Article

Assessing the Carbon Footprint of Biochar from Willow Grown on Marginal Lands in Finland

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Abstract: Willow biochar can help to sequester carbon. However, biomasses should not be grown on arable lands, as it would increase competition with food production and lead to sustainability issues such as increased food prices and decreased food security. The purpose of this study is to calculate the carbon footprint (CF) of willow biochar in Finland and assess the greenhouse gas compensation potential of marginal lands if they are utilized for willow biochar production. The CF of willow biochar is inadequately assessed together with marginal lands in the literature. A cradle-to-grave Life Cycle Assessment (LCA) of willow biochar was conducted. The results were then applied to assess the total CF of marginal lands. It was found that the CF of willow biochar is $-1875 \text{ kgCO}_2\text{eq t}^{-1}$ of dry biochar. Grown on marginal lands in Finland, willow biochar could compensate 7.7% of yearly agricultural greenhouse gas emissions. On buffer zones, willow biochar could also compensate some of the emissions depending on the zone size. The results of the study support current findings of biochar as a carbon negative product. The study also indicates that willow biochar produced in marginal lands can be used to compensate agricultural greenhouse gas emissions to some extent.

Keywords: life cycle assessment; carbon footprint; biochar; pyrolysis; willow; marginal lands; lignocellulosic biomass

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1. Introduction

In the current climate crisis, the efforts to lower greenhouse gas (GHG) emissions seem to be falling short, and GHG reduction alone is no longer adequate to keep the global temperature rise to below 1.5 °C of pre-industrial levels. To keep the temperature rise under control, techniques such as carbon capture and storage (CCS) and negative emissions technologies (NET) are required [1]. Smith et al. [2] list seven different NETs that can be used for GHG removal from the atmosphere. One of these NETs is converting biomass to biochar for use as a soil amendment. According to Smith [3], this NET has fewer disadvantages than many other NETs and is therefore an attractive option for GHG removal. This study focuses on the production of biochar and its usage in soil amendment.

A simplified definition of biochar is given by Lehmann and Joseph [4], who describe it as a carbon-rich product obtained from biomass pyrolysis. This process is quite similar to the production of charcoal, but what distinguishes biochar from charcoal is the intended application, which for biochar is usually soil amendment [4]. Biochar can increase porosity, base saturation, water and nutrient holding capacity, and the cation exchange capacity of the soil [5]. In addition to improving soil conditions, biochar can also mitigate GHG emissions. According to Paustian et al. [6], applying biochar on the soil can increase the C stock of the soil, which results in the net removal of CO₂. In soil, biochar is stored for several decades or longer. However, carbon stability can vary depending on soil conditions,

amendment type and nutrient content [6]. Biochar could also be used in different kinds of filters instead of activated carbon [7] or as a concrete additive to reduce the carbon footprint of buildings [8].

Many types of feedstocks can be used to produce biochar. These feedstocks include all materials of biological origin, such as manure, rendering waste and lignocellulosic biomass [4]. Most of these biomasses are available from agriculture, such as crops and residues (e.g., rice, corn, wheat, soybeans and algae), dedicated energy crops (e.g., switchgrass, miscanthus, fast-growing willow and poplar) [9] and animal waste (e.g., poultry litter and pig manure) [10]. From all these available types of biomass, willow is chosen for this study for two reasons. Firstly, it is the fastest growing and the most high-yielding tree species in Northern Europe [11]; and secondly, willow biochar has been shown to increase clay soil water retention [12]. Thus, willow can provide large amounts of biomass and a biochar product that has great properties for soil amendment.

Biochar has a high carbon sequestration potential. According to the review by Tisserant and Cherubini [13], the carbon footprint (CF) of biochar ranges between net emissions of 0.04 tCO₂eq and a net reduction of 1.67 tCO₂eq per t of feedstock. The wide range of values is caused by different assumptions, feedstocks, system boundaries and substitution effects, and methodological issues in the life cycle assessment (LCA) studies. In a study conducted by Hammond et al. [14], the best carbon abatement was reached with woody biomasses. Carbon abatement values ranged from 2.9 to 3.9 tCO₂eq t^{−1} of biochar depending on the type of woody feedstock and the size of the pyrolysis system [14]. An LCA study by Hamedani et al. [15] found that willow biochar can reduce GHG emissions by 2.2 tCO₂eq t^{−1} of biochar.

The research by Uusitalo and Leino [16] examined the possibility of neutralizing the global warming impacts of crop production using biochar produced from side flows and buffer zone biomass. The study suggests that biochar produced from side flows and buffer zone willow may enable the full neutralization of the GHG emissions of oat production. According to the study, a maximum sequestration potential of 390 kgCO₂ t^{−1} oat can be reached with the willow biochar from buffer zones, which would sequester 56% of oat production emissions (700 kg CO₂eq t^{−1} oat). However, the study did not investigate the CF of the whole life cycle of willow biochar, focusing only on the pyrolysis part. The first primary aim of the current research is therefore to fill that gap and assess the CF of the whole life cycle of willow biochar.

According to the literature reviewed above, in the majority of cases, producing biochar is clearly carbon-negative. However, the origin of the feedstock for biochar should be considered, because the cultivation on arable lands, for instance, can bring some disadvantages. One reason why growing biomass on arable land is not an optimal solution is that the decreased cropland area can lead to higher food prices [17]. It can also lead to the development and a more intensive use of cropland elsewhere, which often means deforestation and increased GHG emissions through land use change [18]. If food and the environmental problems associated with biomass production on croplands are to be avoided, one possible solution could be growing biomass on marginal lands [19,20]. Thus, the second aim of this research is to define the carbon sequestration potential of marginal lands in Finland if they were used to grow willow for biochar production.

In this work, the LCA approach is applied to the assessment of the CF of willow biochar. The LCA method and data used are presented in greater depth in the next two sections. The results and discussion sections consider the main results of the LCA study and the sensitivity analysis. After the sensitivity analysis, marginal lands in Finland and their CF via willow biochar production are assessed. The last part of the discussion considers the issue of willow buffer zones as a way of compensating the GHG emissions of food crop cultivation. Conclusions from the study are drawn and presented in the final section.

2. Materials and Methods

This study is conducted following the LCA methodology described in standards ISO 14040 and 14044, as well as in standard ISO 14067, which gives requirements and guidelines for the quantification of the carbon footprint of products. The LCA methodology standardized by ISO allows for the quantitative assessment of the environmental performance of a system, process or product throughout its whole life cycle. LCA is divided into four steps: goal and scope definition, inventory analysis, impact assessment and interpretation [21,22]. The modeling software is the GaBi professional software (version 9.2.1.68) and the related databases. According to ISO 14067, carbon footprint (CF) is the sum of GHG emissions and GHG removals in a product system and is expressed as CO₂ equivalents. The assessment of the CF is based on an LCA using the single impact category of climate change [23].

The structure of the assessment paper follows the guidelines given in the standards. First, the goal and scope of the LCA are defined, after which the data used for building the LCA model are described in the inventory analysis. The life cycle impact assessment and interpretation are presented in the results and discussion section. The sensitivity analysis is also conducted using the one-at-a-time approach.

2.1. Goal and Scope of the LCA

The goal of the LCA is to estimate the CF of willow biochar. The result of the LCA can then be used to analyze the CF of biochar from willow grown on marginal lands. The production system studied is presented in Figure 1. The approach is cradle-to-grave, or, more specifically, the system is studied from willow cultivation to biochar soil amendment. The cultivation of willow planting rods is excluded from the system as well as the materials and manufacturing of the pyrolysis and drying facilities, the district heating network and the manufacturing of other machinery. Furthermore, the effect of the biochar on soil emissions, fertilizer needs in crop cultivation and crop yields are not considered in this study.

The product system studied consists of multiple processes. The functions of these processes are to produce and handle the willow which is the feedstock of the produced biochar and produce the biochar itself. Furthermore, the studied system contains all the processes needed for the transportation of the willow and biochar and the utilization of the excess heat energy from the pyrolysis. The main function of the whole system is the production of biochar for soil amendment, and the functional unit of the study is therefore 1 t of dry biochar stored in soil for 100 years. The allocation between biochar and the excess heat from pyrolysis is avoided with a substitution method. Heat production for district heating is substituted with excess heat from the pyrolysis.

The chosen impact category for the study is climate change. The impact on climate is presented with the CF calculated with the CML 2001–January 2016 methodology. The results are presented in kilograms of CO₂eq per functional unit. The data for the processes were obtained and calculated from the literature sources and the GaBi database. Data specific for Finland were used when available; otherwise, data from other European countries were used as reference values. The data used are presented in Section 3, describing the life cycle inventory.

Figure 1. System boundaries and processes of the studied system.

2.2. Marginal Lands

To assess the total CF of cultivating willow for biochar production on marginal lands, the area of these lands should be estimated. The total area of marginal lands in Finland was obtained from a report by the Finnish state-owned forestry organization Tapio [24]. Such land includes fields outside of agricultural usage and former peat production land. The following land types were excluded from the study: forest lands, agricultural lands which are covered by agricultural subsidies, areas in nature reserves and urban areas, seashores, yards, valuable traditional biotopes and sites bordered by streams and lakes located in nationally valuable areas, and the immediate surroundings of the sites of endangered species [24]. The assessment is based on geo-spatial analysis, and the values are therefore only estimates. These values are presented in Table 2, in Section 4.2.

Another type of marginal land for which the CF of willow biochar production is assessed are field buffer zones. The full potential of these lands is challenging to estimate because no exact data are available. In this study, we therefore focus on an example field size of 1 ha and calculate how large the buffer zone should be to neutralize the cultivation emissions of the field. We focus on the cultivation emissions of wheat, rye, barley, oat, fava bean, spring rapeseed and potato. The cultivation emissions of the first four crops are obtained from Rajaniemi et al. [25]. The values chosen for this study represent the conventional production of the crops. Rajaniemi et al. [25] also present GHG emissions for cultivation, which includes reduced tillage or direct drilling, but these are excluded from this study. Cultivation emissions for fava bean are obtained from Heusala et al. [26].

The values chosen for this study represent a high yield scenario (3600 kg ha^{-1}) [26], which is in the range of the yield of fava bean in Finland ($2382\text{--}4553 \text{ kg ha}^{-1}$) [27]. Cultivation emissions for spring rapeseed are taken from Fridrihsone et al. [28], who present a cradle-to-gate LCA of spring rapeseed in Latvia. Cultivation emissions for potato are from Pulkkinen et al. [29]. According to their report, the cultivation emissions of potato are in the range $7\text{--}20 \text{ gCO}_2\text{eq } 100 \text{ g}^{-1}$ of potato, the and potato yield is 34 t ha^{-1} . This study uses the average cultivation emissions of $14 \text{ gCO}_2\text{eq } 100 \text{ g}^{-1}$, and the yield of 34 t ha^{-1} is used to calculate potato cultivation emissions per hectare. The calculated cultivation emissions for the different food crops are presented in Table 3.

3. Life Cycle Inventory

The inputs and outputs of the processes are quantified in this section. All these flows are shown in Table A1, Appendix A.

3.1. Willow Yield and Plantation Lifetime

The willow yield depends on the cultivation practices and land type. According to Mola-Yudego [30], the average yield of a short rotation willow plantation in Finland is 6.8 t of dry matter per hectare per year ($\text{t DM ha}^{-1} \text{ a}^{-1}$). In a study by Laasasenaho et al. [31], yield drops to $6 \text{ t DM ha}^{-1} \text{ a}^{-1}$ when willow is cultivated on peatland in Finland. Carbons Finland Oy [32], a Finnish company providing biochar solutions, presents an average yield of $8 \text{ t DM ha}^{-1} \text{ a}^{-1}$. The average yield for the willow used in this assessment is assumed to be $6.9 \text{ t DM ha}^{-1} \text{ a}^{-1}$, which is a mean value of three yields presented. The average moisture content of willow is 52% [33], so the yield of fresh willow is $14.4 \text{ t ha}^{-1} \text{ a}^{-1}$.

The lifetime of a willow plantation is approximately 25 years. Harvesting is done 3–8 times during this lifetime, usually every 3–5 years [34]. According to Hytönen [35], the optimal rotation for willow plantation is 3–6 years. In this study, the length of the cycle is assumed to be 4 years, which means six harvests during the plantation lifetime.

3.2. Tractor Operations

Next, the diesel inputs for each tractor operation are defined. The main sources for the diesel consumption data are Ahokas [36], Handler and Nadlinger [37] and Murphy et al. [38]. If consumption data are found in multiple sources, averages of the values are used in the assessment. The values used for each tractor operation and how often each operation is required during the willow plantation lifetime are presented in Table A2, Appendix A.

During the site preparation, the land is prepared for willow cultivation. First, the land is sprayed with herbicides to kill weeds. The land is then ploughed and power harrowed [39]. The average fuel consumption for herbicide application used in this assessment is 2.03 l ha^{-1} [37,38]. The fuel consumption of ploughing depends on the soil type and the working depth. These are not specified in this study, and therefore the average fuel consumption of 23.97 l ha^{-1} is used for ploughing [36–38]. For power harrowing, the fuel consumption used is 6 l ha^{-1} [37].

Fertilizers are applied before planting the willow. Later in the plantation lifetime, fertilizers are applied after each harvest, excluding the last. Therefore, the total number of fertilization processes during the plantation lifetime is six. According to Handler and Nadlinger [37], the fuel consumption of a tractor-mounted rotating fertilizer spreader is in the range $1.5\text{--}2.5 \text{ l ha}^{-1}$. For this assessment, an average fuel consumption of 2 l ha^{-1} is assumed for fertilizer application.

Willow planting can be done with a modified potato planter, whose average fuel consumption is 10.6 l ha^{-1} [38]. The same value is used in this assessment. After planting, the field is rolled, and herbicides are applied again. The average fuel consumption value used in this study for rolling is 3.64 l ha^{-1} [37,38]. The second application of herbicides reduces the heavy growth weed, which would otherwise leave the willow feeble and reduce its winter resistance in the first year. Insecticide use is not necessary, as pest insects should not be a threat to willow growth [34].

Willow can be harvested using direct chip, whole rod, billet or bale harvesting [39]. According to Sihvonen et al. [40], whole rod harvesting is the most common harvesting method for willow in Finland. The fuel consumption for whole rod harvesting is 50 l ha^{-1} [38]. This value is used in the assessment. After harvesting, the rods are stacked and dried by natural ventilation [39].

At the end of the willow plantation lifetime, the site is restored to its original state. After the last harvest, willow growth is killed with herbicides. This is the third and final time when herbicide application is needed in the plantation lifetime. The field is then cultivated with forestry mulching [39]. For mulching, a fuel consumption of 12.9 l ha^{-1} is used in this assessment [37].

In GaBi, these tractor operations are modeled with a single process called GLO: Universal tractor. The process calculates the emissions of diesel burning during the tractor operation. Emissions are based on the fuel consumption. The diesel input for the process was set to the correct value by adjusting the hourly consumption parameter of the process. The production of diesel was modeled with the process EU-28: Diesel mix at filling stations. This process is also used to supply diesel for all transportation processes.

3.3. Fertilizers and Herbicides

The amount of fertilizer needed is defined by the amount of nutrient that is removed by harvest. The annual nitrogen offtake of the willow is around $60 \text{ kg ha}^{-1} \text{ a}^{-1}$ [39,41]. The other required nutrients are calculated from the desired NPK ratio of 100:14:71 given by Tahvanainen [41]. Thus, the amounts of phosphorus and potassium needed are $8.4 \text{ kg ha}^{-1} \text{ a}^{-1}$ and $43.2 \text{ kg ha}^{-1} \text{ a}^{-1}$, respectively. In GaBi, the NPK ratio does not reflect the amount of elemental phosphorus and potassium but the amount of their oxides phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O). The amount of P_2O_5 needed is defined by dividing the phosphorus need by 0.436 and the K_2O need by dividing the potassium need by 0.830 [42]. The production of these nutrients was modeled in GaBi with the plan GLO: NPK fertilizer mixer.

The amount of N_2O emissions originating from fertilizer use is defined with the IPCC methodology [43]. In the methodology, it is assumed that 1% of the nitrogen added with the fertilizers is emitted as N_2O . The conversion factor used for converting N to N_2O is 44/28 [43]. Therefore, the amount of emitted N_2O from a willow field is $0.94 \text{ kg ha}^{-1} \text{ a}^{-1}$.

During the site preparation, glyphosate is sprayed with an application rate of 4 l ha^{-1} . After the willow has been planted, the field is again sprayed with herbicides, but this time with metazachlor (1.5 l ha^{-1}) [34]. The in-site restoration of willow growth is terminated with glyphosate spraying of 5 l ha^{-1} [39]. DE: Herbicide unspecific process from the GaBi database is used to model the production of these herbicides.

3.4. Willow Drying

The willow is dried twice during its life cycle: first, in a storage pile by natural drying and then before pyrolysis with artificial drying. According to two storage experiments [40,44], a moisture content of 26% is achieved during a storage period of 9–18 months. The average loss of dry matter during storage is 3% [40,44]. These assumptions are used in this assessment. A new process was created in GaBi for natural drying which takes willow rods (52% moisture content) as the input and calculates dry matter losses and a reduction in the willow moisture. The output is a slightly drier willow (26% moisture content).

For artificial drying, the average heat and electricity consumption is 1.251 kWh and 0.070 kWh per kg of removed water, respectively [45,46]. Willow chips are dried to the moisture content of 10%. The production of electricity is modeled in GaBi with the process FI: Electricity grid mix. The heat needed for drying is assumed to be obtained from the pyrolysis process. A new process was created in Gabi for artificial drying which takes willow chips and electricity as the inputs and dried willow chips as the output.

3.5. Chipping and Transportation

There are multiple places during the lifetime of willow when chipping can be done. However, the most common place is the intermediate storage near the field. This approach minimizes the transportation distance of the willow rods, which are harder to transport than homogenous willow chips [45]. Fuel consumption for chipping is obtained from the study by Spinelli et al. [47]. In their study, the fuel consumption of a trailer-mounted drum chipper was examined for eight different raw materials. The raw materials were different tree species and different parts of trees with different moisture contents. The results varied a little (1.68–2.86 l per t of fresh wood), but when they were considered as per dry matter output, these variations evened out. According to the study, the average fuel consumption for chipping is 3.21 l per t of DM [47]. This value is used in this assessment. The emissions from this process are calculated with an emissions factor of 2.676 kgCO₂ per l of diesel [43]. It is assumed that there are no mass losses during the chipping. A new process was created in GaBi for chipping which takes willow rods and diesel as the inputs and CO₂ and willow chips as the outputs.

After chipping, the willow chips are transported to the pyrolysis facility. According to Statistics Finland [48], the average transportation distance for forestry products such as firewood, stumps, brushwood and forest chips is 68 km. It is assumed that this is the distance from marginal lands to the pyrolysis facility. Transportation was modeled in GaBi with the process GLO: Truck-trailer, Euro 6, 34–40 t gross weight/27 t payload capacity, and the distance parameter was set to 68 km.

3.6. Slow Pyrolysis

Pyrolysis covers multiple thermal decomposition processes, but when biochar is the desired product, slow pyrolysis is usually applied. The average biochar yield from the slow pyrolysis of biomass is 35% [49], but the yield can vary in the range of 20–45% [13]. For willow chips, Hamedani et al. [15] report biochar yield of 33.5%. In this assessment, an average biochar yield of 35% is assumed. Consequently, 3175 kg of willow chips (10% moist.) are required to produce 1 t of biochar.

Crombie and Mašek [50] state that in certain conditions, syngas, a side product of pyrolysis, can be used to maintain the process, thus making it self-sustaining in terms of thermal energy. In this study, it is assumed that the pyrolysis is self-sustaining, and no other energy source except electricity is therefore needed. The average electricity consumption of pyrolysis is taken as 0.126 kWh per kg of feedstock [51,52].

Additionally, pyrolysis produces excess heat that can be utilized for different purposes. In a model created by Klinar [53], 29% of the dry biomass energy input was available as hot water or hot air from the process. In their work, the pyrolyzed biomass consisted in wood chips with a moisture content of 10%. The same result was achieved by Roberts et al. [54] when corn stover was pyrolyzed. The moisture- and ash-free heating content of willow chips is 18.6 MJ kg^{−1} [55], which means that 4.9 MJ of excess heat is available when 1 kg of willow chips (10% moist.) is pyrolyzed. In this study, the excess heat is utilized in the artificial drying of the willow chips and district heating. A new process was created in GaBi for pyrolysis which takes willow chips and electricity as inputs. The outputs of the process are heat for district heating and drying and dry biochar. The production of electricity was modeled with the process FI: Electricity grid mix.

Most of the district heating in Finland is produced in combined heat and power (CHP) facilities. The most commonly used fuels for CHP production are natural gas, coal, peat and wood. In 2018, the average emission factor for district heating was 154 kgCO₂ MWh^{−1} [56]. This factor is used in this study when calculating the CF for the substitution of district heating with the excess heat from pyrolysis that is not used in the drying process. A new process was created in GaBi for substituted district heating. The process takes heat and CO₂ as inputs.

3.7. Transportation

Being a small particle, biochar is sensitive to wind losses during handling and transportation. Major [57] reports total losses of 30%, of which 25% occur during spreading, 3% during transportation and 2% during loading. However, the losses can be decreased by moistening biochar. Hammond et al. [14] assumed handling losses of 1% and spreading losses of 3%. In this study, the total losses of biochar are assumed to be 5%. The biochar is moistened to a moisture content of 15% [58]. The transportation of the biochar was modeled with the GaBi process GLO: Truck-trailer, Euro 6, 34–40 t gross weight/27 t payload capacity, and the water for moistening was modeled with EU-28: Tap water from surface water.

3.8. Application to Soil

In large and small field trials, the broadcast and incorporate method has been used for the application of biochar to the soil. For broadcasting, spreading moistened biochar in a manure spreader might be a better solution than using a lime spreader, and any ploughing method can be used for incorporating the biochar into the soil, although moldboard ploughing is not recommended because it does not mix biochar very well and might bury the biochar too deep [57]. In this study, the assumed ploughing method is power harrowing, whose fuel consumption is defined in Section 3.2. Fuel consumption for a manure spreader is taken from Handler and Nadlinger [37], who present 14 l ha^{-1} . The application of the biochar to the soil was modeled with the GaBi process GLO: Universal tractor.

Next, the application rate of the biochar is defined. According to Brandstaka et al. [59], a beneficial application rate in Finnish conditions would be $10\text{--}20 \text{ t ha}^{-1}$. Major [57] reports a positive effect on crop yields with a biochar application rate of $5\text{--}50 \text{ t ha}^{-1}$. According to Hammond et al. [14], an application rate of 30 t ha^{-1} can increase crop production and decrease fertilizer requirements. As there seem to be a lot of variation in recommended biochar application rates, a calculated average of 25 t ha^{-1} is used in this study.

3.9. Biochar Stability and Carbon Content

Mašek et al. [60] studied the slow pyrolysis of willow chips. In their study, a carbon content of 70.7 wt% was achieved for the slow pyrolysis of dry biochar using a pyrolysis temperature of 350°C . Ronsse et al. [61] report a carbon content of 71.3 wt% when pine wood was pyrolyzed with slow pyrolysis. Rasa et al. [12] pyrolyzed willow at 320°C , and the elemental analysis of the biochar revealed a carbon content of 74 wt%. In this study, a carbon content following a pyrolysis of 72 wt% is used, which is the average of the three values.

The decomposition of biochar follows a two-pool behavior. The labile fraction of biochar degrades quickly, and the recalcitrant fraction can stay in the ground for hundreds of years [13]. In their study, Tisserant and Cherubini [13] reviewed 34 different LCA studies on biochar for their most common assumptions. A common assumption for biochar stability was that 68% of the carbon remains in the soil after 100 years. The same assumption is applied in this study.

When the carbon content (72%), biochar stability (68%) and losses during transportation and handling (5%) are taken into account, 465 kg of carbon is stored for a hundred years when 1 t of dry biochar is applied to soil. With atomic masses of carbon (12) and CO_2 (44), one kilogram of carbon will produce 3.67 kg of CO_2 . Therefore, storing 465 kg of carbon means that 1704 kg worth of CO_2 is stored. A new GaBi process was created for modeling the storage of biochar in soil. The inputs of this process are wet biochar and 1704 kg of CO_2 per t of dry biochar applied, which represents the CF of the storage.

4. Results and Discussion

4.1. Carbon Footprint of Willow Biochar

A cradle-to-grave LCA was conducted to assess the CF of willow biochar. Based on the LCA, the CF of willow biochar is clearly negative. Using the assumptions in this study, CF of $-1875 \text{ kgCO}_2\text{eq t}^{-1}$ of biochar can be achieved, as shown in Figure 2. Storing the biochar in soil, including the sequestered carbon during willow growth, has the greatest effect on the result ($-1704 \text{ kgCO}_2\text{eq}$), although the replaced district heating ($-527 \text{ kgCO}_2\text{eq}$) also lowers the CF significantly. The negative CF from the replaced district heating is caused by the assumption that less heat needs to be produced by CHP plants when excess heat from pyrolysis is utilized for district heating. The biggest emitter during the life cycle is the willow cultivation phase ($212 \text{ kgCO}_2\text{eq}$). Most of the emissions from this phase originate from N_2O emissions from the use of a nitrogen fertilizer ($107 \text{ kgCO}_2\text{eq}$) and the production of fertilizers ($84 \text{ kgCO}_2\text{eq}$). The CF for electricity usage during pyrolysis is $84 \text{ kgCO}_2\text{eq}$, and the fuel usage of chipping contributes $25 \text{ kgCO}_2\text{eq}$. The CF for tractor operations is $19 \text{ kgCO}_2\text{eq}$, for transportation $18 \text{ kgCO}_2\text{eq}$, and for electricity consumption during drying $10 \text{ kgCO}_2\text{eq}$. The remaining emissions of $10 \text{ kgCO}_2\text{eq}$ originate from diesel production, soil application of biochar and herbicide production.

Figure 2. CF of processes during the willow biochar life cycle.

Storing the carbon in the ground had the biggest effect on the CF of the willow biochar life cycle. This result is, however, affected by some uncertain parameters, such as the carbon content of the biochar and the carbon stability in the ground. In addition, these parameters are affected by other parameters, such as the pyrolysis and soil conditions. Due to these uncertainties, the carbon content and stability and the biochar yield are studied next in the sensitivity analysis. Furthermore, the changes in the willow yield and excess heat utilization are also studied, as these parameters are likely to change depending on where the willow is cultivated and where the pyrolysis facility is located. For the willow yield, a sensitivity analysis is conducted according to the yield values found in the literature ($5.8\text{--}8 \text{ t DM ha}^{-1} \text{ a}^{-1}$). For the excess heat utilization, we attempted to determine the effect caused if the pyrolysis facility cannot be connected to the district heating network, and therefore the amount of heat for district heating is set to zero. For the biochar yield, the carbon content and the amount of stable carbon in percentual values are just increased and

decreased by 10 percentage points to find out how sensitive the result is to the changes in these three parameters. The changes in the parameters and the results of the sensitivity analysis are presented in Table 1.

Table 1. Results of the sensitivity analysis. Values in brackets indicate how much results have changed compared to the original result of $-1875 \text{ kgCO}_2\text{eq}$ per 1 t of biochar.

Parameter.	Change	Result [kgCO_2eq per 1 t of Biochar]
Willow yield	$6.9 \rightarrow 8 \text{ t DM ha}^{-1} \text{ a}^{-1}$	$-1904 (-1.5\%)$
	$6.9 \rightarrow 5.8 \text{ t DM ha}^{-1} \text{ a}^{-1}$	$-1835 (+2.1\%)$
Heat to district heating	$3422 \rightarrow 0 \text{ kWh}$	$-1348 (+28.1\%)$
Biochar yield	$35 \rightarrow 25\%$	$-1946 (-3.8\%)$
	$35 \rightarrow 45\%$	$-1835 (+2.1\%)$
Carbon content	$72 \rightarrow 62\%$	$-1639 (+12.6\%)$
	$72 \rightarrow 82\%$	$-2112 (-12.6\%)$
Amount of stable carbon	$68 \rightarrow 58\%$	$-1625 (+13.3\%)$
	$68 \rightarrow 78\%$	$-2126 (-13.4\%)$

Based on the sensitivity analysis, the CF of willow biochar rises significantly (28%) when the pyrolysis unit is not connected to a district heating network. The possibility of utilizing the excess heat from the pyrolysis is dependent on the location of the facility. The amount of avoided emissions is also dependent on the fuel used in the district heating production.

The CF also seems to be sensitive to changes in the amount of stable carbon and the carbon content of the biochar. The CF decreases by 13% when the amount of stable carbon increases by 10% and decreases by 12.6% when the carbon content is increased by 10%. These parameters are mostly affected by the pyrolysis conditions and the feedstock. For example, higher pyrolysis temperatures seem to increase the carbon content and the production of recalcitrant biochar. On the other hand, a higher pyrolysis temperature decreases the biochar yield [13,50].

Surprisingly, if the biochar yield decreases by 10%, the CF drops by 3.8%. This result can be explained by the increased amount of heat available for district heating, as more willow needs to be pyrolyzed to produce 1 t of biochar. Changing the willow yield does not seem to affect the results much. The 1.1 t increase in yield lowers CF only by 1.5%.

In the assessment, it was assumed that excess heat can be utilized in district heating. This assumption led to a significant decrease in the CF, as the share of fossil fuels in district heating production in Finland is quite large. The emissions from pyrolysis were assumed to be zero, since the fuel used is renewable biomass, i.e., willow. However, the possibility of feeding excess heat to district heating is dependent on the location of the pyrolysis facility. When choosing the location for pyrolysis, the excess heat utilization possibilities should be mapped out. If there is no opportunity to utilize excess heat, it might be beneficial to use the heat to produce drier feedstocks to reduce the energy consumption of the pyrolysis process. Alternatively, it might be possible to pyrolyze moister feedstock, which would reduce the amount of excess heat, but also reduce the energy consumption of the drying process. An optimal scenario might be if the willow could be pyrolyzed straight after natural drying, when the moisture content is 26%. However, pyrolyzing a higher moisture content feedstock increases the thermal loading and flow rates of the gases, and therefore larger systems for feeding and gas clean-up would be required [4].

The most emitting phase of the lifecycle was willow cultivation, where the production of fertilizers and N_2O emissions were the main source of emissions. The amount of fertilizer needed could be reduced by using wastewater sludge as fertilizer, as in some places willows are already used in wastewater treatment [11]. However, this will probably not reduce the N_2O emissions, since part of the added nitrogen would still be emitted as N_2O . Reducing emissions during tractor operations might be difficult, but some reductions can be achieved by using biofuels instead of conventional diesel.

The results in this study match those presented in earlier studies and suggest that willow biochar has a negative CF. However, earlier studies, for example Hamedani et al. [15] and Hammond et al. [14], seem to suggest that an even lower CF could be achieved. In Hamedani et al. [15], the assessed CF of willow biochar was $-2200 \text{ kgCO}_2\text{eq t of biochar}^{-1}$. This value is $0.3 \text{ tCO}_2\text{eq}$ lower than in this study. The work by Hamedani et al. [15] is quite similar to this study, the main differences being in the utilization of the excess heat and the biochar properties. Hamedani et al. [15] model the excess heat as being utilized in electricity production and use a biochar carbon content of 75% and stable carbon of 80%. However, in the sensitivity analysis, it can be seen that when the share of stable carbon is raised to 78%, the CF drops to $-2100 \text{ kgCO}_2\text{eq}$, which is only $100 \text{ kgCO}_2\text{eq}$ lower than the result in Hamedani et al. [15].

In the study by Hammond et al. [14], a total carbon abatement of $2.9\text{--}3.9 \text{ tCO}_2\text{eq t}^{-1}$ of biochar was reached, which is significantly higher than in this study. Hammond et al. [14] consider the agricultural impacts of biochar in soil, which partly explains the greater abatement. According to their study, applying 30 t ha^{-1} of biochar to winter wheat crops delivers a 10% increase in net primary production, a 10% decrease in the rate of soil organic carbon decomposition, a 10% decrease in N fertilizer requirement, a 5% decrease in P and K fertilizer requirements, and a 25% suppression of soil N_2O emissions. Agricultural impacts accounted for 18–22% of the carbon equivalent balance. The agricultural impacts of biochar were not included in this assessment because of the lack of measured data under Finnish conditions.

4.2. Compensation Potential of Marginal Lands Used for Willow Cultivation

The results of the LCA are now applied to assess the CF of marginal lands and buffer zones when they are used to grow willow for biochar production. The amount of marginal land in counties in Finland varies a lot depending on the location, as can be seen in Table 2. The greatest land masses are available in North Ostrobothnia (20,447 ha), Lapland (15,545 ha) and Kainuu (10,373 ha). These are some of the biggest counties in Finland, which might explain the large marginal land area. Additionally, North Ostrobothnia has the highest number of former peat production sites. The total area of marginal land in Finland is 118,685 ha [24]. If all these lands were to be utilized for producing willow biochar, a carbon sequestration potential of $500 \text{ kt CO}_2\text{eq a}^{-1}$ would be achieved, which means that 7.7% of the yearly agricultural GHG emissions in Finland could be compensated. This value varies in the range of 1.9–36.1% in different counties. The greatest compensation potential is achieved in Kainuu, where agricultural emissions ($121 \text{ kt CO}_2\text{eq a}^{-1}$) are relatively small compared with other counties and the area of marginal land is the third highest. In North Ostrobothnia, where agricultural emissions ($1048 \text{ kt CO}_2\text{eq a}^{-1}$) are highest, 9.3% of these emissions could be compensated with willow biochar from marginal land. The lowest compensation potential of 1.9% is found in Central Ostrobothnia, where the amount of marginal land (1537 ha) is lowest.

The amount of available marginal land is only an estimate, and it should be noted that all these lands might not be suitable for willow cultivation. Some of the available plots of land might be too small to be profitable places to cultivate willow, or the soil conditions might be too poor. Moreover, other options may exist for utilizing these lands that might be more attractive, such as the afforestation or cultivation of food crops. Further research should be done to investigate the profitability of willow cultivation on different sizes and types of land.

Table 2. Amount of available marginal land in different counties in Finland and how much of the region's annual agricultural GHG emissions could be compensated with biochar from willow grown on marginal land [24,62].

County	Agricultural Emissions 2018 [ktCO ₂ eq a ^{−1}]	Marginal Lands [ha]	Carbon Sequestration pot. [ktCO ₂ eq a ^{−1}]	Compensation Potential [%]
North				
Ostrobothnia	1048.4	20,447	−86.2	8.2
Lapland	320.1	15,545	−65.5	20.5
Kainuu	121.2	10,373	−43.7	36.1
North Karelia	293.6	8144	−34.3	11.7
Central Finland	273.7	7694	−32.4	11.9
North Savo	597.9	7547	−31.8	5.3
Pirkanmaa	371.8	7185	−30.3	8.1
South Savo	229.9	6901	−29.1	12.7
Uusimaa	226.5	6362	−26.8	11.8
Southwest Finland	466.5	5469	−23.1	4.9
South				
Ostrobothnia	873.3	5366	−22.6	2.6
Satakunta	315.4	4139	−17.5	5.5
South Karelia	143.6	3438	−14.5	10.1
Kymenlaakso	141.6	2407	−10.1	7.2
Kanta-Häme	199.2	2271	−9.6	4.8
Päijät-Häme	159.4	1950	−8.2	5.2
Ostrobothnia	393.7	1910	−8.1	2.0
Central				
Ostrobothnia	346.7	1537	−6.5	1.9
Total	6523.5	118,685	−500.4	7.7

To neutralize the emissions from a single field, a quite extensive area of willow cultivation is needed. According to Table 3, willow buffer zones in the range 0.20–1.13 ha are required to neutralize the cultivation emissions of a 1-ha food crop field. The cultivation emissions of cereal crops (wheat, rye, barley, oat) are quite close to each other (2330–1800 kgCO₂eq ha^{−1}), as the cultivation procedures are very similar. The willow buffer zone required to neutralize these emissions is in the range 0.43–0.55 ha. Fava bean has the smallest cultivation emissions (828 kgCO₂eq ha^{−1}), and therefore the size of the required willow buffer zone (0.20 ha) is the smallest as well. As a nitrogen-fixing crop, fava bean does not require much nitrogen fertilizer, which reduces cultivation emissions significantly [26]. Cultivation emissions for spring rapeseed are 3170 kgCO₂eq ha^{−1}, and the required willow buffer zone 0.75 ha. The biggest cultivation emissions are found with potato (4760 kgCO₂eq ha^{−1}), and neutralizing those emissions would require a willow buffer zone that is more than the size of the cultivated field (1.13 ha).

Table 3. Cultivation emissions of different food crops [25,26,28,29] and the size of the willow buffer zone needed for biochar production to neutralize these emissions.

	Cultivation Emissions [kgCO ₂ eq ha ^{−1}]	Willow Buffer Zone [ha]
Wheat	2330	0.55
Rye	2270	0.54
Barley	1930	0.46
Oat	1800	0.43
Fava bean	828	0.20
Spring rapeseed	3170	0.75
Potato	4760	1.13

The creation of a carbon neutral field by growing willow for biochar production on a buffer zone would require an average buffer zone of 57% of the field size. Buffer zones of this size would be unreasonable because lots of arable land would be used for growing a non-food crop. To achieve a carbon-neutral field, additional means should be used together with willow biochar production. One possible solution could be producing biochar also from the side flows of the food crop cultivation, as presented in Uusitalo and Leino [16]. Even though a willow buffer zone alone will not make a field carbon-neutral, other benefits should also be considered. For example, a willow buffer zone can reduce nutrient leaching from the field, which in turn can reduce the eutrophication of local waterways [11].

When the CF of marginal lands and buffer zones as willow cultivation sites for biochar production are considered together, it can be seen that the total compensation potential varies a lot depending on the location and the cultivated crop. In some counties in Finland, growing willow for biochar production on marginal land is an attractive option, as over a third of the agricultural GHG emissions could be compensated. When willow cultivation on buffer zones is added, even higher compensation potentials could be achieved. However, to establish the full compensation potential in individual counties in Finland, the total area of buffer zones has to be investigated. Currently, no such data are available for Finland. Despite the missing buffer zone data, it is evident that implementing the production of willow biochar into agricultural practices could lower the carbon footprint of Finnish agriculture, even though full carbon neutrality could not be achieved by this measure alone.

Finally, a number of important limitations need to be considered. First, only the energy consumption of the machinery and facilities was considered in this study. In reality, part of the emissions from the production and maintenance of these machines should be allocated for the biochar, thereby increasing the total CF of the biochar life cycle. Secondly, only the ability of biochar to store carbon in soil was considered in this work. Some studies, such as Cayuela et al. [63], Jeffery et al. [64] and Jeffery et al. [65], state that biochar could also have an effect on soil emissions, fertilization and crop yields, which could offer some climate benefits. However, the magnitude of these soil effects is uncertain in the current literature, and they were therefore not considered. Thirdly, there is some uncertainty regarding the stability of biochar carbon in soil, as it depends on the soil conditions. The effect of carbon stability on the CF was examined in the sensitivity analysis, and it was found out that the result was quite sensitive to changes in carbon stability. Fourthly, the current usage of the marginal lands was not considered in this study. Some of the lands could already be sequestering carbon into biomass, and changing those land areas into willow fields might release the carbon that is sequestered into them. Finally, it was assumed that willow can be grown on all marginal land and have the same yield. In reality, willow yields would vary depending on the land type, and some plots might not be large enough to cultivate willow profitably. When considering the profitability of the marginal land utilization, the opportunity costs should also be considered, as the land might already produce, for example, firewood for the owner. In addition to profitability, the effects of willow cultivation on biodiversity should also be studied, since marginal lands and buffer zones can be important maintainers of biodiversity in agricultural environments [66]. Notwithstanding these limitations, the results of the study are consistent with previous biochar LCA studies and support the idea of biochar as a carbon-negative product. These findings provide a possible approach to get a little closer to achieving carbon-neutral agriculture and the ultimate climate goal of keeping the temperature rise 1.5 °C below pre-industrial levels.

5. Conclusions

This study has extended our knowledge of the CF of willow biochar in Finland, considering it together with the total CF of marginal lands growing willow for biochar production. There is a definite need for assessing possible cultivation sites for these biomass-based solutions if the competition with food production and other sustainability issues are to be avoided. Based on the LCA conducted in this study, the CF of willow

biochar is clearly negative. This result supports the literature's findings, according to which biochar is a carbon-negative product. When the LCA results were studied together with the marginal land potential in Finland, it was found that 7.7% of Finnish agricultural GHG emissions could be compensated if all marginal lands were used for growing willow for biochar production. When examining field buffer zones, it was seen that the average size of the buffer zones should be over 50% of the cultivated area if all cultivation emissions of food crops are to be neutralized.

The results of this study indicate that willow biochar produced from marginal lands can be used for compensating agricultural GHG emissions to some extent. However, to reach the full carbon neutrality of the agricultural sector in Finland, other means are also required, as the amount of marginal land in Finland is limited. Furthermore, other ways of utilizing marginal land exist that might be more attractive to landowners, such as forestry. The results of this paper can be used when evaluating possible uses for marginal land from the perspective of climate impacts. Further research might investigate the profitability of willow cultivation for biochar production, as the CF might not be the only interest of landowners and willow biochar could offer a landowner some additional income, and therefore help to maintain the vitality of rural areas. In addition to profitability, the effect on biodiversity of willow cultivation should also be studied, since marginal land plays an important role in maintaining the biodiversity in agricultural environments. The life cycle model built for this study can also be implemented when studying other uses for willow biochar because the first parts of the life cycle will be the same, and only simple changes to the last processes are needed. Other uses for biochar might be different kinds of filters and concrete additives.

The results of this work raise many interesting questions, and, for example, further research is needed to determine the other soil effects of biochar usage. Some literature sources mention that biochar could reduce fertilizer needs and increase crop yields. However, there is a lot of variation in these reported effects, and they were therefore excluded from the study. If the effects of biochar in soil are better known, more precise life cycle models can be built. Further study could also assess the carbon stability of biochar in soils so that the CF of the biochar can be predicted more reliably. Even though the possible effects on soil were excluded in this work, the cultivation of willow, biochar production and storage in soil appear to be competent mechanisms to remove carbon dioxide from the atmosphere to long-term storage, thus supporting the 1.5 °C climate target.

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Appendix A

Table A1. Life cycle inventory. Inputs and outputs of each process presented per functional unit and data sources.

Process	Input/Output Flow	Unit	Amount	Data Source
Cultivation	Inputs			
	Diesel	kg	5.55	[36–38]
	Nitrogen	kg	25.61	[41]
	Phosphorus pentoxide	kg	8.22	[41]
	Potassium oxide	kg	22.22	[41]
	Glyphosate	l	0.16	[34,39]
	Metazachlor	l	0.03	[34]
	Outputs			
	Willow rods (52% moist.)	kg	6136.48	[30–32]
	N ₂ O emissions	kg	0.40	[67]
Natural drying	Inputs			
	Willow rods (52% moist.)	kg	6136.48	Calculated
	Outputs			
	Willow rods (26% moist.)	kg	3861.00	[40,44]
Roadside chipping	Inputs			
	Willow rods (26% moist.)	kg	3861.00	Calculated
	Diesel	kg	7.63	[47]
	Outputs			
	Willow chips (26% moist.)	kg	3861.00	Calculated
	CO ₂ emissions	kg	24.55	[43]
Transportation	Transport distance	km	68.00	[48]
Artificial drying	Inputs			
	Willow chips (26% moist.)	kg	3861.00	Calculated
	Heat energy	kWh	858.69	[45,46]
	Electricity	kWh	48.05	[45,46]
	Outputs			
	Dried willow chips (10% moist.)	kg	3174.60	
Slow pyrolysis	Inputs			
	Dried willow chips (10% moist.)	kg	3174.60	[53,54]
	Electricity	kWh	400.00	[51,52]
	Outputs			
	Dry biochar	kg	1000.00	Calculated
	Excess heat to artificial drying	kWh	858.69	[53,54]
Biochar moistening	Excess heat to district heating	kWh	3422.25	[53,54]
	Inputs			
	Dry biochar	kg	1000.00	Calculated
	Water	kg	176.47	[57]
	Outputs			
	Wet biochar (15% moist.)	kg	1176.47	Calculated
Transportation	Transport	km	68.00	[48]
Soil amendment	Inputs			
	Diesel	kg	0.81	[37,59]
	Wet biochar	kg	1176.47	Calculated
	Outputs			
	Wet biochar in soil	kg	1176.47	Calculated

Table A2. Fuel consumption of each tractor operation and how often each operation is implemented during the plantation lifetime (25 years).

Process	Frequency [Times Lifetime ⁻¹]	Fuel Consumption [l ha ⁻¹]	Reference
Ploughing	1	23.97	[36–38]
Power harrowing	1	6.00	[37]
Rolling	1	3.64	[37,38]
Herbicide spraying	3	2.03	[37,38]
Fertilization	6	2.00	[37]
Planting	1	10.60	[38]
Harvesting	6	50.00	[38]
Mulching	1	12.90	[37]

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