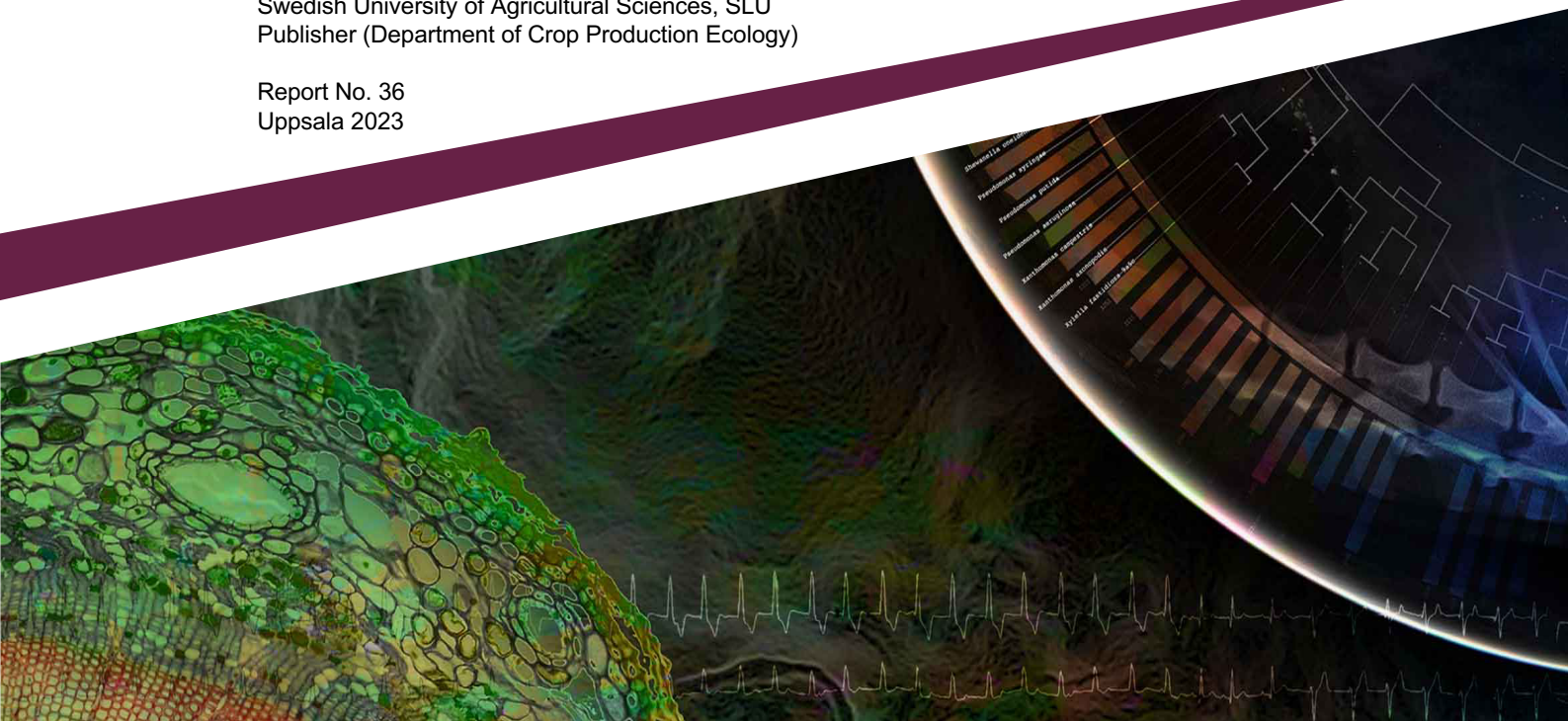
Carbon and energy balance of Lithuanian poplar plantations fertilized with pelleted sludge

Almir Karacic, Anneli Adler and Lorenzo Menichetti

Swedish University of Agricultural Sciences, SLU
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Summary

The NutriBiomass4LIFE project was designed to develop an operational-scale circular economic model for recycling sewage sludge in fast-growing poplar plantations. Using poplar plantations for sludge recycling also represents an opportunity to increase the area of poplars and the availability of raw materials for energy and other purposes. The carbon balance and energy efficiency of this system have been studied by combining Swedish and Lithuanian data and experiences. Our growth model relied mainly on Swedish data from stands grown on slightly different plantation design than the one currently deployed in Lithuania. Three different scenarios were analyzed: unfertilized, fertilized+10%, and fertilized+20%, the two fertilization scenarios representing yield increases of 10% and 20%, respectively. The presented growth models suggest an accumulation of 130- 156 Mg C per hectare over a 20-year rotation period, corresponding to an annual C-accumulation rate of 6.5–7.8 Mg per ha and year. Carbon stored in harvestable aboveground biomass ranged between 104 and 126 Mg per hectare, whereas an additional 25.6 to 30.2 Mg was allocated belowground in coarse roots and stumps. The total primary energy input varied between 101 and 127 GJ per hectare. Fertilized plantations require higher energy input, which is related to sludge spreading and biomass transport. Despite a higher biomass production in fertilized plantations, the energy balance was higher for unfertilized than for fertilized plantations, particularly if the calculation included the optional use of pelleted sludge for direct incineration in district heating plants. When excluding soil carbon change, the system produces a positive CO_2 flux, which is a bit lower for unfertilized compared to fertilized stands (2 respective 3.4 g CO_2 per MJ produced heat). However, due to the increase in soil carbon storage, the global warming potential (GWP100) of this system is negative in the range of -4.750 to -8.192 g CO_2-eq. per MJ produced energy.

Sammanfattning

Huvudsyftet med NutriBiomass4LIFE-projektet var att utveckla en cirkulär ekonomisk modell i stor skala för återvinning av avloppsslam genom gödsling av snabbväxande poppelodlingar. Slamåtervinning i poppelodlingar representerar också en möjlighet att öka arealen med poppel och därmed även tillgången till råvara nödvändig för energi och andra ändamål. Kol- och energibalanser av denna system har studerats genom att kombinera svensk och litauisk data och erfarenheter. Vår tillväxtmodell baserades främst på data från svenska poppelbestånd som etablerades med något annorlunda planteringsdesign jämfört med de odlingar som för närvarande planteras i Litauen. Tre olika scenarier analyserades: ogödslat, gödslat+10%, och gödslat+20%, där de två gödslingscenarierna representerar avkastningsökningar på 10% respektive 20%. De analyserade tillväxtmodellerna antyder en ackumulering av 130-156 Mg C per hektar under en rotationsperiod på 20 år, vilket motsvarar en årlig C-ackummulering på 6,5–7,8 Mg per hektar och år. Kol lagrat i avverkningsbar ovanjordisk biomassa varierade mellan 104 och 126 Mg per hektar, medan ytterligare 25,6 till 30,2 Mg allokerades under marken i grova rötter och stubbar. Den totala primära energiåtgången varierade mellan 101 och 127 GJ per hektar. Gödslade odlingar kräver högre energiåtgång, vilket är relaterat till spridning av slam och transport av biomassa. Trots en högre biomassaproduktion i gödslade odlingar var energibalansen högre för ogödslade än för gödslade odlingar, särskilt om beräkningen inkluderade avsättning av slampellets för direkt förbränning i fjärrvärmeanläggningar. Vid uteslutning av förändringar i markkol, producerar systemet en positiv CO_2-flöde, vilket är något lägre för ogödslade jämfört med gödslade bestånd (2 respektive 3,4 g CO_2 per MJ producerad värme). Däremot innebär kollagring i marken att den globala uppvärmningspotentialen (GWP100) för detta system blir negativ inom intervallet -4.750 till -8.192 g CO_2-ekv. per MJ producerad energi.

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1. Introduction

Transition to a circular economy and sustainable land and material use can be achieved by improving the availability of locally produced renewable materials. One such resource with high potential is woody biomass from fast-growing *Populus* plantations. Poplar plantations are highly efficient biomass producers capable of providing multiple ecosystem services. In the Nordic-Baltic context, poplar feedstock can be used for heat and electricity production or mixed with other wood sources for pulping industries. However, the potential utilization of poplar wood is much broader. It includes traditional wood products such as particle boards, panels, sawn timber, and packaging, but also novel technologies for the production of alcohol fuels, oils, and fibers in lignin-first processes (Adler et al., 2022).

The current and potential use of poplar wood and its economic impact largely depend on the feedstock supply. Our estimates suggest that the area of poplars and hybrid aspen grown in the Nordic-Baltic region is at most 10,000 hectares, with most of this area being planted in the recent decade. Poplars are mostly planted on set-aside agricultural land, but some plantations occurred even on forestland as a substitute or alternative tree species on storm-damaged spruce sites (Fahlvik and Böhlenius, 2022). It is difficult to predict a further increase in the area planted with fast-growing Populus species, as this depends not only on poplar biomass productivity and the usability of its wood but also on more complex land use and climate change issues (Energimyndigheten, ER 2021:19). One promising option for increasing the functionality of fast-growing poplar plantations is to use them as a part of the circular economy system where fertilizing with sewage sludge plays a crucial role. This approach has multiple benefits, including recycling nutrients, increasing carbon storage, and producing more biomass per unit area. It also partly solves the problem of sludge handling and storage.

The productivity potential of fast-growing poplar plantations in the region has been well-documented in several studies (Karacic et al., 2003; Karacic et al., 2021; Rytter et al., 2011; Johansson & Karacic, 2009). Typically, poplars are expected to produce 7-12 tons dry matter (DM) per hectare annually, within a 20-25 year rotation. However, these production levels are based on a production system with approximately 1,000 trees per hectare. Denser initial spacing with, for example, 1,600 trees per hectare have been tested in the NutriBiomass4LIFE project, and are expected to achieve high production levels within shorter rotations.

To successfully grow *Populus* species in the Nordic-Baltic region, it is crucial to develop climate-adapted plant material that can withstand frost and diseases. This will ensure a stable and resistant short-rotation forestry culture. Recent studies have focused on climate adaptation mechanisms, including the work of Adler et al. (2021), Vico et al. (2021), Karacic et al. (2021), and Richards et al. (2020).

Spreading wastewater sewage sludge on agricultural fields is a common practice in Europe, and the amounts deposited in this way have remained relatively constant in most European countries over the past decade (https://data.europa.eu/data/datasets/g1a4auwbnkfrmzm3dg6zg?locale=en, accessed in June 2023). In Nordic-Baltic region, the total amount of deposited sludge in 2021 varied between 20,000 tons in Estonia and 191,000 tons in Sweden. Agricultural deposition accounts for the largest share of deposited sewage sludge, ranging between 26% in Latvia and 86% in Estonia. In Lithuania, incineration and composting are both larger than agricultural deposition, while in Finland, is the largest share (Figure 1). In Sweden, there has been a marked increase in sludge deposition in agriculture, with amounts doubling in 2021 compared to 2010 (Figure 2).

In this project, we are examining the carbon cycling in poplar plantations fertilized with pelleted sludge from the final step of sludge processing in the Vilnius wastewater plant. The carbon cycling model is part of working on development of business model that aims to ensure the sustainable reuse of phosphorus and other nutrients in the agricultural sector, as outlined in the Roadmap for a Resource-Efficient Europe. In Lithuania, digestate pelleting has been a part of the sludge management program since 2006, which involves the installation of modern technologies for sludge thickening, anaerobic digestion, drying, and processing into digestate pellets. This program has the capacity to process 85% of Lithuania's total annual sludge production. The processed sludge is then recycled for biomass yield improvement in short-rotation poplar plantations, established on abandoned arable and marginal land, which represents a key element of an integrated solution. Alternatively, the digestate pellets can be used as fuel in waste incineration plants.

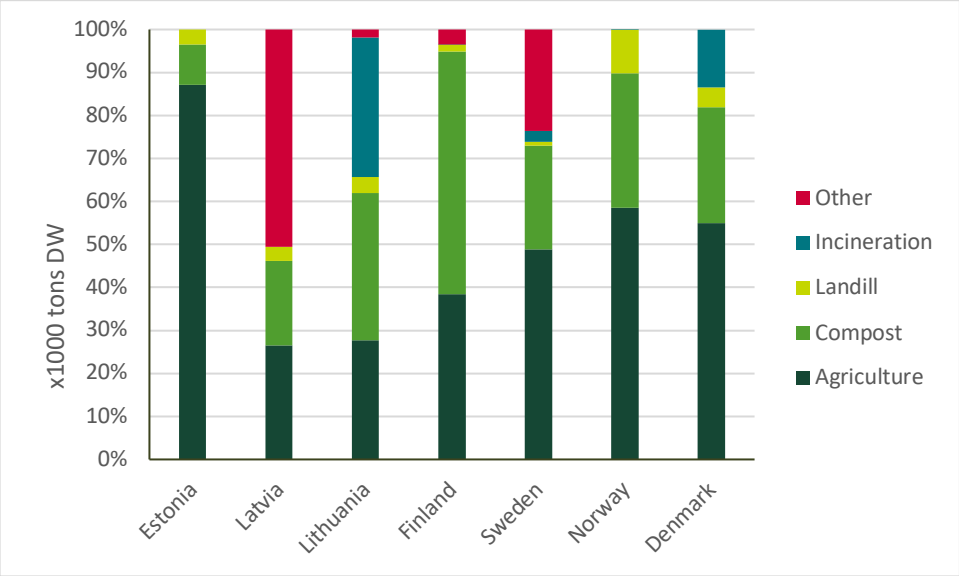


Figure 1. The destionation of deposited sewage sludge in the Baltic and Nordic countries.

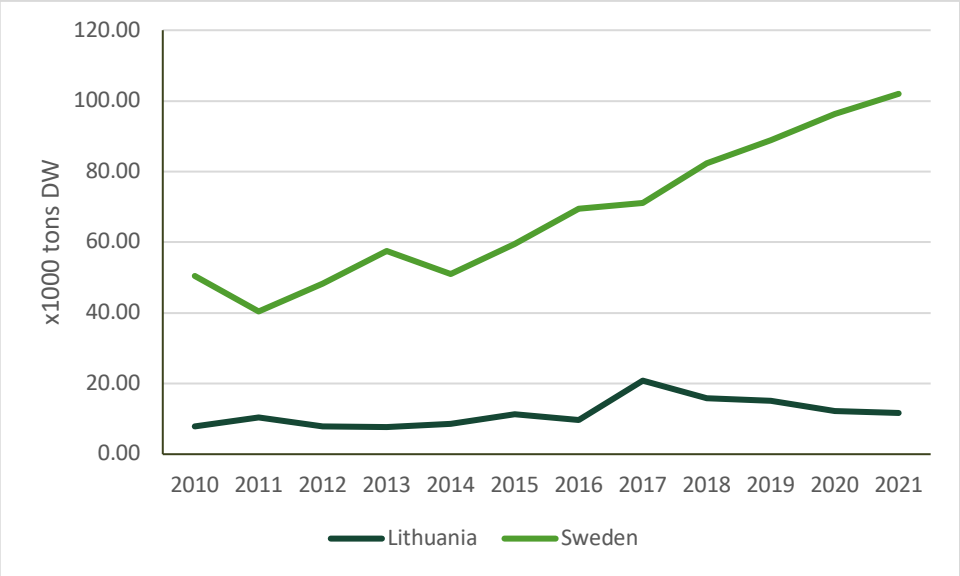


Figure 2. The trends of agricultural deposition of sewage sludge in Sweden and Lithuania.

1.1 System boundaries

We calculated the energy and carbon balance of poplar cultivation per hectare and the amount of energy produced in MJ at the district heating plant (Figure 3). The sludge drying process and alternative methods for handling sludge were not included in the system. However, we provided a rough estimate of the energy balance for transporting and combusting sludge pellets at waste incineration facilities. Our main focus was on the carbon balance and energy efficiency of the cultivation system. We compared unfertilized plantations with those fertilized with sludge pellets, assuming an expected increase in biomass growth and soil organic carbon stock (SOC) in fertilized plantations.

1.2 Biomass production system with poplars

Poplar cultivation depends on various factors like the intended end product, growing conditions, plant material, available machinery for tending and harvest, economic considerations, and the specific goals of the landowner. When grown at dense stocking with 4,000-10,000 trees per hectare, poplar biomass is harvested in short cutting cycles and used as a fuel in district heating. This type of short-rotation coppice plantations is common in warmer temperate climates where poplars perform better than willows. Poplars established at lower initial densities of 1,600 to 2,000 trees per hectare are harvested in 5-8-year cutting cycles and used for bioenergy or wood panels. Plantations established with 1,000 trees per hectare are usually grown for pulpwood and sawn-wood timber.

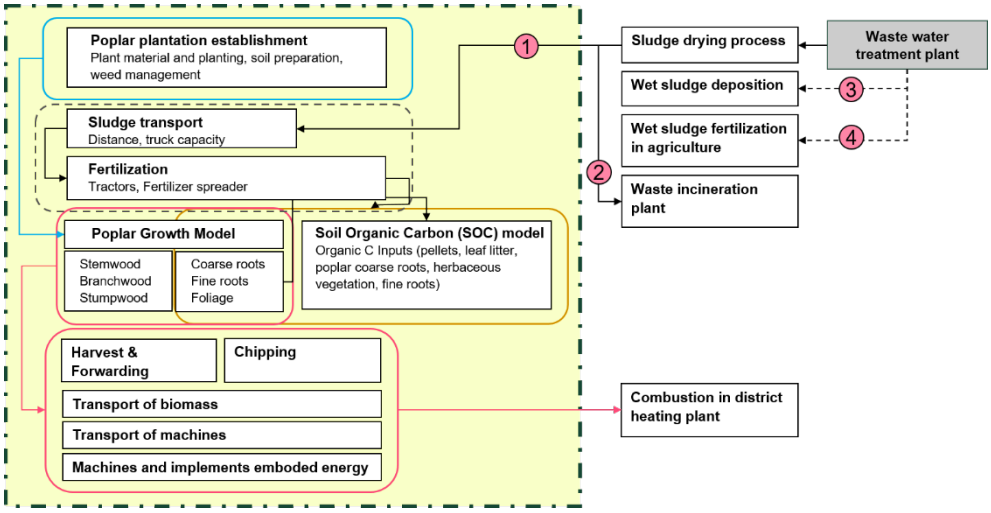


Figure 3. Flowchart of poplar biomass supply for the plantations established on set-aside agricultural land and fertilized with pelleted sludge

The climate limitations in Scandinavia and the Baltic Region require longer rotations to achieve maximum production levels (Rytter et al., 2011; Adler et al., 2022). In Sweden, poplars are typically planted at a quadratic spacing with around 1,000–1,400 trees per hectare. However, this initial stocking is frequently reduced by 5-10% due to browsing and other damages. Thinning is also a common practice in Swedish poplar plantations, which involves reducing the number of trees to approximately 500-700 per hectare. The growing system used in Sweden is flexible and allows for adjustments of rotation length.

This research focuses on poplar plantations established at a density of 1,000 trees per hectare. Our choice has been motivated by the relative abundance of Swedish growth data for poplar stands of similar design. Lithuanian plantations established in recent years have had an initial density of around 1,600 trees per hectare but are now being increasingly designed according to Swedish practice. Thinning is not included in our system, which is expected to have a final stocking of approximately 900 trees per hectare and to be harvested at the age of 20 years.

Under the NutriBiomass4LIFE project, poplars are planted on unused farmland without any herbicide treatment before or after planting. The soil is plowed and harrowed, and the plantation is established with dormant, unrooted, 1-2-year-old poles. During the first two or three years, mechanical weed control is performed once a year. Sludge fertilization is introduced in years 3, 7, and 11, combined with disc harrowing to mix the sludge pellets into the soil. Conventional forestry techniques, with a combination of harvester and forwarder, are used for harvesting operations. The logs are transported to the district heating plant and chipped, while tops and branches (T&B), are chipped on-site using a mobile chipper.

2. Growth and biomass production of poplar plantations

The presented poplar production system assumes careful management to ensure rapid early growth. An integrated weed management strategy is deployed to improve competitiveness of a poplar crop and reduce production losses and mortality during the initial stages of plantation development, which includes soil preparation, the use of productive clones, robust planting material, and mechanical weed.

2.1 Aboveground biomass production

The allocated biomass was divided into stump, coarse roots, fine roots, a harvestable stem, top and branches, and foliage.

2.1.1 Woody biomass

The estimates of poplar growth were obtained from the data collected in Sweden and Lithuania (Figure 4), representing the stands of different. The growth curve is expressed by the function:

$$Y = ae^{(-bA^{-c})}$$

where a, b, and c are estimated parameters and A is the age of the plantation. The resulting curve of the mean annual increment (MAI) for total aboveground biomass growth was obtained by dividing the resulting equation with the age of a stand (Figure 4).

Observations in Swedish poplar stands with a stocking of 650-850 trees per hectare indicate that the MAI remains relatively constant around maximum values when the plantation is between 20 and 30 years old. The growth model used in this project implies several assumptions. One of the assumptions is that the growth development curve in fertilized and unfertilized stands is almost identical. This assumption, however, harbors significant uncertainty regarding the long-term effects of fertilization on the growth of poplar stands. According to the study by Dimitriou & Mola-Yudego (2017), fertilization resulted in increased biomass growth in only one of the four trials. In a 7-year-old stand of clone 'OP42' the growth increased by 6%. This is a relatively small effect, and it is impossible to predict the long-term fertilization impact without follow-up studies on the effects of different fertilization regimes. The highest reported yield increase in fertilized poplar plantations was adopted to be 20% (Stanturf & van Oosten, 2014).

We set the total biomass production of fertilized plantations to increase by 10% and 20% at the harvesting age of 20 years (Figure 5). This yield increase has been assumed on top of an already high biomass production, which resulted in the aboveground woody biomass MAI of 10.9, 12.1, and 13.4 m^3 per hectare

and year for 'unfertilized', 'fertilized+10%', and 'fertilized+20%' plantations (Table 1). Similar production levels have previously been used in the studies of energy and carbon balance in poplar and willow plantations at northern latitudes (Nordborg et al., 2018; Porsjö & Hansson, 2014).

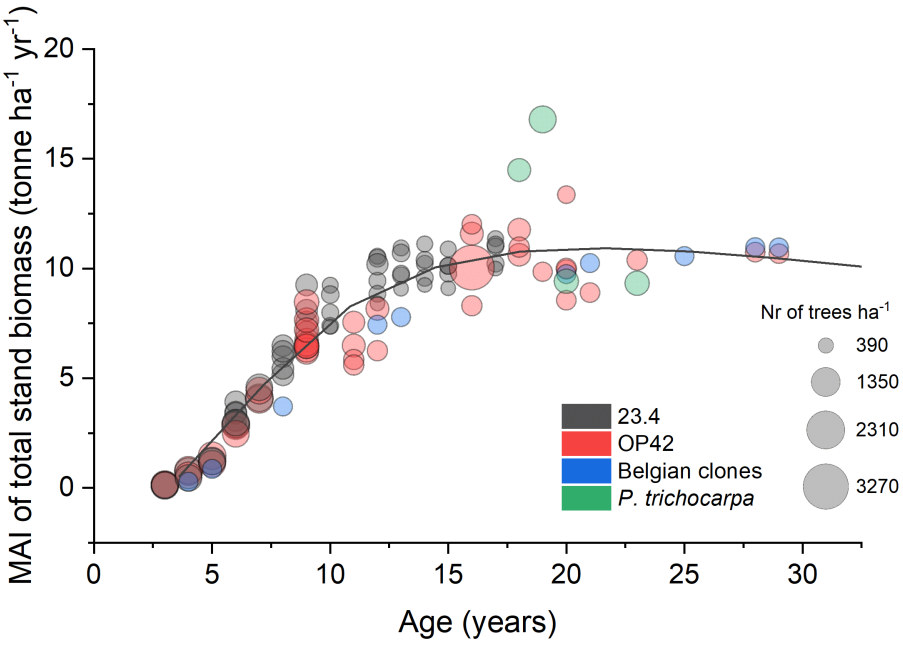


Figure 4. The mean annual increment (MAI) for total aboveground woody biomass was estimated for a large number of poplar plots located in Sweden and Lithuania. The circle size represents the stocking of measured stands. For most of the plots, but not all of them, the biomass removed through thinning was taken into account.

It is difficult to predict the long-term effects of sludge fertilization based on current data. A demonstration trial in a 3-year-old poplar plantation in central Sweden resulted in a 25% increase in stand basal area (BA – the sum of the cross-cut area of trees at 1.3 m height for all the trees on one hectare) two years after the treatment. However, the quantity of yield increase at the end of the rotation period is uncertain. Nonetheless, we believe that fertilization in Lithuanian poplar plantations, which are often established on sandy loams, has the potential to achieve a yield increase of 10% and 20%.

2.1.2 Leaf biomass

Leaf biomass estimates are based on literature data about leaf area index (LAI - the ratio of the total leaf area of all trees on one hectare and the area of one hectare). The maximum LAI (in any year) for densely cultivated poplar plantations has been reported by multiple sources to range from 3.5 to 9.4 (Cannell, 1989; Impens et al., 1990; Milne et al., 1992; Tripathi et al., 2015). In our case, we modeled LAI against the stand BA using a quartic polynomial (Figure 6). The BA at the end of the rotation was 49 to 56 m^2 per hectare for unfertilized and fertilized+20% stand, respectively. After canopy closure, LAI is expected to decrease due to individual tree

competition and the resulting relative (and absolute) reduction of crown length. In our model, LAI is assumed to level off until BA≈60, when LAI decreases as a result of the lowered vitality of trees and the onset of self-thinning. However, we disregarded the shape of the LAI curve for BA>60. In our poplar cultivation system, the maximum LAI is reached at age 8-10, achieving values of 3.4-3.8.

The specific leaf area (SLA – the ratio of leaf area and leaf dry weight) of 10 m^2 per kg was obtained for mature poplar leaves from the Swedish fertilization trial in central Sweden. Consequently, the LAI values in Figure 6 correspond to the weight of annual leaf biomass expressed in Mg per hectare.

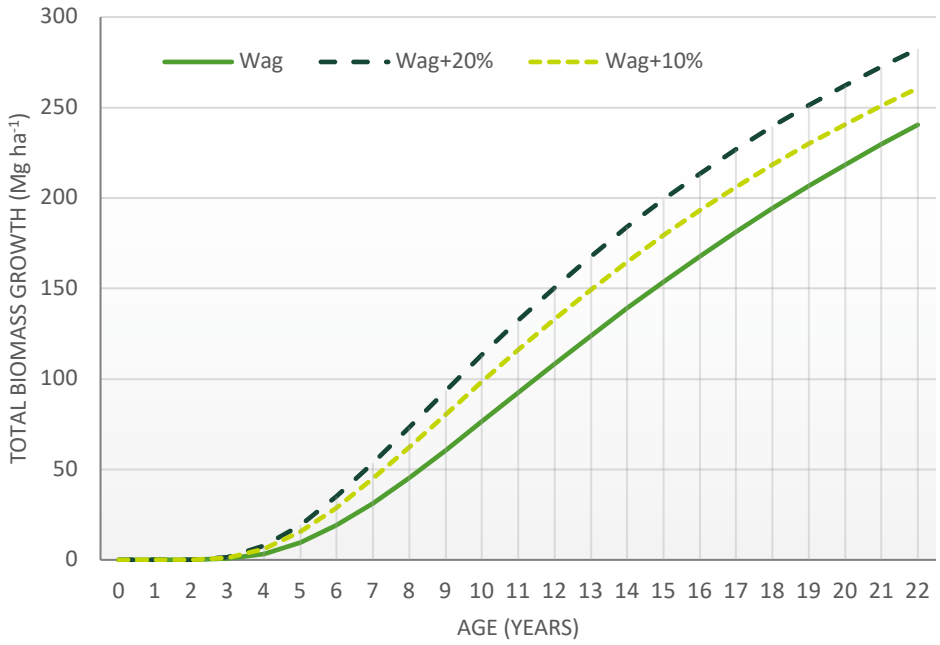


Figure 5. Projected biomass growth of well-managed poplar plantations in Lithuania established with climate-adapted and highly productive clones. The function parameters for W_{ag} are $a = 638.69$, $b = 20.518$, and $c = 0.985$, for W_{ag}+20% $a = 560$, $b = 19.05$ and $c = 1.076$ and W_{ag}+10% $a = 555$, $b = 19.4$ and $c = 1.05$. W_{ag} represents above ground woody biomass.

2.1.3 Biomass of herbaceous ground vegetation

Although the herbicide use in poplar cultivation is minimal compared to agricultural crops, the poplar plantations established within NutriBiomass4LIFE project exclude chemical weed treatment in order to comply with the EU Green Deal's objective of reducing pesticide use by 50% by 2030. Instead, the ground vegetation is controlled through soil preparation and between-row cultivation after the plantation establishment. This cultivation is performed only once per growing season, allowing substantial ground vegetation to grow under the poplar canopy until it closes at the age of 8-10 years. By the end of the first growing season, ground vegetation will occupy cultivated soil between the rows and the uncultivated soil within the rows. The within-row area of uncultivated soil is estimated to be 25% of the total stand area. After the canopy closure, the ground vegetation waneshes and its biomass is assumed to be equal to zero.

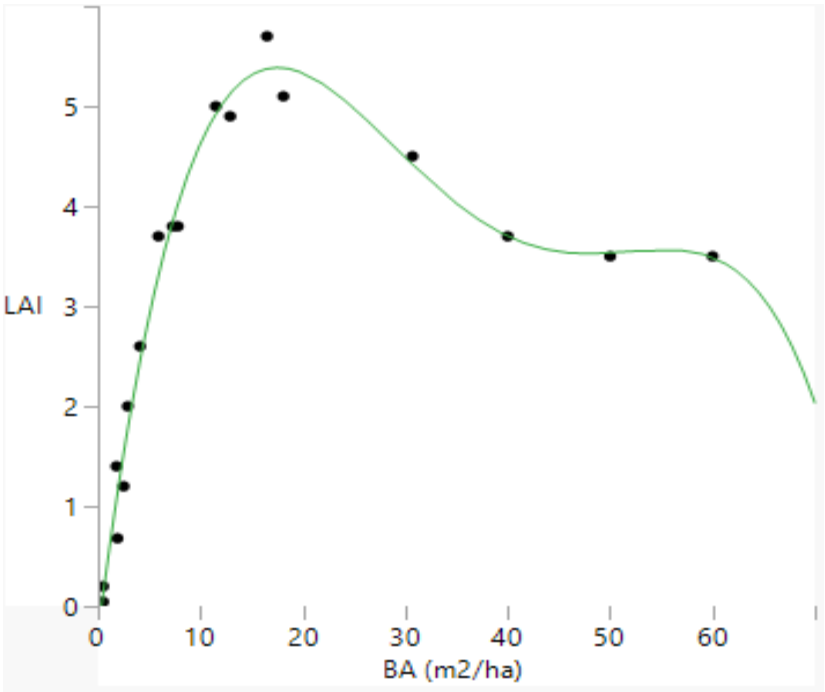


Figure 6. Development of LAI in a modeled poplar stand as related to the stand basal area (BA). The polynomial has following parameters: Intercept = -0.28025; Slope = 0.8156462; Quadratic = -0.039093; Cubic = 0.0007044; Quartic = -4.367e-6. The value of LAI is expressed as an index (m^2 m^{-2}). Given the values of specific leaf area of 10 m^2 kg^{-1} dry weight leaves the presented LAI corresponds also to the weight of leaf biomass per hectare.

The estimates of ground vegetation biomass were based on sampling the herbaceous vegetation in the Hillebola demonstration trial located in central Sweden. The aboveground biomass was harvested on 0.25 m^2 sample plots, dried at 75°C, and weighed in the laboratory. Four sample plots were distributed across four blocks within each of 16 poplar production plots. The 16 poplar production plots represented four treatments: No cultivation (Control), Cultivation, Cultivation+NPK, and Cultivation+Sludge. The mixed-model analysis with treatment as a fixed factor over random blocks revealed that cultivation performed at the beginning of June substantially decreased the amount of ground vegetation biomass sampled at the end of September (Figure 7). However, it was assumed that ground vegetation biomass production would decrease in subsequent years as a result of canopy closure. In Hillebola, ground vegetation completely disappeared after six years at initial planting densities of 1,400 trees per hectare, compared to an adjacent trial planted with 1,100 trees per hectare, where ground vegetation cover still was abundant after seven growing seasons.

We determined the ground vegetation biomass on cultivated, but not fertilized plots. We estimated the aboveground biomass of ground vegetation at the end of the first growing season to be 2.83 Mg per hectare, which corresponds to the average values measured on the cultivated between-row soil in the third year of growth. This estimation was made after taking into account the soil preparation before planting and additional cultivation during the first year of growth. For years 2-4, how-

ever, we used higher values (4.15 Mg per hectare) because the within-row area contains more herbaceous biomass. In years 5-10, a linear decrease of ground vegetation biomass is assumed, being zero after the canopy closure.

In grasslands, the belowground biomass constitutes a significant portion of the total biomass. In Hillebola, the ground vegetation cover consisted of 17% herbs, while the remaining part was composed of rhizomatous grasses. The belowground biomass of ground vegetation contains rhizomes and fine roots. The rhizome biomass was calculated using simple polynomial extracted from the data for managed grasslands in the Check Republic (Ottaviani et al., 2021):

$$RH = 0.0004AG_{GV} + 0.3061AG_{GV}$$

where RH is rhizome biomass and AG_{GV} represents the aboveground biomass of herbaceous vegetation (g m^{-2}). We used the data from Klimešova et al. (2020) to relate the fine root production rhizome biomass. The ratio of annual biomass increment between aboveground biomass, rhizomes, and root biomass was found to be 41:8:51. The turnover rates for rhizomes and fine roots were estimated to be three and one year, respectively. Based on this, we calculated that 25 Mg herbaceous vegetation per hectare would be produced during a 20-year-long rotation period.

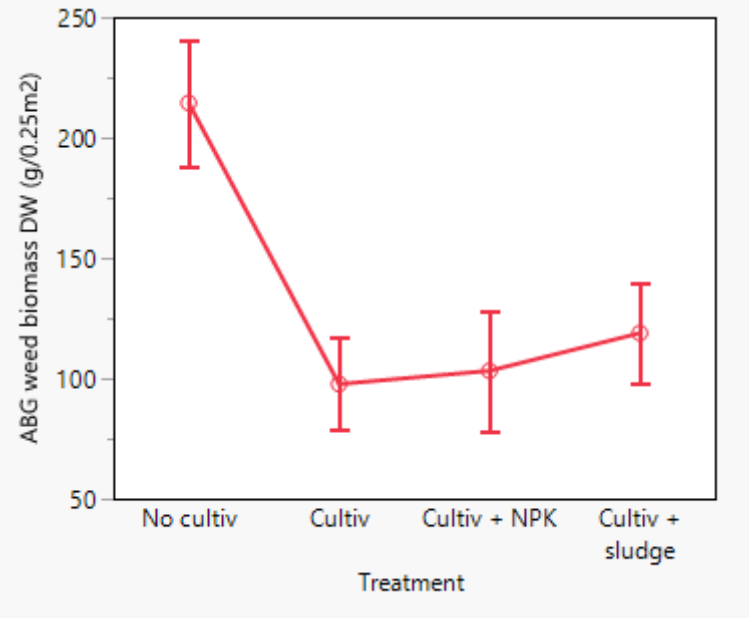


Figure 7. Aboveground biomass of herbaceous vegetation at a poplar fertilization trial in Hillebola, central Sweden. The fertilization treatments applied at the beginning of June 2019 did not have significant effects on the aboveground biomass of herbaceous vegetation at the end of the growing season in September. The values on Y-axes correspond to the aboveground biomass in grams per sample plot of 0.25m^2. Consequently, the amount of aboveground herbaceous biomass on cultivated plots reaches 4 Mg ha^{-1} and more than twice as much in the control plots that were not cultivated or fertilized.

2.2 Accumulation of belowground biomass in poplars

The stump and coarse root biomass was estimated using the Swedish poplar data (Johansson & Hjelm, 2012) and the data obtained from root excavation in 6-year-old Lithuanian trials sampled in Kaišiadorys. The estimates were made for individual trees explaining the relationships between aboveground biomass and the biomass of stump and coarse roots. The obtained ratios between below and aboveground woody biomass and belowground and total woody biomass were 0.24 and 0.19, respectively. The biomass of fine roots was estimated based on the reported ratios between the fine root annual production and total poplar biomass annual production (Rytter, 2012).

2.2.1 Coarse root biomass

The proportion of coarse root biomass (>2 cm in diameter) vs aboveground woody biomass decreases from 0.35 for small trees of approximately 5 cm in DBH (diameter at breast height, i.e., 1.3 m above ground) to around 0.1 for the large trees at the end of the 20-year long rotation period (Figure 8). The relationship between proportion of coarse root biomass (P_{CR}) and aboveground tree weight was described by the exponential function:

$$P_{CR} = 0.5395AG^{-0.307}$$

where AG represents the aboveground biomass (stem + branches) of the mean tree in a stand.

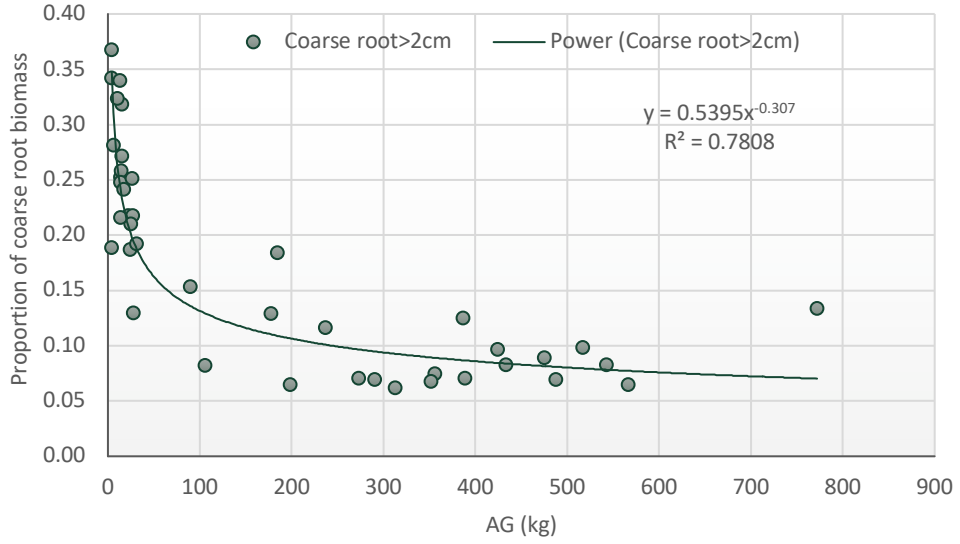


Figure 8. Coarse root biomass proportion related to the aboveground biomass dry weight of individual poplar trees sampled across Sweden. The smallest trees were sampled in Kaisiadorys, Lithuania.

2.2.2 Stump biomass

Stump biomass was defined as the "stump proper above the ground" (Hakilla, 1989) and its direct continuation below ground. It was expressed as a proportion of the aboveground biomass in the same manner as for the coarse roots, using the logarithmic equation:

$$P_{SP} = 0.007 \ln AG + 0.1058$$

where P_{SP} is the weight of the poplar stump, and AG represents the aboveground biomass. The estimated ratio was just below 0.15 over almost the entire range of the aboveground dry weights (Fig. 9).

2.2.3 Fine root biomass

Fine root biomass was estimated according to the reduced annual fine root biomass increment proportion as outlined by Rytter (2012) for 2-3-year-old willows cultivated in lysimeters. Initially, the annual production of fine root biomass was approximated at around 25% of the total annual aboveground biomass increment. Subsequently, this estimate was fine-tuned by aligning the annual growth of fine roots with leaf biomass in unfertilized poplars, under the assumption of a consistent fine-root/foliage relationship even for fertilized stands. This adjustment aimed establish a steady-state annual increments of fine roots that should be anticipated within a closed canopy environment.

It is important to note that the estimates of fine root biomass production and turnover are burdened with a considerable degree of uncertainty. In the context of short rotation poplars, reported values often exhibit a magnitude of variation that is challenging to elucidate (Dickmann & Pregitzer, 1992). Furthermore, according to the same authors, minirhizotron studies may overestimate the root growth and turnover rates. As an illustration, the turnover rates 5.7 reported by Rytter (2012) suggest that 40% of the total annual biomass production is allocated to fine roots. This underscores the need for caution and critical interpretation when considering the accuracy and reliability of fine-root biomass estimates in such ecosystems.

The lifespan of fine roots in poplars has been reported to range from 100 to 200 days (Pregitzer & Friend, 1996), indicating a turnover rate of 1 to 3. The reported annual carbon input through fine roots in steady-state forest systems exibits a range of 0.5 to 3 Mg per hectare and year (Gill & Jackson, 2000; Brunner & Godbold, 2007). Considering the notably high biomass production observed in poplar plantations, we made the assumption that conditions of steady-state fine-root biomass would occur after the canopy closure and correspond to the annual leaf biomass production. This assumption was grounded in the expectation that the annual leaf biomass production would serve as a benchmark for the establishment of equilibrium in fine-root biomass within the plantation ecosystem.

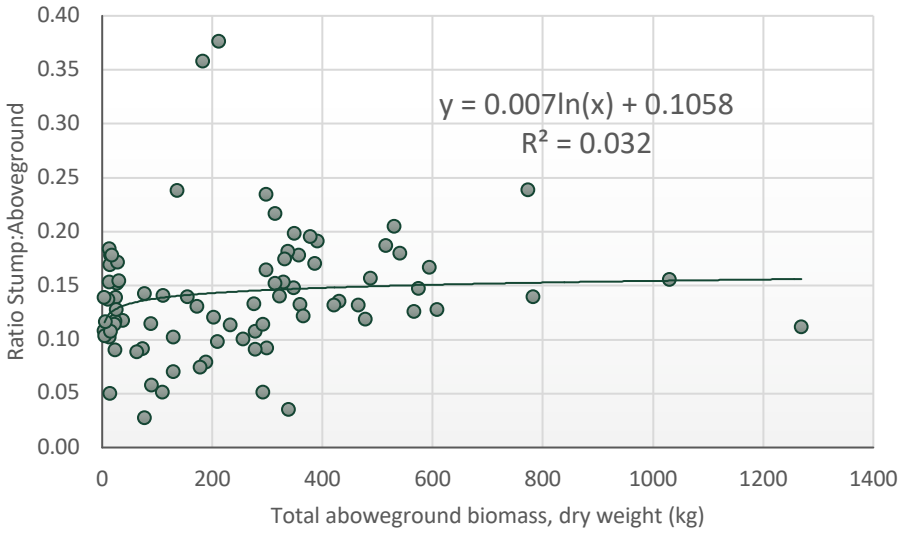


Figure 9. The proportion of stump biomass related to the harvestable aboveground biomass of poplars sampled across Sweden. The smallest trees were sampled in Kaisiadorys, Lithuania.

2.3 Biomass and carbon accumulation

The average diameter at breast height (DBH) at the end of the rotation period was estimated to range between 262 and 282 mm for unfertilized and fertilized+20% stands, respectively. Simultaneously, the corresponding mean tree height was estimated to be 24.5-25.4 m, with a fixed density of 900 trees per hectare. We propose that the increased production of fertilized stands is, in part, attributable and reflected in the elevated average LAI and fine root production. The biomass allocation reveals that belowground stump and coarse root biomass constitute approximately 19.5% of the total woody biomass accumulated over 20-year period, while 72% of the aboveground biomass is harvested as logs (Table 1; Karacic et al., 2003; Rytter et al., 2011). The anticipated total biomass production (comprising aboveground, belowground, foliage, and fine roots) over the 20-year rotation period is expected to range between 483 and 551 Mg per hectare for unfertilized and fertilized+20% stands, respectively. Approximately 56-59% of this biomass is accumulated as woody biomass (272-325 Mg ha^{-1}), with only 45-48% allocated to harvestable aboveground woody biomass (218-262 Mg ha^{-1}). The combined total of foliage and fine root biomass production varies between 69 and 76 Mg ha^{-1} and 85-94 Mg ha^{-1}, respectively (Fig. 10).

The carbon content of poplar wood is established at 48% through the of wood samples performed as a part of the NutriBiomass4LIFE project. In accordance, with IPCC (2006) reccomendations for broad-leaved tree species, the same carbon content was applied for the stump and coarse root biomass. For fine roots, a carbon content of 40% was assigned based on findings of Al Afas et al. (2008). Additionally, foliage carbon content, determined through projectvanalyses, wasidentified to be 37%.

Table 1. Stand characteristics and partitioning of harvestable aboveground biomass in the 20-year-old poplars. The production levels for fertilized stands were assumed to be 10% and 20% higher while retaining the same stocking and proportions related to biomass allocation.

Tree & stand variables	**Units**	**Unfertilized**	**Ferti-lized+10%**	**Ferti-lized+20 %**
Age	Year	20.00	20.00	20.00
DBH over bark (OB)	Mm	262.46	272.77	282.14
DBH under bark (UB)	Mm	252.50	262.80	272.00
H (mean tree height)	M	24.50	24.90	25.40
Number of trees	No ha^{-1}	900.00	900.00	900.00
Wood density	Mg m^{-3}	0.33	0.33	0.33
Bark Vol & DW proportion	%	0.13	0.13	0.13
Pulpwood Vol & DW proportion	%	0.90	0.90	0.90
Stem proportion of total AG DW	%	0.80	0.80	0.80
Branch proportion of total AG DW	%	0.20	0.20	0.20
Harvestable stem volume proportion	%	0.90	0.90	0.90
Water content - fresh wood	%	0.48	0.48	0.48
Mean tree biomass partitioning				
Total AG DW	Mg	0.24	0.27	0.29
Stem DW (OB)	Mg	0.19	0.21	0.23
Stem DW (UB)	Mg	0.17	0.19	0.20
Bark DW (whole stem)	Mg	0.03	0.03	0.03
Branch DW	Mg	0.05	0.05	0.06
Stem top DW	Mg	0.02	0.02	0.02
Stem top & branches DW	Mg	0.07	0.07	0.08
Pulpwood DW (OB)	Mg	0.17	0.19	0.21
Pulpwood DW (UB)	Mg	0.15	0.17	0.18
Bark DW (pulpwood)	Mg	0.02	0.03	0.03
Stem Vol (OB)	m^3	0.59	0.65	0.71
Stem Vol (UB)	m^3	0.51	0.56	0.61
Bark Vol	m^3	0.08	0.08	0.09
Stem FW (OB)	Mg	0.37	0.41	0.45
Pulpwood FW (OB)	Mg	0.32	0.36	0.39
Stem top & branches (FW)	Mg	0.13	0.14	0.16
Stand biomass partitioning				
Total DW	Mg ha^{-1}	218.41	240.78	262.27
Stem DW	Mg ha^{-1}	174.73	192.63	209.82
Top DW	Mg ha^{-1}	17.47	19.26	20.98
Branch DW	Mg ha^{-1}	43.68	48.16	52.45
Tops & Branches DW	Mg ha^{-1}	61.15	67.42	73.44
Tops & Branches DW - 10%*	Mg ha^{-1}	55.04	60.68	66.09
Pulpwood DW (OB)	Mg ha^{-1}	157.25	173.36	188.84
Pulpwood DW (UB)	Mg ha^{-1}	136.81	150.83	164.29
Stem Vol (OB)	m^3 ha^{-1}	529.48	583.72	635.81
Stem Vol (UB)	m^3 ha^{-1}	460.64	507.84	553.16
Pulpwood Vol (OB)	m^3 ha^{-1}	414.58	457.05	497.84
Pulpwood Vol (UB)	m^3 ha^{-1}	360.68	397.64	433.12
Bark DW (pulpwood)	Mg ha^{-1}	53.90	59.42	64.72
Pulpwood FW (OB)	Mg ha^{-1}	302.41	333.39	363.15
Tops & branches (FW)	Mg ha^{-1}	117.60	129.65	141.22
Tops & branches (FW - 10%)*	Mg ha^{-1}	105.84	116.69	127.10

*10% of tops and branches are lost in harvesting operations

The amount of carbon assimilated over a 20-year rotation was 212-244 Mg ha^{-1} (Fig. 10). Woody biomass serves as primary carbon repository, with a range of 130.4 to 156 Mg per hectare, corresponding to an annual carbon accumulation rate of 6.5–7.8 Mg per hectare and year. Harvestable aboveground biomass contains carbon in the range of 104.8 to 125.9 Mg per hectare, while an additional 25.6 to 30.2 Mg per hectare is allocated belowground, encompassing coarse roots and stumps left in the soil for decomposition.

The poplar plantations modelled in this project exhibit a higher carbon accumulation compared to the values reported by Rytter (2012) and Rytter & Rytter (2020) for 9-22 year-old poplars. The prior reports assumed a stem volume MAI of 20 m^3 per hectare, whereas our estimates are based on an MAI of 26-32 m^3 per hectare. The subsequent fate of belowground biomass depends on the plantation establishment methods in successive poplar rotations. If new clones are introduced, stump reradication with herbicides becomes necessary.

Decomposition of belowground biomass may extend over several decades, depending on climate and soil conditions. Alternatively, if the next poplar generation is established through coppicing, a significant portion of the stump- and coarse root biomass may persist as functional through multiple cutting cycles. This often leads to the assumption of a constant belowgrground woody biomass in carbon balance estimates (Porsjö & Hansson, 2014).

Estimates for the mean annual production of foliage and fine root biomass range between 3.4-3.8 and 4.3-4.7 Mg per hectare and year, respectively, corresponding to 1.3-1.4 and 1.7-1.9 Mg per hectare and year of sequestered carbon (see Fig. 10). Notably, foliage and fine root carbon constitute the principal inputs contributing to SOC storage post land conversion.

3. Accumulation of soil carbon (SOC) in poplar plantations

The change of SOC after land conversion can be calculated according to the IPCC's (2006) methodology as follows:

$$\Delta C = \frac{SOC_0 - SOC_{(0-T)}}{D}$$

where SOC_0 represents soil carbon content in the last year of the 20-year inventory period, which also corresponds to the length of one poplar rotation, whereas $SOC_{(0\text{-}T)}$ represents the initial SOC value of the converted cropland.

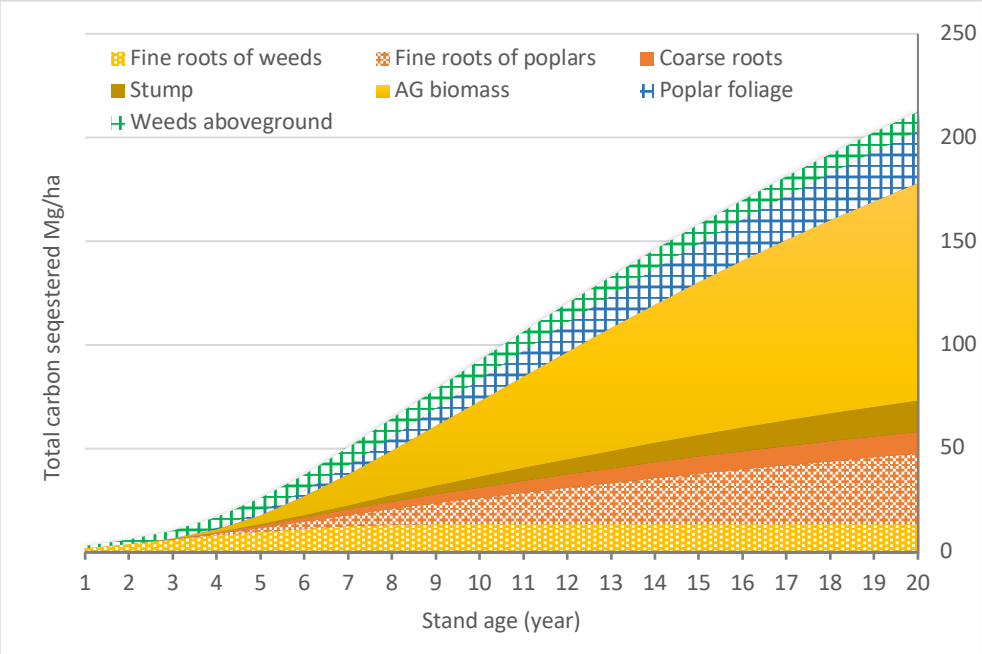


Figure 10. The total cumulative carbon sequestered in unfertilized poplar stand during a 20-year-old rotation period. AG – aboveground. Foliage and fine root biomass are turned over annually.

According to IPCC's methodology, the SOC_0 and $SOC_{(0\text{-}T)}$ can be calculated by a simplified (generalized), Tier1 method, which uses relative carbon stock-change factors:

$$SOC = SOC_{REF} F_{LU} F_{MG} F_I$$

where F-factors are provided for both the end of the 20-year period since afforestation (SOC_0) and the period before land-use change for set-aside agricultural land ($SOC_{(0\text{-}T)}$).

In the context of land conversion of agricultural or any other land use, the F-factors for SOC_0 are all conventionally assigned a uniform value to be equal to 1 (Table 2). Employing this method, the estimated SOC change fluctuated in a range of -0.26 to +0.62 Mg per hectare and year when $F_{I(0)} = 1$ was applied. However, considering highly intensive and rapid growth of poplars, a higher $F_{I(0)}$ factor of up to 1.1 could also be adopted, extending the resulting SOC change rate from 0.09 to 0.97 Mg per hectare and year. This adjustment recognizes the unique dynamics of poplar ecosystems, offering a more accurate reflection of their impact on SOC accumulation over time.

Table 2. Land-conversion factors of the SOC-change down to 30 cm soil depth. The conversion is to forest land from set-aside agricultural land. The calculated values apply to the first 20 years after the land conversion. Adapted from Annex 1 of the 2006 IPCC guidelines.

Notation	Quantity	Value	Unit	Source
SOC_{REF}	Reference carbon stock for the climate and soil combination	71	ton C ha^{-1}	Table 2.3[1]
D	A single inventory period = one poplar rotation	20	years	Default value
$F_{LU(0)}$	Stock change factor for the land-use system (forest)	1.0	-	Section 4.3.3.2
$F_{MG(0)}$	Stock change factor for management in the last year of an inventory period	1.0	-	Section 4.3.3.2
$F_{I(0)}$	Stock change factor for C-input in the last year of the inventory period	1.0-1.1	-	Section 4.3.3.2
$F_{LU(0-T)}$	Stock change factor for the land use at the beginning of the inventory period (grassland)	1.0	-	Section 6.2.3.2
$F_{MG(0-T)}$	Stock change factor for management regime at the beginning of the inventory period	0.95 ± 13%	-	Section 6.2.3.2
$F_{I(0-T)}$	Stock change factor for C input at the beginning of the inventory period	1.0	-	Section 6.2.3.2

3.1 Soc accumulation modelled by ICBM

SOC changes within poplar plantations have also been assessed using a modified version of the Introductory Carbon Balance Model (ICBM) (Andrén & Kätterer, 1997), specifically adapted for variable annual input (Andrén et al., 2004). The model parametrizes two distinct carbon pools: the young C pool (Y-pool), receiving inputs (i) from leaf litter, fine roots, and root exudates, and the old pool (O-pool), formed from a proportion of the Y-pool migrating into the O-pool. This proportion is governed by a separate parameter (h), while the outflow of carbon from both pools is regulated by two decay constants (k_y and k_o). Additionally, a variable representing external factors, such as climate (r_e) further influences the carbon exchange dynamics in the model:

$$\frac{dY}{dt} = i - k_y r_e Y$$

$$\frac{dO}{dt} = h k_y r_e Y - k_o r_e O$$

The stump- and core root biomass enter the SOC pool after the harvest, with an initial stock set to 82 Mg per hectare (0-60 cm depth) according to the data from the paired-site comparison in southern Sweden (refer to the section 3.2).

The growth model predicts a higher influx of litter- and rhizosphere carbon into the soil in fertilized poplar stands. Nevertheless, the disparities in annual carbon

input between fertilized and unfertilized stands are expected to to be relatively modest, specifically in the range of 4.25 to 5.18 Mg per hectare and year, inclusive of the carbon content in the sludge fertilizer. It is assumed that 93% of the root biomass is concentrated within the 0-60 cm layer.

The calculations of sludge pellet quantities adhered to Swedish regulations, except for the spreading frequency, which is seven years in Sweden and only three years in Lithuania. Additionally, we assumed three sludge applications during one rotation period at 3, 7, and 11 years of age. The total carbon influx from sludge was estimated to be 9 Mg per rotation period, i.e. 0.45 Mg per hectare and year. The decomposition dynamics of sludge are presumed to mirror those of leaf litter and fine roots.

According to the ICBM model, the projected SOC accumulation is 10.6 to 16.8 Mg per hectare in unfertilized and fertilized+20% stands, respectively (Table 3). These predictions closely align with the SOC increase observed in the Swedish poplar stands, as evidenced in our comparative study (see section 3.2), as well as with the SOC changes calculated using the IPCC's Tier1 method (see above).

Table 3. The change of SOC (Mg ha^{-1}) after a 20-year-long poplar rotation. Average annual carbon inputs are presented for fine roots and foliage litter of poplars and weeds, including rhizomes and exudates. Both fertilized+10% and fertilized+20% stands have received the same amount of sludge pellets on three occasions, at 3, 7, and 11 years, containing 9 Mg carbon.

Input	Unit	Unfertilized	Fertilized+10%	Fertilized+20%
Rhizosphere	Mg ha^{-1} yr^{-1}	2.536	2.797	2.877
Foliage litter	Mg ha^{-1} yr^{-1}	1.716	1.798	1.850
Sludge	Mg ha^{-1} yr^{-1}	0.000	0.450	0.450
Total	Mg ha^{-1} yr^{-1}	4.252	5.045	5.177
SOC increase	Mg ha^{-1}	10.263	16.823	17.563

The modeled SOC increase spanning 100-year timeframe presupposes the cyclical replanting of poplars and retention of harvested tree stumps in the soil (Fig. 11). Consequently, both stump and coarse root biomass contributes to the SOC stock after the harvest. While acknowledging potential variations in decomposition rates based on stump and root dimensions, it is posited that the breakdown of coarse root and stump biomass would likely conclude within a 20-year timeframe. We anticipate the absence of root-suckering population during the first growing season of each successive rotation period.

An alternative SOC trajectory unfolds when the ensuing poplar generation regenerates from stump and root suckers. The Swedish experiences of the vegetative poplar regeneration suggest that growth remains robust, with the produced biomass being equally usable as that in the first generation. Nonetheless, the dynamics of belowground biomass and poplar's ability to re-sprout several times remains relatively uncertain. The belowground woody biomass of a coppice generation remains constant after the initial rotation (Fig. 12; Ericsson et al., 2013).

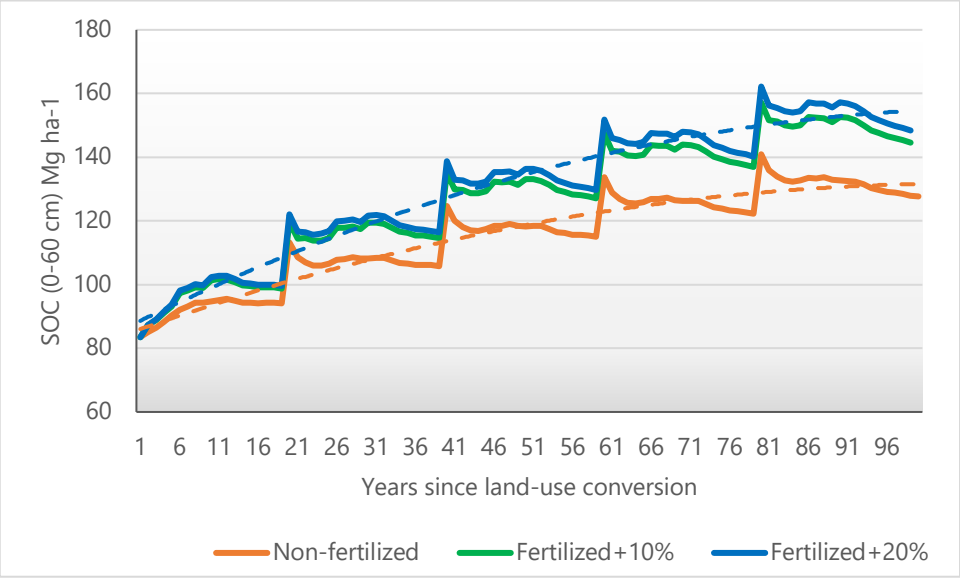


Figure 11. The SOC development under poplar plantation over 100 years including five rotation periods. Stump and coarse root biomass enter SOC stock after each rotation.

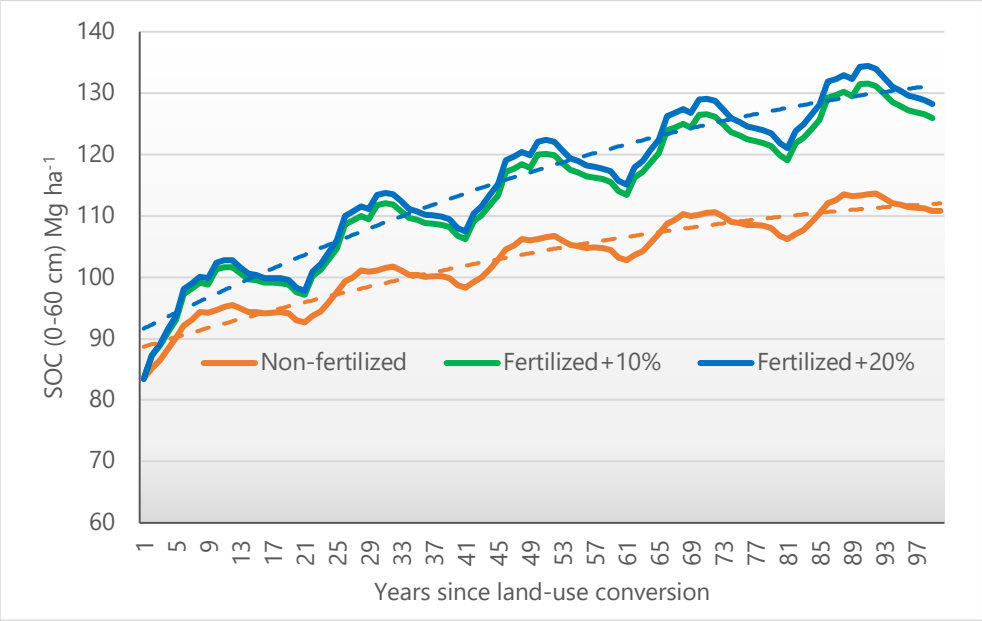


Figure 12. The SOC development under poplar plantation over 100 years including five rotation periods. Stump and coarse root biomass is not included into the model, but regarded as the continuous living biomass carbon stock.

3.2 SOC accumulation under different types of vegetation cover

The conversion of agricultural land into bioenergy crops or grassland is known to exert significant impacts on SOC and both below- and aboveground biomass carbon stocks (Post & Kwon, 2000). Conversely, the conversion of natural vegetation cover, typicallt grassland or forestland, to cultivated land is likely to result in SOC loss. This depletion can manifest within a short span of just a few years, while the post-reforestation recovery period may extend over several decades (Paul et al., 1999; Laganière et al., 2010). However, different species and management systems vary in biomass productivity, leading to distinct carbon imputs through leaf litter and rhizosphere.

Short-rotation forestry systems with fast-growing broad-leaved tree species are productive and frequently used to convert abandoned farmland into more extensive land use (Rytter et al., 2016; Tullus et al., 2016). Hybrid aspen and poplars are particularly renowned for their rapid growth, and are deemed suitable for land-use conversion. In Sweden and the Baltic countries, abandoned agricultural land has traditionally been reforested with spruce and birch or, albeit less frequently, with slow-growing, "noble" deciduous tree species (Eriksson et al., 2011). However, forest cover has been reported to elicit both recovery and further depletion of SOC in cool temperate climates (Post & Kwon, 2000). The considerable variations in studies reporting SOC development after reforestation of arable land can be attributed to differences in prior land management practices, soil types, moisture conditions, levels of previous SOC depletion, and the age of the planted forest cover.

3.2.1 Methods used in the field study of SOC accumulation under different types of vegetation cover

In this study, a paired-site methodology was used, encompassing comparative analysis across seven distinct locations featuring three different land-use types: cropland cultivated with cereals and other annual agricultural crops, grassland, and forestland. The primary focus was on contrasting SOC levels between the original land use (cropland with annual crops) and the alternative land use scenarios. However, achieving the requisite uniformity of soil conditions posed challenges, especially when considering plots with diverse tree species and grassland in the comparative framework. Variations in soil conditions and management histories across sites introduced additional sources of potential error

SOC data from seven locations was initially collected in 2000, and additional soil samples were acquired in 2020. Unfortunately, the 2020 sampling could not be repeated to estimate SOC changes between the two points in time due to a lack of a detailed methodological documentation, including precise sampling positions. While some plots could be relatively closely identified, others, especially in grassland and cropland, faced challenges in exact identification. Consequently, the 2020 data were utilized to supplement SOC information for specific locations and soil layers sampled in 2000. To facilitate a comprehensive

analysis, all the data were amalgamated for a unified examination comparing SOC levels across different land use types, including hybrid aspen, birch, poplar, cropland, and grassland.

The analysis primarily focused on discerning whether any SOC increase could be observed in plots planted with fast-growing broad-leaved tree species compared to cropland. We hypothesized that such an increase in SOC might manifest in the topsoil after 10-15 (as of the 2000 sampling) and 30-35 (as of the 2020 sampling) years after the establishment of forest cover. The analysis was performed on an unbalanced data set due to the absence of representation for all land-use types at each location. The soil texture varied between sand and heavy clay, with a generally high biomass production potential observed on all sites except in Långaveka, a sandy site in southern Sweden (Table 4).

Soil was sampled at four depths, 0-7.5, 7.5-25, 25-45, and 45-60 cm, and soil analysis included various parameters, such a texture, SOC, and pH. In 2020, bulk density was sampled at the 10-20 cm depth. In addition, we recorded DBH and tree heights for each forest plot, allowing for the estimation of standing biomass. Furthermore, the total aboveground biomass production for thinned plots was reconstructed utilizing historical data. To predict soil bulk densities for samples collected in 2000, a model incorporating organic carbon content, location, and land use was employed, utilizing random forest regression (Liaw and Wiener, 2002). A linear regression model was constructed to predict bulk density in deeper layers, relying on clay content in Swedish soils (Kirchmann., 1991; Håkansson, 1985; Kirchmann et al., 2005). The bulk density of the 45-60 cm layer was calculated and linearly interpolated across different depth layers, leveraging the bulk density in the top layer in both 2000 and 2020.

3.2.2 Poplars, but not birch, increase SOC accumulation after the land conversion

The unbalanced data set introduces a degree of uncertainty regarding the significance of any identified differences in SOC levels across different types of land use. We analyzed the data in a mixed model, where SOC per layer served as the dependent variable, and 'Location' was treated as a random factor. Introducing Soil depth ('Layer') and land use ('CropType') as fixed factors, SOC was computed based on sampled organic C concentration and bulk density of a given soil layer. Given variations in the thickness of each 'Layer', we standardized its value to reflect the average SOC quantity per hectare and per cm of layer depth. This transformation did not change the effects of 'Location' and 'CropType' while rendering the impact of 'Layer' independent of its varying thickness(7.5, 17.5, 20, and 15 cm for the four layers). Finally, the dependent variable was square-root transformed to achieve a normal distribution. Thus, the analyzed dependent variable now represents the square root of the average SOC levels per hectare and per cm of layer thickness. The model was as follows:

$$SOC = \eta + Loc + CT + Lr + Loc \times CT + Loc \times Lr + CT \times Lr + err$$

where η represents the overall mean, Loc is the effect of location, CT is the effect of land use, and Lr is the effect of the soil layer.

'Location' emerged as a predominant factor, contributing to 48.9% of the variance components in the mixed model (Table 5). Both random interaction terms, 'Location × CropType' and 'Location × Layer,' were significant at the $p<0.05$ level, while the main effect 'Location' did not attain significance. Similarly, the differences in SOC levels across layers were significant as well as the interaction between the 'CropType' and 'Layer,' whereas the isolated effect of 'CropType' itself lacked statistical significance (Table 6). The model exhibited a high level of predictability as indicated by $R^2adj = 77.5\%$.

The highest SOC quantities were recorded for the clay soil in Bodarna, while the lowest were observed in the sandy loam in Sångletorp (Table 7). A departure in the pattern of layer SOC distribution was observed in Malmön, where the soil profile was built up through the deposition of the lake bottom material from the nearby industrial harbor. In Malmön, SOC quantities were similar among the soil layers at 7.5 to 60 cm, with somewhat elevated SOC levels in the uppermost 0-7.5 cm layer.

The mixed-model analysis did not reveal significant differences in SOC levels across the crop types over the entire soil profile of 0-60 cm. However, noteworthy differences in estimated SOC were identified between grassland and birch plots, amounting to 35 Mg per hectare (Table 8). The lower SOC levels in birch plots might be related to their low productivity in Bullstofta and Rydsgård. Conversely, the grassland plots on these sites, particularly in Rydsgård, share comparable soil conditions with birch plots but exhibit substantially higher SOC levels. The lower SOC content in soil planted with birch warrants further investigation, with a focus on locations where soil conditions are more homogeneous across various treatments (land uses). The SOC content at the 45-60 cm depth in birch plots was comparatively not lower (Table 9; Fig. 13), which suggests that either birch plots did not initially had lower SOC levels, or that birch stands excel in accummuklating SOC in deeper layers. A plausible explanation is that altered ranking of SOC levels at 45-60 cm depth is indicative of the minimal impact of land use on this layer. Therefore, the shift in SOC content ranking at this depth may serve as an indicator of satisfactory randomness in the spatial allocation of different land uses at each site.

SOC estimates for cropland had almost indentical levels per unit volume (cm×ha) in the top 7.5 cm as in the 7.5-25 cm layer. This is likely an consequence of soil cultivation practices, mixing the crop residues down to ca 25 cm depth. The 'Location × CropType' interaction significantly affected SOC estimates across the entire soil profile. The comparison of SOC levels between poplar plots and agricultural land was feasible for five out of seven sites. Over the entire profile (0-60 cm), poplar plots displayed 5-24 Mg higher SOC levels per hectare compared to cropland on four out of five sites. In Bullstofta, however, cropland exhibited almost 27 Mg per hectare higher SOC than poplar plots. The SOC levels on cropland in Bullstofta demonstrated substantial variation between the 2000 and 2020 samplings, with significantly higher levels recorded in 2020. Despite both samplings being taken in the same field, the observed differences could occur due to spatial variation, because the unknown exact position of the previous sampling. Additionally, in Bullstofta, numerous pockets of organic soil may have been inadvertently sampled in 2020. Excluding Bullstofta from the

analysis, it appears evident that poplar plots would have accumulated approximately 15 Mg per hectare more SOC compared to cropland over a 60 cm profile depth during approximately 20-year rotation period (Table 10).

Table 4. Overview of the sites included in the "pair-site" analysis of SOC at seven sites in southern and central Sweden.

Sites (Lat)	Land use (age)	Nr of plots	Soil texture class top-soil 7.5-25 cm depth	Bulk density topsoil 7.5-25 cm depth	MAI bio-mass Mg ha^{-1}	Total above-ground biomass production since conversion (Mg ha^{-1})*
Sturup (55º 34')	Hyb aspen (7)	1	Loam	1.26	5.2	31.2
	Grassland	1	Sandy loam	1.47	-	-
	Cropland	1	Sandy loam	1.47	8	56
Långaveka (56º 51')	Poplar (15)	2	Sand	1.33-1.40	4.5	30
	Birch (15-35)	2	Sand	1.22-1.50	4.6	139.1 (98.6-179.6)
	Grassland	2	Sand	1.49-1.51	-	-
Sångletorp (55º 31')	Poplar (10-30)	6	Sandy loam	1.26-1.48	7.87	178.6 (47.9-330.5)
	Grassland	1	Sandy loam	1.41	-	-
	Cropland	3	Sandy loam	1.25-1.75	8	80-240
Rydsgård (55º 32')	Poplar (10-30)	6	Sandy loam/loam	1.17-1.44	7.2	154.3 (55.6-276.8)
	Birch (10-30)	4	Sandy loam	1.08-1.22	3.4	102.6 (93-107.8)
	Cropland	3	Sandy loam	1.25-1.32	8	80-240
	Grassland	1	Sandy loam	1.23	-	-
Bullstofta (55º 59')	Poplar (10-30)	5	Loam	1.04-1.34	7.9	138.8 (78-257.6)
	Hyb. aspen (10-30)	4	Sandy loam	1.26-1.49	6.4	129.9 (55.4-219.1)
	Birch (15)	1	Sandy loam/loam	1.42	1.1	32.1
	Cropland	2	Sandy loam	1.39-1.49	8	80-240
	Grassland	1	Loam	1.2	-	-
Malmön (59º 28')	Poplar (15-35)	3	Silty clay	1.04-1.32	6.9	152.4
	Hyb. aspen (15-35)	3	Silty clay	1.01-1.32	8.6	210
	Birch (35)	2	Silty clay	0.89-0.99	6.7	201
	Cropland	2	Silty clay	1.21-1.34	6	90-210
	Grassland	1	Silty clay	1.17	-	-
Bodarna (59º 50')	Poplar (10-30)	3	Clay	1.02-1.09	5.9	127.9 (63.9-191.8)
	Hyb. aspen (10-30)	6	Clay	0.95-1.09	7	141.7 (55.4-219.1)
	Birch (30)	2	Clay	0.89-0.99	5.5	164.7 (135.9-193.5)
	Cropland	3	Clay	1.15-1.21	6	60-180
	Grassland	1	Clay	1.17	-	-

Table 5. Variance components of SOC analysis. The three-way interaction between Location, CropType and Land was excluded from the analysis.

Source	Var	% of Total	SE Var	Z-Value	P-Value
Location	0.057839	48.89	0.037393	1.546780	0.061
Location×CropType	0.015337	12.96	0.007684	1.996014	**0.023**
Location×Layer	0.006622	5.60	0.003918	1.690307	**0.045**
Error	0.038511	32.55	0.003831	10.053314	**0.000**
Total	0.118309				

Table 6. The fixed effects of the mixed model analysis of SOC levels in different types of vegetation cover.

Term	DF Num	DF Den	F-Value	P-Value
CropType	4.00	14.29	1.40	0.282
Layer	3.00	16.35	29.00	**0.000**
CropType×Layer	12.00	215.82	2.33	**0.008**

Table 7. Pairwise comparison of SOC levels for the whole soil profile (0-60 cm) between different locations expressed in Mg ha^{-1} cm^{-1}.

Location	N	SOC (0-60 cm)*	SOC (0-60cm)	Grouping
		Mg ha^{-1} cm^{-1}	Mg ha^{-1}	
Bodarna	56	3.108	186.494	A
Malmön	36	2.352	141.149	AB
Bullstofta	48	2.008	120.470	ABC
Sturup	10	1.718	103.057	BC
Långaveka	24	1.454	87.255	BC
Rydsgård	51	1.386	83.162	BC
Sångletorp	40	1.284	77.049	C

Table 8. Pairwise comparison of SOC levels for the whole soil profile (0-60 cm) between different types of vegetation cover 10-35 years after planting.

CropType	N	SOC/cm	SOC (0-60cm)	Grouping
		Mg ha^{-1} cm^{-1}	**Mg ha^{-1}**	
Grassland	31	2.154	129.254	A
Poplar	84	1.949	116.927	A
Cropland	54	1.837	110.220	A
Aspen	52	1.760	105.619	A
Birch	44	1.610	96.620	A

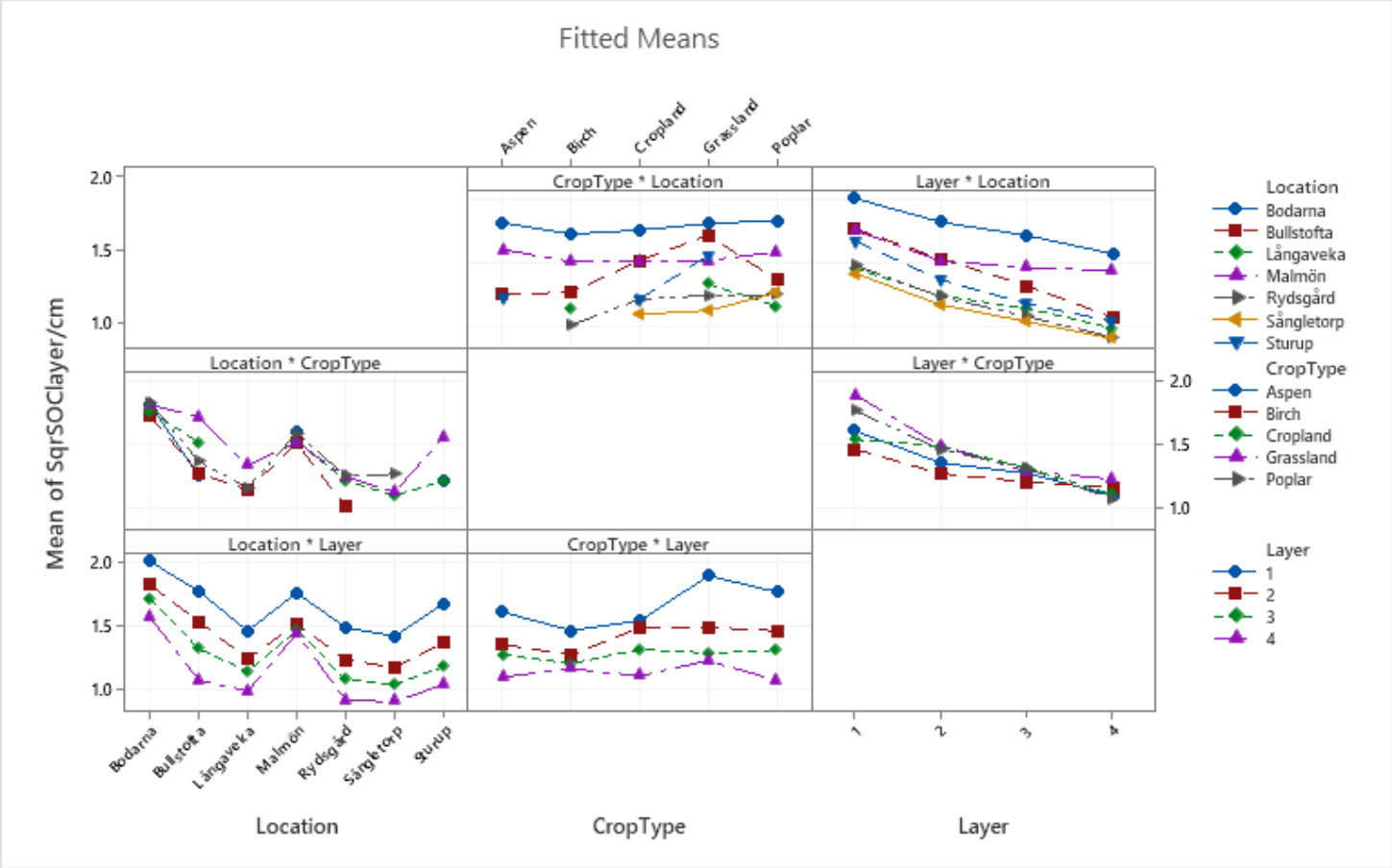


Figure 13. The factorial plot of SOC level per cm soil layer analyzed for the whole profile depth of 60 cm. Interactions for random and fixed factors.

Since SOC at the 45-60 cm layer was not affected by 'CropType', we repeated the analysis excluding this layer. In this particular model run, the 'Location×Layer' interaction did not have a significant effect, while the P-value decreased for the 'CropType' effect. Subsequently, we systematically excluded one layer at a time, culminating in the analysis of the pooled SOC for the two uppermost levels (0-25 cm). The principal outcome of these sequential analysis highlights the significance of the 'CropType' effect for both the individual assessment of the two uppermost layers and their amalgamation into a pooled layer.

One intriguing outcome of this analysis was the unexpectedly low SOC estimation for plots planted with birch. One possible explanation might lie in slightly lower biomass production observed in birch plots compared to hybrid aspen and poplars (4.3 vs 7 Mg ha^{-1} yr^{-1}). But, on the other hand, the total biomass production for birch plots was only 15-20 Mg per hectare lower, a magnitude unlikely to account for the observed differences in SOC levels. More balanced studies are necessary to comprehensively evaluate the effects of various fast-growing species on carbon balance and storage in Nordic-Baltic short rotation forestry. Such studies would

provide a more accurate comparison of SOC storage under different species, contributing to better assessments of their impacts on carbon dynamics in this context.

Our data set was imbalanced and would require improved representation of grasslands and croplands, along with enhanced knowledge of land-use history before and after the land-use conversion. Despite these limitations, our analysis points toward a positive impact of poplars on SOC levels. While the model estimates suggested a whole profile (0-60 cm) SOC increase of 6.7 Mg ha^{-1} over an average period of 20 years after the conversion (33.5 g m^{-2} yr^{-1} or 0.335 Mg ha^{-1} yr^{-1}), it is crucial to acknowledge the exaggerated impact of the Bullstofta site, which strongly deviated from other sites in terms of SOC levels in agricultural plots. Consequently, We contend that the SOC levels in Bullstofta are influenced by factors not considered in our, and the true increase of SOC in poplar plots compared to agricultural fields is lakely around 15 Mg per hectare (75 g m^{-2} ha^{-1} or 0.75 Mg ha^{-1} yr^{-1}) 20 years after the land conversion. This adjusted estimate aligns reasonably well with the calculated range of SOC increase using the IPCC methodology and the outcomes derived from ICBM modeling.

Table 9. Pairwise comparison of SOC levels for the interaction between 'CropType' and the soil layer, 1 = 0-7.5 cm, 2 = 7.5-25 cm, 3 = 25-45 cm and 4 = 45-60 cm.

CropType*Layer	**N**	**SOC/cm**	**SOC/layer**	**Grouping**
		Mg ha^{-1} cm^{-1}	Mg ha^{-1}	
Grassland 1	8	3.565	26.741	A
Poplar 1	22	3.102	23.268	AB
Aspen 1	13	2.566	19.247	ABC
Cropland 1	14	2.354	17.652	ABCD
Grassland 2	8	2.197	38.448	BCDEF
Cropland 2	14	2.190	38.325	ABCD
Birch 1	11	2.126	15.949	ABCDEF
Poplar 2	22	2.116	37.025	CDE
Aspen 2	13	1.819	31.828	BCDEF
Cropland 3	14	1.712	34.243	CDEF
Poplar 3	20	1.699	33.985	CDEF
Grassland 3	8	1.639	32.783	CDEF
Aspen 3	13	1.604	32.096	CDEF
Birch 2	11	1.600	28.002	CDEF
Grassland 4	7	1.489	22.333	CDEF
Birch 3	11	1.433	28.655	CDEF
Birch 4	11	1.336	20.037	CDEF
Cropland 4	12	1.208	18.117	EF
Aspen 4	13	1.188	17.812	DEF
Poplar 4	20	1.133	16.996	F

Table 10. Pairwise comparison of SOC levels for the interaction between 'Site' and 'CropType'.

Location*CropType	N	SOC/cm	SOC/0-60 cm	Grouping
		Mg ha^{-1} cm^{-1}	Mg ha^{-1}	
Bodarna Poplar	8	3.342	200.502	A
Bodarna Aspen	24	3.285	197.081	A
Bodarna Grassland	4	3.263	195.783	ABC
Bodarna Cropland	12	3.073	184.399	ABC
Bodarna Birch	8	2.963	177.772	ABCD
Bullstofta Grassland	4	2.934	176.068	ABCDE
Malmön Aspen	8	2.563	153.773	ABCDEF
Malmön Poplar	8	2.504	150.237	ABCDEF
Sturup Grassland	3	2.419	145.165	ABCDEFG
Malmön Cropland	8	2.293	137.608	ABCDEFG
Bullstofta Cropland	8	2.292	137.501	ABCDEFG
Malmön Grassland	4	2.291	137.461	ABCDEFG
Malmön Birch	8	2.257	135.517	ABCDEFG
Bullstofta Poplar	16	1.848	110.881	BCDEFGH
Långaveka Grassland	8	1.767	106.018	BCDEFGH
Bullstofta Birch	4	1.592	95.528	BCDEFGH
Sångletorp Poplar	24	1.589	95.310	EFGH
Bullstofta Aspen	16	1.565	93.923	FGH
Rydsgård Poplar	20	1.550	93.013	EFGH
Rydsgård Grassland	4	1.531	91.875	DEFGH
Sturup Aspen	4	1.477	88.594	DEFGH
Rydsgård Cropland	11	1.464	87.861	EFGH
Sturup Cropland	3	1.460	87.588	CDEFGH
Långaveka Poplar	8	1.330	79.773	FGH
Långaveka Birch	8	1.294	77.648	FGH
Sångletorp Grassland	4	1.252	75.124	FGH
Sångletorp Cropland	12	1.187	71.228	GH
Rydsgård Birch	16	1.007	60.424	H

4. Energy and carbon balance of poplar plantations

The energy and carbon balance has been analysed for unfertilized, fertilized+10%, and fertilized+20% scenarious, where biomass is used as a fuel in a nearby district heating plant. The unfertilized and fertilized systems differ mainly in the energy and emissions related to biomass transports, and the transport and spreading of pelleted sludge. The production of sludge pellets itself was left outside the system boundaries.

4.1 Plant production

Poplar plantations are typically established using dormant, 1-2-year-old unrooted poles, which may vary in length and thickness, commonly measuring around 1.5-2 m and ca 30 mm, respectively. Currently, insights into pole pole production

practices in the Nordic-Baltic region are primarily derived from experimental material production in Sweden, small-scale commercial production at the Ramlösa forest plant nursery in southern Sweden, and the pole production initiatives in Lithuania, and Romania. For optimal growth, poplar poles are cultivated on light-textured soils under intensive tending, involving fertilization, soil cultivation, and weed control. The established stool beds can be repeatedly harvested as long as their vigor and health remain satisfactory.

Outdoor pole production consumes less energy than the production of containerized plant material for conventional forestry. Aldentun (2002) and Rytter et al. (2011) reported the energy demands of nursery plant production to be 1,194 and 1,360 MJ per 1,000 containerized seedlings, a process requiering heated greenhouses. In contrast, uur energy demand estimates for pole production were only 345.6 MJ per 1,000 poles. The estimates were derived from data provided by Ramlösa plant nursery (pers. com. Max Jensen 10th of May 2021), specializing in the production of bare-root plants of various forest species. Ramlösa nursery reported a comprehensive energy input of diesel and electric energy, amounting to 129.6 MJ per 1,000 seedlings. We adjusted this figure to account for the energy consumption associated with fertilizer use in the nursery. Poles are grown in a 2×0.2 m^2 spacing (Pageldyniu plantacija UAB, pers. com. Mindaugas Silininkas 12th of March 2022), corresponding to a production of 31,250 poles per hectare. Assuming the primary energy demand for the manufacture of one kg N fertilizer of 45 MJ (Börjesson, 2006), and a fertilizer application of 150 kg N per hectare per production cycle, we estimated the embodied energy of fertilizer to be 216 MJ per 1,000 poles (Table 11).

Table 11. Energy consumption of pole production in Lithuania.

Pole production in Lithuania	Amount	Unit
Pole density in nursery	31250.00	No ha^{-1}
Fertilization N	150.00	Kg ha^{-1}
Energy embodied in fertilizer in the nursery	6750.00	MJ ha poles^{-1}
Energy embodied in fertilizer	216.00	MJ 1000 poles^{-1}
Diesel + electricity	129.60	MJ 1000 poles^{-1}
Energy demand for the production of 1000 poles	**345.60**	**MJ 1000 poles^{-1}**

4.2 Plantation establishment and management

The poplar cultivation applied within NutriBiomass4LIFE strives to avoid the use of herbicides. Instead, weeds are controlled by disc harrowing between the poplar rows, while a fast early stand development is additionally enhanced by planting poles. At the beginning of fourth growing season, and assuming the appropriate weed management, poplar trees should be able to withstand the weed competition. Weeds are expected to disappear by the time for the canopy closure at the age of 8-10 years.

4.2.1 Soil preparation

Soil is typically plowed and harrowed in the spring before planting. The deep plowing is the largest eneegy input requiring 1.7 hours per hectare (Pageldyniu plantacija UAB, pers. com. Mindaugas Silininkas, April 2021), and consuming 37.3 liter diesel per hectare. The total energy consumption of soil preparation, including the embodied energy of tractors and implements, is calculated to be approximately 3 GJ per hectare (Tables 12-14).

Table 12. Energy consumption of plowing abandoned agricultural land before planting poplars.

Plowing (Lithuania for poplars) x 1	**Amount**	**Unit**
Effective plowing time	1.70	Hour ha^{-1}
Plowing diesel consumption	37.30	Liters ha^{-1}
Plowing energy input	1723.26	MJ ha^{-1}
Tractor embodied energy	72.74	MJ ha^{-1}
Plow embodied energy	55.86	MJ ha^{-1}
Plowing total energy input	**1851.85**	**MJ ha^{-1}**

Table 13. Energy consumption of soil cultivation on abandoned agricultural land before planting poplars.

Cultivation before planting	**Amount**	**Unit**
Effective time for disc harrowing	1.20	Hour ha^{-1}
Tractor fuel consumption	18.70	Liters ha^{-1}
Disc harrow embodied energy	76.04	MJ ha^{-1}
Cultivating energy consumption	863.94	MJ ha^{-1}
Tractor embodied energy	45.17	MJ ha^{-1}
Cultivation of total energy input	**985.16**	**MJ ha^{-1}**

Table 14. Harrowing the cultivated soil before planting poplars on abandoned agricultural land.

Harrowing cultivated land x 1	**Amount**	**Unit**
Effective harrowing time	0.20	Hour ha^{-1}
Harrowing diesel consumption	3.74	Liters ha^{-1}
Harrow embodied energy	12.67	MJ ha^{-1}
Harrowing energy input	172.79	MJ ha^{-1}
Tractor embodied energy	8.56	MJ ha^{-1}
Harrowing total energy input	**194.02**	**MJ ha^{-1}**

4.2.2 Planting poplars

Poles are planted from a platform attached to a tractor. The bottom of the platform is equipped with a deep-ripping blade opening furrow in which two operators insert poles (Fig.14). The effective time for planting of one hectare is two hours and the total energy consumption is 2.3 GJ per hectare (Table 15).



Figure 14. Planting poles on a NutriBiomass4LIFE site in Lithuania. Photo Mindaugas Silininkas.

Table 15. The energy input for poplar planting operations using unrooted poles.

Planting poles Lithuania	**Amount**	**Unit**
Effective time for pole planting	2.00	Hour ha^{-1}
Tractor fuel consumption for pole planting	48.00	Liter ha^{-1}
Pole planting platform embodied	18.78	MJ ha^{-1}
Pole planting energy consumption	2217.60	MJ ha^{-1}
Tractor embodied	85.57	MJ ha^{-1}
Pole planting total energy consumption	**2321.95**	**MJ ha^{-1}**

Pole transports to the planting site require higher energy input per hectare than transport of seedlings (rooted cuttings) or cuttings, equaling the energy input of 0.22 GJ per 1,000 poles. Calculations of pole transport were based on diesel consumption of heavy trafficking vehicles (Lindholm, et al., 2011) of 0.46 liters per km. One load of poles for planting 10 hectares was assessed to weight 7 Mg.

Table 16. The primary energy input is related to the transport of poles from the nursery to the field.

Pole transport	**Amount**	**Unit**
Pole transport distance	50.00	km
Number of poles per 10 ha	10000.00	No 10 ha^{-1}
Weight of poles for 10 ha	7.00	Mg 10 ha^{-1}
Diesel consumption of pole transport	0.46	Liter km^{-1}
Diesel consumption for pole transport	46.00	Liter 50 km^{-1} (x 2)
Energy consumption pole transport /10 ha	2125.20	MJ 10 ha^{-1}
Energy consumption pole transport	212.52	MJ ha^{-1}
Truck embodied energy	7.11	MJ/ha^{-1}
Pole transport total energy input	**219.63**	**MJ/ha^{-1}**

4.2.3 Mechanical weed control and fertilization with pelleted sludge

Establishing poplar plantations with poles is not a sufficient measure to secure the rapid development of young trees. It is still necessary to control weeds mechanically through soil cultivation between poplar rows. Mechanical weed control is particularly important when the site is not pre-treated with herbicides during the summer prior to the year of planting. However, the robustness of poles allows us to restrict cultivation to only one occasion per growing season. The first fertilizatio in the third year can be combined with mechanical soil cultivation, which is required also at the second and third occasion of fertilizer application in years 7 and 11 in order to work in fertilizer into the soil (Table 17).

Table 17. Cultivation between the rows of planted poplars years 1-3, 7, and 11. The cultivation in years 3, 7, and 11 is performed in conjunction with fertilization.

Cultivation between rows x 5	**Amount**	**Unit**
Effective time cultivation between rows Lit	1.20	Hour ha^{-1}
Tractor fuel consumption for disc harrowing	18.70	Liter ha^{-1}
Disc harrow embodied	161.94	MJ ha^{-1}
Cultivating energy consumption	4319.70	MJ ha^{-1}
Tractor embodied for cultivation	256.71	MJ ha^{-1}
Cultivation between rows total E input	**4738.36**	**MJ ha^{-1}**

Manure spreaders can be used for the application of sludge pellets in poplar plantations. Rollforce 5013 spreader, weighting 5.3 Mg was used to calculate performance using its loading capacity of ca 6 Mg or 13 m^3 pelleted sludge. The density of pelleted sludge is 460 kg per m^3, requiring two loads to fertilize one hectare of poplar plantations. The application of pelleted sludge requires 1.6 hours per hectare, and involves a tractor, a spreader, and a loader (tractor). The loader is estimated to work 0.34 hours per ha fertilized plantation, with a diesel consumption of 7 L per hour (Table 18). The fertilization is repeated three times, soresulting in an energy input of 6.3 GJ per hectare. An additional energy input of 0.54 GJ per hectare (Table 19) is related to the transport of sludge pellets from the wastewater treatment plant to the poplar site, with an average transport distance set to 50 km (one direction). The total energy input related to sludge fertilization also includes soil cultivation to mix the fertilizer into the soil, consequently 8.7 GJ.

4.3 Harvesting operations in poplar stands

Harvesting operations in poplar plantations are executed utilizing technology from conventional forestry, employing a harvester and forwarder. Within the context of the NutriBiomass4LIFE project, the envisioned utilization of poplar biomass involves combustion in the local district heating plant. However, it is quite likely that poplar logs can find more profitable markets in the pulp industry or the manufacture of wood panels. Irrespective of the ultimate destination, the processing of tops ivolves chipping at the site, followed by transportation to the biomass conversion site. Notably, poplar logs can be chipped either at the roadside or at the conversion site. The energy consumption of harvesting operations remains relatively

unaffected by the size of the plantation, with only a minor fraction of energy input associated with machine transport to the harvesting site.

Table 18. Energi input when spreading sludge pellets in poplar plantations.

Spreading the pelleted sludge x 3	**Amount**	**Unit**
Diesel and oil energy content	46.20	MJ Liter^{-1}
Tractor fuel consumption	24.00	Liter hour^{-1}
Application of fertilizer	1.60	Hour ha^{-1}
Tractor as a loader fuel consumption	7.00	Liter hour^{-1}
Weight of sludge pellets	0.46	Mg m^{-3}
Spreader load	12.00	m^3
Spreader load	5.52	m^3
Fertilizer amount	11.00	Mg ha^{-1}
Loading time	0.17	Hour load^{-1}
Loading time	0.34	Hour ha^{-1}
Oil consumption	0.07	Liter hour^{-1}
Embodied energy tractor	205.37	MJ ha^{-1}
Embodied energy pellet loading tractor	43.64	MJ ha^{-1}
Embodied energy fertilizer spreader	407.10	MJ ha^{-1}
Energy content of pellet spreading	5322.24	MJ ha^{-1}
Energy content of pellet loading	329.87	MJ ha^{-1}
Total energy fertilization spreading	**6308.22**	**MJ ha^{-1}**

Table 19. Energy input for the transportation of sludge pellets from the wastewater treatment plant to the poplar plantation.

Sludge transport	**Amount**	**Unit**
Sludge transport distance 50 km	50.00	km
Diesel consumption of sludge transport / ha	0.46	Liter km^{-1}
Diesel consumption of one sludge transport	69.00	L/50 km^{-1} (x 2)
Diesel energy consumption	3187.80	MJ 10 ha^{-1}
Energy consumption of sludge transport / ha	318.78	MJ ha^{-1}
Truck embodied energy for sludge transport	73.31	MJ ha^{-1}
Sludge transport total energy input	**538.72**	**MJ ha^{-1}**

4.3.1 Harvester felling operations

The energy input in harvesting one m^3 of poplar timber depends mainly on the mean stem volume. Nordborg et al. (2018) calculated with an average stem volume of 0.36 m^3 in a system planted with 1350 trees per ha and harvested after 24 years. In our study, the stocking is 900 trees per hectare with a mean diameter of 26-28 cm and a mean height of 24.5-25.4 m. The mean stem volume was first calculated from the assessed total biomass production, allocation to branches of 20%, and stem wood density of 330 kg per m^3. The resulting mean stem volume over bark ranged between 0.59 and 0.71 m^3, which corresponded to the volume below the bark of 0.51 to 0.61 m^3. Almost the same volume over bark was obtained when entering the above stem diameters and heights into the volume equation for individual poplartrees developed for Swedish conditions by Hjelm & Johansson (2012):

$$V = 4.4055^{(2+\frac{D}{H})} - 0.6317 \times H^2 + 0.0557 \times D \times H^2$$

where D (cm) and H (m) are the diameter at breast height and the total height of trees. The anticipated DBH of approximately 26 cm after 20 years was also estimated from Canadian poplar spacing trials of similar stocking (data provided by Barb Thomas, 2021, University of Alberta).

Finally, the performance of the large harvester was set to 26 m^3 per hour, with a fuel use calculated according to the equation (Brunberg 2013):

$$FU_{Harv} = 0.46 + \frac{0.1}{Vol_{UB}}$$

where Vol_{UB} corresponds to the average tree stem volume under the bark. The total energy consumption for harvester operations was estimated to be 15.5-17.7 GJ per ha for the unfertilized and fertilized+20% poplar stands, respectively (Table 20).

4.3.2 Forwarding operations

The average forwarding distance has been calculated for a plantations size of 10 hectares. We also assumed a near-quadratic shape of the plantation (~330×300 m), with biomass evenly distributed across the site, which gave the shortest average transport distance of 150 m. However, we applied a correction factor of approximately 30% to compensate for the non-optimal positioning of the log landings and for the fact that forwarders cannot always drive the shortest way across the site. Thus, the average forwarding distance was set to 200 m, and the fuel consumption was calculated according to the equation (Brunberg, 2013):

$$FU_{forw} = 0.53 + 0.00046 \times Dist$$

where $Dist$ corresponds to the average forwarding distance. The total energy consumption of harvesting and forwarding operations is ultimately affected by biomass production and will differ between the three production scenarios, ranging between 36.1 and 42.5 GJ per ha for unfertilized and fertilized+20% poplar stands, respectively (Table 20).

4.3.3 Biomass comminution

Mobile chippers are used for chipping tops and branches at the roadside landing. Poplar logs, on the other hand, can either be transported as logs and processed at the industry/biomass conversion site using large terminal chippers or chipped at the roadside together with tops and branches. Whether biomass is transported as wood chips or logs did not change the energy input in our model. However, using a large terminal chipper did decrease the energy input for comminution by 22.6%. The performance and energy efficiency of comminution aggregates were set according to Bergström & Di Fulvio (2019), who reviewed a large number of studies and commercial brochures of chipping equipment. For the roadside comminution, we selected a 500-kW chipper with an average performance of 30 Mg DW per hour and fuel consumption of 3.4 liters diesel per Mg DW. According to this review,

there was no reduction in energy demand with the increasing power of chippers. However, several studies indicate that large terminal chippers have better energy efficiency. Thus, we calculated the energy input for the comminution of poplar logs at the terminal to be 2.34 liters diesel per Mg DW (Table 21).

Table 20. Energy consumption of harvesting operations in a 20-year-old poplar plantation.

Harvester operations	**Non-fert**	**Fert+10%**	**Fert+20%**	**Unit**
Harvested volume UB	460.64	507.84	553.16	m^3 (UB) ha^{-1}
Mean stem volume UB	0.51	0.56	0.61	m^3 (UB)
Harvester performance	26.00	26.00	26.00	m^3 h^{-1}
Top&Branch - 10% DW Mg/ha	55.04	60.68	66.09	Mg ha^{-1} DW
Top&Branch - 10% FW Mg/ha	105.84	116.69	127.10	Mg ha^{-1} FW
Fuel consumption per m3 fub	0.66	0.64	0.62	L m^{-3} fub
Oil consumption per m3 fub	0.03	0.03	0.02	L m^{-3} fub
Fuel consumption harvester final har-	301.90	323.60	344.45	L ha^{-1}
Oil consumption harvester final harvest	12.08	12.94	13.78	L ha^{-1}
Energy consumption harvester final	14505.50	15548.57	16550.21	MJ ha^{-1}
Embodied Energy harvester final har-	964.78	1063.63	1158.54	MJ ha^{-1}
Harvester total energy input	**15470.29**	**16612.20**	**17708.75**	**MJ ha^{-1}**
Forwarder roundwood final harvest				
Forwarding distance	200.00	200.00	200.00	m
Fuel consumption per m3 fub	0.62	0.62	0.62	L m^{-3} fub
Oil consumption per m3 fub	0.02	0.02	0.02	L m^{-3} fub
Fuel consumption forwarder final har-	286.52	315.87	344.06	L ha^{-1}
Oil consumption forwarder final har-	9.46	10.42	11.35	L ha^{-1}
Energy consumption forwarder final	13674.07	15074.98	16420.26	MJ ha^{-1}
Embodied Energy forwarder final har-	985.78	1086.78	1183.76	MJ ha^{-1}
Forwarder total energy input round-	**14659.85**	**16161.76**	**17604.02**	**MJ ha^{-1}**
Total energy input Harv + Forw	**30130.14**	**32773.96**	**35312.77**	**MJ ha^{-1}**
Forwarder T&B final harvest				
Forwarding distance	200.00	200.00	200.00	m
Fuel consumption per Mg T&B FW	1.16	1.16	1.16	L Mg^{-1} T&B
Oil consumption per Mg T&B FW	0.04	0.04	0.04	L Mg^{-1} T&B
Harvester operations	**Non-fert**	**Fert+10%**	**Fert+20%**	**Unit**
Fuel consumption forwarder final har-	122.41	134.95	147.00	L ha^{-1}
Oil consumption forwarder final har-	4.04	4.45	4.85	L ha^{-1}
Energy consumption forwarder final	5842.13	6440.66	7015.41	MJ ha^{-1}
Embodied Energy forwarder final har-	171.39	188.95	205.81	MJ ha^{-1}
Forwarder total energy input T&B	**6013.52**	**6629.61**	**7221.23**	**MJ ha^{-1}**
Total energy input Harv + Forw to-	**36143.66**	**39403.56**	**42534.00**	**MJ ha^{-1}**

4.3.4 Biomass and machine transports

A substantial part of the primary energy input is related to biomass transport, and the transport distance will strongly affect the energy input (Fig. 15). Much smaller energy inputs are related to the transport of plant material, fertilizer, and machines, and they are affected by both transport distance and the average plantation size. The transport distance for harvesting machines and chipper was set to 30 km. The harvesting and forwarding machine is transported by lorry, while the chipping machine is pooled to the site by tractor (Table 22).



Figure 15. Loading of the timber truck with poplar logs. This poplar plantation has been harvested after only seven years of growth. Photo Mindaugas Silininkas.

The biomass transport distance is set to 50 km (one direction), and diesel consumption is calculated per Mg and km according to the equation (Brunberg et al., 2016):

$$DC = 0.0212588 \times 0.419179/TD$$

where TD is the transport distance (i.e., 50 km). The weight of the truck is 21 Mg, and the weight of an average load is 40 Mg for both poplar logs and chipped biomass. We also calculated the truck's embodied energy, which constitutes approximately 4% of the energy input (Table 23). Biomass transport required 10.3-12.3 truckloads per hectare and the total energy input of 28.9 and 34.7 GJ per ha for unfertilized and fertilized+20% plantations, respectively.

4.3.5 Energy balances

The energy ratio of unfertilized poplar plantations is slightly higher compared to fertilized plantations (Table 24). When comparing energy yield and ratio we assumed the biomass energy content of 18.7 MJ per kg DW (higher heating value) and 19.5 MJ per kg DW for sludge pellet. The energy yield represents the sum of energy contained in produced biomass. The energy contained in the sludge pellets was added to the unfertilized system and reduced for the energy of transport to the waste incineration site, using a transport distance of 50 km.

The total primary energy input varied between 101 and 127 GJ per ha for unfertilized and fertilized+20% stands, respectively. These figures are lower than those reported by Nordborg et al. (2018), where the total energy input for unfertilized and fertilized poplar plantations was 131 and 145 GJ per ha over a 24-year long rotation period. The higher inputs in Nordborg et al. (2018) are related to P and K fertilizer (after the stump lifting) and stump lifting that was included in this particular study. However, the annual average energy inputs of 4.7-6.0 GJ per ha and year in our poplar systems are quite similar to 5.5-6.0 GJ per ha and year reported by Nordborg et al. (2018) or the inputs of 7.3 GJ per ha and year calculated for Swedish willow plantations (Börjesson, 2006). In willow coppice fertilized with conventional NPK fertilizer, fertilization stands for 50% of the energy input. For poplar fertilized on two occasions with a total of 150 kg N ha^{-1} of mineral fertilizer, the energy input related to fertilization was approximately 20% of the total (Nordborg et al., 2018).

In our system, the energy cost for the production of sludge pellets was excluded, regarding the fertilizer as a waste product. The analysis of energy balance and environmental impact of drying sludge compared to other alternative paths of sludge treatments and storage falls out of the scope of this study and the system boundaries. Consequently, fertilization and fertilizer transport corresponded only to 7-9% of the total energy input, while a large share of energy input was invested in harvesting operations, the comminution of biomass, and biomass transports (Table 25). The establishment operations, production, and transport of poplar poles required an equal amount of energy input as fertilization.

The energy balance ranged from 37.6 for fertilized+20% to 39.3 for unfertilized plantations. The energy balance of unfertilized plantations increases to 45.7 when the energy of sludge incineration is added to this option (Table 24). Finally, if the conversion efficiency at district heating plant is set to 91%, the input of primary energy per produced GJ heat energy is 0.024 GJ (2.4%) for unfertilized poplar plantations, up to 0.030 GJ (3%) for fertilized+10% poplar plantations.

Table 21. Energy consumption of roadside chipping and a combination of roadside and terminal chipping of poplar biomass.

Chipping all biomass at the roadside	**Unfert**	**Fert+10%**	**Fert+20%**	**Unit**
Total biomass chipped	212.29	234.04	254.93	Mg ha^{-1} DW
Diesel consumption	717.61	791.13	861.73	L ha^{-1}
Oil consumption	7.18	7.91	8.62	
Energy consumption	30875.93	34039.18	37076.80	MJ ha^{-1}
Energy embodied in a chipper	167.69	184.87	201.37	MJ ha^{-1}
Energy consumption – all at the roadside	**31043.61**	**34224.04**	**37278.16**	**MJ ha^{-1}**
Chipping T&B roadside	**Unfert**	**Fert+10%**	**Fert+20%**	**Unit**
T&B biomass chipped	55.04	60.68	66.09	Mg ha^{-1} DW
Diesel consumption	186.05	205.11	223.41	L ha^{-1}
Oil consumption	1.86	2.05	2.23	L/ha^{-1}
Energy consumption	8004.87	8824.97	9612.50	MJ ha^{-1}
Energy embodied in a chipper	43.47	47.93	52.21	MJ ha^{-1}
Energy consumption T&B - roadside	**8048.34**	**8872.90**	**9664.71**	**MJ ha^{-1}**
Chipping at the terminal	**Unfert**	**Fert+10%**	**Fert+20%**	**Unit**
Stem biomass chipped	157.25	173.36	188.84	Mg ha^{-1} DW
Diesel consumption	367.95	405.65	441.84	L ha^{-1}
Oil consumption	3.68	4.06	4.42	L ha^{-1}
Energy consumption	15831.36	17453.29	19010.80	MJ ha^{-1}
Energy embodied in a chipper	136.54	150.53	163.96	MJ ha^{-1}
Energy consumption stemwood - terminal	**15967.90**	**17603.81**	**19174.76**	**MJ ha^{-1}**
Energy consumption - roadside + terminal	**24016.24**	**26476.71**	**28839.47**	**MJ ha^{-1}**

T&B – tops and branches

Table 22. Energy consumption of machine transports related to the harvesting operations of poplar plantations

Harvester, forwarder and chipper transport	**Amount**	**Unit**
Harvester transport distance	30.00	km
Diesel consumption of harvester and forwarder transports	0.04	L/Mg/km
Diesel consumption of harvester transport /10 ha	22.83	L/10 ha
Diesel consumption of harvester transport /ha	2.28	L/ha
Diesel consumption of forwarder transport /10ha	21.67	L/10 ha
Diesel consumption of forwarder transport /ha	2.17	L/ha
Diesel consumption of driving chipper to the site	2.80	L/ha
Energy consumption of large harvester transport	105.47	MJ/ha
Energy consumption of large forwarder transport	100.10	MJ/ha
Energy embodied in truck per ha	7.46	MJ/ha
Energy consumption of chipper transport to the site	129.36	MJ/ha
Energy embodied in the transport of chipper	8.56	MJ/ha
Energy consumption harvester and forwarder transport total	**350.96**	**MJ/ha**

Table 23. Energy consumption for biomass transports from Unfertilized, Fertilized+10%, and Fertilized+20% poplar production systems.

Biomass transports	**Amount**	**Unit**
Pulpwood transport distance	50.00	km
Diesel consumption of biomass transport	0.03	L/Mg km
Log biomass Unfertilized	302.41	Mg/ha FW
Log biomass fertilized+10%	333.39	Mg/ha FW
Log biomass fertilized+20%	363.15	Mg/ha FW
Chipped biomass Unfertilized	105.84	Mg/ha FW
Chipped biomass fertilized+10%	116.69	Mg/ha FW
Chipped biomass fertilized+20%	127.10	Mg/ha DW
Diesel consumption of log transport, Unfertilized	448.21	L/ha
Diesel consumption of log transport, fertilized+10%	494.13	L/ha
Diesel consumption of log transport, fertilized+20%	538.23	L/ha
Diesel consumption of chipped biomass transport, Unfertilized	156.87	L/ha
Diesel consumption of chipped biomass transport, Fertilized+10%	172.95	L/ha
Diesel consumption of chipped biomass transport, Fertilized+20%	188.38	L/ha
Diesel consumption load/unload logs Unfertilized	48.64	L/ha
Diesel consumption load/unload logs fertilized+10%	53.12	L/ha
Diesel consumption Load/unload logs fertilized+20%	58.24	L/ha
Oil consumption Unfertilized	1.31	L/ha
Oil consumption fertilized+10%	1.44	L/ha
Oil consumption fertilized+20%	1.57	L/ha
Energy consumption Unfertilized	60.40	MJ/ha
Energy consumption fertilized+10%	66.55	MJ/ha
Energy consumption fertilized+20%	72.52	MJ/ha
Energy consumption loading/unloading logs Unfertilized	2247.17	MJ/ha
Energy consumption loading/unloading logs Fertilized+10%	2454.14	MJ/ha
Energy consumption loading/unloading logs Fertilized+20%	2690.69	MJ/ha
Log transport energy consumption, Unfertilized	20707.33	MJ/ha
Log transport energy consumption, fertilized+10%	22828.80	MJ/ha
Log transport energy consumption, fertilized+20%	24866.02	MJ/ha
Chipped biomass transport energy consumption, Unfertilized	7247.56	MJ/ha
Chipped biomass transport energy consumption, fertilized+10%	7990.08	MJ/ha
Chipped biomass transport energy consumption, fertilized+20%	8703.11	MJ/ha
Embodied truck energy log transport Unfertilized	945.50	MJ/ha
Embodied truck energy log transport fertilized+10%	1032.58	MJ/ha
Embodied truck energy log transport fertilized+20%	1132.11	MJ/ha
Embodied truck energy chipped biomass transport Unfertilized	335.90	MJ/ha

Biomass transports	Amount	Unit
Embodied truck energy chipped biomass transport fertilized+10%	360.78	MJ/ha
Embodied truck energy chipped biomass transport fertilized+20%	398.10	MJ/ha
Energy input of biomass transport Unfertilized	**31207.96**	**MJ/ha**
Energy input of biomass transport fertilzed+10	**34372.16**	**MJ/ha**
Energy input of biomass transport fertilzed+20%	**37464.44**	**MJ/ha**

Table 24. Energy balance of poplar plantations over a 20-year long rotation period.

Energy output	unit	Unfertilized	fertilized+10%	fertilized+20%
Energy output	GJ/ha	3969.883	4376.599	4767.162
Sludge incineration	GJ/ha	642.961		
Energy output	GJ/ha/yr	198.494	218.830	238.358
Sludge incineration	GJ/ha/yr	32.148		
Net energy yield	GJ/ha/yr	225.919	213.256	232.385
Heat produced (91% eff)	GJ/ha/yr	209.884	199.135	216.906
Energy input (sum)	GJ/ha	101.019	118.107	126.692
Pole production	GJ/ha	0.346	0.346	0.346
Pole transport	GJ/ha	0.220	0.220	0.220
Pole planting	GJ/ha	2.322	2.322	2.322
Soil preparation	GJ/ha	3.031	3.031	3.031
Weed management	GJ/ha	2.843	2.843	2.843
Fertilization	GJ/ha	0.539	8.742	8.742
Harvest	GJ/ha	15.470	16.612	17.709
Forwarding	GJ/ha	20.673	22.791	24.825
Chipping	GJ/ha	24.016	26.477	28.839
Machine transport	GJ/ha	0.351	0.351	0.351
Biomass transport	GJ/ha	31.208	34.372	37.464
Energy balance poplar	ratio	39.298	37.056	37.628
Energy balance poplar + sludge incineration	ratio	45.663		

Table 25. The share of energy input for different stages of poplar production system over a 20-year-long rotation period.

Energy input	Unit	Unfertilized	fertilized+10%	fertilized+20%
Establishment	GJ/ha	8.761	8.761 (7.9%)	8.761 (7.3%)
Fertilization	GJ/ha	0.000	8.742 (7.8%)	8.742 (7.3%)
Harvest and chipping	GJ/ha	54.497	59.602 (53.5%)	64.503 (54.0%)
Transports	GJ/ha	31.208	34.372 (30.8%)	37.464 (31.4%)
Sum	GJ/ha	94.467	111.477	119.471

5. Emissions in poplar production systems fertilized with pelleted sludge

The emission data is gathered from the literature, focusing on Swedish studies. The functional unit is 1 MJ of heat produced at the district heating plant at an efficiency of 91% (Porsjö & Hansson, 2014, Börjesson, 2006). The environmental effects included in the study are listed in Table 26, whereas Table 27

contains the conversion factors for different emissions effects within the selected environmental categories.

The main difference between the systems is in the primary energy and emissions related to fertilization. Apart from the energy related to the application of fertilizer, fertilization also affects emissions through increased biomass yields, i.e., the emissions related to harvesting operations and biomass transports.

Table 26. The environmental effects included in the evaluation of poplar production systems.

Category of the environmental effects	Type of emissions	Expressed as
Global warming potential, GWP	CO_2, CO, CH_4, N_2O	CO_2-eq
Eutrophication potential, EP	NO_x, NH_3, NO_3	PO_4^{2-}-eq
Acidification potential, AP	SO_2, NO_x, NH_3	SO_2^--eq
Photochemical oxidant creation potential, POCP	CO, HC, CH 4	C_2H_2-eq
Emission particles	particles	Particles
Energy consumption		Primary energy

Table 1. The conversion factors within different environmental effect categories.

Emissions	GWP* g CO_2-ekv g^{-1}	EP* g PO_4-ekv g^{-1}	AP* g SO_2-ekv g^{-1}	POCP* g C_2H_2-ekv g^{-1}	
CO_2	1				
CO	2				0.032
NO_x		0.13	0.7		
NH_3		0.35	1.9		
SO2			1		
HC					0.42
CH_4	28				0.007
N_2O	265				
NO_3 to water		0.1			

*Abbreviations explained in table 26

The study did not include emissions from the drying, and pelleting of sludge. It can be argued that the inclusion of these emissions would be appropriate in the same manner as it is practiced for the mineral fertilizers. However, LCA studies of hydrothermal carbonization (HTC) are relatively rare. So far, it has been suggested that the higher energy expenses within the HTC process cannot be compensated by additional energy produced or increased biomass yields (Meisel, et al., 2019). An optimized HTC process may lead to a significant reduction in GHG emissions even if the concepts of agricultural valorization are generally not advantageous compared to energetic valorization, as was also shown in the comparison of unfertilized and fertilized poplar plantations in this study.

The pelleted sludge is assumed to contain 3.25% N, corresponding to 1,072.5 kg N per ha applied to poplar plantations over the rotation period or 53.6 N kg per ha and year. Consequently, the amount of nitrogen added was similar to the levels applied in the Swedish intensive willow coppice (Börjesson, 2006). The emissions of N_2O are the direct effect of fertilization and were set to 1.25% of added nitrogen according to the IPCC (2006) recommendations. Even though the environmental monitoring within the NutriBiomass4LIFE could not detect N-leaching from the sludge-fertilized fields, we decided to include NO_3 leaching, which corresponds to 12.6 kg per ha and year. This effect was considered only in the case of fertilized plantations, and it was assumed that 0.75% of the leached nitrogen was emitted as

N_2O. The reason for the inclusion of NO_3-leaching was that N-leaching has been detected in older poplar plantations, particularly in autumn, and most probably due to leaf litterfall and turnover of fine roots (Dimitriou & Mola-Yudego, 2017). Thus, it is also reasonable to assume some leaching will occur from fertilized plantations. Whether this environmental effect can be disregarded for the Lithuanian poplar plantations is a later question that can be answered only through long-term monitoring. The biogenic emissions from leaf litter were not considered, assuming that recently captured CO_2 is quickly decomposed and emitted, except for the C added to the SOC pool. Emissions related to the described poplar production system are presented in Table 28. The inputs of energy and emissions of the establishment phase are the same for both fertilized and unfertilized plantations.

Table 29 summarizes the environmental effects of poplar plantations without SOC change. Exclusion of SOC accumulation over 100 years results in a positive CO_2 flux, which is a bit lower for unfertilized compared to fertilized stands (2 respective 3.4 g CO_2 per MJ produced heat) and represents only 25% to 46% of the CO_2 flux for willow coppice. Similar CO_2 emissions of 3.3 g CO_2-equivalents per MJ were reported by Porsö & Hansson (2014) for densely planted poplar plantations grown on 10-year rotations used for the production of wood pellets. The eutrophication and acidification potential are high for fertilized compared to unfertilized poplar plantations. This was partly due to N-leaching and higher energy inputs for harvesting operations and biomass transports. Particle emissions were lower in poplar plantations compared to literature estimates for willow coppice (Börjesson, 2006).

When accounting for SOC change, the estimates of GWP100 can be calculated for two different types of systems. First, the above-described growing system which assumes replanting after each rotation period after treating the stumps of harvested trees with herbicides. This is technically possible but not a very likely choice of plantation renewal, even if it is practiced in some countries to avoid the expenses of stump harvest. In the Baltic-Nordic conditions, and assuming the projected use of biomass for bioenergy or textile pulp, the probable method of renewing the stand will be through the abundant stump and root coppicing followed by a relatively early cleaning in the regenerated population of young poplar stems. However, in such a system, the primary energy inputs and emissions related to weeding, soil preparation, plant production, plant transport, and planting are omitted for all the subsequent rotations. At the same time, the stump and coarse root biomass need to be regarded as staying active and representing a constant living belowground biomass carbon stock.

*Table 28. Energy inputs and emissions **per hectare and year** from poplar plantations. The establishment part is common for all the plantations, whereas fertilization and increased biomass production in the fertilized poplar stands result in increased emissions. The additional emissions of N_2O from decomposing litter and the belowground biomass were not included.*

Input categories	Energy (MJ)	CO_2 (kg)	CO (g)	NOx (g)	SO2 (g)	HC (g)	CH4 (g)	Part. (g)	N2O (g)	NH3 (g)	NO3 (kg)
Plant production[1]	17.280	1.744	0.717	3.388	1.848	0.141	0.272	0.115	0.000	0.000	0.000
Plant transport[1]	10.981	0.860	0.172	7.835	0.275	0.450	0.255	0.131	0.000	39.595	0.232
Plowing[1]	92.593	7.625	7.734	75.490	2.723	4.575	6.427	1.089	0.000	0.000	0.000
Harrowing + cultivation[1]	58.959	4.848	4.586	44.547	1.703	3.013	4.062	0.786	0.000	0.000	0.000
Planting of poles[1]	116.097	9.675	11.997	91.330	3.483	6.192	8.127	1.548	0.000	0.000	0.000
Mechanical weeding year 1-3[1]	142.151	11.677	11.880	115.853	4.265	7.006	9.747	1.726	0.000	0.000	0.000
Unfertilized ha^{-1} yr^{-1}											
Fertilization + cultivation x 2	-	-	-	-	-	-	-	-	-	-	-
Transport of sludge pellets	26.936	2.109	0.421	19.219	0.675	1.104	0.626	0.322	0.000	97.120	0.569
Harvesting + forwarding	1807.183	148.295	346.767	1305.105	53.897	122.357	124.483	22.218	0.000	0.000	0.000
Chipping	1200.812	98.537	230.415	867.198	35.812	81.302	82.715	14.763	0.000	0.000	0.000
Transport of machines and biomass	1577.946	123.569	24.669	1125.898	39.560	64.674	36.671	18.891	0.000	5689.496	33.337
Sum Unfertilized	5050.938	408.939	639.357	3655.864	144.242	290.814	273.385	61.590	0.000	5826.212	34.138
Fertilized+10% ha^{-1} yr^{-1}											
Fertilization + cultivation x 2	410.178	33.635	41.929	430.481	12.214	21.512	28.257	5.013	670.313	1340.625	12.563
Transport of sludge pellets	26.936	2.109	0.421	19.219	0.675	1.104	0.626	0.322	0.000	97.120	0.569
Harvesting + forwarding	1970.178	161.671	378.042	1422.816	58.758	133.393	135.711	24.222	0.000	0.000	0.000
Chipping	1323.836	108.632	254.021	956.043	39.481	89.631	91.189	16.275	0.000	0.000	0.000
Transport of machines and biomass	1736.156	135.958	27.143	1238.784	43.526	71.158	40.347	20.785	0.000	6259.942	36.679
Sum fertilized+10%	5905.345	478.433	738.642	4405.786	168.953	338.176	325.020	72.014	670.313	7737.282	50.043
Fertilized+20% ha^{-1} yr^{-1}											
Fertilization + cultivation x 2	410.178	33.635	41.929	430.481	12.214	21.512	28.257	5.013	680.313	1340.625	12.563
Transport of sludge pellets	26.936	2.109	0.421	19.219	0.675	1.104	0.626	0.322	0.000	97.120	0.569
Harvesting + forwarding	2126.700	174.514	408.076	1535.853	63.426	143.990	146.492	26.146	0.000	0.000	0.000
Chipping	1441.973	118.327	276.689	1041.359	43.005	97.630	99.327	17.728	0.000	0.000	0.000
Transport of machines and biomass	1890.770	148.066	29.560	1349.104	47.402	77.495	43.940	22.636	0.000	6817.425	39.946
Sum fertilized+20%	6334.618	513.079	793.761	4714.460	181.020	363.109	347.532	77.242	680.313	8294.765	53.309

Table 29. The summary of the environmental effects for the poplar production systems (MJ^{-1} heat produced at 91% efficiency). The Unfertilized option includes the heat obtained by the energetic valorization of the amount of sludge pellet spread in fertilized stands. The environmental effects of the intensive willow coppice cultivation were presented for comparison with poplars.

System	GWP 100 (g CO_2-eq)	EP (mg PO_4^{2-} eq)	AP (mg SO_2 eq)	POCP (mg C_2H_2-eg)	Parti-cles
Unfertilized	1.991	28.245	65.623	0.689	0.293
Fertilized+10%	3.348	41.605	90.159	0.843	0.362
Fertilized+20%	3.249	40.787	88.708	0.831	0.356
Willow (Börjesson 2006)	7.9	18	54	0.88	1.4

Table 30. The global warming potential with and without SOC. SOC option one includes replanting the poplars and allowing the stump and coarse root biomass to enter SOC. The second option assumes a constant stump and coarse root biomass after the first harvest, without decomposition and additional inputs to SOC.

System	GWP without SOC	GWP with SOC 1	GWP with SOC 2
Unfertilized	1.991	-6.041	-3.230
Fertilized+10%	3.348	-8.192	-4.938
Fertilized+20%	3.249	-7.992	-4.750

6. Conclusion

This study reveals that in terms of climate change mitigation, it is advantageous to produce heat utilizing chipped wood from poplar plantations where pelletized sludge has been recycled as fertilizer to enhance tree biomass growth and increase soil carbon accumulation. This system's global warming potential (GWP100) is negative in the range of -4.750 and -8.192 g CO_2-eq per MJ produced energy, compared to -3.230 and -6.041 g CO_2-eq per MJ when pelleted sludge is directly incinerated in waste incineration plants.

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