Therefore, it seems that the subsidies required locally to make biochar application economically feasible exceed EU ETS carbon price but overlap to an extent the range of carbon credit prices in the voluntary carbon market.

The economic feasibility of biochar in the future depends on advancements in biochar production technology that would lower material costs, as well as on trends in the marginal costs of alternative carbon mitigation methods and the tightening of mitigation targets, which will be reflected in the future EU ETS price. Our results reflect the uncertain biochar market conditions (Table A.6, supplementary material) which may be a result of low biochar demand and supply [9,21,50]. The future of biochar costs and carbon prices remain unclear, but there are solid grounds for assuming certain trends. Firstly, since the biochar market is young, and the production has not been scaled yet, biochar may follow significant price reductions as it is observed with other emerging technologies such as solar power [9]. Currently, European biochar production is growing by 50% annually [21]. It is reasonable to expect a decrease in unit costs due to economies of scale and heightened demand, which may attract more R&D investment. Secondly, while the biochar carbon credit prices in the voluntary carbon market are expected to reduce to below 100 EUR/ton CO_2eq [57], foresight studies have estimated a significant increase in EU ETS prices to between 125–160 EUR/ton CO_2eq by 2030 [59]. However, EU ETS price has decreased to 65 EUR/ton CO2eq over the last year [58]. If these assumed trends materialise, it is expected that biochar could become economically viable in the near future. With the reduction in biochar costs, income resulting from agricultural biochar benefits would also become more relatively important.

Policy considerations of biochar in reaching the climate neutrality target

Theoretical estimations for how much biochar could be produced nationally are still needed. A study in Norway found that local forestry waste could be converted to biochar at a volume equivalent to 0.6–2 million tons of CO_2eq annually, which covers 13–40% of Norwegian agricultural emissions[42]. Compared to Norwegian annual agricultural emissions, Finnish annual agricultural emissions are 2.1 million tons CO2eq higher [60]. In addition, Finland has around 2 times bigger tree growing stock volume [61,62] and more than five times larger roundwood production [63]. If there were no competing use of waste material, it is estimated that Finland could have 3.1 million tons of forestry waste, such as bark, woodchips, and sawdust, per year for biochar production aside from agricultural and sludge waste [64]. This could result in 5 to 12 million tons of CO2eq of biochar per year using IPCC constants [11]. Thus, biochar produced from Finnish forestry waste could potentially cover a large part of the Finnish annual agricultural emissions in the Effort Sharing sector (6.4 million tons CO2eq/year) which have been somewhat steady for the past 20 years [36].

In this paper we studied one possible policy scheme. This paper is an ex-ante study that offers estimations on how much it would cost the state to use biochar as a tool to reduce net greenhouse gas emissions given a modelled policy setting. Currently, there is no operating carbon farming policy in the EU that would provide economic incentive for farmers to increase soil carbon [54,65]. The provisional carbon farming policy assessment does not include biochar [65] even though biochar has a moderate to high climate mitigation potential [8]. A study in Norway found that 96% of farmers have not used or do not know anyone who has used biochar in the fields yet [66]. As a contrast, the voluntary carbon market is adopting biochar carbon dioxide removal (CDR) technology willingly. The biochar carbon removal credits offer the biggest volume [56] and 75% of biochar produced in Europe is certified for carbon removal [21]. The forthcoming EU-level regulation on carbon removal credits, including biochar CDR, will establish coherence in the carbon credit markets [67,68]. The carbon accounting in the EU determines that generally, all voluntary carbon credits are contribution credits, that is, the buyer adds to the national carbon sink where the credit project occurs [69]. However, biochar and other technological carbon capture and storage methods are currently excluded from this and are claimed as offsets [70].

Assumptions and future research

Our results are subject to several assumptions, and relaxing them would require additional ecological and economic research. Firstly, we assumed that all plots of the empirical studies are comparable and, therefore, the recorded effects could be combined regardless of soil type [31], initial soil carbon content [2,4,48], or initial soil pH [48]. Secondly, we also assumed that the crop yields benefit from biochar via improved water holding capacity as opposed to using parameters from field experiments. This is because the literature provides conflicting results. While most of the literature on field experiments in Finland suggests that biochar does not increase crop yields [37,48,71–73], there was one study that reported high crop yield improvements [12]. Thirdly, a lack of long-term empirical studies led us to use an IPCC carbon stock model. IPCC considers this model to be conservative for boreal conditions because it describes biochar dynamics in a warm climate where decomposition is faster [11], however, it has been used in Norway as well [41]. We assume that the improvements in barley yields and fertilizer savings decrease at the same rate as the biochar carbon stock decreases. Lastly, we assumed that all biochar is produced in the same way and the market prices that were collected reflect a uniform product. The biggest assumptions in our model regarding the biochar carbon stock dynamics, optimistic crop yield improvement, and climate change effect on crop yields were tested in the sensitivity analysis. It revealed that these assumptions have little impact on the NPV distributions as other terms in the NPV equation have more weight.

We excluded some aspects in our model, such as biochar effects on soil's pH and biodiversity. Our review of the literature suggests that biochar does not seem to have a significant impact on soil biodiversity [74] and grain nutrition [37,48]. Biochar is an alkaline material which should increase pH level in soil, but in a Finnish soil field experiment it was found not to have a significant effect on the soil pH level [37]. The variation in the alkalinity of biochar is wide and depends on pyrolysis temperature and feedstock and most of the studies on biochar's effect on soil's pH are pot experiments [75].

Further research could consider other specifications in the analysis. Firstly, it could be studied how different types of biochar feedstock can change the results. Wood biochar feedstock, which is likely in Finland, has larger carbon concentrations and higher permanence than other feedstocks [10]. Secondly, the economic analysis could be repeated for alternative management regimes such as different biochar application frequencies and quantities. While the biochar application costs would increase due to the increased number of application operations, the extension would allow the consideration of various scenarios for biochar cost paths development. Another extension could allow for testing simultaneous biochar and lime or fertilizer spreading. Lastly, biochar application visibly darkens the soil which results in poorer soil's ability to reflect sunlight, the albedo effect. Albedo could be considered as darker surfaces increase soil temperature and water evaporation, and emit heat fluxes [76]. Field studies found an absolute percentage decrease in albedo between 5–12% with higher than 30 tons/ha application when conventional tillage is applied [76,77].

Conclusions

In this paper, we studied the economic feasibility of biochar application for increasing carbon stock in mineral agricultural soils in Finland. We find that the increase in farmer's income from crop yield improvement, fertilizer savings, and carbon subsidy income is too small to lead to positive economic outcomes under current price and cost levels for carbon and biochar. Thus, with subsidies at the EU ETS carbon price of 88 EUR/ton of CO2eq and yet underdeveloped biochar markets, the farmers have hardly any economic incentive to use biochar even if the society would be willing to pay for the carbon stock increase. Our study reveals that biochar use in mineral agricultural soils in Finland could be achieved by a sizable increase in carbon subsidy, a decrease in biochar cost, or both. Achieving these conditions may be challenging. The planner should be willing to pay two to nine times larger carbon subsidies than the EU ETS carbon price for the current range of biochar costs. Otherwise, simultaneous doubling of cabon price and halving of biochar average cost could make the application of biochar feasible. The required subsidy levels are similar to what is paid for biochar carbon credits in the voluntary carbon market.

The conclusions of the paper are contingent on the parameter values that may shift already in the near future. The breakeven analysis that we provide is a reference tool for a policy maker to estimate what level of carbon subsidy is needed for the available biochar cost. Since the biochar market is young, it may follow significant cost reductions as it is observed with other emerging technologies. The reductions may arise from increased biochar supply as production is rapidly growing. These developments are necessary to enable the efficient use of biochar at scale, as biochar-based carbon dioxide removal is recognized as an important strategy for supporting climate neutrality objectives.

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Author contributions

Medilė Jokubė contributed to the conception and design of the model, data curation, coding, obtaining the results and interpretation of the results, visualisation, writing of the original draft, revising and editing.

Matti Hyyrynen contributed to the conceptualization, coding, interpretation of the results, writing parts of the original draft, revising and editing.

Sampo Pihlainen contributed to the conceptualization, manuscript revising and editing.

Kari Hyytiäinen contributed to the conceptualization, coding, interpretation of the results, writing parts of the original draft, revising and editing.

All authors agree to be accountable for all aspects of the work and approve the final version.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data used in this paper is obtained from grey and peer-reviewed literature and was referenced where appropriate.

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