Chapter 5
Understanding Soil Organic Carbon Dynamics of Short Rotation Plantations After Land Use Change—From Establishment to Recultivation

Enrique Alejandro Perdomo Echenique and Franziska Hesser

Abstract The increase in soil organic carbon (SOC) stocks has the potential to contribute to climate mitigation strategies by reducing atmospheric CO_2. Short rotation plantations (SRP) provide bio-based resources and can possibly accumulate SOC. Estimating the potential SOC stocks of short rotation plantations can help decision-makers to implement strategies that reduce SOC loss and thus contribute to climate change mitigation. The dynamic changes in SOC were estimated for a case study using the RothC carbon turnover model. The results indicate that SOC stocks increased from 37.8 to 48.52 t C/ha within 20 years of the plantation's lifetime. Thus, an annual average increase of 0.535 t C/ha year is expected. Given the importance of implementing strategies that support the potential climate mitigation benefits of SRP, a sensitivity analysis was employed to identify the relevant factors that affected SOC prediction. For instance, the influence of soil condition heterogeneity, such as clay content, can vary the estimations of SOC accumulated. This highlights the relevance of obtaining primary data at different locations within the plantation's areas: to obtain a variety of SOC stock estimations that give a better representation of SOC accumulation. Such analysis help to propose suggestions that mitigate the climate effect of short rotation plantations.

Keywords Life cycle assessment · Soil organic carbon · Short rotation plantation · Poplar · Land use change · Wood · Bioeconomy

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-031-29294-1_5.

E. A. Perdomo Echenique (✉)
Institute of Marketing and Innovation, University of Natural Resources and Life Sciences, Vienna, Feistmantelstraße 4, 1180 Vienna, Austria
e-mail: alejandro.perdomo@boku.ac.at

F. Hesser
Wood K plus – Competence Center for Wood Composites and Wood Chemistry, Kompetenzzentrum Holz GmbH, Altenberger Straße 69, 4040 Linz, Austria

F. Hesser et al. (eds.), *Progress in Life Cycle Assessment 2021*,
Sustainable Production, Life Cycle Engineering and Management,
https://doi.org/10.1007/978-3-031-29294-1_5

5.1 Introduction

In light of the global need to deal with the predicted consequences of anthropogenic generated climate change, it has become imperative to implement strategies for atmospheric CO_2 reduction (IPCC 2022). An increase in global soil organic carbon (SOC) stocks is considered one of the most promising and important climate change mitigation (CCM) strategies to date (Minasny et al. 2017), as indicated at the 21st Conference of the Parties in Paris in 2015, where the “4 per 1000 soils for Food Security and Climate” initiative was launched. It was proposed that with an annual increase of 0.4% of SOC stocks in the top soil layers (within 1 m), a reduction of 20–35% of global anthropogenic greenhouse gasses (GHG) emissions could be achieved, allowing nations committed to the Paris accord to make significant strides towards that goal (Fantin et al. 2022; Rumpel et al. 2020).

Considering the increase in biomass demand for material use and renewable energy (Schmidt-Walter 2019), SRP might help to provide another source of woody material (Buchholz et al. 2005; Zanchi et al. 2013). The cultivation of fast-growing trees, such as poplar (*Populus*) in SRP like short rotation coppice, agricultural wood production, short rotation wood cultivation) has been presented as an attractive agricultural practice to provide woody bio-mass and simultaneously increment SOC stocks, particularly when substituting previous agricultural land or marginal land (Don et al. 2012). Compared to annual crops, SRP are perennial crops that lower soil disturbance, which allows better incorporation of root and leaf litter into the soil, consequently maintaining or generating SOC accumulation (Don et al. 2012).

Growing number of scientific research studies on Life Cycle Assessments (LCA) of SRPs and their potential contribution to climate change mitigation demonstrate the relevance of estimating SOC dynamics to evaluate the mitigation potential and develop strategies that support the sustainable management of SRP (Clarke et al. 2019; Lockwell et al. 2012; Petersen et al. 2013; Rytter et al. 2015). For instance, by identifying the agricultural practices that affect SOC accumulation, strategies to increase SOC in SRP can be deduced. A main issue in deducing such strategies is the challenge of calculating SOC ex-ante to SRP establishment when primary data is still absent (Rowe et al. 2020). As for previous LCA studies (e.g., Barancikova et al. 2010; Berhongaray et al. 2017), the focus of this study is mainly on SOC computation, however, with the specific goal of closing the knowledge gap regarding modeling of SOC for SRP ex-ante to its establishment.

Methods for assessing SOC changes in agricultural LCA have been previously classified between those based on observation, emissions factors, and simulation models (Goglio et al. 2015. Observation methods are grounded in direct field measurements, providing the highest certainty level of primary data for LCAs (e.g., McClean 2014; Pacaldo et al. 2013). However, the long-term nature of SRP and the inherent required time (e.g., one year) to accumulate SOC, inhibit performing direct measurements and consequently they are not viable for early assessments. Emissions factors, such as those used by the IPCC Tier 1 method (IPCC 2019), were developed from national and international statistical data; however, they lack spatial and temporal precision to account for site-specific soil and climate characteristics (Hillier et al. 2009). Alternatively, carbon turnover (CT) simulation models (e.g., RothC) allow for the integration of soil (e.g., clay content) and climate (e.g., temperature changes) effects. Goglio et al. (2015) classified CT models between Simple Carbon Models (SCM), and Dynamic Crop-climate-soil Models (DCM). SCM involves a simpler set of equations, as they do not include crop production interactions and are usually operated on a monthly or yearly basis. DCM includes the interactions between crop production, SOC change, Nitrogen cycles, and GHG emissions on a daily time-step basis (e.g., CENTURY, DNDC). Nevertheless, for both SCM and DCM, the results are fully dependent on the model's calibration and the data entry into the models (Goglio et al. 2015; Rampazzo Todorovic et al. 2010). In comparison to DCM, SCM are easier to implement due to lower data requirement. Such A characteristic makes SCM an attractive option for estimating soil carbon accumulation ex-ante to SRP establishment or in early phases. Nevertheless, there are at least three critical challenges that make implementing models to quantify soil organic carbon dynamics/stocks difficult in the context of recently established SRP and SOC predictions: (1) SCT model accuracy depends on the availability and quality of data to calibrate the models to similar field conditions (Ericsson 2015; Fantin et al. 2022); (2) Heterogeneity of local conditions (e.g., soil type, microclimate) and its spatial effects (Goglio et al. 2015); (3) Accounting for the plantation's lifetime (Harris et al. 2015).

The present study aimed to analyze these three challenges, as well as deliver suggestions on how to deal with them in the context of implementing SCT models for predicting SOC dynamics, and subsequent effects on climate impacts of Poplar SRP during the early stages of establishment. Moreover, by predicting the SOC dynamics at an early stage, we attempted to deduce agricultural strategies that support SOC accumulation in SRP. Therefore, a case study of a Slovakian SRP was studied. The case investigated is part of the European funded demonstration project Dendromass for Europe (D4EU), which aims to establish sustainable SRP-based regional dendromass cropping systems on marginal land that feeds its dendromass into the production of bio-based products.

The specific objectives of the study are to:

1. Calculate the potential SOC accumulation of Poplar under the site conditions at Brodské, Slovakia by using a SCT model.
2. Assess the climate impacts from growing Poplar SRC in a 5, 10 and 20-year timespan.
3. Identify the factors that affect predicting SOC dynamics during the early stages of an SRC value chain.

5.2 Methods

The objectives of the study were addressed through the combination of a literature review and experiences from a case study described below (Sects. 5.2.1 and 5.2.2). The carbon turnover model RothC V.26.3 by Coleman and Jenkinson (2014) was used to model SOC levels. The RothC model was selected since it is one of the most used SCM implemented in LCA (Albers et al. 2020). Subsequently, the results were combined with the results of an LCA study (Perdomo et al. 2021) to estimate the climate impacts of growing Poplar SRC in a 5-, 10- and 20-year timespan, which is the five-year rotation cycle for harvesting the woody material. The climate impacts were assessed based on the Global Warming Potential 100 (GWP_{100}) indicator. Within the following sub-sections, the case study and the SOC calculations are described.

5.2.1 System Description

The Poplar SRP was planned for a cultivation of 20 years with a five-year harvesting cycle. As illustrated in Fig. 5.1, the first operational step is preparing the land for planting the poplar rods with the activities of heavy disking, ploughing, and harrowing. The rods were planted by combining manual labor and machinery. During the first four years of plantation, disk harrowing was necessary for weed control. Singling and partially pruning were done manually to select the supporting dominant shoot, as such a step was necessary after every harvest. In the harvesting phase, a multi-stem fully mechanized harvesting approach was implemented every fifth year. The last harvest is done after 20 years to complete four harvesting cycles. It is assumed that the end of the life of the plantation is constituted by ploughing the land and extracting the wood stems and roots so that the land can be converted back to annual arable cultivation conditions. It must be noted that the effects of recultivating the land after 20 years of SRP cultivation were only accounted for in the calculations of the potential environmental impacts of the agricultural operations. The consequences of ploughing the land, wood stems, and root extraction were not considered within the SOC stock estimation. Such exclusion presents a limitation of the present study, and it is justified by the lack of SOC primary data. Firstly, the collection of such data was not possible since the plantation's end of life has not been reached yet, making the data collection unviable. Secondly, as this data is not available, it was decided to not model the end of life effects as the SCM RothC V.26.3 carbon turnover model needs reference data to reduce the uncertainties of the results. Nevertheless, the relevance of the impacts of plantations' end of life on SOC is deliberated within the discussion section.

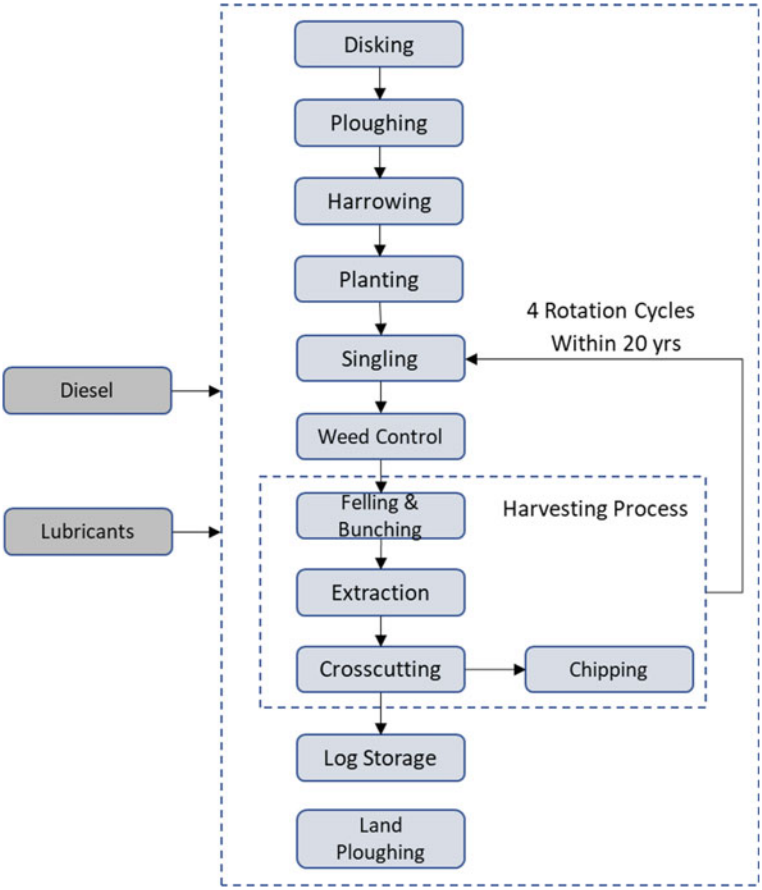


Fig. 5.1 Flow diagram for SRP production system

5.2.2 Site Conditions and Field Data

The SRC plantation is in Malacky, within the Pannonian Basin. Primary climate data, such as temperature and precipitation (Table 5.1), were measured in Brodské, Slovakia (Fontenla-Razzetto et al. 2022). Since Brodské and Malacky are located within the Pannonian Basin it was assumed that the climate data were transferable for both areas, since both areas are within the same biogeographic region. The former land use was a cornfield, which presented an SOC content at 0–30 cm soil depth of 37.8 t ha^{-1}, with a bulk soil density of 1.25 t $(m^3)^{-1}$, and 4.9% clay content (Rossi 2018). Field trails estimated an average poplar yield of 8.1 dry t ha^{-1}.

Table 5.1 Climate data used for RothC V.26.3 (modified from Fürtner et al. 2022)

Date	Average mean temperature (°C)	Average mean precipitation (mm)	Average mean ETP Penman–Monteith (mm)
May.18	20.40	1.00	4.107
Jul.18	20.95	1.23	4,002
Sep.18	16.03	3.56	2.02
Nov.18	9.02	0.47	0.34
Jan.19	0.17	1.51	0.43
Mar.19	7.17	0.76	0.97
Jun.19	22.02	1.06	4.56
Aug.19	21.17	1.69	3.25
Oct.19	10.86	0.92	0.68
Dec.19	2.52	1.65	0.16
Feb.20	5.59	1.0	0.84
Mar.20	5.85	0.76	1.39

5.2.3 Soil Organic Carbon Modeling

The RothC V.26.3 carbon turnover model was used to estimate the SOC levels during a 20-year timespan. The model has been used to evaluate carbon turnover in arable soils in England; nevertheless, its use has extended to other ecosystems by calibrating the model to site-dependent conditions (Barancikova et al. 2010). SOC in non-waterlogged surface soils is calculated in a monthly time step as a function of vegetation cover, climate conditions, soil type, and soil management. The model is based on the physical–chemical interactions of four active pools, such as Resistant Plant Material (RPM); Decomposable Plant Material (DPM); Microbial Biomass (BIO); Humified Organic Matter (HUM), and one inactive pool Inert Organic Matter (IOM), which is not involved in the turnover processes. The RothC model was calibrated to the SRP site climate condition based on the procedures Rampazzo Todorovic et al. (2010) described. Thus, the RothC model was translated to a Microsoft Excel spreadsheet, where inverse modeling was used to integrate the site climate conditions and calculate the model initialization parameters (RPM, DPM, RPM, and BIO) which are based on the distribution of initial SOC (SOC_{in}) (Morais et al. 2018). As presented in Fig. 5.2, before the calibration procedure, the measured SOC_{in} (SOC_{in} MS), % clay content, and climate data as Temperature (T), Pressure (P) and Evapotranspiration (ET) were entered into the model as constant variables. Afterward, the calibration was done by modifying the plant input data until the SOC_{in} (MS) and calculated SOC_{in} (SOC_{in} (C)) had reached a root square mean error below 0.5. After the match between SOC_{in} (MS) and SOC_{in} (C) was achieved, the new model initialization parameters (IOM, RPM, HUM and BIO) were utilized to represent the distribution of organic C in the soil pools. Figure 5.3 presents the calibration results.

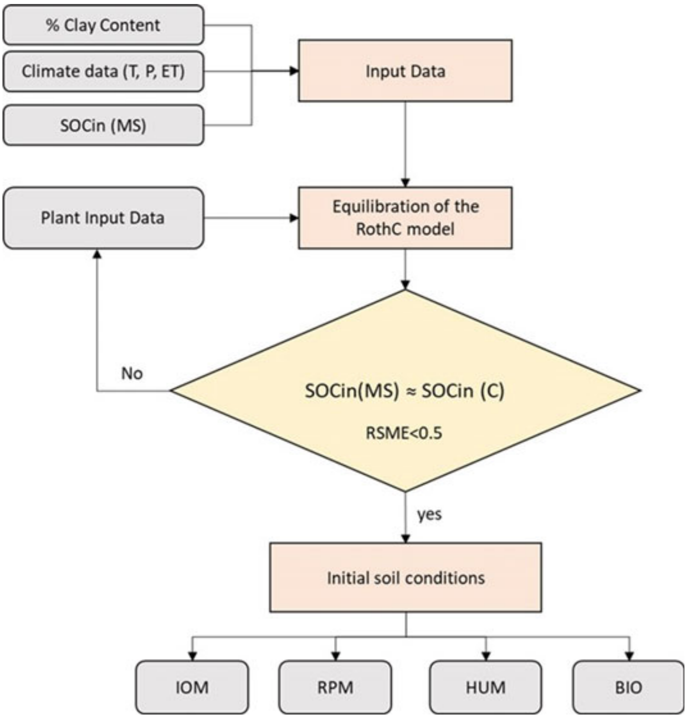


Fig. 5.2 Calibration process of RothC model

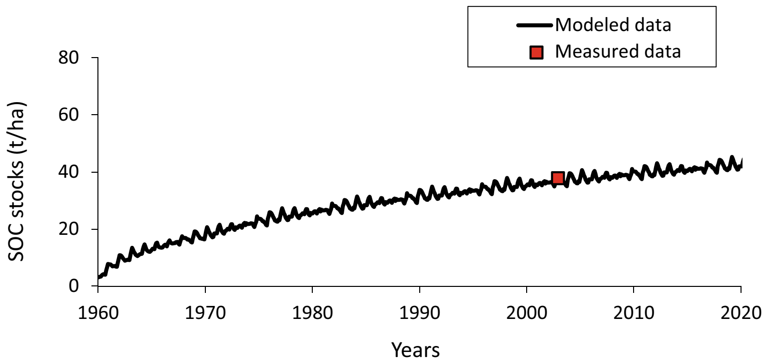


Fig. 5.3 Results of calibration of RothC model

SOC predictions were calculated after the carbon turnover model was calibrated. The main input data were plant carbon input, which was divided between belowground and aboveground carbon input (BGC and AGC). For the AGC, it was assumed that during the harvesting event, no woody material was left on the field; thus, the only carbon input comes from the leaf material. As no direct measurements for either AGC and BGC were available, it was necessary to estimate the inputs based on empirical equations and previous field data. Thus, following Eqs. 5.1, 5.2, and 5.3 by Gorgan and Matthews (2002) both carbon pool inputs were estimated. The procedure is described below.

$$\text{Aboveground input}\ \left(W_{Cin};\ t_C ha^{-1}\right):\quad W_{Cin} = \frac{LAI \cdot f_C}{SLA} + W_{AG}, f_{wa} \qquad (5.1)$$

where,

W_{Cin} = Aboveground carbon input in tons (t_C) per ha (from leaves and wood);

LAI = Leaf Area Index;

f_C = fraction of carbon in leaves;

SLA = Specific Leaf Area;

W_{AG} = Carbon input from woody material (assumed to be zero);

f_{wa} = fraction of carbon in woody material.

The SLA and LAI were estimated by combining primary data from a previous field study (Heilig et al. 2020), and by corresponding regression analysis between variables. The field study provided the following: diameter at breast height (DBH), height (m), and leaf area index (LAI), as in Table 5.2 such values were used to estimate the missing LAI for the subsequent years (displayed as "?" in Table 5.2). The procedure is visualized in Figs. 5.4 and 5.5.

Parting from a similar procedure, Eq. 5.2 presents the method from Gorgan and Matthews (2002) to estimate BGC input. The first part of the equation represents input due to fine root turnover (root senescence, root respiration, and root rhizodeposition), whereas the second part considers the input due to death and decay of structural roots. Table 5.3 presents a summary of the data used to calculate the BGC input. As shown, a combination of literature and primary data was used. Primary data were available

Table 5.2 Relationship between measured and calculated tree parameters (Heilig et al. 2020)

Age	DBH (cm)	h (m)	Leaf area index
2.5	2.7	4.1	0.35
2.5	3	5.4	0.56
3.5	5.4	7	1.38
3.5	8.4	7.7	2.77
3.5	11.4	9.5	5.01
4	9.7	9.9	?
4	8.3	8.7	?
5	15.2	12	?
6	?	?	?

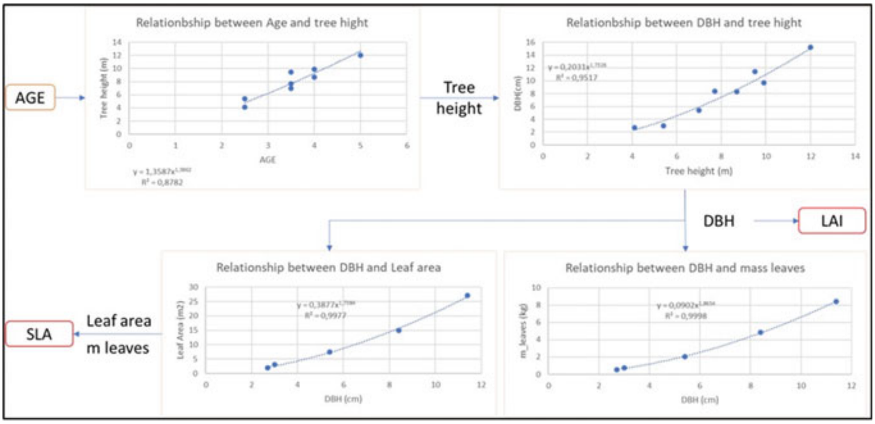


Fig. 5.4 Procedure for estimating SLA and LAI

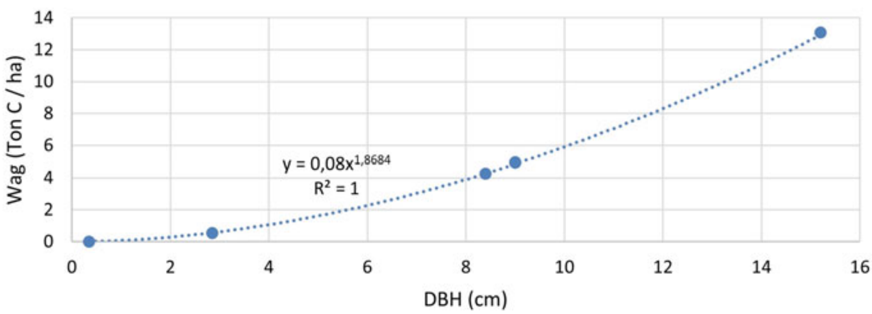


Fig. 5.5 Estimated Relationship between DBH and aboveground carbon input

from previous field studies.

$$\text{Belowground input } \left(W_{Rin};\ t_C ha^{-1}\right): \quad W_{Rin} = W_{yield},\ Fr,\ F_{frto} + W_{BG} \cdot f_{wb} \quad (5.2)$$

where, belowground carbon input in tons (t_C) per ha

W_{yield} = Above ground yield;

Table 5.3 Belowground carbon input data

F_{frto}	0.85	(Grogan P.* and Matthews 2002)
Fr	0.205	Primary data (Meyer M. et al., 2021)
W_{yield} (t_C ha^{-1} a^{-1})	3.85	Primary data provided by project partners
W_{BG} (t_C ha^{-1} a^{-1})	0.788	Primary data provided by project partners
T	5	Number of years since the last coppicing cycle

Fr = Root to Shoot Ratio;

F_{frto} = Fraction of below ground carbon lost due to fine root turnover;

W_{BG} = Weight of carbon below ground in the root system;

f_{wb} = fraction of the below ground carbon input that enters the fresh carbon.

The total plant carbon input C_i was estimated by summing the above and belowground carbon input as presented in Eq. 5.3.

$$\text{Total plant carbon input } \left(C_i;\ t_C ha^{-1}\right):\quad C_i = W_{Cin} + W_{Rin} \tag{5.3}$$

5.2.4 *Sensitivity Analysis*

Based on information from previous field studies and literature data, a sensitivity analysis was conducted by varying the value of one parameter, while maintaining the others constant. The main three observed parameters were soil conditions with the indicator of % clay, aboveground wood production, and time horizons. The parameters were selected in order to understand the effects of data variability, heterogeneity in local conditions, and different time horizons. Consequently, it was assumed that climate conditions would remain constant. Furthermore, the results of the sensitivity analysis scenarios were compared to the total climate impact from agricultural operations, which were previously estimated through an LCA study (Perdomo et al. 2021).

5.3 Results

5.3.1 *Prediction of SOC*

Starting from the initial SOC content of 37.8 t_C ha^{-1} before the land use changes from annual cropping to SRP, the results indicate that after 20 years there is SOC accumulation to about 48.52 t_C ha^{-1} (Fig. 5.6), corresponding to a total annual average increase of 0.535 t_C ha^{-1} a^{-1}. During the first four years of plantation, a decrease of approximately 9.1% in SOC occurred due to less carbon input from AGC and BGC compared to the carbon turnover processes of the SRC plantation. After the 5th year, SOC increased above the initial amount; however, during the first years after the first harvesting event, SOC stocks decreased. Approximately, after year 10, when the second harvest occurred, SOC stocks remained above the initial SOC levels. These results indicate that for the poplar SRC plantation case study, it takes approximately 10 years for the SOC stocks to be constantly above the initial SOC.

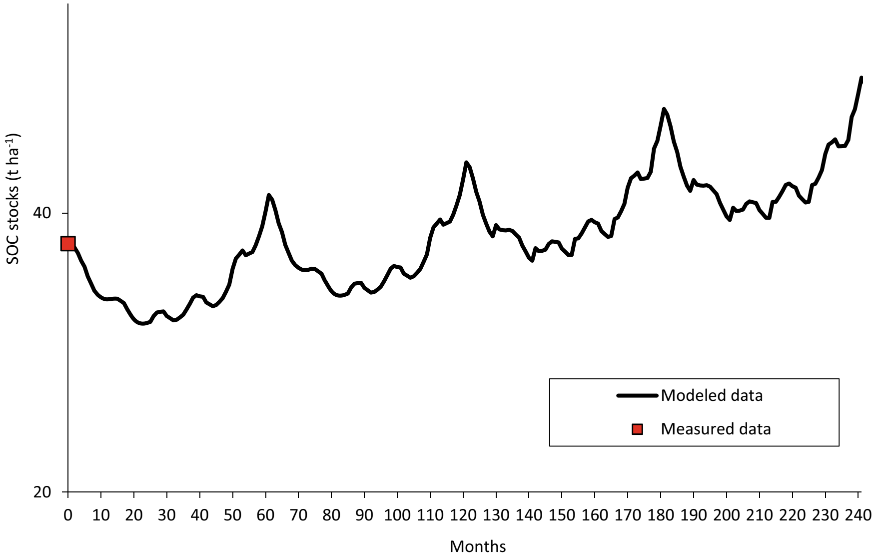
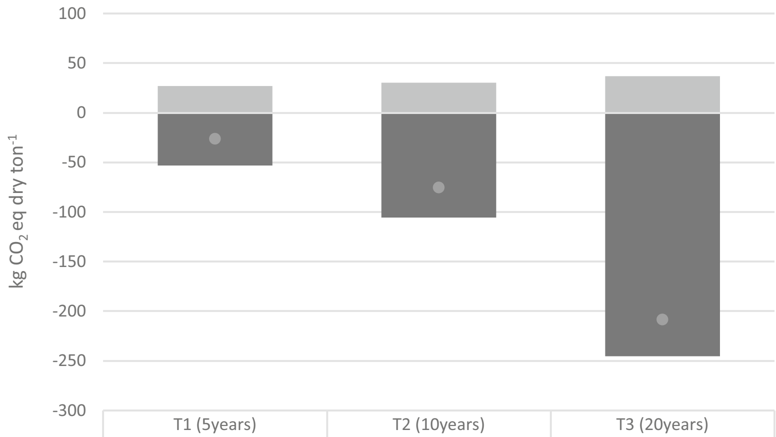


Fig. 5.6 SOC stocks during 20 years of plantation

5.3.2 *Influence of Plantation Lifetime*

The sensitivity analysis results for the net SOC stocks, the climate impacts from the agricultural operation, and the net carbon balance are shown in Fig. 5.7. A negative value of carbon balance means that there is a net decrease of GHG concentration in the atmosphere, consequently generating a CM effect. Considering the scenarios T1 (5 years), T2 (10 years), and T3 (20 years), the results (Fig. 5.7) show how the scenarios with the lowest lifetime have a lower SOC accumulation and consequently a smaller amount of net carbon mitigation. The influence of the plantations lifetime can be further understood by the results of the carbon fluxes (Fig. 5.8). During the first two years, and after each harvesting event, the carbon turnover processes generate higher amounts of emitted carbon to the atmosphere than the carbon sequestered by the trees. Thus, positive values (Fig. 5.8) of carbon flow (t ha^{-1}) occur. After the third year of the initial plantation and each harvesting event, the amount of carbon sequestered is higher than the emitted carbon. Moreover, it is between years four and five, when the negative carbon fluxes (Fig. 5.8) generate a higher SOC stock than the initial SOC (Fig. 5.6). We noticed that the increases in SOC accumulation through the plantation's lifetime outstand the emissions from the agricultural operation. Hence, the climate mitigation potential increases substantially together with the SRP lifetime since higher levels of SOC accumulation are achieved. It must be noted that the effects related to recultivation were only accounted for in the calculations of the potential environmental impacts of the agricultural operations—the SOC could not be modeled due to a lack of data.



	T1 (5years)	T2 (10years)	T3 (20years)
Agricultural operations	27	30	37
SOC	-53	-106	-245
Net Balance	-26	-75	-209

Fig. 5.7 Sensitivity analysis for plantation lifetime. Net carbon balance

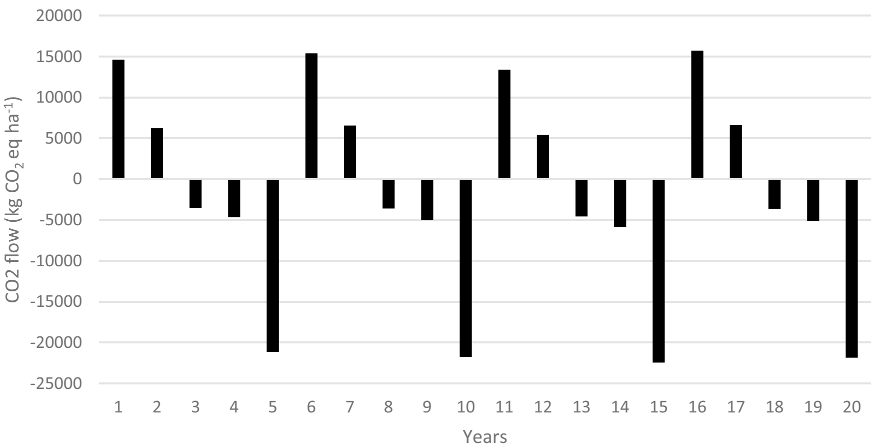


Fig. 5.8 Result of the carbon fluxes (difference between carbon emitted to the atmosphere and carbon sequestered)

5.3.3 Influence of Clay Content

The heterogeneity of soil conditions was assessed by changing the clay content between 3.7 and 10.60%. The scenarios analyzed are presented in Table 5.4. As a consequence of different clay contents, the SOC varies from about 48 to 51 t_C ha^{-1} (Fig. 5.9). The higher the clay content, the higher the SOC accumulation. During the

Table 5.4 Scenarios for soil heterogeneity based on different clay content

Scenarios	% of Clay
S1	3.70
S2	4.20
SBase	4.95
S3	7.60
S4	10.66

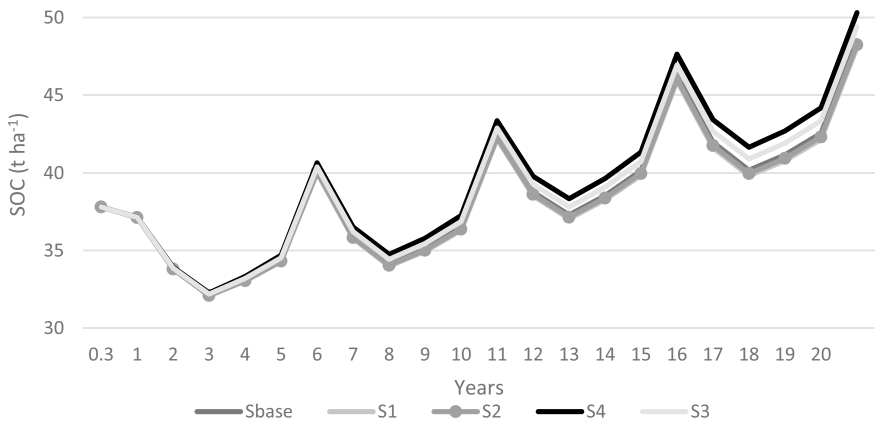


Fig. 5.9 Predicted relationship between clay content and SOC stocks

first six years, the impact of different clay content can be considered to be indifferent, as the differences between the scenarios are minimal. However, after the seventh year, the scenarios with the higher clay content (S3 and S4) start to show greater SOC levels. The impact of different clay contents is reflected in the total carbon balance of the system, which varies between −37.64 and −45.89 t_{CO2eq} ha^{-1}, indicating that the system acts as a carbon sink.

5.3.4 Influence of Aboveground Wood Production

To understand the influence of different yield amounts on SOC, the sensitivity analysis varied the aboveground wood production (AGWP) between the annual averages of 5 (Y1), 8 (Ybase), and 10 (Y3) dry tons. The results presented in Figures SM 5.1 and SM 5.2 (electronic supplementary material) show a minimal difference between the studied scenarios. For example, scenarios Y1 and Y3, which represent the 5 and 10 dry ton $year^{-1}$ scenarios, result in a relative difference of the SOC of 0.003%.

5.4 Discussion

5.4.1 *Plantation Lifetime and Consideration of Wood-Carbon in the C-Balance*

The analysis of the SRP revealed that its cultivation within a 20-year period can potentially mitigate climate change, as it presents a net SOC sock (Fig. 5.7). Previous studies on SRP have indicated similar results. For instance, Mishra et al. (2013) showed how the conversion from cropland to SRC-based miscanthus presented an SOC rate of 0.16–0.82 t_C ha^{-1} a^{-1}. Besides the benefits during the plantation lifetime, Whittaker et al. (2016) discussed how the end of life of the plantation, specifically, the land rehabilitation steps to recultivate the land to other land use, could disturb the SOC levels and reverse the CM benefits gained. Therefore, the carbon sequestration effect could be temporary and is dependent on the impact of the recultivation method used to terminate the plantation, as well as the subsequent land use applied. Contrary, Wachendroft et al. (2017) reported that the SOC accumulation in coarse SRP could last even after years of termination, mainly when stumps and roots that are broken down are left in the field. This emphasizes the importance of including the impacts of land transformation on SOC stocks accounting. Furthermore, it is essential that management plans also consider the factors that could reduce the CM effect. For example, regarding management plans, Rowe et al. (2020) mentioned the post-removal land management and the longevity of the SRC crop prior to reversion and soil type. Such discussion shows how considering the plantations lifetime already at the early stages of the project development supports the knowledge of the potential climate mitigation benefits of SRC plantations. For example, by knowing the potential SOC accumulation, the carbon payback period, which indicates the minimum years that are needed for sufficient SOC to accumulate and overcome emissions from agricultural practices and the generation of related products, could be estimated (Jonker et al. 2014).

5.4.2 *Soil Conditions and SOC*

The heterogeneity in land conditions was represented by analyzing the influence of different clay content values on SOC stocks. The analysis presented that soils with higher clay content result in greater SOC accumulation, indicating that clay content is an important factor driving the CM potential of SRP. Moreover, the results indicate the importance of understanding and accounting for heterogeneity in soil conditions. Especially, for SRP that extend to large plantation areas where geographical variation and greater heterogeneity in soil conditions are likely, accounting for such heterogeneities is of most importance. Similar findings have been recorded by Agostini et al. (2015), in which they discuss the effect of clay content on carbon retention and storage in soil, with an emphasis on its role in long-term carbon retention. The influence of clay content has been previously mentioned; for example, Jagadamma and Lal (2010) reported that the clay fraction of agricultural soils accumulated more SOC than other fractions (e.g., sand and silt fraction). Adding to this knowledge, Zhong et al. (2018) mention that the relationship between SOC and clay content is strongly influenced by climate conditions, particularly due to moisture conditions.

Besides clay content, another relevant factor influencing the net CM effect is the effect of initial SOC stocks, which are also dependent on the previous land use (Hillier et al. 2009). Parting from this knowledge, it is estimated that if for our case study the initial SOC stocks were below 34 t C ha^{-1}, combined with low clay content and a short project lifetime of 5 years, the net carbon balance would tend to be positive, thus reducing the CM effect.

5.4.3 Aboveground Carbon and SOC

There is a minimal influence of AGWP on SOC stocks (Fig. 5.9), as Peterson and Lajtha (2013) uncovered. The authors expected a positive relationship between AGWP and SOC due to the link between AGWP and leaf fall to carbon input. However, no correlation to SOC stocks, C content of the soil, or the dissolved organic carbon pool was found. An additional explanation of this result is the influence of the assumptions carried in the calculations of carbon plant input. First, it was assumed that the total aboveground wood and branches were fully collected during the harvest process; thus, the only carbon input was generated from leaf carbon input (Eq. 5.1). For estimating the leaf carbon input, the correlations presented in Fig. 5.4 show the relationship between the variables: tree age, tree height, leaf area index, and specific leaf area. However, it was not possible to establish a relationship between the previous variables and aboveground wood production (yield). Hence, it was assumed that for the scenarios (Y1, Y2, and Y3), the leaf carbon input remained constant as in the initial base case. Second, the aboveground wood production influences the carbon input through the root system (Eq. 5.2). Though, the effects due to the increase or decrease in wood yield to the root system were minimal. Therefore, the total carbon input from the scenarios studied (Y1, Y2 and Y3) had little influence on the total SOC accumulated. Similar conclusions were discussed by Hillier et al. (2009), who highlighted that variations in SOC for SRP were mainly due to the calibration of plant carbon input to soil vs yield, rather than only production yields, thereby emphasizing the need for calibration based on primary data. In conclusion, to better understand the influence of aboveground wood production, it would be necessary to deal with the assumptions described above.

5.4.4 Data and SOC Calculation

The scarcity of data is one of the biggest challenges in determining the potential CM effects of SRC-based projects. The influence of spatial heterogeneity, as clay content, indicates that SOC should be estimated at several locations within the SRP, particularly, for projects with large plantation areas. Thus, agreeing with Kalita et al. (2021), the estimation of SOC stocks should not be transferable between projects in, for instance, different geographical regions.

5.5 Conclusion

The importance of estimating the potential SOC accumulation is demonstrated by its influence on the total carbon balance of SRP production systems. Particularly, as mentioned in the Introduction, the estimation of SOC levels ex-ante or during early stages of the plantation establishment and its potential evolution during the plantation's lifetime can serve to design strategies that aid in achieving a climate mitigation effect. For instance, through the case study and sensitivity analysis in this study, the following suggestions are derived:

(i) In terms of the management plan for SRC plantations, it is suggested that during the conversion from previous land use to SRP, soil disturbances that have a negative impact on SOC stocks should be reduced (e.g., soil tillage);
(ii) Plantation maintenance, such as weed control, should be carried out by methods that have a low negative or even a positive impact on SOC stocks, for instance, manual instead of mechanical weed control;
(iii) Regarding the data collection for predicting SOC levels, decision-makers should develop a monitoring plan at the early stages of the project that involves the collection of yield, soil, climate data. Such data would serve to run the first modeling of SOC dynamics, as well as update the model together with the plantation development. Consequently, a feedback loop between data input and SOC modeling is elaborated;
(iv) Knowing the initial SOC from previous land use is essential for predicting the potential CM effect. Thus, within the project management plan, representative soil samples should be taken before the plantation's establishment;
(v) After predicting the potential development of SOC, the payback period necessary for the project to have a climate mitigation effect should be estimated.
(vi) In order to estimate accurately the potential carbon mitigation effect of SRC projects, it is necessary to include the impacts of the plantation's end of life.

In conclusion, integrating the prediction of SOC stocks into the early development stages of a SRP-based project can help project managers understand the potential CM benefits of the project, and also support the planning of sustainable management strategies that improve the CM effect. Data on SOC generated ex-ante are expected to play an important role for evaluation and decision-making including environmental considerations of investments This provides arguments for establishing such a plantation on lands where the SOC stocks could be improved by SRP. The present study has highlighted the relationship between plantation lifetime, clay content, aboveground biomass, and SOC accumulation. Thus, it shows the importance of designing SRP projects that include consistent evaluation of SOC stocks from the very beginning of the project development, as this would determine the potential CM benefits.

Acknowledgements This work received funding by the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement number 745874 and the Austria Research Promotion Agency (FFG) under the COMET program grant number 865905.

References

Albers A, Avadí A, Benoist A, Collet P, Hélias A (2020) Modelling dynamic soil organic carbon flows of annual and perennial energy crops to inform energy-transport policy scenarios in France. Sci Total Environ 718:135278. https://doi.org/10.1016/j.scitotenv.2019.135278

Agostini F, Andrew S, Goetz G, Richter M (2015) Carbon sequestration by perennial energy crops: is the jury still out? BioEnergy Res 8(3):1057–1080. https://doi.org/10.1007/s12155-014-9571-0

Barancikova G, Halás J, Gutteková M, Makovníková J, Nováková M, Skalský R, Tarasovičová Z (2010) Application of RothC model to predict soil organic carbon stock on agricultural soils of Slovakia. Soil Water Res 5:1–9. https://doi.org/10.17221/23/2009-swr

Berhongaray G, Verlinden MS, Broeckx LS, Janssens IA, Ceulemans R (2017) Soil carbon and belowground carbon balance of a short-rotation coppice: assessments from three different approaches. GCB Bioenerg 9:299–313. https://doi.org/10.1111/gcbb.12369

Buchholz T, Volk TA, Tennigkeit T, Da Silva IP (2005) Designing decentralized small-scale bioenergy systems based on short rotation coppice for rural poverty alleviation. 2–5

Clarke R, Sosa A, Murphy F (2019) Spatial and life cycle assessment of bioenergy-driven land-use changes in Ireland. Sci Total Environ 664:262–275. https://doi.org/10.1016/j.scitotenv.2019.01.397

Coleman K, Jenkinson DS (2014) RothC—a model for the turnover of carbon in soil

Don A, Osborne B, Hastings A, Skiba U, Carter MS, Drewer J, Flessa H, Freibauer A, Hyvönen N, Jones MB, Lanigan GJ, Mander Ü, Monti A, Djomo SN, Valentine J, Walter K, Zegada-Lizarazu W, Zenone T (2012) Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. GCB Bioenerg 4:372–391. https://doi.org/10.1111/j.1757-1707.2011.01116.x

Ericsson N (2015) Time-dependent climate impact of short rotation coppice willow-based systems for electricity and heat production. Acta Universitatis Agriculturae Sueciae. Swedish University of Agricultural Sciences. https://doi.org/10.13140/RG.2.1.3508.0164

Fantin V, Buscaroli A, Buttol P, Novelli E, Soldati C, Zannoni D, Zucchi G, Righi S (2022) The RothC model to complement life cycle analyses: a case study of an Italian olive grove. Sustainability (Switz) 14. https://doi.org/10.3390/su14010569

Fontenla-Razzetto G, Wahren FT, Heilig D et al (2022) Water use of hybrid poplar (Populus deltoides Bart. ex Marsh × P. nigra L. 'AF2') growing across contrasting site and groundwater conditions in western Slovakia. Bioenerg Res

Fürtner D, Perdomo Echenique EA, Hörtenhuber SJ, Schwarzbauer P, Hesser F (2022) Beyond monetary cost-benefit analyses: combining economic, environmental and social analyses of short rotation coppice poplar production in Slovakia. Forests 13(2):349

Goglio P, Smith WN, Grant BB, Desjardins RL, McConkey BG, Campbell CA, Nemecek T (2015) Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. J Clean Prod 104:23–39. https://doi.org/10.1016/j.jclepro.2015.05.040

Grogan P and Matthews R (2002) A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use Manage 18(3):175–183. https://doi.org/10.1111/j.1475-2743.2002.tb00237.x

Harris ZM, Spake R, Taylor G (2015) Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioenerg 82:27–39. https://doi.org/10.1016/j.biombioe.2015.05.008

Heilig D, Heil B, Kovács G, Veperdi (2020) Deliverable 2.3 field trials, growth inventory

Hillier J, Whittaker C, Dailey G, Aylott M, Cassela E, Richter GOETZM, Riche A, Murphy R, Taylor G, Smith P (2009) Greenhouse gas emissions from four bioenergy crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenerg 1:267–281. https://doi.org/10.1111/j.1757-1707.2009.01021.x

IPCC (2019) Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. In: Generic methodologies applicable to multiple land (Chapter 2), pp 1–96

IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Contribution of Working Group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press. In Press

Jagadamma S, Lal R (2010) Distribution of organic carbon in physical fractions of soils as affected by agricultural management. Biol Fertil Soils 46:543–554. https://doi.org/10.1007/s00374-010-0459-7

Jonker JGG, Junginger M, Faaij A (2014) Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. GCB Bioenerg 6:371–389. https://doi.org/10.1111/gcbb.12056

Kalita S, Potter HK, Weih M, Baum C, Nordberg Å, Hansson PA (2021) Soil carbon modelling in salix biomass plantations: variety determines carbon sequestration and climate impacts. Forests 12. https://doi.org/10.3390/f12111529

Lockwell J, Guidi W, Labrecque M (2012) Soil carbon sequestration potential of willows in short-rotation coppice established on abandoned farm lands. Plant Soil 360:299–318. https://doi.org/10.1007/s11104-012-1251-2

McClean GJ (2014) The impact of land-use change for lignocellulosic biomass crop production on soil organic carbon stocks in Britain. The University of Edinburgh

Meyer M, Morgenstern K, Heilig D, Heil B, Kovács G, Leibing C, Krabel D (2021) Biomass allocation and root characteristics of early-stage poplars (populus spp.) for assessing their water-deficit response during SRC establishment abstract. BioEnergy Res 14(2):385–398. https://doi.org/10.1007/s12155-021-10264-6

Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z, Cheng K, Das BS (2017) Soil carbon 4 per mille. Geoderma 59–86

Mishra U, Torn MS, Fingerman K (2013) Miscanthus biomass productivity within US croplands and its potential impact on soil organic carbon. GCB Bioenerg 5:391–399. https://doi.org/10.1111/j.1757-1707.2012.01201.x

Morais TG, Silva C, Jebari A, Álvaro-Fuentes J, Domingos T, Teixeira RF (2018) A proposal for using process-based soil models for land use life cycle impact assessment: application to Alentejo, Portugal. J Clean Prod 192:864–876

Pacaldo RS, Volk TA, Briggs RD (2013) No significant differences in soil organic carbon contents along a chronosequence of shrub willow biomass crop fields. Biomass Bioenerg 58:136–142. https://doi.org/10.1016/j.biombioe.2013.10.018

Perdomo EEA, Brunnhuber N, Hesser F (2021) Deliverable 5.5 integration of LCA in value chain establishment: preliminary results. https://cordis.europa.eu/project/id/745874/results

Petersen BM, Knudsen MT, Hermansen JE, Halberg N (2013) An approach to include soil carbon changes in life cycle assessments. J Clean Prod 52:217–224. https://doi.org/10.1016/j.jclepro.2013.03.007

Peterson FS, Lajtha KJ (2013) Linking aboveground net primary productivity to soil carbon and dissolved organic carbon in complex terrain. J Geophys Res Biogeosci 118:1225–1236. https://doi.org/10.1002/jgrg.20097

Rampazzo Todorovic G, Stemmer M, Tatzber M, Katzlberger C, Spiegel H, Zehetner F, Gerzabek MH (2010) Soil-carbon turnover under different crop management: evaluation of RothC-model predictions under Pannonian climate conditions. J Plant Nutr Soil Sci 173:662–670. https://doi.org/10.1002/jpln.200800311

Rossi V (2018) IKEA LUC guidance pilot: methodological points of the Slovakia case studies

Rowe RL, Keith AM, Elias DMO, McNamara NP (2020) Soil carbon stock impacts following reversion of Miscanthus × giganteus and short rotation coppice willow commercial plantations into arable cropping. GCB Bioenerg 12:680–693. https://doi.org/10.1111/gcbb.12718

Rumpel C, Amiraslani F, Chenu C, Garcia Cardenas M, Kaonga M, Koutika LS, Ladha J, Madari B, Shirato Y, Smith P, Soudi B, Soussana JF, Whitehead D, Wollenberg E (2020) The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49:350–360. https://doi.org/10.1007/s13280-019-01165-2

Rytter R-M, Rytter L, Högbom L (2015) Carbon sequestration in willow (Salix spp.) plantations on former arable land estimated by repeated field sampling and C budget calculation. Biomass Bioenerg. https://doi.org/10.1016/j.biombioe.2015.10.009

Schmidt-Walter W (2019) Evaluation of environmental impacts of short rotation coppice with regard to the amount and quality of groundwater recharge. Georg-August-University Göttingen

Wachendorf C, Stuelpnagel R and Wachendorf M (2017) Influence of land use and tillage depth on dynamics of soil microbial properties soil carbon fractions and crop yield after conversion of short-rotation coppices. Soil Use Manage 33(2):379–388. https://doi.org/10.1111/sum.2017.33.issue-2, https://doi.org/10.1111/sum.12348

Whittaker C, Macalpine W, Yates NE, Shield I (2016) Dry matter losses and methane emissions during wood chip storage: the impact on full life cycle greenhouse gas savings of short rotation coppice willow for heat. BioEnerg Res 9:820–835. https://doi.org/10.1007/s12155-016-9728-0

Zanchi G, Frieden D, Pucker J, Bird DN, Buchholz T, Windhorst K (2013) Climate benefits from alternative energy uses of biomass plantations in Uganda. Biomass Bioenerg 59:128–136. https://doi.org/10.1016/j.biombioe.2012.03.023

Zhong Z, Chen Z, Xu Y, Ren C, Yang G, Han X, Ren G, Feng Y (2018) Relationship between soil organic carbon stocks and clay content under different climatic conditions in Central China. Forests 9. https://doi.org/10.3390/f9100598