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Carbon negativity of black locust and poplar plantation in different management systems in Hungary

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Abstract. Carbon negativity is one of the promising strategies to uptake carbon emissions from the atmosphere and reduce carbon emissions to the atmosphere. Forests have been proven to sequester atmospheric carbon emissions through photosynthesis and store them as tree biomass. However, forest operations also emit carbon into the atmosphere via fertilizer, pesticides, and fuel consumption. This study aims to compare the carbon negativity of black locusts and poplar plantations in different management systems. Carbon dynamics in short and long-rotation systems was analysed using CO_2FIX software. Meanwhile, the carbon emission in forest operations was estimated through the life cycle assessment method. In the simulation period of 45 years, black locust and poplar plantations in short and long-term management systems have shown carbon negativity. The amount of carbon sequestration was higher than carbon emission. Furthermore, carbon negativity in long-rotation management systems was better than in short-rotation coppice management systems.

1. Introduction

Article 2 of the Paris Agreement states clearly, "*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" [1]. Implementing the Paris Agreement's target, every country that ratified the Paris Agreement has submitted its National Determined Contribution (NDC) to the United Nations Intergovernmental Panel on Climate Change (IPCC). In the Updated NDC 2023 of the European Union, Hungary set the target for 2030 to remove the emissions -934Kt CO_2eq [2].

Net zero emissions, carbon neutrality, and carbon negativity have more popular in climate change mitigation actions. Marchi et al. [3] have used the terminology carbon footprint offset to describe the net carbon difference resulting from carbon sequestration and carbon footprint in the managed bamboo plantations. Furthermore, Kharissova et al. [4] have proposed the idea of a carbon negative footprint, which means reducing carbon emissions and the carbon dioxide from the atmosphere. In contrast, the carbon positive footprint refers to the amount of carbon emission that pollutes the atmosphere [4]. In this study, we used the terminology carbon negativity to describe the amount of net carbon emission reductions through carbon sequestration and carbon emission during plantation management.

According to Mulyana et al. [5], black locust and poplar plantations in short-rotation coppice systems in Hungary have shown the ability to absorb CO_2 emissions and store the carbon above and below ground. However, the forest operation in energy plantation with short-rotation coppice system also has released some greenhouse gas emissions by application of agrochemicals and fuel consumption [6–8]. Thus, a study on integrating the estimation of forests as carbon sequesters and emitters should be conducted to better understand carbon negativity.

Furthermore, this study aims to compare the carbon negativity between short-rotation coppice systems and long-rotation management systems for black locust and poplar plantations. Our hypothesis follows the study from Kharissova et al. [4] that managed land and forest have sequestered more carbon than the emission from the forest operations.

2. Materials and methods

2.1 Data collection

A study on carbon negativity requires analyzing carbon sequestration and emissions released by forests during a specific period. Carbon sequestration is modeled by CO_2FIX software, while carbon emissions are estimated through the life cycle assessment (LCA) method. Furthermore, data should be collected for carbon sequestration and emissions.

In this study, growth rate data for black locust and poplar were derived from a yield table developed by Rédei et al. [9,10] from 105 and 90 sampling plots of black locust and poplar, respectively. The climate data series of Hungary was collected from the Orszagos Meteorologiai Szolgalat [11]. Furthermore, the data of relative growth to stem (foliage, branches, and coarse roots), turnover rate (foliage, branches, and coarse roots), product allocation (logwood pulp wood, and slash), and the average lifetime of products (long-term, medium-term, and short-term) followed the research findings of Quinkenstein and Jochheim [12] and de Jong [13].

Collecting data for life cycle inventory (LCI) is vital in the LCA processes. However, the challenges in the LCI are data availability and accessibility. Furthermore, collecting data in LCI can be derived from some literature and then re-calculated or made some estimation as the proxy data [14,15].

2.2 Data analysis

Carbon sequestration and stock for black locust and poplar in different management systems was projected through the CO_2FIX software. According to Mulyana et al. [16], in the last three decades, the software CO_2FIX has been applied to many types of forests in 27 countries.

The carbon footprint of black locust and poplar was estimated using the LCA method. One of the impact categories in life cycle impact assessment (LCIA) is global warming potential (GWP). LCA can be applied to estimate the carbon footprint of a product or system from raw material (cradle) to product disposal (grave) [4]. For analyzing the life cycle impact assessment, we used the GaBi Education software to calculate the impact categories of forest operations for short— and long-rotation management systems.

3. Result and discussion

3.1 Plantation management systems

Forest management for plantations remains less significant than that of natural forests. Since the 1990s, forest management standards and guidelines have mainly concentrated on natural or semi-natural forests, with less emphasis on forest plantation [17]. FAO has categorized forests as natural regeneration and planted forests, which account for 93% and 7% of the world's forest area [18]. In 1990, there were 123 million ha of forest plantations, which expanded to 294 million ha by 2020 [18]. Moreover, establishing forest plantations worldwide is vital to meet the increasing wood demand for some industrial purposes because of the rising human population [19]. In some estimations, around half of the roundwood demand will be supplied from the plantation of the planted forest by the year 2040 [20].

SRC is an old practice of plantation management with a different name, such as short-rotation hardwood crops [21], short-rotation forestry [22–26], coppice culture [27], and short-rotation woody crop [28]. Furthermore, in Hungary, the terminology for SRC is short-rotation energy plantation [8,29] and short-rotation energy crops [30,31]. Short-rotation characteristics include using fast-growing species, high density, a cutting cycle of fewer than ten years, and a harvesting method using a chipper (Table 1).

Table 1. Characteristics of plantation management systems.

	Short-rotation coppice	Long-rotation	References
Purpose	Bioenergy	Veneer, pulp and paper, constructions, furniture	[32–35]
Length of rotation	10, 20, 25 years	20, 25, 40, 50, 80, 100 years	[34,36–38]
Cutting cycles	2, 3, 4, 5, 7, 8 years	End of rotation	[34,36–41]
Planting density	2,500 – 22,222 trees/ha	25 – 1,100 trees/ha	[37,42–44]

According to Gabira et al. [35], who analyzed 255 research articles, found that planting density influences stand growth (stem diameter and volume; the high-density stand has a smaller individual volume). Furthermore, Gabira et al. [35] discovered that the high-density planting was for pulp and paper or biomass industries, but the low-density plantation produced larger stem diameters utilized for sawmill industries. Plantation rotation for industrial purposes varies depending on the output of wood-based products. The rotation of poplar plantations to supply the veneer industry in Hungary ranges from 12 to 25 years [37]. In the tropical region, plantation rotation for industrial products ranged from 5-20 years for wood pulp and 10-40 years for lumber-sized materials [34].

3.2 Carbon negativity in short-rotation coppice systems

Carbon dynamics in the forest is a complicated system. Carbon accumulates in vegetation via photosynthesis and is then returned into the atmosphere through combustion or decomposition [45]. Bosner et al. [45] described the complexity of carbon dynamics, including the life cycle of forest products, the production chain, and the connection among products, by-products, and waste materials. In this study, the life cycle of wood for bioenergy (short life span) and industrial purposes (long life span). An analysis of carbon storage and footprint was applied to aboveground biomass. The system boundaries for life cycle assessment to estimate carbon footprint were cradle to grave (timber production). In timber production, the potential input that releases carbon emissions comes from plantation establishment, tree growth maintenance, and harvesting activities by consumption of fertilizer, pesticide, and fuel during the operations.

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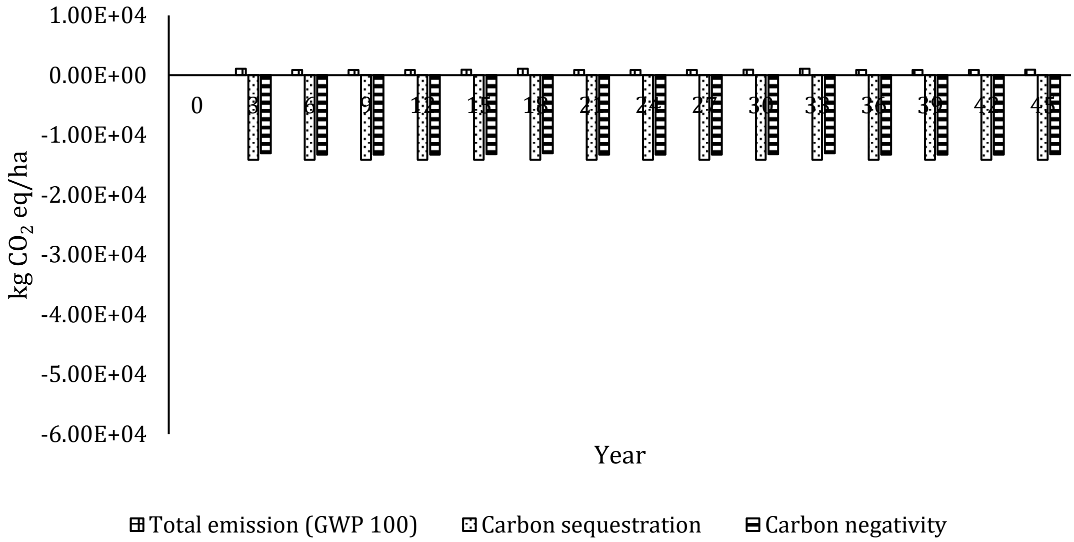
In the short-rotation coppice management systems, either black locust or poplar plantations, carbon sequestration is higher than carbon emission (Figure 1). This proves the hypothesis that the forest has sequestered more carbon than the emissions emitted from the forest operations. Carbon emission occurs yearly but looks higher in the third, sixth, eighth, eleventh, and fifteenth years (due to scheduled management activities) or each harvesting period.



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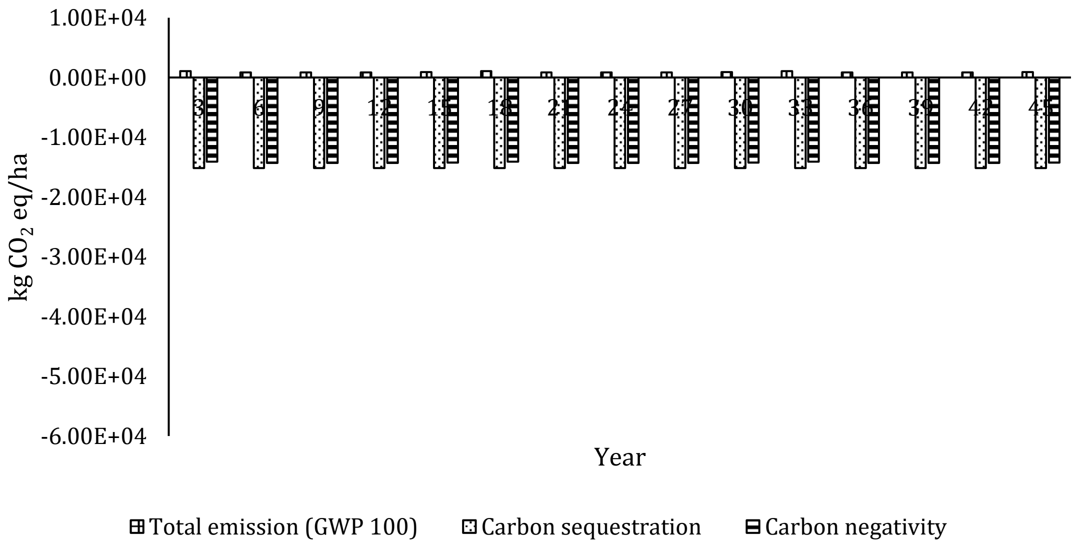

(b)

Figure 1. Carbon negativity of 3-year cycle short-rotation coppice systems a). black locust, b). poplar.

According to Figure 1, negative values show the quantity of CO_2 emission captured by trees (black locust or poplar) and processed during photosynthesis. As a result, carbon is stored as biomass in the tree's organs. On the other hand, the positive values represent the quantity of CO_2 emitted by forest activities (fuels of machinery and the utilization of pesticides and fertilizer) and harvested biomass. In the SRC management system chosen as an example, the amount of carbon stored in a tree's biomass for three years will be removed as harvested wood. For this reason, the bioenergy derived from wood biomass is called carbon neutral.

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The SRC plantations support the environment by producing wood for biomass and providing ecosystem services such as reducing soil erosion, improving water quality, increasing biodiversity, and mitigating climate change through their ability to capture CO_2 emissions from the atmosphere. According to Figure 1, our research reveals that the black locust and poplar plantation with SRC management systems have proved to uptake the CO_2 emission from the atmosphere and store the carbon in the tree body parts as biomass. Although forest activities influence the environment- particularly carbon emission from the consumption of fuel, lubricant, pesticide, and fertilizer - carbon absorption outperforms carbon emission.

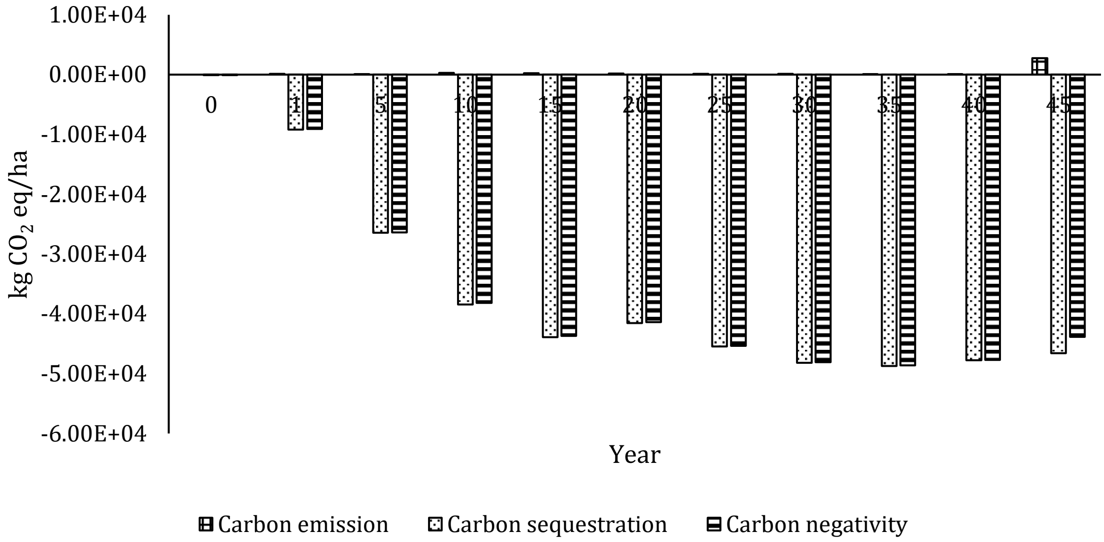
The first- and second-year carbon sequestration in black locust SRC management systems are 8.1E+03 and 6.0E+03 kg CO_2 eq/ha, respectively. Furthermore, in the third year, the harvested biomass is 8.31 dry tons/ha, equal to 3.85 tons C/ha. To produce 1 kg of carbon in plant biomass requires 3.67 kg of CO_2 from the atmosphere to be processed in photosynthesis. Thus, harvesting operation in the black locust SRC management system has removed the 3.85-ton C/ha or equal to 14.1E+03 kg CO_2 per harvesting.

Furthermore, the carbon sequestration in the poplar SRC management system is similar to that of black locust. Carbon sequestration in the first and second years is 8.5 and 6.7E+03 kg CO_2 eq, respectively. Meanwhile, the harvesting has removed 15.2E+03 kg CO_2 eq. Regarding carbon sequestration, the poplar SRC management system is better than the black locust plantation. The carbon balance will also be similar because the poplar SRC management system is better than black locust on carbon sequestration. In this research, we assumed the silvicultural system of the SRC management system of poplar and black locust is similar. The first, second, third, fourth, and final cycle carbon emissions were 1.06E+03, 0.84E+03, 0.84E+03, 0.84E+03, and 0.91E+03 kg CO_2 eq. Thus, the carbon emission from using energy (fuel and lubricant) and agrichemicals (fertilizer and pesticide) was lower than the ability of SRC plantations to absorb carbon emission from the atmosphere.

3.3 Carbon negativity in long-rotation systems

The total carbon footprint for a whole process of long-rotation plantation management for poplar and black locust are 4.3E+03 and 4.0E+03 kg CO_2 eq., respectively. Harvesting activity primarily contributed to poplar or black locust carbon footprint. In the harvesting activity, the utilization of fuel and lubricant is more significant than in the thinning activities (Figure 2). It happened because of the large number of trees that should be harvested in the final harvesting compared to the thinning activities.

Harvesting operations are a major source of carbon emissions in forestry activities, as reported by other researchers. Kuka et al. [14,15] have reported that carbon emissions in harvesting operations during birch and pine roundwood timber production were the highest compared to plantation establishment and thinning activities. Klein et al. [46] also revealed similar findings. They reviewed articles on life cycle assessment in the forestry sector over the last twenty years and found that the harvesting operation was the dominant source of carbon emissions.



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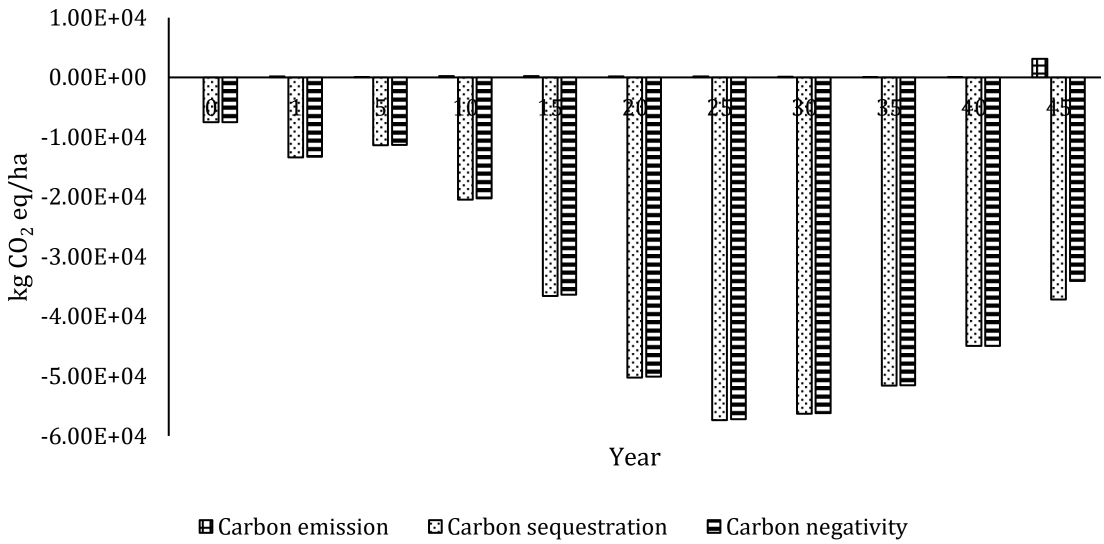

(b)

Figure 2. Carbon negativity for long rotation plantation of a). black locust, b). poplar.

Figure 2 shows that poplar plantations have a better carbon balance than black locust plantations. Carbon management can be conducted by avoiding deforestation, managing existing forests, restoring forests, and improving wood utilization [47]. Furthermore, in the production forest in Hungary, the transition of forest rotation to continuous forest cover is one of the strategies to increase carbon sequestration [48]. Carbon negativity decreases significantly at the end of the rotation. At the end of the rotation, the black locust and poplar plantation will be harvested using the clear-cutting method. Harvesting activity reduces the carbon balance because emissions are higher than other silvicultural activities (forest planting, tree maintenance, and thinning). Harvesting is affecting the forest carbon sinks and can be an instrument for emission reduction [49]. Furthermore, Hyyrynen et al. [49] explained that by harvesting the forest, the carbon is removed from the forest and moved to wood-based products.

The total carbon balance for black locust and poplar long-rotation plantations are 2.3E+06 and 2.2E+06 kg CO_2 eq., respectively. Although the total carbon is relatively similar, however, the pattern or carbon balance of black locust and poplar are different. In the black locust plantation, the carbon balance stabilized at the year 15. The carbon balance in the 15 years was 4.3E+04 kg CO_2 eq. The highest carbon balance was 4.8E+04 kg CO_2 eq. at the years 30 and 35. Furthermore, the carbon negativity decreased to 4.3E+04 kg CO_2 eq. at the end of rotation. In contrast, the pattern in the poplar plantation is similar to a bell shape. It started at 0.7E+04 kg CO_2 eq. at the beginning of rotation and reached its peak at year 25 (5.7E+04 kg CO_2 eq.). In the following year, the carbon balance decreased gradually. At the end of the rotation, it was 3.4E+04 kg CO_2 eq.

4. Conclusion

In conclusion, the plantation forest in Hungary, either short or long-rotation management systems, has shown the ability to carbon negativity. In short-rotation coppice management systems, the total carbon negativity for 45 years was 4.3E+03 and 4.0E+03 kg CO_2 eq., respectively. Furthermore, the total carbon negativity for 45 years in long-rotation management systems for black locust and poplar were 2.3E+06 and 2.2E+06 kg CO_2 eq., respectively. Based on our findings, from the perspective of carbon negativity, long-rotation plantation management systems outperformed short-rotation coppice management systems.

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