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Carbon dynamics of poplar and black locust plantations with different management strategies

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Written in order to obtain Doctoral (PhD) degree
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Abstract

Long-term forest carbon modeling is helpful in climate change mitigation actions. Estimating potential carbon sequestration in forests can be considered the long-term strategy for low carbon and climate resilience in the National Determination Contribution. In Hungary, the black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* sp.) are prominent and dominant species in reforestation and afforestation projects. The research aimed to estimate the carbon dynamics of black locust and poplar plantations in different forest management scenarios, to estimate the potential carbon stock and describe the carbon distribution of the short rotation coppice bioenergy plantation above and below ground. Various sources were used to acquire parameterization data for developing forest carbon dynamic models. CO2FIX modeling V.3.2 was utilized in the data analysis to estimate the total carbon stock in biomass, soil, harvested wood products, and bioenergy compartments. CO2FIX modeling projected carbon dynamics for 45 years of rotation. Thirty-six forest management scenarios were developed from two species, six yield classes, and tree wood utilization. Furthermore, estimating carbon footprint used life cycle assessment approach and using Sphera LCA for Experts Education License version 9.2.1.68. Our findings have shown that class yield I resulted in the highest carbon stock compared to class yield II–VI. In long-rotation plantations, black locust plantations have stored more carbon than poplar plantations. In contrast, in short-rotation plantations, the total carbon stock of hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai at the end of simulation period (45 years) are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Furthermore, the total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. The accumulative of aboveground carbon of hybrid black locust and poplar in short-rotation coppice system is higher than the accumulative belowground carbon. In terms of wood utilization, harvested black locust or poplar wood contributed the most extensive carbon stock if used for pulp. From 36 forest management scenarios, the best scenario was black locust plantation in class yield I and the purpose for pulp that stored the 101.75 Mg C/ha carbon at the end of rotation. In contrast, the lowest carbon stock is poplar plantation at yield class VI to supply the board industry (23.75 MgC/ha). In the long rotation system during the 45-year simulation, the accumulative of aboveground carbon of black locust and poplar are lower than the accumulative belowground carbon. Furthermore, the total carbon footprint was 17.7E+03 kg CO_2 eq for short-rotation coppice management system, while the long-rotation plantation management system for black locust and poplar were 4.0E+03 and 4.4E+03 kg CO_2 eq, respectively. Thus, the total carbon balance in hybrid black locust plantations for 45 years for the cultivar Jászkiséri, Kiscsalai, Nyírségi, and Üllői were 2.0E+05, 3.4E+05, 2.0E+05, and 2.4E+05 kg CO_2 eq, respectively. Furthermore, total carbon balance in hybrid poplar cultivar Agathe-F, I-214, Pannónia, and S 298-8 for 45 years were 2.5E+05, 1.4E+05, 2.7E+05, and 1.4E+05 kg CO_2 eq, respectively. In comparison, the carbon balance for long-rotation plantation for black locust and poplar were 2.3E+06 and 2.2E+06 kg CO_2 eq., respectively. Therefore, more attention should be paid to below ground allocation through environmentally friendly soil management. Thus, conserving the soil as the dominant carbon pool is vital for future policy recommendations.

List of acronyms and abbreviations

AGB	Aboveground biomass
AGC	Aboveground carbon
BGB	Belowground biomass
BGC	Belowground carbon
CML	*Centrum voor Milieukunde Leiden*
CO_2	Carbon dioxide
CTL	Cut-to-length
ECO	Ecological scarcity
EF	Environmental footprint
EPS	Environmental priority strategies in product design
ET	Environmental theme
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gases
GWP	Global warming potential
IO	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MDF	Medium density fiber
NCDS	National Clean Development Strategy
OD	Oven dried
PA	Process analysis
PCC	Percentage carbon content
SRC	Short-rotation coppice
WTH	Whole tree harvesting

I. INTRODUCTION

1.1. Research background

The forestry sector can be essential in supporting renewable energy policies, particularly bioenergy, from using biomass with multipurpose tree management. Forest also can be utilized considering various objectives such as wood and non-wood (Miina et al. 2010; Tahvanainen et al. 2018), timber production and marginal land rehabilitation (Rédei et al. 2011; Nicolescu et al. 2018), wood and wildlife conservation (Toyoshima et al. 2013), as well as wood with environmental services to absorb forest carbon (Nölte et al. 2018; Mulyana et al. 2023a, b, 2024). Carbon sequestration is a potential indicator in measuring environmental services for regulating global climate change (Groot et al. 2010). Moreover, adaptation to climate change could be integrated into the agroforestry system, which provides multifunctional systems (Marosvölgyi and Vityi 2019; Kovács and Vityi 2022).

Some North countries have developed short rotation coppice (SRC) plantations in marginal land using multipurpose forest management approaches to mitigate climate change. For instance, Canada develops willow and poplar species for bioenergy sources, land rehabilitation, and carbon sequestration (Amichev et al. 2010; Lupi et al. 2015; Jego et al. 2017). European countries also have been developing SRC plantations, such as Poland (Stolarski et al. 2018), Bulgaria (Marinov et al. 2013), Belgium (Laureysens et al. 2005), Italy (Bacenetti et al. 2016a), Germany (Faasch and Patenaude 2012), Hungary and Romania (Nicolescu et al. 2018) for mitigating climate change and increasing on energy demand. The development of SRC plantations has multiple effects, such as enhancing the bioeconomy and providing environmental services.

Hungary has been developing bioenergy plantations using fast growing species with short-rotation coppice system. According to Hungarian law, Decree No. 45 of 2007 (VI.11.) FVM decree, the allowed species in woody energy plantations in Hungary are 13 species. The species are White summer (*Populus alba*), Black summer (*Populus nigra*), Gray summer (*Populus x canescens*), Vibrating summer (*Populus tremula*), White willow (*Salix alba*), Basket weaving willow (*Salix viminalis*), White acacia (*Robinia pseudoacacia*), Gummy alder (*Alnus glutinosa*), Tall ash (*Fraxinus excelsior*), Narrow-leaved ash (*Fraxinus angustifolia*), Red oak (*Quercus rubra*), Black walnut (*Juglans nigra*), and Early maple (*Acer platanoides*).

The other potential species for bioenergy plantation in other European countries are willow (*Salix* sp.), poplars (*Populus* sp.), and elm (*Ulmus pumilla*) (Yuzhakova et al. 2012). Black locust (*Robinia pseudoacacia*) and poplars (*Populus* sp.) are the prominent species in forests of West and Central European countries. Black locust and poplars were the most planted broadleaf species in the world after Eucalyptus sp. (Nicolescu et al. 2020). Black locust (*Robinia pseudoacacia* L.), a native species in North America and then introduced to Central Europe, has been utilized for timber production, bioenergy biomass, and degraded soil rehabilitation (Vítková et al. 2017; Nicolescu et al. 2020). Ecologically, black locust and poplar are important to stabilize the soil, revegetation species for mining reclamation, and carbon sequestration (Nicolescu et al. 2020). Furthermore, the development of perennial industrial plantations, such as black locust, poplar, and willow, in the marginal land will provide environmental and economic benefits (Amaducci et al. 2017; Matyka and Radzikowski 2020; Radzikowski et al. 2020). However, the black locust was also listed as an invasive species and threatened the native species in Central Europe (Vítková et al. 2017).

The development of forest plantations also will support the energy transition and climate change mitigation in Hungary. The government of Hungary sets an energy target from carbon-neutral and renewable energy sources at least 21% of total energy consumption by 2030 (International Energy Agency 2022). Furthermore, based on data from the International Energy Agency (2022), Hungary's energy production was 10.8 Mtoe, which comes from nuclear (38.9%), bioenergy (25.8%), natural gas (12.2%), oil (9.6%), coal (8.6%), solar (2.1%), geothermal (1.4%), wind (0.5%), and hydro (0.2%). Using fast-growing species, such as black locust and poplars, from bioenergy plantations with short rotation coppice systems is a promising solution to support energy transition (Németh et al. 2018; Marosvölgyi and Vityi 2019). Furthermore, developing industrial plantations is vital to face the shortages of wood supply in the near future (Ábri et al. 2022).

SRC plantations are suitable for supporting bioenergy sources, while long-rotation forest plantations supply wood for industries and sequester atmospheric carbon emissions during the rotation. Hungary's National Clean Development Strategy (NCDS) has used the projections and modeling to reduce greenhouse gas (GHG) emissions through business as usual, late action climate neutrality, and early action climate neutrality scenarios by 2050 (Ministry For Innovation And Technology Hungary 2021). Estimating and modeling the carbon dynamics from SRC bioenergy plantations and long rotation forest plantations are helpful in better understanding the carbon cycle and the strategy to achieve lower carbon policies. Estimating carbon stock in the ecosystem will influence the direction of policy on climate change mitigation, either lowering greenhouse gas emissions or increasing carbon sequestration (Jin 2023). However, research trends on carbon stock and carbon footprints of bioenergy plantations in Hungary are still rare (Mulyana et al. 2023b).

Understanding carbon footprints through a life cycle assessment approach is vital to estimating potential GHG emissions in the whole process of forest operations (forest establishment, maintenance, thinning, and harvesting), especially carbon dioxide (CO_2) emissions. For instance, carbon footprint assessment has been conducted in different harvesting systems for short rotation (Polgár et al. 2018, 2019). Furthermore, Polgár (2023) has analyzed the carbon footprint of wood utilization from short wood forestry work systems (beech, oak, spruce, black locust, and hybrid poplar) and showed that the absolute carbon footprint of black locust was higher than hybrid poplar. Thus, research on environmental assessment, especially carbon footprint and forest carbon dynamics, still needs to be carried out in various forests in Hungary.

1.2. Problem statement and research rationale

According to Mulyana et al.'s (2023b) research, Hungary's forest carbon dynamics and life cycle assessment were still rare. Based on data retrieved from the Scopus database in March 2023, there were 1,528 documents related to the keywords “Forest” or “Forestry” and “Hungary”, and only ten documents related to poplar carbon in Hungary (Mulyana et al. 2023b). Furthermore, Mulyana et al. (2023b) found 1 document on poplar life cycle assessment in Hungary. These findings strengthen our reasons for researching forest carbon dynamics and life cycle assessment.

This research examines whether 1 ha will be cultivated with poplar or black locust with short or long-rotation management systems. Choosing a functional unit is vital in the LCA approach because this phase determines the input and output. Some researchers used 1 m^3 of timber production (Proto et al. 2017; Kuka et al. 2019; Sahoo et al. 2021), and others also used functional unit 1 ha (Bacenetti et al. 2014, 2016a, b; Cantamessa et al. 2022). In Hungary, Polgár et al. (2018) used functional unit 1 ha to assess LCA in different harvesting systems in short-rotation energy plantations. The parameters for consideration were carbon balance calculated from carbon stock and carbon emissions. Furthermore, we propose the main question: which forest management model produces the most significant carbon balance?

1.3. Research aims and hypotheses

This research attempts to address the following research objectives:

1. To estimate the forest carbon stock in short rotation coppice systems
2. To estimate the forest carbon stock in forest plantation for industrial purposes

3. To quantify the carbon footprint through life cycle assessment in short rotation coppice systems
4. To quantify the carbon footprint through life cycle assessment in forest plantations for industrial purposes.
5. To determine the carbon balance in short rotation coppice systems.
6. To determine the carbon balance in forest plantations for industrial purposes.

1.4. Research assumptions

In this research, I have used some assumptions as follows.

1. Data on black locust and poplar growth was collected from some experimental sites in Hungary; hence, the forest carbon simulation assumed that it could be applied in Hungary.
2. Black locust and poplar treatments in short-rotation coppice systems (plantation establishment, treatment, harvesting) were assumed to be similar; hence, the life cycle assessment of black locust and poplar were similar.
3. Black locust and poplar treatments in long-rotation systems (forest establishment, thinning, and final harvesting) were assumed to be similar; hence, the life cycle assessment of black locust and poplar were similar.

1.5. Research questions

In this research, we have some research questions as follows

1. What is the carbon stock of short-rotation coppice systems in the simulation period?
2. How much carbon stock is stored in forest plantations for industrial purposes during the simulation period?
3. How much carbon emission is emitted in short-rotation coppice systems?
4. How much carbon emission is produced in forest plantations for industrial purposes?
5. Which plantation management scenarios provide benefits in the carbon balance of short-rotation coppice systems?
6. Which plantation management scenarios provide benefits in the carbon balance of forest plantations for industrial purposes?

1.6. Dissertation structure

This dissertation comprises five chapters, and its contents have been published in some international journals (indexed by Scopus). The structure of the dissertation and its publication can be explained as follows:

a. Chapter 1 Introduction. The introduction section explained the research background, problem statement, rationale, aims and hypotheses, assumptions, and questions.
b. Chapter 2 Literature review. Based on the introduction, we have summarized the related articles on forest management (short-rotation coppice systems and forest plantation for industrial purposes), forest carbon dynamics (forest carbon pools and modeling), and environmental impact assessment.
c. Chapter 3 Research methodology. In this chapter, we describe how to collect and analyze the data. In general, two pieces of data are required: data for forest carbon dynamics and data for life cycle assessment. We also describe the approaches and software we used to process these data, such as CO2FIX software for forest carbon modeling and Sphera LCA for Experts Education License version 9.2.1.68 software to analyze the life cycle assessment.
d. Chapter 4 Result and discussion. Our findings on forest carbon dynamics and carbon footprint (short-rotation coppice systems and long rotation forest plantation for industrial purposes) were elaborated in this chapter.
e. Chapter 5 Conclusion and recommendations. In the last chapter, we answer the research questions and give some feedback on potential research and suggestions for stakeholders who work or are interested in climate change mitigation policy.

Furthermore, our dissertation has been published and on progress for publication in some journals and conference proceedings as follows:

1. **Mulyana, B.**, Polgár, A., and Vityi, A. 2023. Research trends in the environmental assessment of poplar plantations in Hungary: A bibliometric analysis. *Ecocyle* 9(3): 23-32. https://www.ecocycles.net/ojs/index.php/ecocycles/issue/view/22 . (Scopus Q4)
2. **Mulyana, B.**, Polgár, A., and Vityi, A. 2023. Three Decades of Forest Carbon Dynamics Modeling Using CO2FIX: A Bibliometric Analysis. *EVERGREEN* 10(4): 2105-2119. https://www.tj.kyushu-u.ac.jp/evergreen/contents/EG2023-10_4_content/ . (Scopus Q3).
3. **Mulyana, B.**, Polgár, A., and Vityi, A. 2024. Forest carbon modeling in poplar and black locust short rotation coppice plantations in Hungary. *Jurnal Sylva Lestari* 12(2):324-337. https://sylvalestari.fp.unila.ac.id/index.php/JHT/article/view/883 . (Scopus Q3).

4. **Mulyana, B.**, Polgár, A., and Vityi, A. Modeling of forest carbon dynamic in different forest management scenarios: a case study on poplar and black locust plantations in Hungary. *Journal of Forestry Studies*. https://mi.emu.ee/et/teadusinfo/metsanduslikud-uurimused/early-view-accepted-papers/ . (In press/Scopus Q3).
5. **Mulyana, B.**, Polgár, A., and Vityi, A. Life cycle assessment of bioenergy production from short rotation coppice plantation in Hungary. (ready to be submitted to a journal).
6. **Mulyana, B.**, Polgár, A., and Vityi, A. Life cycle assessment of black locust and poplar timber production in Hungary. (ready to be submitted to a journal).
7. **Mulyana, B.**, Polgár, A., and Vityi, Carbon negativity of black locust and poplar plantation in different management systems in Hungary. (Presented at the 6th International Conference on Natural Resources and Technology and under review to be published in IOP).

II. LITERATURE REVIEW

The literature review chapter discussed general information about forest plantation management, forest carbon dynamics, and environmental management. Forest plantation management depicts the management of short-rotation systems to produce biomass for energy and long-rotation systems to produce timber. Furthermore, the sub-section of forest carbon dynamics elaborates on forest carbon pools and forest carbon modeling. The sub-section on environmental management elaborates on the research trends of environmental management in Hungary and the life cycle assessment approach. The author has read relevant literature and summarized them into this chapter to assist the readers in getting a better understanding of our research on carbon dynamics (carbon stock modeling and carbon footprint).

2.1. Forest operations

The forest is a complex system and should be managed sustainably to support human needs. Due to the complexity, researchers and practitioners have developed experimental silvicultural treatments to increase forest productivity. According to Fahey et al. (2018), they have reviewed research articles from 1995 to 2017 and found that there are 18 silvicultural experiments and simplification of the forest complexity to develop more predictable forest production through ecological silviculture. Researchers and practitioners perform forest operations in ecological silviculture practices, such as maintaining nutrients, structuring and composing tree species, and conducting environmentally friendly harvesting operations.

Climate change and the increasing need for forest products require re-thinking forest operations to support sustainability (Marchi et al. 2018). Furthermore, Marchi et al. (2018) propose five indicators to ensure sustainable forest operation: environment, ergonomics, economics, quality optimization of products and production, and people and society. Through sustainable forest operations, forest managers or owners will benefit from high-quality wood products, ecosystem services, and climate change mitigation, and forest workers' health and safety will be ensured.

The sustainability of forest management, either natural or planted forest, should be considered to ensure sustainable development. Sustainable development covers a wide range of activities but lacks an operational definition of what should be sustained (Jabareen 2008). In the forestry sector, stakeholders are still debating sustainable development. Baumgartner (2019) described a complex relationship in the forestry sector to achieve sustainable development goals and proposed integrated assessment approaches to analyze a relationship on policy or strategy that positively contributes to sustainable development. Furthermore, Schweier et al. (2019) also proposed a schematic to achieve sustainable development in the forestry sector by describing the operational and valuation frameworks to manage the forest (Fig. 2.1.).

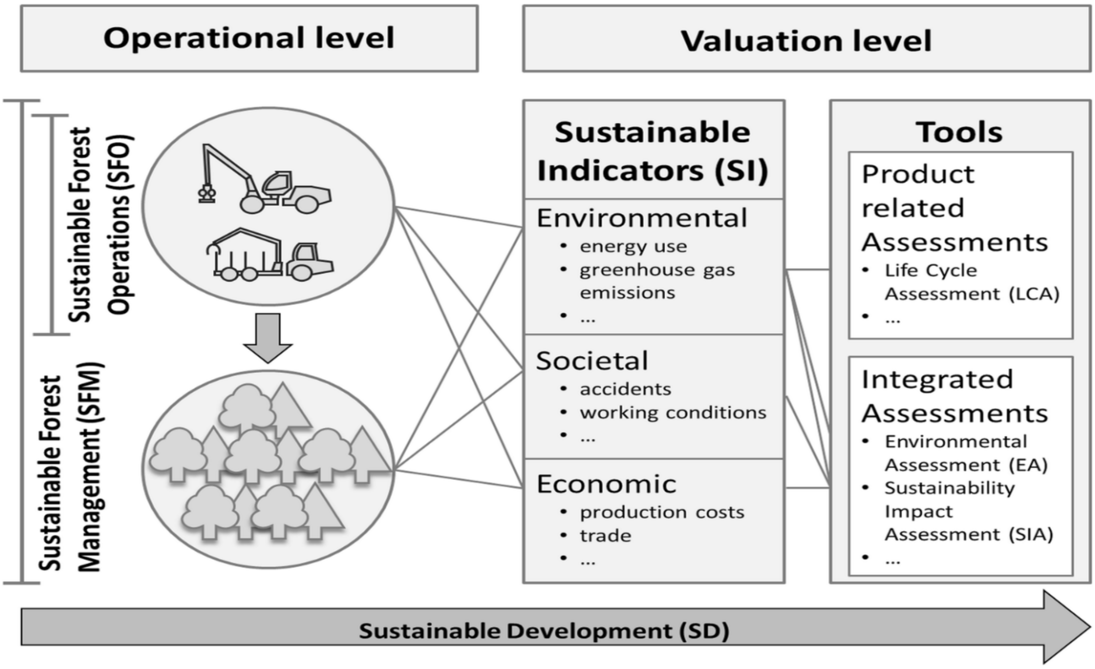


Fig 2.1. Sustainable forest management for natural and planted forest
(source: Schweier et al. (2019))

Studies in plantation forest operations are vital for forest managers and owners to achieve sustainability. Forest operation in the plantation was influenced by many factors, such as growth rate and maturity level, planting schemes, and technology forest harvesting (Kunickaya et al. 2020). Studies have shown that the biomass growth rate in many forest types increased and positively affected the carbon cycle and biodiversity (McMahon et al. 2010).

Forest operations can be detailed in soil preparation, seedling preparation and planting, weed control, thinning, and harvesting operations. Activities in seedling preparation and planting can be done manually by extensive labor or mechanization system using machinery (Sobocki et al. 2023). Furthermore, Sobocki et al. (2023) found that the mechanization in seedling preparation and planting provides work efficiency and ensures the seedlings can be planted in the field properly and precisely. However, the utilization of machinery in planting also affected the amount of fuel consumption.

Commercial thinning in forest plantations aims to increase the growth rate by removing some trees to provide more space for the others. The study showed that commercial thinning by cutting 32-40% of the existing stand can increase the mean diameter (12-18%) and gross merchantable volume (27-38%) than the stand without thinning (Gauthier et al. 2015). Thinning also provides positive benefits in carbon stock in the forest plantation (D'Amato et al. 2011). During the commercial thinning operations (whole-tree, tree-length, and cut-to-length method), the thinning machine productivity is affected by tree diameter and travel distance (Chang et al. 2023).

There are two types of tree transport in the harvesting systems from the harvesting site to the yard. In the single pass system, the whole tree is transported to the yard and then delimbed and bucked. In contrast, in the double pass system, the tree is delimbed, bucked in the harvesting site, and then sent to the yard using the vehicle (Spinelli et al. 2019). According to Vanbeveren et al. (2017), who have reviewed 25 articles, the harvesting system of a single pass system has been trialed in 125 sites, and 16 sites have used double pass systems.

2.1.1. Plantation management

Forest loss is still hot issues in the worldwide and needs serious action to tackle deforestation. According to data from the Food and Agriculture Organization of the United Nations (FAO) (2020), forest loss in the world during 1990-2000, 2000-2010, and 2010-2020 were 7.84, 5.17, and 4.74 million ha/year, respectively. Increasing the forest cover, plantations with shorter rotation than natural forest have been introduced worldwide to enhance the socio-economic and ecological benefits (Farooq et al. 2021). Furthermore, Farooq et al. (2021) explained that plantations with fast-growing species and high yields through afforestation and reforestation projects have supported the forest industries. Although forest plantation is dominated by monoculture, it can reduce the pressure on natural forests by contributing to timber production and supporting the ecosystem services as natural forests (Masiero et al. 2015).

Forest management for plantations is still less important than that of natural forests. Since the 1990s, forest management standards and guidelines have been focused on natural or semi-natural forests, while the standards and guidelines for planted forests or plantations have been paid less attention (Masiero et al. 2015). FAO has classified forests into natural regeneration and planted forests with 93% and 7% of the world's forest area (Food and Agriculture Organization of the United Nations 2020a). In 1990, the forest plantations were 123 million ha and increased to 294 million ha in 2020 (Food and Agriculture Organization of the United Nations 2020a). Moreover, establishing forest plantations worldwide is vital to meet the increasing wood demand for some industrial purposes because of the increasing human population (Fox 2000). In some estimations, around half of the roundwood demand will be supplied from the plantation of the planted forest by the year 2040 (Kanninen 2010).

A forest plantation is an artificial forest established by humans by planting specific species to produce specific products. Furthermore, FAO has defined forest plantation as "*forest of introduced species and in some cases native species, established through planting or seeding, with few species, even spacing and/or even-aged stands*" (Food and Agriculture Organization of the United Nations 2006). Forest plantation that are planted with native or exotic species and managed in long-rotation is called semi-natural forests (Siry et al. 2005). Some types of forest plantation are industrial plantations (short or long-rotation), small-scale home and farm plantations, agroforestry plantations, managed secondary forests with planting, and forest plantations for protection purposes, such as soil protection, windbreaks, erosion control, site reclamation, and wildlife management (Kanninen 2010). However, according to Hungarian law, Act LIV of 1996 on Forests and the Protection Forests, planted a row of trees, a tree group, and wooded pasture are classified as tree plantations. This research focused on the tree plantation planted with black locust and poplar species with short and long-rotation systems.

Forest plantations, either production or protection plantations, provide ecosystem services, such as soil protection, windbreaks, erosion control, and the carbon cycle. Poplar plantations around the riparian buffer zone in Canada provide ecosystem services on windbreaks, soil fertility, erosion control, and carbon sequestration (Fortier et al. 2013a, b, 2015, 2016, 2020; Truax et al. 2015). Forest carbon dynamics were affected by the type of forest ecosystems, length of stand rotation, and forest management practices (Newell and Vos 2012). For example, the capability of forest plantations (gliricidia and cajuput) to sequester and store carbon above and belowground were different (Mulyana and Purwanto 2020; Mulyana et al. 2020a, b, 2021; Purwanto et al. 2022). Meanwhile, biomass production in SRC was affected by plantation management regime, harvesting methods, plant density, and length of rotation (Rodrigues et al. 2021).

In general, there is a similarity between short and long-rotation plantations. The plantations have similar activities: site selection, cultivation/growth management, harvesting, logistics, and transportation. However, the difference between short and long rotations is the treatment of growth management and harvesting operations. Details of short and long-rotation plantations will be discussed in the following sub-sections.

2.1.1.1. Short-rotation plantation

Trial experiments of short-rotation plantations have been conducted in the UK to assess biomass production. Short-rotation plantation systems for energy purposes were developed in the mid-1970s by The Wood Supply Research Group (Mitchel et al. 1991). Furthermore, Mitchel et al. (1991) divided the short-rotation as a single stem and coppice system with a cutting cycle of about 3-5 years. In the single stem systems, after harvesting, the plantation will be planted again using the new seedling (Sims et al. 2001). The species in single stem were Scots pine (*Pinus sylvestris*)*,* Corsican pine (*Pinus nigra*)*,* Douglas fir (*Pseudotsuga menziesii*)*,* Western hemlock (*Tsuga heterophylla*)*,* Sitka spruce (*Picea sitchensis*)*,* Hybrid larch (*Larix x eurolepis*)*,* Sycamore (*Acer pseudoplantanus*)*,* Silver birch (*Betula pendula*)*,* Ash (*Fraxinus excelsior*)*,* and European silver fir (*Abies alba*). Meanwhile, the short-rotation coppice system species are *Salix* sp., *Populus* sp., *Alnus* sp., *Eucalyptus* sp., and *Nothofagus* sp (Mitchel et al. 1991).

Short-rotation coppice (SRC) systems from fast-growing species are promising plantation management and have been distributed worldwide to supply bioenergy needs. For instance, the short-rotation coppice systems for bioenergy production has been applied in Brazil (Eufrade-Junior et al. 2018), Canada (Jego et al. 2017), China (Zhou and Gao 2016), Costa Rica (Tenorio et al. 2016), Chech Republic (Štochlová et al. 2019), Germany (Huber et al. 2018; Langhof and Schmiedgen 2023), Hungary (Rédei et al. 2010b, 2011; Schiberna et al. 2021), Italy (Sabatti et al. 2014), Papua New Guinea (Nuberg et al. 2015), Portugal (Pereira et al. 2016), Romania (Werner et al. 2012), United Kingdom (Aylott et al. 2008), and United States (Alig et al. 2000; Merry et al. 2017).

SRC is an old practice of plantation management with a different name, such as short-rotation hardwood crops (Rose and DeBell 1978), short-rotation forestry (Veli 1983; Willebrand et al. 1993; Weih 2004; Pannacci et al. 2009; Rédei et al. 2011), coppice culture (Afas et al. 2008), and short-rotation woody crop (Vanbeveren et al. 2015). Furthermore, in Hungary, the terminology for SRC is short-rotation energy plantation (Rédei and Veperdi 2009; Polgár et al. 2018) and short-rotation energy crops (Rédei et al. 2010b; Deák and Ferencz 2017). Short-rotation characteristics are using fast-growing species, high density, cutting cycle of fewer than ten years, and harvesting method using chipper (Table 2.1).

Tree species cultivated in SRC plantations management, either in experimental sites or tree plantations, differ for each site. For instance, SRC plantations in the experimental sites of the University of Warmia and Mazury in Poland used black locust, poplar, and willow (Stolarski and Stachowicz 2023). Furthermore, the Forest Research Institute of Hungary has used black locust and poplar in their SRC experimental sites (Rédei 2000; Rédei et al. 2006, 2010a; Rédei and Veperdi 2009). In Canada, small-scale private forest owners have used hybrid poplar with SRC management in the intensive production zone (Truax et al. 2015).

Table 2.1. Characteristics of short-rotation coppice systems

		References
Species	Poplar, black locust, eucalyptus, willow	Bergante et al. (2016); Ferreira et al. (2017); Oliveira et al. (2018a)
Cutting cycle	1, 2, 3, 4, 5, 7, 8 years	Barro et al. (2020); Rodrigues et al. (2021); Schiberna et al. (2021); Johnston et al. (2022); Stolarski and Stachowicz (2023)
Rotation	15, 20, 25 years	Rodrigues et al. (2021); Schiberna et al. (2021)
Purpose	Bioenergy (fuelwood, biofuel)	Hart et al. (2015); Pereira and Costa (2017)
Harvesting	Single pass cut-and-chip harvester, double pass cut-and-store harvester, cut-and-bale harvester, cut-and-billet harvester	Vanbeveren et al. (2017); Eisenbies et al. (2021)
Density	2,500 – 22,222 trees/ha	Rédei (1999); Rédei et al. (2006, 2010a); Schiberna et al. (2021)

The selection of tree species for SRC plantation management refers to biomass yield productivity. In New Zealand, four promising species examined as SRC were eucalyptus, willow, poplar, and acacia (Sims et al. 2001). Moreover, in Romania, the selected tree species planted in the experimental site were black locust, poplar, and willow (Stolarski and Stachowicz 2023). They select tree species for SRC based on their growth rate, high biomass yield, and survival rate. Moreover, the resprouting capacity also should be considered. Poplars have the resprouting ability around 5-25 shoot per tree and reduced up to 75% after the first cutting cycle (Verlinden et al., 2015). Furthermore, large number of shoots per tree is positive indication for the better resprouting capacity (Štochlová et al. 2019).

The cutting cycle and rotation in SRC are different for many sites. In one rotation, the trees can be harvested many times. Rodrigues et al. (2021) explained that the short-rotation is around 20 years or more divided into several cutting cycles (2-5 years). Furthermore, in one rotation, the trees can be harvested around 4 – 7 times and then replaced with the new plantation at the end of the rotation (Rodrigues et al. 2021). In Hungary, the poplar SRC rotation is limited to 15 years, but based on research, it can be extended to 20-25 years (Schiberna et al. 2021). Meanwhile, in Poland, the SRC plantations (black locust, poplar, and willow) were harvested three times in a four-year cutting cycle (Stolarski and Stachowicz 2023).

SRC is designed to support the need for raw materials for bioenergy. Black locust, poplar, and willow plantations with SRC systems supply energy (electricity and heat) (Hauk et al. 2014). Furthermore, Hauk et al. (2014) reviewed 37 studies on SRC and found that SRC systems for bioenergy were feasible from an economic perspective. Hungary's break-even point of poplar plantations for biomass production was 6-8 oven dry tons/ha year (Schiberna et al. 2021). SRC plantations of species black locust, poplar, willow, and eucalyptus have the potential to reach high biomass production of around 12 – 14 tons/ha year (Rodrigues et al. 2021).

Generally, the harvesting method for biomass production in SRC plantations can be divided into cut-and-chip and cut-and-store (Pecenka and Hoffmann 2015). Furthermore, Pecenka and Hoffmann (2015) explained that the cut-and-chip method harvests and chips trees in a single line, while the cut-and-store method produces harvested wood as a whole tree. According to Vanbeveren et al. (2017), the researchers have analyzed the use of machinery for harvesting SRC in 166 field sites and found that harvesting methods in SRC plantations were single pass cut-and-chip harvester (127 cases), double pass-cut-and-billet harvester (22 cases), double pass cut-and-store harvester (16 cases), and cut-and-billet harvester (1 case).

Tree density for SRC varies depending on the tree spacing and cutting cycle. For instance, the tree density in the 2-3 years cutting cycle was 6,000 – 8,000 trees/ha, while the five-year cutting cycle was 1,100 – 1,600 trees/ha (Rodrigues et al. 2021). Black locust plantation in marginal land in Hungary was planted in a spacing 1.5 x 1.0 m, or the tree density was 6,666 trees/ha (Rédei et al. 2011).

2.1.1.2. Forest plantations for industrial purposes

Forest plantation is one of the solutions to reduce deforestation and increase forest cover to support climate change mitigation. However, forest plantations cannot replace natural forests; they only reduce the pressure on deforestation (Ghazoul 2013). Furthermore, Ghazoul (2013) explained that the establishment of forest plantations on degraded or marginal land could be one of the sources of supply for wood industries such as roundwood, pulpwood, and fuelwood. According to data from Global Forest Resources Assessment 2020 released by FAO, the total forest area in the world is 4.060 billion ha, of which 3.750 billion ha (97%) is naturally regenerating forest, and 290 million ha (3%) is planted forest (Food and Agriculture Organization of the United Nations 2020b).

In 2018, wood-based products (roundwood, sawn wood, wood-based panels, wood pulp, wood charcoal, and pellets) have reached the highest amount of production and trade in global production since the FAO released the global forest products statistics in 1974 (Food and Agriculture Organization of the United Nations 2019). Furthermore, the Food and Agriculture Organization of the United Nations (2019) explained that the use of wood pellets for bioenergy production had increased significantly in Europe (55% of global production), which was generated by the European Commission's policies to reach carbon neutrality. The consequence of the increasing production is the number of forest plantations that are also increasing to supply the bioenergy industry.

Sustainable forest plantation management is vital to benefit the environment and socio-economic. In general, the purpose of the development of forest plantations is for production and environmental protection (Fortier et al. 2013a, 2016; Truax et al. 2015). However, to ensure the sustainability of the forest plantation, the manager of the forest plantation should prepare the management plans. Based on the Global Forest Resources Assessment 2020, most of the forests in Europe have management plans, and more than 25% of forests in Africa and less than 20% in South America have management plans (Food and Agriculture Organization of the United Nations 2020b). Management plans contain the timeframe for each silvicultural activity to ensure that the purpose of forest plantation can be achieved.

Forest plantations can be developed on a small or industrial scale for many purposes. Small-scale plantations around the villages are essential to support the domestic need for wood materials for fencing, fuel, and local construction (Ghazoul 2013). Village plantations in rural areas established through social forestry programs have provencal community empowerment and give economic benefits, such as fuel, animal feed, and building materials (Charnley 2006). In general, the small-scale forest plantation in rural areas is known as community forest, village forest, or private forest (Yadav et al. 2003; Pagdee et al. 2006; Cronkleton et al. 2012; Truax et al. 2015). However, small-scale forest plantations have attributes in the implementation management plans, such as property rights regimes, institutional arrangements, incentives, and community interest (Pagdee et al. 2006). The characteristics of long-rotation plantations can be seen in Table 2.2.

Table 2.2. Characteristics of long-rotation plantation

		References
Species	Broad leave and coniferous species	Evans (2004); Farooq et al. (2021); Gabira et al. (2023)
Cutting cycle	End of rotation	Evans (2004)
Rotation	20, 25, 40, 50, 80, 100 years	Evans (2004); Farooq et al. (2021); Schiberna et al. (2021)
Purpose	Veneer, pulp and paper, constructions, furniture	Evans (2004); Gabira et al. (2023)
Harvesting	Whole tree, tree length, cut-to-length	Schweier et al. (2019); Spinelli et al. (2022); De Francesco et al. (2022)
Density	25 – 1,100 trees/ha	Gabira et al. (2023)

Even though short- and long-rotation plantations perform similar silviculture operations such as planting, growth maintenance, and harvesting, each system has some specific activities. Different from the silviculture operation of short-rotation coppice systems plantations, in the long-rotation plantation, the seed will be grown in the forest nursery for six months to 3 years (Evans 2004). Furthermore, Evans (2004) explained that before the young trees are planted in the field, there are some activities on land preparation, such as vegetation clearance, cultivation, tillage, bedding, drainage, fertilizing, and fencing. The example of species in long-rotation for timber production are eucalyptus, pinus, teak, acacia, poplar (Kallio et al. 2012; Zhou et al. 2017; Lovarelli et al. 2018; El Haouzali et al. 2020; Gabira et al. 2023). Specifically for poplar, poplar has been used in the pulp and paper industry (Zhou et al. 2017),

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 (Schiberna et al. 2021). In the tropic region, plantation rotation for industrial products ranged from 5-20 years for wood pulp and 10-40 years for lumber-sized materials (Evans 2004). In comparison, the plantation rotation for industrial products in temperate regions is twice or five times as long as in the tropics (Evans 2004). Commonly, the determination of plantation rotation was calculated based on the economic optimum rather than biological maturity (Farooq et al. 2021).

Harvesting in the industrial plantation uses a clear-cutting method for the efficiency of the harvesting operation (Evans 2004; Farooq et al. 2021). Harvesting methods in forest plantations for industrial purposes are whole tree harvesting (WTH) or full tree (FT), tree length (TL), and cut-to-length (CTL) (Schweier et al. 2019; Spinelli et al. 2022; De Francesco et al. 2022). The yield of harvesting in long-rotation plantations for industrial purposes is 3-20 m^3/ha year (temperate region), 5-35 m^3/ha year (Mediterranean region), and 5-50 m^3/ha year (tropical region) (Evans 2004).

According to Gabira et al. (2023), who reviewed 255 selected articles, planting density affects stand growth (stem diameter and volume; the high-density stand has a smaller individual volume). Furthermore, Gabira et al. (2023) found that the high-density plantation was for pulp and paper or biomass industries, while the low-density plantation would produce bigger stem diameters used for sawmill industries.

2.2. Forest carbon cycle

Carbon stock and carbon sequestration are two different terms. Carbon sequestration uses a time factor (MgC/ha year), which is the addition of carbon on a certain period and specific area, meanwhile the carbon stock without time factor (MgC/ha) (Nair 2012). For instance, carbon stock at year$_t$ is X$_t$ MgC/ha. Furthermore, re-measurement at year$_{t+n}$ results in the carbon stock being X$_{t+n}$ MgC/ha. Carbon sequestration is the value of carbon stock at year$_{t+n}$ that is more significant than that at year$_t$. Meanwhile, the carbon emission is the value of carbon stock at year$_{t+n}$ lower than that at year$_t$ (Fig. 2.2.).

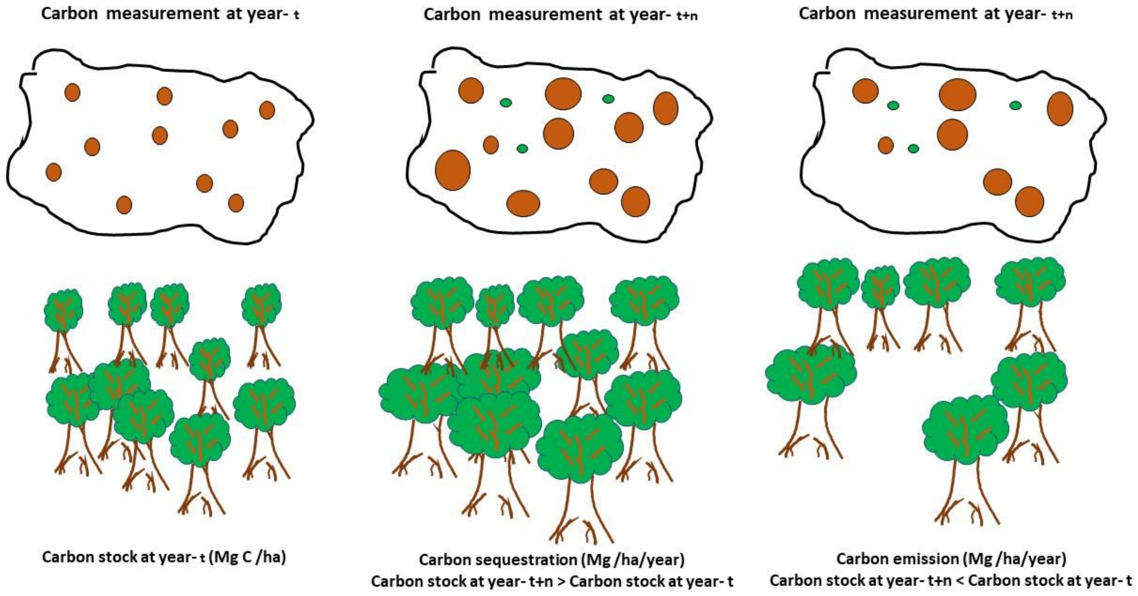


Fig. 2.2. Illustration on carbon stock, carbon sequestration, and carbon emission

Based on Fig. 2.2., carbon sequestration can occur due to the growth dendromass mechanism (diameter and height). The other possibility is tree regeneration (natural or artificial), which can add new biomass to that area. Moreover, carbon emission occurs when the biomass at year$_{t+n}$ is lower than at year$_t$ due to plant removal (harvesting or die). Thus, carbon sequestration and emission can be calculated based on at least two carbon measurements in the same area at different times. The equations to calculate carbon sequestration/emission at the specific area are as follows:

$$C_{total} = C_{aboveground} + C_{belowground} \quad \text{(1)}$$

$$C_{aboveground} = C_{stem} + C_{branches} + C_{leaves} + C_{understorey} + C_{litter} \quad \text{(2)}$$

$$C_{belowground} = C_{root} + C_{soil} \quad \text{(3)}$$

$$Carbon\ (sequestration\ or\ emission) = \frac{Total\ carbon_{t+n} - Total\ carbon_{t}}{n} \quad \text{(4)}$$

If the value is positive, it means the addition of biomass and carbon or carbon sequestration (MgC/ha year). While the value is negative, it means biomass, carbon reduction, or carbon emission (MgC/ha year). Where n is the period of measurement (year), and total carbon is carbon aboveground and belowground (MgC/ha).

Based on simulation using empirical, semi-empirical, and soil models in 100-year forests, carbon sinks in above and belowground carbon pools are proven (Schmid et al. 2006). However, the carbon stock in forests can decrease due to natural disturbance (forest fire, mountain eruption) and anthropogenic disturbance (forest harvesting, land use change, infrastructure development) (Newell and Vos 2012).

2.2.1. Forest carbon pools

According to the Intergovernmental Panel on Climate Change (2006), forest carbon pools are aboveground biomass, belowground biomass, litter, and soils. Forests continuously recycle carbon through photosynthesis and decomposition processes. The carbon dynamics in the vegetation and soil also change depending on the time scale of site conditions, disturbance, and forest management systems (Dixon et al. 1994). Carbon was stored in some vegetation organs such as leaves, fruits, branches, stems, and roots (Fig. 2.3.). The deadwood/necromass, organic matter in the soils, and understorey plants also store carbon.

Assessing AGB and BGB uses direct measurement and indirect measurement. The direct measurement uses destructive sampling, which cuts the samples and weighs the biomass of stems, branches, leaves, and fruits, then determines the laboratory's dry weight and percentage carbon content (PCC) (Intergovernmental Panel on Climate Change 2006). Although there is no standard yet, the output is a similar unit. Estimating carbon stock is the amount of carbon stored in a specific area (MgC/ha), and carbon sequestration is the amount of carbon stored in a particular area and specific time (MgC/ha year). Carbon stock estimation can be measured using some parameters. When estimating aboveground biomass, the parameters are diameter at breast height (Dbh), crown dimension, and height. At the same time, the parameters for belowground carbon are soil bulk density, root weight, and soil weight.

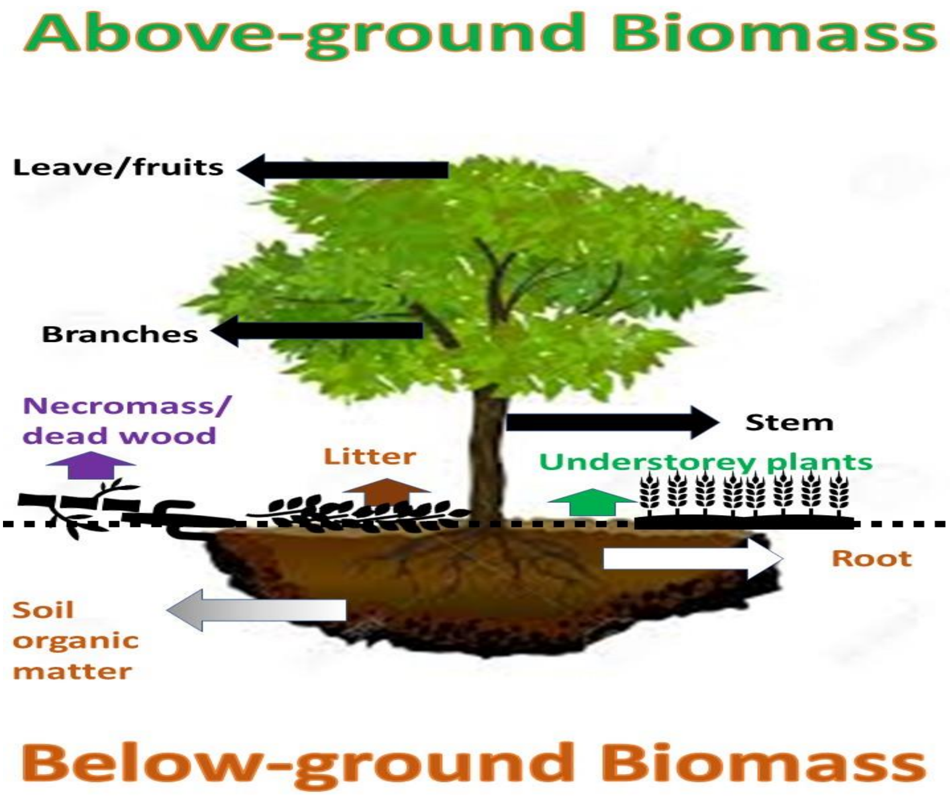


Fig. 2.3. Forest carbon pools

Furthermore, the Intergovernmental Panel on Climate Change (2006) explained that indirect measurement uses the allometric equation or volume equation multiplied by its wood density to estimate the dry weight biomass of trees, and the PCC from previous research works was used. The common equation to estimate the biomass of trees is as follows.

$$\boldsymbol{Biomass = \beta_0 D^{\beta_1}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{5}$$

$$\boldsymbol{Carbon\ content = Biomass * \ PCC} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{6}$$

Where Biomass is dried weight (kg), D is the diameter at breast height (cm), PCC is percentage carbon content (%), and β_0 and β_1 are intercepts.

The allometric equation is not only used to estimate aboveground biomass but also used to estimate root biomass. According to Johansson and Hjelm (2012), the allometric equation to estimate the root biomass of poplar was

$$\boldsymbol{W = 0.00001x\ D^{2.529}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{7}$$

where W is dried-weight biomass (kg), and D is diameter at breast height (cm).

Using the following equation, carbon above and belowground at the sampling plot (m^2) will be upscaled to the total research area.

$$\boldsymbol{C = \frac{\sum_{i=1}^{n} C_n}{plot\ size}\ x\ 10,000} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{8}$$

$$C_{total\,area} = C\ x\ total\ area \quad (9)$$

$$CO_{2_{eq}} = C_{total\,area}\ x\ 3.67 \quad (10)$$

Where C is carbon per ha (MgC/ha), C_n is carbon per tree (MgC/tree), plot size (m^2), total area (ha), and $C_{total\ area}$ is carbon total for the total area (MgC).

2.2.2. Forest carbon modeling

Understanding forest carbon dynamics is essential to better understanding the distribution of carbon pools (trees, soil, and wood products). Tree species diversity, geography, and climate conditions challenge forest carbon dynamics modeling (Sarkar et al. 2021). Some software has been developed to simulate forest carbon dynamics. It estimates carbon stocks based on photosynthetic processes and empirical growth data (Kurz et al. 2009; Kim et al. 2015). Furthermore, terrestrial carbon cycle modeling can be classified based on biogeographic models (BIOME, MAPSS) and biogeochemical models (CENTRY, BIOME-BGC, and TEM) (Xiaodong and Junfang 2007).

Referring to Mulyana et al. (2023a), the review articles on CO2FIX was conducted in 2015 emphasized comparing four forest carbon dynamics software types. This review article analyzes forest carbon dynamics modeling using empirical growth data, namely, CBM-CFS3, CO2FIX, CASMOFOR, and EFISCEN (Kim et al. 2015). Furthermore, Kim et al. (2015) observe that carbon dynamics modeling with empirical growth data (CBM-CFS3, CASMOFOR, EFISCEN, CO2FIX) has been widely used by researchers because growth data is more user-friendly to measure than the photosynthetic process.

The CO2FIX model is good software for developing empirical models of forest carbon dynamics because of its precision and ease of use (Sarkar et al. 2021). The use of CO2FIX in modeling forest carbon dynamics has been applied to various forest types in both tropical and temperate regions. CO2FIX has been extensively implemented to estimate carbon dynamics in forestry, agriculture, and agroforestry sectors (Das et al. 2019). It has some additional modules based on the cohort approach, which is appropriate for people interested in a wide range of carbon dynamics in small-scale forests (Kim et al. 2015).

CO2FIX modeling is simulation model in stand level to quantify the carbon stock and fluxes in the forest biomass, soil organic matter, and wood product by calculating changes of carbon stock in all carbon pools during the simulation period (Schelhass et al. 2004). In detail, the principles of CO2FIX model have been described in the chapter of Research Method, sub-section 3.5 Data analysis, 3.5.1. Framework of CO2FIX modelling.

CO2FIX has been applied in a wide range of land uses, such as tropical forests (natural and plantation), subtropical forests (natural and plantation), temperate forests (natural and plantation), shifting fallows, and agricultural land (Bordoloi et al. 2022). Furthermore, the CO2FIX in forest carbon dynamics is also applied in forest types based on topography, geography, and climate variations. Topographically, the application of CO2FIX on a projection of forest carbon dynamics has been applied in lowlands (Prada et al. 2016; Sarkar et al. 2021), sub-mountain (Jia et al. 2016), and mountainous areas (de Jong et al. 2007; Álvarez and Rubio 2013; Alvarez and Rubio 2016). Geographically and climatically, estimation of forest carbon dynamics using CO2FIX has been conducted in tropical lowland forests (Nabuurs and Mohren 1995), tropical dryland forests (Almulqu 2017), tropical humid forests (Álvarez and Rubio 2013), tropical savannas (Kåresdotter et al. 2022), temperate semi-arid forests (Ajit et al. 2013, 2017; Jia et al. 2016), temperate semi-humid forests (Ajit et al. 2013, 2017; Jia et al. 2016), temperate humid forests (Rodríguez-Loinaz et al. 2013), and boreal forests (Gaboury et al. 2009). Thus, CO2FIX is applied in many types of forests, from lowland to mountainous areas within tropical to temperate regions.

For almost three decades, the implementation of CO2FIX dominated the forest plantation and agroforestry systems (Mulyana et al. 2023a). Only a little research was conducted in natural, conservation, and community forests. Referring to Nabuurs and Schelhaas (2002), in the early stages of the development of CO2FIX, this software was tested in 16 types of forests across Europe. Nowadays, based on forest management purposes, CO2FIX is applicable in natural forests (Nabuurs and Mohren 1995; Álvarez and Rubio 2013), forest plantations (Nabuurs and Mohren 1995; Rodríguez-Loinaz et al. 2013; Jia et al. 2016; Mulyana et al. 2024), conservation forests (He et al. 2021), community forests (Alvarez and Rubio 2016), afforestation and reforestation projects (Nabuurs and Mohren 1995; Ma and Wang 2011; Akmalluddin et al. 2019), and agroforestry systems (Ajit et al. 2013, 2017).

The purpose of CO2FIX modeling for forest management was to provide a source of wood supply for fuel wood and wood products (sawn, pulp and paper, veneer, and furniture). Moreover, based on the time span of simulation, there were less than 25 years (Kaipainen et al. 2004; Rugani et al. 2015; Das et al. 2019), 25–50 years (Ajit et al. 2013, 2017; Chavan et al. 2021), 50–100 years (Markewitz 2006; Gaboury et al. 2009), and more than 100 years (Rodríguez-Loinaz et al. 2013; Kiss et al. 2015; Jia et al. 2016; Almulqu 2017).

2.3. Environmental management

2.3.1. Life cycle assessment

Environmental impacts are one of the hot issues in climate change mitigation. Emissions from various human activities caused by greenhouse gases should be reduced to minimize environmental impact. Life cycle assessment (LCA) is one of the techniques to address the potential impacts associated with the production processes of products or services to protect the environment (International Organization for Standardization 2006). LCA is also scientific-based evidence of a product's sustainability and environmental performance (Sahoo et al. 2019).

LCA was standardized in 1997 in the ISO 14040, environmental management-life cycle assessment-principles and frameworks (International Organization for Standardization 2006b) and updated in 2006 as ISO 14044, environmental management-life cycle assessment-requirements and guidelines (International Organization for Standardization 2006). However, the LCA was not widely used in the forestry sector until the end of 2010 (Heinimann 2012; Klein et al. 2015). In Hungary, the research on LCA in forestry sectors, which the articles indexed in Scopus or Web of Science, started in the early 2010s (Mulyana et al. 2023b). Environmental assessment through LCA has been conducted in the forest operation of short rotation energy plantations (Polgár et al. 2018, 2019) and wood utilization (Király et al. 2022; Polgár 2023).

Forest-based products were generally derived from roundwood and then processed into various end products (wood chips, plywood, pulp, and other wood products). In the forestry sector, the LCA can be classified as cradle-to-gate, gate-to-gate, gate-to-grave, and cradle-to-grave. According to Sahoo et al. (2019), the cradle in forest activities was forest establishment, the gate converting wood into products, and the grave-ended use and disposal.

Forest operation is complex due to cover from on-site operation (site preparation, silvicultural operations, infrastructure development, transportation) to off-site operation (products manufacturing and distribution). Furthermore, the system boundaries in forest operations vary among the studies or research on LCA for forestry operations. A study on LCA with the system boundaries cradle-to-grave approach covers from site preparation until wood product disposal at the consumer (Schweier et al. 2019). Moreover, the cradle-to-farm gate system boundaries cover the site preparation, silvicultural operation, and ending in plantation harvesting (Lovarelli et al. 2018). This research used the system boundary cradle-to-farm gate because we focused on the on-site forest operation.

Results of LCA in the forestry sector are varied among the forest management systems. Klein et al. (2015) reviewed the 22 articles and found that the essential issues in conducting LCA were the goal of studies, system boundaries, functional units, involved processes, and impact categories. Referring to ISO 14044, the LCA framework consists of four phases: 1). goal and scope definition; 2). inventory analysis; 3). impact assessment, and 4). interpretation (International Standardization Organization 2006). Furthermore, the ISO 14044 explained in detail that

1. The goal should clearly state the intended application, the motivation for conducting the study, and the intended audience, and the results should be a comparative result that must be disclosed to the public. Meanwhile, the scope emphasized clarifying the system boundary, functional unit, allocation procedure, limitations, assumptions, and data requirement.
2. Inventory analysis was conducted to collect the data (qualitative and quantitative) that was used within the system boundary. The data can be measured, calculated, and estimated to quantify the inputs and outputs from processes. The collected data is then validated and aggregated as completed inventory data.
3. Impact assessment contains a selection of impact categories, category indicators, and characterization models. Assignment of life cycle impact to the selected impact categories (classification) and calculating category indicator results (characterization).
4. The interpretation phase should identify the critical issues based on the life cycle impact analysis and evaluate the completeness, sensitivity, and consistency. The last were conclusions, limitations, and recommendations.

In this research, we must define the goal and scope (Fig 2.4.). We made a boundary to emphasize the forest plantation process, from the planting to the harvesting stages. Specifically, the research aims to compare the environmental impacts of black locust and poplar plantations for bioenergy (short-rotation system) and industrial purposes (long-rotation system).

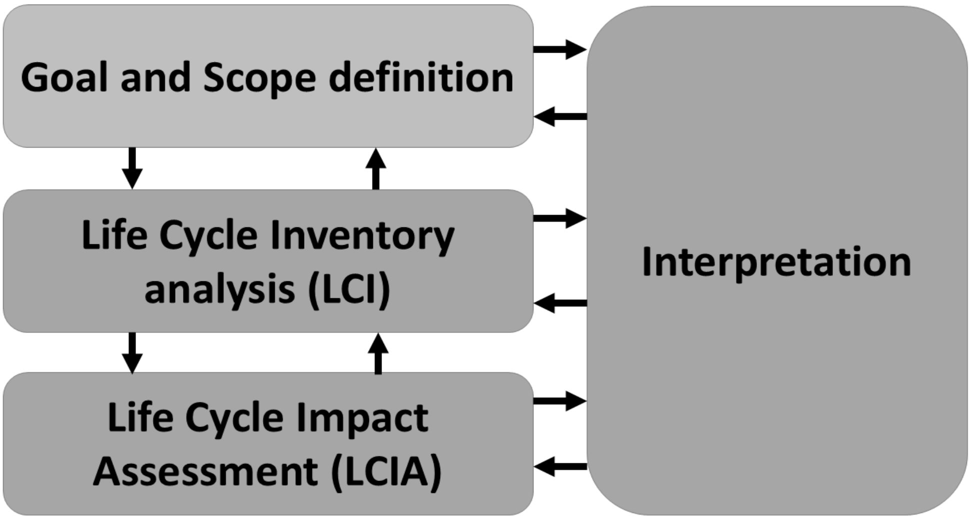


Fig. 2.4. Life cycle assessment processes
(source: International Organization for Standardization (2006b))

Goal and scope

This research aimed to determine environmental impacts in the tree production systems for poplar and black locust plantations. The scope of this work was cradle-to-gate LCA of wood production for various industrial purposes (chips wood for bioenergy and roundwood for wood industries). The cradle-to-gate LCA for forestry activities has been applied in poplar biomass production (Cantamessa et al. 2022; Krzyżaniak et al. 2023) and biochar production from forest residues (Puettmann et al. 2020).

The first phase of defining goal and scope is vital to elaborate on the purpose of the study of LCA. The critical issues in the phase goal and scope definitions determine system boundaries and define functional units (Heinimann 2012). Goal is essential because it will influence the next phase of LCA (Bjørn et al. 2018a). Furthermore, Bjørn et al. (2018a) described that defining the goal of LCA should contain aspects of

1. The intended applications of the results
2. Limitations from methodological choices
3. Decision context and reasons for carrying out the study
4. Target audience
5. Comparative studies will be presented to the public
6. The investigator of the study and other key stakeholders

System boundaries

Based on the defined goals, the scoping phase determines the study's area, depth, and specificity (International Organization for Standardization 2006a). Furthermore, the LCA study applies the scope definition by determining the system boundaries. The system boundaries will determine the utilization of resources and quantify the emissions and outputs (Martínez-Blanco et al. 2015).

According to Klein et al. (2015), the processes of forest operation can be divided into six groups:

- Site preparation, the activities in the site preparation are clearing, burning, pilling, and soil scarification.
- Site tending, the activities after planting to protect the plantation, such as fencing, fertilization, and pesticide.
- The silvicultural operation, a process linked to improving the plantation growth, such as pruning, thinning, final harvesting, and loading timber to trucks.
- Secondary processes, off-site processes to support the forest operation include planning forest operation, machinery maintenance, road construction, accommodation and housing, seed production, and transportation.
- Transport, the process of moving raw wood from the forest to industries or consumers.
- Chipping, in the short-rotation plantation, the wood will be used as bioenergy, and chipping is a single process.

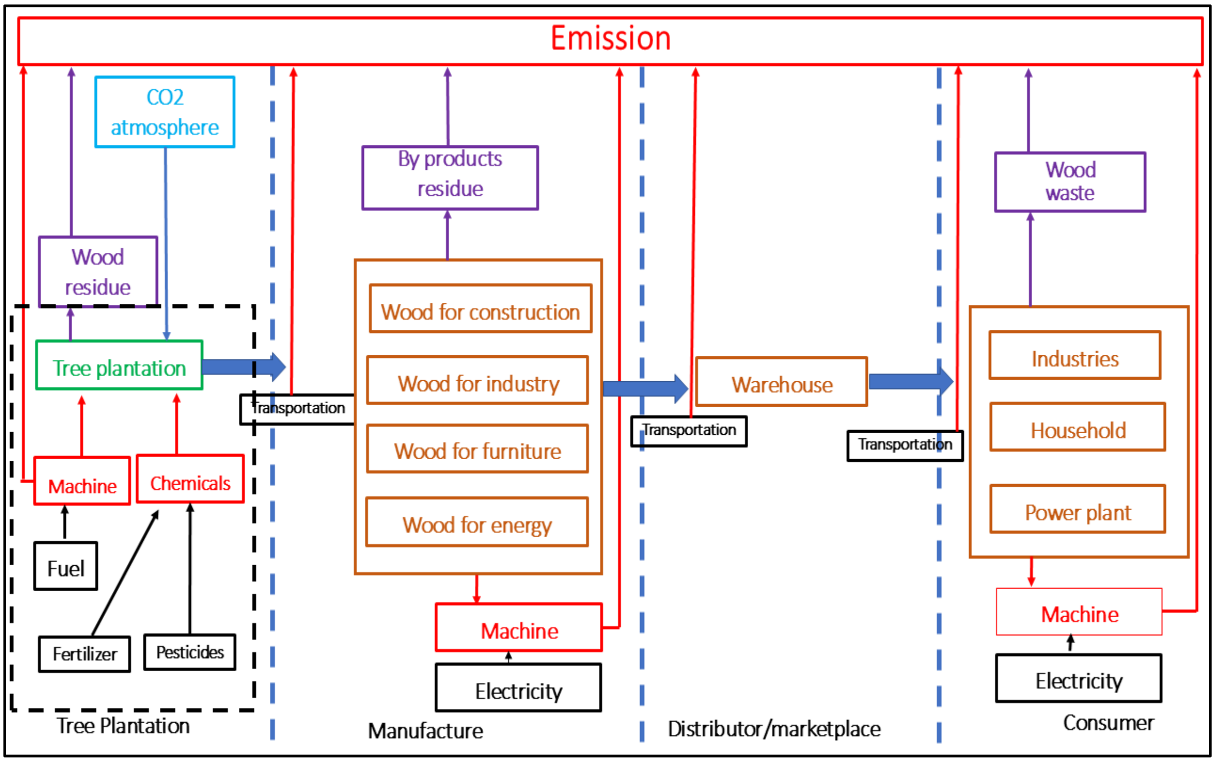


Fig. 2.5. System boundaries of tree production systems

In this research, the system boundary (black line) is the forest operation in the site (cradle-to-gate). The system boundary is the nursery, planting, stand management, and harvesting activities. Furthermore, the input and output were calculated for the activities that were included in the system boundary.

Functional unit

The selection of functional units is vital to analyzing the input and output in the life cycle assessment. In this research, we have chosen the functional unit as 1 ha of poplar/black locust stands, either in short rotation coppice system or long rotation. We follow Bacenetti et al. (2014, 2016b) and Cantamessa et al. (2022), who use the functional unit of area (1 ha) in their life cycle assessment in the agricultural production systems. Polgár et al. (2018) used the functional unit 1 ha in assessing the carbon footprint of different harvesting work systems in short-rotation energy plantations in Hungary.

Life cycle inventory

Life cycle inventory analysis (LCI) is a step in the LCA phase to compile and quantify the inputs and outputs of products (International Organization for Standardizations 2006a). Input data in the plantation management are seedlings, agricultural chemicals (fertilizer and pesticides) during the stand growth, fuel, and lubrication for maintenance and harvesting activities (Oneil and Puettmann 2017; Zhang et al. 2020). Furthermore, the outputs from forest plantations are logs, harvesting residues, and waste.

LCI can be collected through many approaches. According to Islam et al. (2016), LCI can be divided into three techniques: process-based modeling, input-output LCI, and hybrid method. Each technique provides advantages and limitations. Process-based LCI is more accurate but lacks system boundary completeness, input-output LCI provides system boundary completeness but meets data uncertainty, and hybrid LCI improves accuracy and system boundary comprehensiveness but suffers from data double counting and mathematical complexity (Islam et al. 2016).

Inventory analysis is the heart of the LCA process, which requires an extensive data set, mapping the structure and function of product systems (Heinimann 2012). Furthermore, Heinimann (2012) explained that inventory analysis needs skill in developing a process flow diagram of input-output that will model the materials, energy, emissions, waste, and outputs. Life cycle inventory is a time-consuming phase because the main activity in this phase is collecting and compiling the data for all processes in the product systems using various methods (Bjørn et al. 2018b). According to Heinimann (2012), the processes of inventory analysis are

1. Identification of functions and flows of the product systems.
2. Quantification of flows.
3. Quantitative modeling of all flows into a specific set of output flows.

Life cycle impact assessment

Life cycle impact assessment (LCIA) is a phase to analysis the specific impacts categories such as depletion of renewable and non-renewable resources, greenhouse gas emissions effects or global warming potential (GWP), acidification, eutrophication, toxicological stress on human health and ecosystems, photooxidant formation (smog), and ozone depletion (Pennington et al. 2004; Heinimann 2012). According to Baumannt and Rydberg (1994), methods of life cycle impact assessment are:

1. Ecology scarcity (ECO) method refers to the relationship between a pollutant's critical load and potential anthropogenic emissions in a specific location.
2. The environmental theme (ET) method and the total impacts of the ET method follow three steps. i). The environmental loads of the product are grouped into selected environmental themes, and by measuring the relative equivalence of the pollutants, the impacts caused by the product are calculated per theme. ii). The sum of equivalent loads of a theme is divided by the corresponding total pollution of the same theme within the geographical delimitation relevant to the study. iii). The impact fractions may be summarized to a total impact after applying weight factors to take into account the relative severity of the different environmental themes.
3. Environmental priority strategies in product design (EPS) method, environmental impacts calculated through resource and emission indices.

Life cycle impact assessment (LCIA) is derived from the life cycle inventory analysis using software or manual calculation. Referring to ISO standards 14040 and 14044, there are two steps in LCIA: mandatory and optional (International Organization for Standardization 2006a, b) (Table 2.3). Furthermore, Rosenbaum et al. (2018) explain that the mandatory steps in LCIA, such as selection impact, category indicators, and characterization model, are important to assist in collecting information in inventory analysis.

Table 2.3. Mandatory and optional steps on life cycle impact assessment.

No	Mandatory steps	Optional steps
1	Selection of impact categories, category indicators, and characterization model	Normalization
2	Classification impacts	Weighting
3	Characterization impacts	Grouping

The result of life cycle assessment analysis can be analyzed in many methodologies, such as CML 2001, IPCC AR5, EF, and ReCiPe 2016. In our comparison of the life cycle assessment analysis results, we used the CML 2001 method because this method has been used widely by other researchers. CML is *Centrum voor Milieukunde Leiden*, a leading institution in Europe that is actively developing methodologies for life cycle assessment, and their methodologies have been recognized internationally (Gabathuler 1997). Furthermore, the LCIA methodology of ReCiPe's first edition has been developed as ReCiPe 2008 (Goedkoop et al. 2009) and then updated as ReCiPe 2016 (Huijbregts et al. 2017).

LCA researchers and practitioners widely use CML 2001 and ReCiPe 2016 due to the Center of Environmental Science in Leiden (CML) and the Dutch National Institute for Health and Environment (RIVM) active in developing the environmental theme (ET) method for LCIA (Baumannt and Rydberg 1994). According to the European Commission (2010) regarding the International Reference Life Cycle Data System (ILCD), the impact categories can be seen in

Table 2.4. Impact categories in life cycle assessment

No	CML 2001	EF 3.0	ReCiPe 2016 midpoint
1	Abiotic Depletion (ADP elements) [kg Sb eq.]	Acidification terrestrial and freshwater [Mole of H+ eq.]	Climate change, including biogenic carbon [kg CO_2 eq.]
2	Abiotic Depletion (ADP fossil) [MJ]	Cancer human health effects [CTUh]	Fine Particulate Matter Formation [kg PM2.5 eq.]
3	Acidification Potential (AP) [kg SO_2 eq.]	Cancer human health effects (Inorganic) [CTUh]	Fossil depletion [kg oil eq.]
4	Eutrophication Potential (EP) [kg Phosphate eq.]	Cancer human health effects (Metal) [CTUh]	Freshwater Consumption [m^3]
5	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	Cancer human health effects (Organic) [CTUh]	Freshwater ecotoxicity [kg 1,4 DB eq.]
6	Global Warming Potential (GWP 100 years) [kg CO_2 eq.]	Climate Change [kg CO2 eq.]	Freshwater Eutrophication [kg P eq.]
7	Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO_2 eq.]	Climate Change (biogenic) [kg CO_2 eq.]	Human toxicity, cancer [kg 1,4-DB eq.]
8	Human Toxicity Potential (HTP inf.) [kg DCB eq.]	Climate Change (fossil) [kg CO_2 eq.]	Human toxicity, non-cancer [kg 1,4-DB eq.]
9	Marine Aquatic Ecotoxicity Potential (MAETP inf.) [kg DCB eq.]	Climate Change (land use change) [kg CO_2 eq.]	Ionizing Radiation [kBq Co-60 eq. to air]

No	CML 2001	EF 3.0	ReCiPe 2016 midpoint
10	Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	Ecotoxicity freshwater [CTUe]	Land use [Annual crop eq.·y]
11	Photochemical Ozone Creation Potential (POCP) [kg Ethene eq.]	Ecotoxicity freshwater (Inorganic) [CTUe]	Marine ecotoxicity [kg 1,4-DB eq.]
12	Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	Ecotoxicity freshwater (Metals) [CTUe]	Marine Eutrophication [kg N eq.]
13		Ecotoxicity freshwater (Organic) [CTUe]	Metal depletion [kg Cu eq.]
14		Eutrophication freshwater [kg P eq.]	Photochemical Ozone Formation, Ecosystems [kg NOx eq.]
15		Eutrophication marine [kg N eq.]	Photochemical Ozone Formation, Human Health [kg NOx eq.]
16		Eutrophication terrestrial [Mole of N eq.]	Stratospheric Ozone Depletion [kg CFC-11 eq.]
17		Ionizing radiation - human health [kBq U235 eq.]	Terrestrial Acidification [kg SO_2 eq.]
18		Land Use [Pt]	Terrestrial ecotoxicity [kg 1,4-DB eq.]
19		Non-cancer human health effects [CTUh]	
20		Non-cancer human health effects (Inorganic) [CTUh]	
21		Non-cancer human health effects (Metals) [CTUh]	
22		Non-cancer human health effects (Organic) [CTUh]	
23		Ozone depletion [kg CFC-11 eq.]	
24		Photochemical ozone formation - human health [kg NMVOC eq.]	
25		Resource use, energy carriers [MJ]	
26		Resource use, mineral and metals [kg Sb eq.]	
27		Respiratory inorganics [Disease incidences]	
28		Water scarcity [m^3 world equiv.]	

According to Table 2.4, the impact categories in LCIA from CML 2001, EF 3.0, and ReCiPe 2016 Midpoints are different. However, the impact categories can be used for some items in the practice. For example, LCA of meat production in Denmark only focused on three potential environmental impacts: global warming, eutrophication, and acidification (Dijkman et al. 2018). Furthermore, this research will be focused on the environmental impacts potential of global warming potential (GWP). In the GWP, we will assess the effects of greenhouse gas emissions released during the forest management process, either in short or long-rotation systems.

In the LCIA phase, we will focus on environmental impacts in the form of GWP. Global warming potential assesses the impact of processes on producing products or services focused on greenhouse gas emissions, especially CO_2 emissions.

Life cycle interpretation

Life cycle interpretation is the last step in formulating conclusions and recommendations on the environmental performance of product systems that should be improved or alternative to other systems (Heinimann 2012). LCA is a tool for environmental performance from processes of producing products of services. As a tool, the interpretation of environmental impacts can be used by stakeholders to determine further policies or actions to minimize the environmental impacts.

Life cycle assessment in forestry sector

Forest is a renewable natural resource that provides economic, socio-cultural and environmental benefits to people. Forest-based products (i.e. roundwood, biomass, wood panels, etc) should be assessed properly using life cycle assessment to get the information on the potential environmental impacts that is affected from forestry operations (forest establishment, growth maintenance, and harvesting), wood manufacturing, product delivery to consumer, and disposal (Sahoo et al. 2019). For instance, the LCA has been used to assess the potential environmental impacts of bioenergy production from poplar plantation in Italy due to the application of fertilizer, pesticides, and fuels in the forestry operations (González-García et al. 2012a). Furthermore, in the manufacturing of medium-density fiberboard potential negative impacts to environment were also shown (Kouchaki-Penchah et al. 2016). Specifically, the harvesting residues that are left in the forest also can be estimated to the global warming potential (GWP) using LCA method to get the information on the potential biogenic CO_2 emission (Guest et al. 2013).

In forestry sector, GWP get more attentions than other parameters because GWP (often called as the carbon footprint) has close connections to climate change mitigation actions (Sahoo et al. 2019). For example, LCA was used to estimate net carbon dioxide exchange in timber and bioenergy production in Finnish forest (Kilpeläinen et al. 2011). Nowadays, the

GWP is often used by scholar and practitioners to get information on the potential climate impacts of forest operations (Holtsmark 2015).

Forest biomass utilization has been assumed as carbon neutral. However, this hypothesis has been challenged by introducing the GWP to assess the potential biogenic CO_2 emission (Liu et al. 2017). The potential chemical compounds in estimating GWP in forestry operations are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) that can be released from deforestation, forest fire, and natural processes, such as decomposition (Rabbi and Kovács 2024). Thus, in this research, we emphasized GWP to get information on the potential carbon emission that released from the forest operations.

III. RESEARCH METHODOLOGY

The research methodology chapter describes the method of projecting forest carbon dynamics, carbon footprint, and carbon negativity. We used CO2FIX software to model the forest carbon dynamic. Similarly, a life cycle assessment (LCA) approach was used to estimate the potential environmental impact of carbon footprint. Furthermore, researchers have implemented the method of carbon negativity to see the difference between a system/products/services storing carbon and releasing carbon emissions.

3.1. Overview

This research examined forest carbon dynamics to determine carbon stock and life cycle assessment to calculate carbon emissions. The simulation period used in modeling forest carbon dynamics and life cycle assessment was 45 years. The choice of 45 years is based on forest management scenarios for long-rotation 45 years and 15 years for short-rotations (Mulyana et al. 2024). Thus, for a short-rotation of 45 years, there will be three times of final harvesting for plant replacement.

The species cultivated for both types of rotation are black locust and poplar. In a long-rotation 45 years, the harvesting output of black locust and poplar is round wood for wood industries, such as veneer, plywood, pulp, and construction. Meanwhile, in short-rotation, the harvesting output from black locust and poplar is chip wood to supply bioenergy plants (electricity or heating).

We used some software to model the forest carbon dynamics and life cycle assessment. Software CO2FIX estimates the carbon dynamics for short and long-rotation plantation management with a simulation period of 45 years. The outputs of CO2FIX modeling were carbon stock in biomass, soil, bioenergy, and product compartments. Furthermore, we used manual calculations and Sphera LCA for Experts Education License version 9.2.1.68 software to estimate carbon emissions using a life cycle assessment approach. Based on CML 2001, LCA outputs are eutrophication, acidification, ozone depletion, and global warming potential. In this research, we focused on the potential results of global warming, which indicate the amount of carbon emissions released during forest operations.

3.2. Plantation management scenarios

In this research, we developed 36 forest carbon dynamic scenarios for long-rotation system from two species (black locust and poplar), three wood utilization (sawn mill, board, and pulp), and six yield classes (Table 3.1). We used CO2FIX software version 3.1 to estimate the 36 forest carbon dynamics scenarios for the 45-year simulation period. The CO2FIX software has been applied to simulate the forest carbon dynamic in 16 forest types in Europe (Nabuurs and Schelhaas 2002) and applies to different forest management systems such as afforestation projects, agroforestry systems, and forest selective harvesting systems (Schelhaas et al. 2004a, b). Furthermore, CO2FIX has also been applied to a wide range of forest types, such as tropical, temperate, and boreal forests in 27 countries (Mulyana et al. 2023a).

Table 3.1 Description of forest management scenarios in the forest plantation for industrial purposes

	Poplar			**Black locust**		
	Sawmill	**Board**	**Pulp**	**Sawmill**	**Board**	**Pulp**
Yield Class I	TC_{psI}	TC_{pbI}	TC_{ppI}	TC_{bsI}	TC_{bbI}	TC_{bpI}
Yield Class II	TC_{psII}	TC_{pbII}	TC_{ppII}	TC_{bsII}	TC_{bbII}	TC_{bpII}
Yield Class III	TC_{psIII}	TC_{pbIII}	TC_{ppIII}	TC_{bsIII}	TC_{bbIII}	TC_{bpIII}
Yield Class IV	TC_{psIV}	TC_{pbIV}	TC_{ppIV}	TC_{bsIV}	TC_{bbIV}	TC_{bpIV}
Yield Class V	TC_{psV}	TC_{pbV}	TC_{ppV}	TC_{bsV}	TC_{bbV}	TC_{bpV}
Yield Class VI	TC_{psVI}	TC_{pbVI}	TC_{ppVI}	TC_{bsVI}	TC_{bbVI}	TC_{bpVI}

Note: TC is total carbon, p is poplar, b is black locust, s is sawmill, b is board, p is pulp, and I-VI are yield class

The yield class/site class/site index was derived from the mean height of dominants and co-dominants. The yield class is written in Roman numerals from I (the best site) to VI (the worst site) (Rédei et al. 2012, 2014). Furthermore, Rédei et al. (2012, 2014) developed a yield class classification for black locust and poplar species in Hungary based on the expected height value of poplar and black locust at the reference age of 25 years.

The development of the SRC bioenergy plantation is focused on fast-growing species, such as black locust (*Robinia pseudoacacia*) and poplar (*Populus* sp.). Black locust and poplar were Hungary's prominent and dominant species in reforestation and afforestation projects (National Food Chain Safety Office 2016). In this research, we estimated the total carbon stock of black locust and poplar in the simulation period of 45 years. In the modeled SRC, bioenergy plantation will be harvested every three years, naturally re-sprouting and growing until the next harvest. After five times harvesting, the plantation will be replaced by new seedlings of black locust or cuttings of poplars.

Harvested wood products in Hungary in the period 1964-2020 have been used for fuelwood and industrial roundwood (paper and paperboard, wood-based panel, and sawn wood) (Király et al. 2022). Poplar is used as a bioenergy source, pulp, and solid wood product in temperate regions (Truax et al. 2018). Moreover, in the products module of CO2FIX modeling, product allocation of the production line is divided into sawmill, board, pulp, and firewood (Schelhaas et al. 2004a, b). Therefore, this research grouped the wood utilization into sawmill, board, and pulp. Meanwhile, the firewood allocation is not related to the carbon stock but the value of carbon emissions replacing fossil fuels to generate energy.

3.3. Research approaches

3.3.1. CO2FIX modeling

Selecting forest carbon model is essential in the forest carbon dynamics research. Generally, the forest carbon modelling can be divided into modelling based on photosynthesis process and empirical growth data (Kurz et al. 2009; Kim et al. 2015). Furthermore, Kim et al. (2015) reviewed four carbon modelling model based on empirical growth data (CBM-CFS3, CASMOFOR, EFISCEN, CO2FIX) and found that the empirical growth data is more user-friendly than the photosynthesis process. Moreover, Mulyana et al. (2023a) reviewed the CO2FIX model was used widely in 27 countries for many types of forest.

Estimating aboveground biomass/aboveground carbon (AGB/AGC) is necessary for climate change mitigation strategies. AGB/AGC is the biomass distributed on the tree (stem, branches, leaves, and fruits), litter, understorey plants, and necromass (Badan Standarisasi Nasional, 2011a; Intergovernmental Panel on Climate Change, 2006). Furthermore, they explain that the belowground biomass/belowground carbon (BGB/BGC) is biomass in the soil and roots.

Assessing AGB and BGB uses direct measurement and indirect measurement. The direct measurement uses destructive sampling, which cuts the samples and weighs the biomass of stems, branches, leaves, and fruits, then determines the laboratory's dry weight and percentage carbon content (PCC) (Intergovernmental Panel on Climate Change, 2006). Although there is no standard yet, the output is a similar unit. Estimating carbon stock is the amount of carbon stored in a particular area (MgC/ha), and carbon sequestration is the amount of carbon stored in a particular area and specific time (MgC/ha year). Carbon stock estimation can be measured using some parameters. When estimating aboveground biomass, the parameters are diameter at breast height (Dbh), crown dimension, and height. At the same time, the parameters for belowground carbon are soil bulk density, root weight, and soil weight (Table 3.2).

Table 3.2. Biomass cohort for CO2FIX model for each clone and length of rotation

Cohort	Component	Required data	Unit	Sources
Biomass	Stem	Percentage carbon content	%	Literature
		Wood density	gr/cm^3	Literature
		Initial carbon	Tones/ha	Data of forest inventory from poplar plantation
	Foliage	Percentage carbon content	%	Literature
		Initial carbon	Tones/ha	Data of forest inventory from poplar plantation
		Growth correction factor		Default
		Relative growth to stem		Default
		Turnover rate	1/year	Default
	Branches	Percentage carbon content	%	Literature
		Initial carbon	Tones/ha	Data of forest inventory from poplar plantation
		Growth correction factor		Default
		Relative growth to stem		Default
		Turnover rate	1/year	Default
	Roots	Percentage carbon content	%	Literature
		Initial carbon	Tones/ha	Data of forest inventory from poplar plantation
		Growth correction factor		Default
		Relative growth to stem		Default
		Turnover rate	1/year	Default
	Mortality	Natural mortality rate. The mortality rate is usually high in the lower ages and decreases in the middle and old ages.	%	Data of forest inventory from poplar plantation
	Competition	Model default		
	Management Mortality	Model default		
	Thinning-harvesting	- Fraction removal - Stems slash - Branches slash - Foliage slash (slash firewood and slash soil)		

Notes: default means the calculation using the given value of the CO2FIX software

- Percentage carbon content is the amount of carbon in the dried samples (stem, branch, foliage, root).
- Wood density is the weight per volume of the sample.
- The initial carbon content is the carbon stock in seedlings (black locust) or cuttings (poplars) during the planting phase. For example, the weight of the seedling is x gr/seedling (weight of the seedling is a summation from the weight of the seedling stem, seedling foliage,

seedling branches, and seedling roots), and the initial stand density is y seedling/ha. The initial carbon of the stem is the weight of the seedling stem multiply stand density; foliage is the weight of seedling foliage multiplied by stand density; branches are the weight of seedling branches multiply stand density; and roots are the weight of seedling roots multiply stand density.

- Relative growth to the stem can be calculated if the poplar forest plantation company has detailed measurements of biomass allocation (stem, foliage, branches, and roots). We can also try calculating the diameter from the forest inventory data using allometric equations and assumptions.
- Mortality rate: The mortality rate can be calculated from the data of the number of surviving trees during the rotation.

3.3.2. Life cycle assessment approach

Characteristics of LCA

Forests are complex ecosystems that provide a wide range of products for human consumption. Forest establishment needs inputs such as machinery fuel, fertilizer to enrich soil quality, and agrochemicals to prevent pest and plant diseases. Life cycle assessment is a promising approach to providing scientific measures for forest-based products, especially the potential impacts on the environment (Sahoo et al. 2019).

According to ISO 14040, LCA is "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its „life cycle*" (International Organization for Standarization 2006b). Furthermore, the key features of LCA are

- *LCA studies should systematically and adequately address the environmental aspects of product systems, from raw materials acquisition to final disposal*. In this research, we follow the methodological frameworks of LCA to analyse the potential environmental impact of short and long-rotation forest plantations. However, in the boundary systems, this research focuses on wood production at the site level (cradle-to-gate) due to data source limitations.
- *The depth of detail and time frame of an LCA study may vary greatly, depending on the goal and scope*. Data from the yield table of poplar and black locust in Hungary were developed by Rédei et al. in 2012 and 2014. The data is still relevant because there has been no updated data on the growth modeling of poplar and black locust until now.

- *The scope, assumptions, descriptions of data quality, methodologies, and output of LCA studies should be transparent*. In this research, we assumed the database of poplar and black locust growth, fuel, fertilizer, and agrochemicals consumption are still relevant until now. The source of data comes from international peer-reviewed journals and other literature produced by government institutions, such as universities and government agencies.
- *Provisions should be made, depending on the intended application of the LCA study, to respect confidentiality and proprietary matters*. We highly respect the copyright of the data used in this study. The data can be accessed openly and mentioned in the references.

Role of LCA in relation to product

In this study, the primary role of LCA is to provide scientific information on the carbon footprint of different forest plantation management strategies. The stakeholders can consider this finding scientific evidence in policy formulation, especially for climate change mitigation policy. In the academic community, applying the LCA approach in the forestry sector should be improved better to understand the potential environmental impacts of forestry operations.

Stakeholders, especially forest managers, and owners, can use the LCA result to label their forest-based products environmentally. A carbon footprint label is essential for consumers to know the number of emissions released during production (Neitzel 1997; Schmidt 2009).

Limitations of LCA

According to ISO 14040, LCA's studies on data quality, methodologies, and output should be transparent. Furthermore, in this research, we declare the limitations of the LCA study due to the limited access to the data. However, the proxy data is acceptable in the LCA approach as long as the data sources are trusted literature or databases (Kouchaki-Penchah et al. 2016). In this study, the boundary focused on forestry activities at the site level and not discussed economic, social, and technological development.

Steps of LCA

According to The International Organization for Standardizations (2006a), life cycle assessment is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Phase 1, goal and scope definition, defines the system boundary and level of detail.

Phase 2, inventory analysis, is an inventory of input and output data with regard to the system being studied to meet the goals of the defined study.
Phase 3, life cycle impact assessment (LCIA), assesses a product system at phase 2 (life cycle inventory) to understand its environmental significance.
Phase 4, interpreting the results, summarises the conclusion and recommendation per the goal and scope definition.

Data required as inputs were fuel and lubricant, fertilizer, and pesticide consumption during the rotation. Data on fossil fuel consumption for machinery and agricultural chemicals (pesticide and fertilizer) can be collected from literature or databases (Oneil and Puettmann 2017; Zhang et al. 2020). In this research, due to the limitation of data on fuel consumption, we follow Cantamessa et al. (2022) to estimate fuel consumption using this equation. Estimation through calculations from many data sources has also been applied in some research, such as in the Northwest United States (Oneil and Puettmann 2017), and China (Zhang et al. 2020).

$$\mathbf{F = Sc \times P \times d \times t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Where F is fuel consumption (Kg/ha), Sc is specific fuel consumption (fixed to 0.25 kg/KWh), P is maximum engine power (KW), d is power utilization in %, and t is time (hours).

In summary, the input data for LCI can be seen in Table 3.3.

Table 3.3. Input data for LCI either poplar for bioenergy or poplar for industrial purposes.

Stages	Input	Parameter	Unit
Land preparation	Machine	Fuel consumption	kg/ha
	Chemicals	Chemical compounds	kg/ha
Planting	Machine	Fuel consumption	kg/ha
	Fertilizer	Chemical compounds	kg/ha
Maintenance/treatment	Machine	Fuel consumption	kg/ha
	Chemicals	Chemical compounds	kg/ha
Harvesting	Machine	Fuel consumption	kg/ha
Field wood Chipping	Machine	Fuel consumption	kg/ha

The life cycle assessment of tree production for various purposes can be seen in Fig. 3.3. The inputs are poplar, energy flows (fuel in machine and fertilizer), and the processes are planting, maintenance, and harvesting. At the same time, the outputs are wood products and emissions from the utilization of machines and/or burning/decomposition of the harvesting residuals (leaves, branches, and stump).

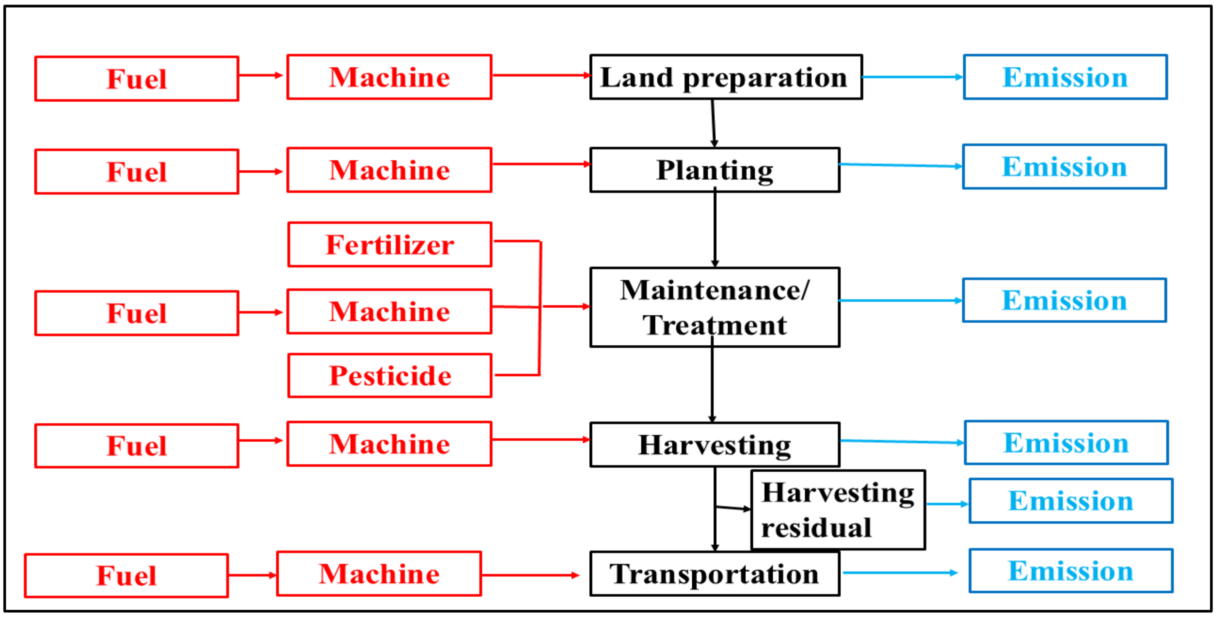


Figure 3.1. Input-output in poplars and black locust plantation

Referring to Fig. 3.1, the primary data for input are the number of machines and dose of fertilizer and agrochemicals. Understanding the amount of fuel consumed is essential to estimate the impact of greenhouse gas (CO_2 emission). Moreover, the utilization of fertilizer will affect acidification and eutrophication. Hence, primary data on input during forest operations is vital to analyze the potential environmental impacts.

The concept of carbon footprint came from Wakernagel and Rees (1996) as a subset of the terminology of ecological footprint. In the development, the concept of carbon footprint is related to the GWP, which is one of the impacts of life cycle impact assessment (Pandey et al. 2011; Durojaye et al. 2020). Furthermore, Pandey et al. (2011) explained that GWP was calculated mathematically and expressed relative to CO_2, and the unit was carbon dioxide equivalent (CO_2 eq).

Methods for calculating carbon footprint are divided into two approaches, namely bottom-up or process analysis (PA) and top-down or input-output analysis (IO) (Pandey et al. 2011; Durojaye et al. 2020). PA-based LCA will face obstacles if implemented in large entities such as industry, general household, and government. In contrast, the IO-based LCA can be calculated in large entities but less accurately (Pandey et al. 2011; Durojaye et al. 2020). In this research, we use the IO-based LCA to estimate the carbon footprint of forest operations in short and long-rotation systems.

3.4. Data collection

3.4.1. Data parameterization to develop CO2FIX model

CO2FIX software was developed in the CASFOR-II project from 1999 to 2004. The latest update of CO2FIX software was version 3.1, released in 2004 (Schelhaas et al. 2004a, b). The CO2FIX software divides carbon dynamics into biomass, soil, and products. Each module requires data, such as current annual increment, climatology data, and wood product allocations (Table 3.4.).

Data on black locust growth in long-rotation was derived from the local black locust yield table developed by Rédei et al. (2014) from 105 sampling plots in the Nyírség region, Hungary. Poplar growth in long-rotation was collected from a local poplar yield table constructed from 90 sampling plots in the sandy ridges between Danube and Tisza, Hungary (Rédei et al. 2012). Black locust and poplar growth were measured until their end of rotation in 45 years. Thus, this research estimates the forest carbon dynamic for one rotation period (45 years). From yield table data, annual increment data was used as the main parameter in the biomass module. The biomass module converted a volumetric annual increment to carbon stock (Lemma et al. 2007).

Growth data for short-rotation for hybrid poplar (I-214, Pannónia, Agathe-F, and S-298-8) was collected from Schiberna et al. (2021) and hybrid black locust (Üllői, Jászkiséri, Nyírségi, and Kiscsalai) referred to Rédei et al. (2010b; 2011) (Table 3.5). Furthermore, growth rate modification factors for 1, 2, 3, 4, and 5 harvesting cycle are 100, 100, 95, 90, and 85%, respectively (Schiberna et al., 2021).

In the soil module, the primary data was litter production and climatology data. The CO2FIX model uses the YASSO modeling to estimate the soil carbon dynamics. YASSO modeling is considered in predicting the soil organic dynamic in the temperate region (Mao et al. 2019). Furthermore, Mao et al. (2019) explained that the YASSO model simulates the annual carbon stock based on the annual litter inputs. The litter inputs come from the turnover (foliage, branches, and roots) and harvest residual data in the biomass module (Schelhaas et al. 2004a, b; Lemma et al. 2007).

Harvested wood products (HWP) are essential in estimating carbon stock. In the CO2FIX model, the carbon dynamics were affected by product allocations (sawn mill, board, pulp, and firewood) and half-life span for recycling (Schelhaas et al. 2004a, b). Furthermore, Schelhaas et al. (2004a, b) explained that the carbon is still stored in the products until they are no longer used and are sent to the mill site dump or landfill or burned as fuelwood.

Table 3.4. Model parameterization to develop CO2FIX modeling in short rotation coppice systems

Parameters	Unit	Value		References
		Black locust	Poplar	
Survival rate	%	60.8	90.3	Stolarski and Stachowicz (2023)
Wood density	kg/m^3	727	336	Klašnja et al. (2013); Rédei et al. (2017)
Carbon content	%			Ciuvăţ et al. (2013); Oliveira et al. (2018)
- Aboveground		49	47	
- Belowground		45	46	
Climatic condition				Országos Meteorológiai Szolgálat (2022)
- Degree days (above zero)	^{o}C	4129.6	4129.6	
- Potential evapotranspiration in the growing season	mm	595.6	595.6	
- Precipitation in the growing season	mm	599.3	599.3	
Relative growth to stem (first year; harvested year)	-			Quinkenstein and Jochheim (2016)
- Foliage		1.50; 0.50	0.31; 0.31	
- Branches		0.24; 0.01	0.05; 0.05	
- Coarse roots		4.20; 0.45	0.22; 0.22	
Turnover rate	Year^{-1}			Quinkenstein and Jochheim (2016)
- Foliage		1.000	1.000	
- Branches		0.030	0.010	
- Coarse roots		0.022	0.022	
Products allocation	-			de Jong et al. (2007)
- Logwood		0.000	0.000	
- Pulp wood		0.000	0.000	
- Slash		1.000	1.000	
The average lifetime of products	Year			de Jong et al. (2007)
- Long-term products		30	30	
- Medium-term products		15	15	
- Short-term products		1	1	
- Mill-site dump		10	10	
- Landfill		50	50	

Note: - is dimensionless, source Mulyana et al. (2024)

Table 3.5. Growth rate for hybrid poplar and black locust in Helvécia at age 3 years.

Cultivar	Yield (Ton OD/ha/year)	Spacing	Density	Location	References
Hybrid poplar I-214	1.8 – 3.2 (2.5)	1.5 x 1.0 m	6,667	Helvécia	Schiberna et al. (2021)
Hybrid poplar Pannónia	4.1 – 6.1 (5.1)	1.5 x 1.0 m	6,667	Helvécia	Schiberna et al. (2021)
Hybrid poplar Agathe-F	3.2 – 6.2 (4.7)	1.5 x 1.0 m	6,667	Helvécia	Schiberna et al. (2021)
Hybrid poplar S-298-8	1.7 – 3.5 (2.6)	1.5 x 1.0 m	6,667	Helvécia	Schiberna et al. (2021)
Hybrid black locust Üllői	3.0	1.5 x 1.0 m	6,667	Helvécia	Rédei et al. (2010b; 2011)
Hybrid black locust Jászkiséri	2.4	1.5 x 1.0 m	6,667	Helvécia	Rédei et al. (2010b; 2011)
Hybrid black locust Nyírségi	2.4	1.5 x 1.0 m	6,667	Helvécia	Rédei et al. (2010b; 2011)
Hybrid black locust Kiscsalai	4.2	1.5 x 1.0 m	6,667	Helvécia	Rédei et al. (2010b; 2011)

Note: () is the average from the lowest and highest yield

Table 3.6. Model parameterization to develop CO2FIX modeling in forest plantation for industrial purposes

No	Parameters	References	
		Black locust	Poplar
1	Growth	Rédei et al. (2014)	Rédei et al. (2012)
2	Biomass allocation	Rédei et al. (2017)	Jiao et al. (2022)
3	Survival rate	Quinkenstein and Jochheim (2016)	Afas et al. (2008)
4	Wood product allocation	Quinkenstein and Jochheim (2016)	Zhang et al. (2018, 2019); Zbieć et al. (2022)
5	Percentage carbon content	Quinkenstein and Jochheim (2016)	Ma et al. (2022)
6	Soil and root turnover rate	Quinkenstein and Jochheim (2016)	Ajit et al. (2013)
7	Relative growth of tree components	Lemma et al. (2007); Rédei et al. (2017)	Nabuurs and Mohren (1995); Ajit et al. (2013)
8	Foliage, branches, root turnover rate	Quinkenstein and Jochheim (2016)	Nabuurs and Mohren (1995); Quinkenstein and Jochheim (2016)
9	The average lifetime of products	de Jong et al. (2007)	de Jong et al. (2007)
10	Growth reduction rates due to competition	de Jong et al. (2007)	de Jong et al. (2007)
11	Parameter of bioenergy module	de Jong et al. (2007)	de Jong et al. (2007)
12	Lumber recovery products	Prada et al. (2016)	Prada et al. (2016)
13	Climatology data of Hungary	Országos Meteorológiai Szolgálat (2021)	Országos Meteorológiai Szolgálat (2021)

3.4.2. Data requirement for life cycle assessment

In this research, the required data refers to the system boundaries. The system boundaries started with land preparation and ended with harvesting. During the silvicultural operations, different stand management treatments exist for short and long-rotation plantations. Thus, the life cycle inventory analysis (LCIA) is essential to describe the inputs and outputs of plantation management, either short or long-rotation systems.

Input data for life cycle inventory stages can be collected through many sources. Availability of inventory data is the biggest challenge in the LCA process, and practitioners solve this issue by using proxy data (Kouchaki-Penchah et al. 2016). Furthermore, Kouchaki-Penchah et al. (2016) explained that the proxy data can be retrieved from literature, such as the Ecoinvent database, ETH-ESU 96 database in Simapro 8 software, reports, and reviewed publications.

Table 3.7. Input for short rotation coppice systems

Year	Activities	Input (kg/ha)					Remarks
		Fuel	Lube	Pesticide	Fertilizer	Electricity	
1	A. Plantation establishment						6700 trees/ha
	- Fuel tractor	44					
	- Lube		1.98				
	- Fuel car	14.25					
	- Chemical			1.650; 0.240; 0.140		1.5 KW	
	- Electricity						
	B. Maintenance						
	- Fuel	35.2					
	- Lube		1.584		162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
	- Fertilizer						
2	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
3	Harvesting						
	- Fuel tractor	8.80					
	- Lube tractor		0.396				
	- Fuel combine harvester	7.50	0.135				
	- Fuel combine harvester						
4	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		

Year	Activities	Input (kg/ha)					Remarks
		Fuel	Lube	Pesticide	Fertilizer	Electricity	
5	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
6	Harvesting						
	- Fuel tractor	8.80					
	- Lube tractor		0.396				
	- Fuel combines	7.50					
	harvester		0.135				
	- Fuel combine harvester						
7	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
8	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
9	Harvesting						
	- Fuel tractor	8.80					
	- Lube tractor		0.396				
	- Fuel combine	7.50					
	harvester		0.135				
	Fuel combine harvester						
10	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		

Year	Activities	Input (kg/ha)					Remarks
		Fuel	Lube	Pesticide	Fertilizer	Electricity	
11	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
12	Harvesting						
	- Fuel tractor	8.80					
	- Lube tractor		0.396				
	- Fuel combine	7.50					
	harvester		0.135				
	Fuel combine harvester						
13	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
14	Maintenance						
	- Fuel	35.2					
	- Lube		1.584				
	- Fertilizer				162 kg N; 30 kg Ca; 42 kg CaO; 18 kg Mg; 30 kg MgO		
15	A. Harvesting						
	- Fuel tractor	8.80					
	- Lube tractor		0.396				
	- Fuel combine harvester	7.50					
	- Lube combine harvester		0.135				
	B. Liquidation						
	- Fuel	17.60					
	- Lube		0.792				
	- Chemical			2.4			

Source: Barbara (2018)

Table 3.8. Estimation of fuel consumption for forest plantation for industrial purposes

Year	Activities	Parameter					References
		Specific fuel consumption (Kg/kWh)*	Maximum engine power (KW)**	Power utilization (%)***	Time (hours)****	Fuel consumption (Kg/ha)	
1	Plantation establishment and maintenance						Fiala and Bacenetti (2012); Cantamessa et al. (2022)
	- Soil preparation	0.25	85	60	1.67	21.29	
	- Fertilization	0.25	55	60	0.33	2.72	
	- Planting	0.25	65	60	1.43	13.94	
5	Thinning	0.25	50	64	0.54	4.32	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
10	Thinning	0.25	50	64	0.54	4.32	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
15	Thinning	0.25	50	64	0.54	4.32	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
20	Thinning	0.25	75	65	0.58	7.07	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
25	Thinning	0.25	75	65	0.58	7.07	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
30	Thinning	0.25	75	65	0.58	7.07	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
35	Thinning	0.25	124	67	0.63	13.09	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)

Year	Activities	Parameter					References
		Specific fuel consumption (Kg/kWh)*	**Maximum engine power (KW)****	**Power utilization (%)*****	**Time (hours)********	**Fuel consumption (Kg/ha)**	
40	Thinning	0.25	124	67	0.63	13.09	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)
45	Final harvesting	0.25	25	67	0.70	14.67	Eisenbies et al. (2017); Cantamessa et al. (2022); Spinelli et al. (2022); De Francesco et al. (2022)

Note: Reference for * is Cantamessa et al. (2022), ** is Spinelli et al. (2022); De Francesco et al. (2022), *** is Eisenbies et al. (2017), **** is Eisenbies et al. (2017)

Table 3.9. Input for forest plantations for industrial purposes

Year	Activities	Input					Remarks
		Fuel*	**Lube****	**Pesticide**	**Fertilizer**	**Electricity**	
1	Plantation establishment and stand maintenance	119.00		4.5 L/ha (Glyphosphate), 4.8 L/ha (Pyretroid-comp.), 18.0 L/ha (fungicide)	495 Kg/ha (urea superphosphate), 250 kg/ha (KCL),		González-García et al. (2014); Lovarelli et al. (2018)
5	Thinning	4.32	0.21				
10	Thinning	4.32	0.87				
15	Thinning	4.32	0.90				
20	Thinning	7.07	0.78				
25	Thinning	7.07	0.57				
30	Thinning	7.07	0.42				
35	Thinning	13.09	0.27				
40	Thinning	13.09	0.18				
45	Final harvesting	14.67	12.63				

Note: * refer to table 3.7, **lube consumption (hydraulic and transmission oil) was 30 l/1,000m^3 (Athanassiadis et al. 1999) multiplied by the volume of thinning or harvesting (Rédei et al. 2012).

3.5. Data analysis

3.5.1. Framework of CO2FIX modeling

CO2FIX V 3.2 is a free-to-use software to estimate the carbon dynamics in biomass, soil, wood products, and bioenergy at afforestation, reforestation, agroforestry, and selective logging systems (Schelhaas et al. 2004a, 2004b). Furthermore, CO2FIX is free for end users to use for carbon sequestration projects. In Europe, the CO2FIX has been implemented in sixteen forest types (Masera et al. 2003). In this study, CO2FIX was used to simulate forest carbon dynamics at SRC black locust and poplar bioenergy plantations.

According to Schelhaas et al. (2004b), total carbon stock in the time-t is the summation of carbon stock in the living biomass, soil organic matter, and wood products. The equation used to calculate the changes in carbon stocks can be displayed below.

$$\boldsymbol{CT_t = Cb_t + Cs_t + Cp_t} \quad \ldots\ldots \quad (12)$$

where:

CT_t is total carbon at time-$_t$ (MgC/ha)

Cb_t is carbon stock in biomass (stem, branches, leaves, and roots) at time-$_t$ (MgC/ha)

Cs_t is carbon stock in soil organic matter (MgC/ha) at time-$_t$

Cp_t is carbon stock in wood products (MgC/ha) at time-$_t$

In the product cohort of the scenario, SRC black locust and poplar bioenergy plantations supplied the fuelwood for industries. Therefore, wood was used only for fuelwood in the product cohort, and the half-life cycle span was short. Based on the flow of CO2FIX modeling (Fig. 3.2), the product of black locust and poplar and the potential wastes will be converted as bioenergy.

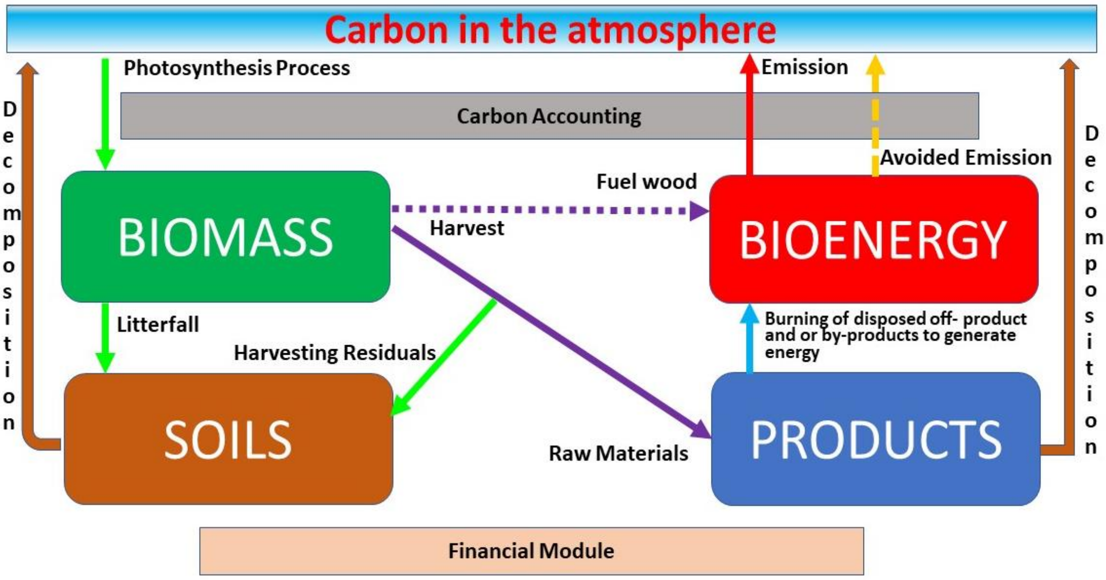
In the bioenergy module, carbon value represents the avoided emission if the wood substitutes the fossil fuel (Schelhaas et al. 2004b). The total carbon absorption from the atmosphere can be estimated using the equation as follows:

$$\boldsymbol{A = CT_t + Cbio_t} \quad \ldots\ldots \quad (13)$$

where:

A is the total atmospheric effect

$Cbio_t$ has avoided emissions from bioenergy use at time-$_t$



Note: the flow of CO2FIX adopted from Schelhaas et al. (2004b)

Fig. 3.2. Carbon dynamics in CO2FIX modelling (Mulyana et al. 2024)

3.5.2. Framework of life cycle assessment

Analysis of input-output for each wood production stage. Input is product, material, or energy flow that enters a unit process (The International Organization for Standardizations 2006a). Furthermore, the International Organization for Standardizations (2006a) has defined process as a set of interrelated or interacting activities that transform inputs into outputs, and output is a product, material, or energy flow that leaves a unit process. Data required in poplar plantation stages are carbon stock (MgC/ha), fuel consumption (liter), wood production (m^3 or Mg), harvesting residual (m^3 or Mg), and emission (Mg). Forest management of poplar plantations for wood production will differ from bioenergy production. Poplar's bioenergy production will consume less fuel, but the timber production and carbon sequestration are also lower than poplar's plantation for timber production.

Analysis of LCA's data of poplar plantations for bioenergy and industry purposes can use manual methods or software assistance. This research will use Sphera LCA for Experts Education License version 9.2.1.68 software to calculate the environmental impacts. The main inputs for Sphera LCA for Experts Education License version 9.2.1.68 software are energy consumption (electricity, fuel, and lube) and agrochemicals to support tree growth treatment (fertilizer and pesticides).

Referring to Monti et al. (2009); Fazio and Monti (2011), the impact categories can be estimated through the following general equation.

$$\boldsymbol{IC_j = \sum_j E_j \; x \; CF_{ij}} \; \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

Where IC_j is the impact category, E_j is the emission release or input consumption, and CF_{ij} is the characterization factor.

These formulas can be used for specific estimation of certain emissions (Table 3.9).

Table 3.10. Equations to estimate the emission.

Equations	References
Emission (electricity) = QL x FE	Intergovernmental Panel on Climate Change (2006)
Emission (fuel) = QF x NK x FE	Intergovernmental Panel on Climate Change (2006)
Emission (fertilizer) = QP x N x FE	European Environment Agency (2019)
Emission (pesticides) = QPs x FE	Intergovernmental Panel on Climate Change (2006)

Note: QL is electricity consumption, QF is fuel consumption, QP is fertilizer consumption, QPs is pesticide consumption, NK is heating value, N is nitrogen, and FE is emission factor.

According to Winter et al. (2010) and Directorate-General for Energy European Commission (2012), equations to estimate the total emission of greenhouse gases in agriculture production are as follows.

$$\boldsymbol{e_{ec} = e_{fert} + e_{seeds} + e_{N2O} + e_{fuel}} \qquad (15)$$

Where e_{ec} is total greenhouse gas emissions, e_{fert} is emission from fertilizer application, e_{seeds} is emission from seeds, e_{N2O} is direct and indirect emission N_2O according to IPCC 2006 guideline, e_{fuel} is emission from fossil fuel consumption.

Data from the life cycle inventory should be validated through a literature review. Validation is vital to ensure the input data is valid for further analysis.

Table 3.11. Validation of fuel consumption for short-rotation coppice systems

Activities	Inventory data				Validation				References
	F	P	Fe	E	F	P	Fe	E	
Planting	44	2.03		1.5	10.4 – 33.33	5.5		1.1	Winter et al. (2010); González-García et al. (2012)
Maintenance/ Growth treatment	35.2		162 kg N		1.9 – 7.9		276 kg N 216 kg P 324 kg K		
Harvesting	16.3				32.5 – 57.5				

Note: F is fuel, P is pesticide, Fe is fertilizer, and E is electricity

Table 3.12. Validation of fuel consumption for long-rotation systems

Activities	Our estimation	References		
		*	**	***
Planting	37.95		38	33.98
Thinning	4.32 – 13.09	10.67		7.02
Final harvesting	14.67	14.63		

Note: * is Nordfjell et al. (2003), ** is Koprivica et al. 2021), *** is Bosner et al. (2012)

Due to the environmental impact assessment in this research, which will be focused on carbon footprint, data on fuel consumption is vital in our calculations. Furthermore, calculating carbon footprint for fuel consumption following the greenhouse gas emission calculator proposed by the United Nations Framework Convention on Climate Change (UNFCCC). The greenhouse gas emission calculator version 02.6 document was published in September 2022 (UNFCCC 2022).

The emission factors from pesticide and fertilizer applications are useful in estimating the emissions from non-gas CO_2 emissions. According to Winter et al. (2010) and the Directorate-General for Energy European Commission (2012), emission factors for nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and pesticides are 5.8806, 1.0107, 0.5761, and 10.971 kg CO_2 eq/kg. Furthermore, the emission factor for seed ranges from 0 to 0.7299 kg CO_2 eq/kg seeds (Directorate-General for Energy European Commission 2012).

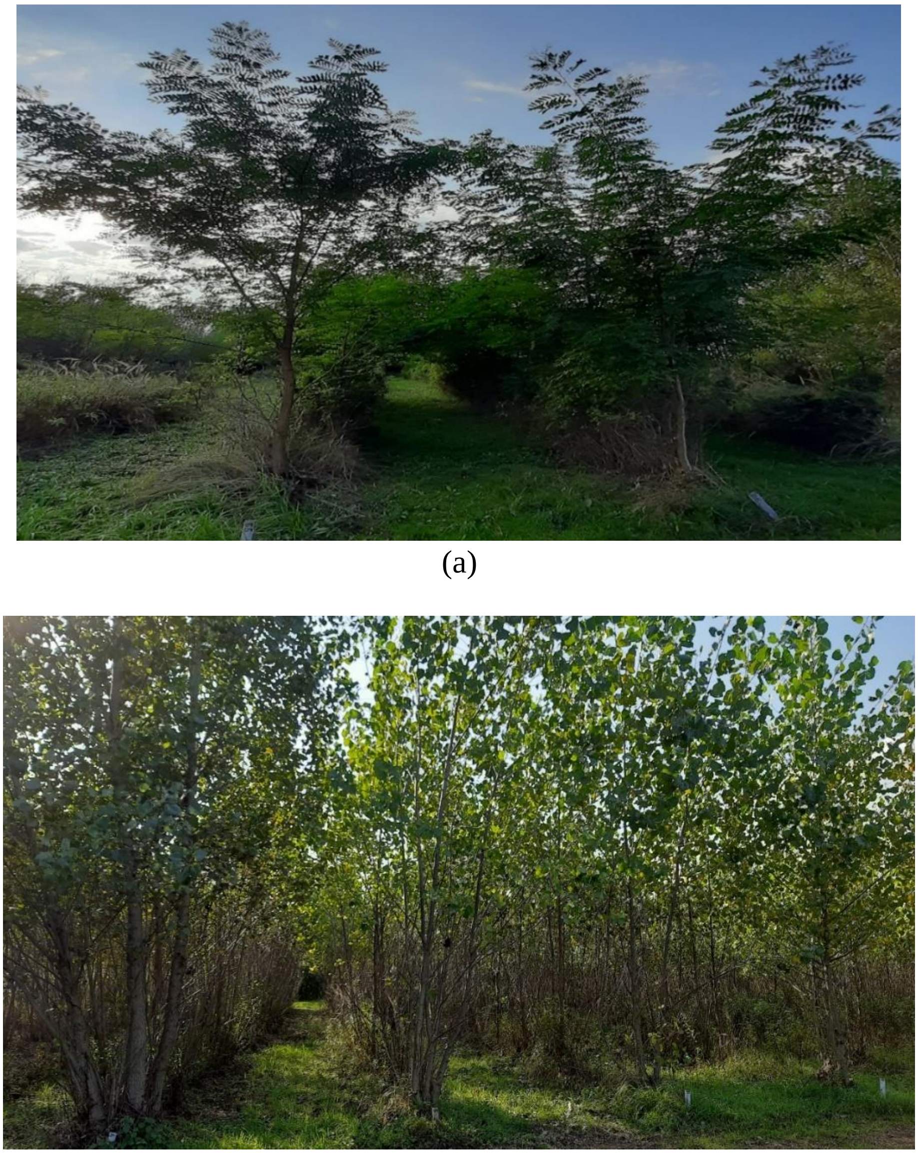
IV. RESULT AND DISCUSSION

This research has assessed the carbon dynamic of poplar and black locust plantations in short and long-rotation for 45-year simulation period. In general, forest plantations have the ability to absorb carbon dioxide (CO_2) from the atmosphere and store it in above and below-ground biomass. Although forests have been proven to reduce carbon emissions, forest operations in short and long-rotation have released pollutants into the air (carbon emission), water, and soil (residues from fertilizer and agricultural chemicals). However, the amount of carbon emissions during forest operations is lower than the forest's ability to absorb and store the carbon emissions.

In detail, for short-rotation coppice systems for bioenergy purposes, the total carbon (biomass, soil, product, and bioenergy) of poplar and black locust plantations at the end of the simulation period (45 years) around 53.28 – 119.74 MgC/ha, respectively. Furthermore, the total carbon for long-rotation systems for poplar and black locust plantations in the site index I - VI are around 23.75 – 101.75 MgC/ha, respectively. However, the carbon footprint for short-rotation coppice system and long-rotation (poplar and black locust) are 5.9E+03 and 4.3E+03 kg CO_2 eq, respectively. Hence, short- and long-rotation carbon negativity has shown that carbon stock is more significant than carbon emission.

4.1. Overview

The short rotation coppice system has got attention in European countries, including Hungary, as a potential source of renewable energy and reducing greenhouse gas emissions to support climate change mitigation. In Hungary, the most prominent species as SRC for bioenergy plantation are black locust (*Robinia pseudoacacia*) and poplars (*Populus* sp.). Both are characterized as fast-growing species and high yield for biomass production. As a coppice system, the harvested stand will re-sprouting new multi-stems and can be harvested many times during the rotation (Fig.4.1).

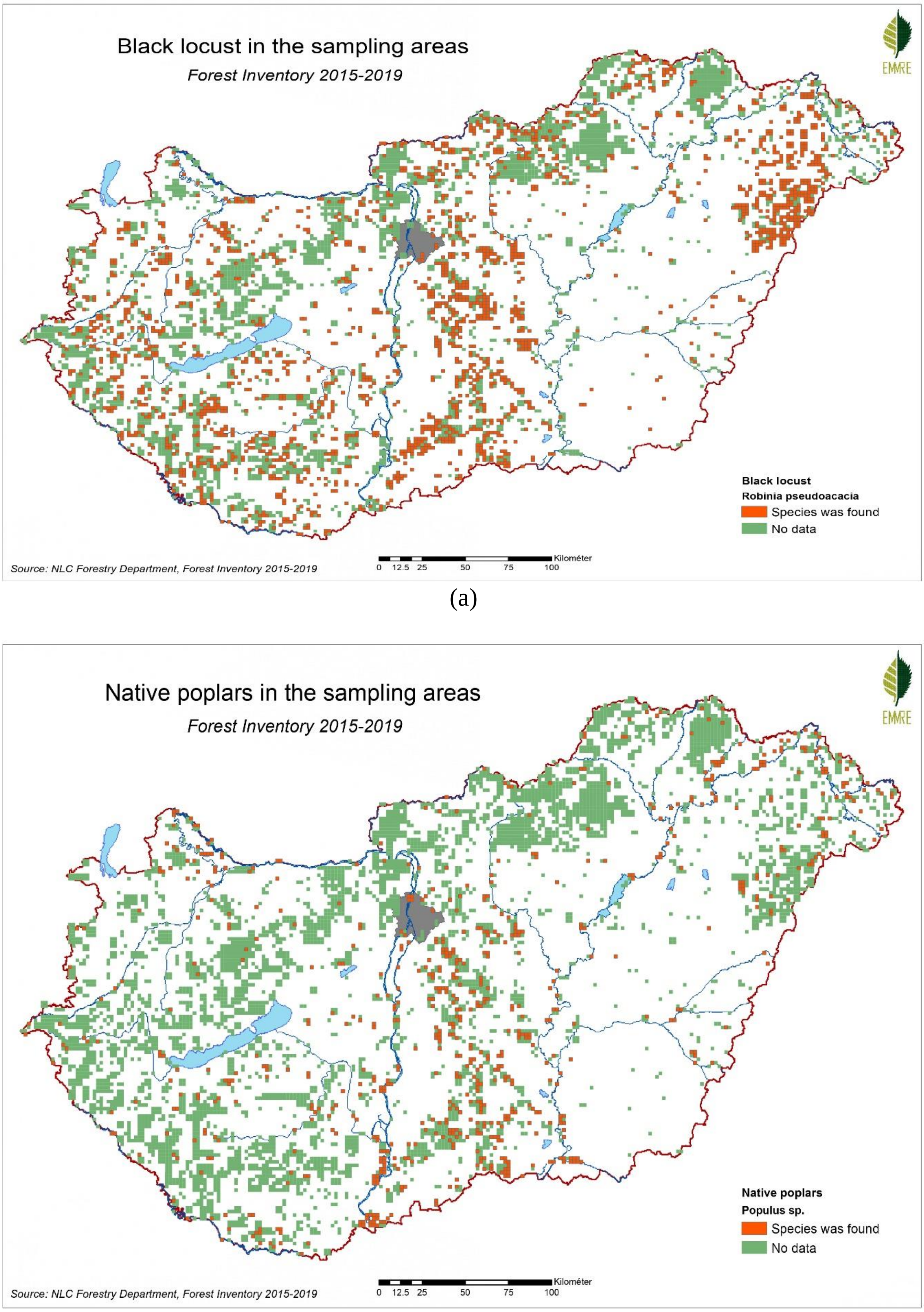


(a)

(b)

Fig. 4.1. Short-rotation coppice system of a). black locust, b). poplars in the experimental site of the Forest Research Institute of the University of Sopron, Hungary (Mulyana et al. 2024)

In Hungary, one-third of black locust stands were seedling plantations, while two-thirds were coppiced plantations that the purpose for industry and energy supply in the coppice system (Rédei 1999). The region suitable for black locust cultivation in Hungary is distributed in South and Southwest Transdanubia, the Danube-Tisza Interfluve, and Northeast Hungary (Rédei 1999; Rédei et al. 2006, 2007, 2011, 2014, 2017). According to the Hungary National Forest Inventory, the distribution of black locust and poplar species can be seen in Fig. 4.2.



(a)

(b)

Fig. 4.2. Distribution of black locust and poplars in Hungary (source: National Land Center Forestry Department (2024))

Furthermore, poplar cultivation uses native and hybrid poplar species. The native poplars in Hungary are white poplar (*Populus alba* L), grey poplar (*Populus x canescens*) (Rédei et al. 2012a, 2012b), black poplar (*Populus nigra* L.) and common aspen (*Populus tremula* L.). There are also promising hybrid poplars for biomass production, such as H-337 and H-384 (*P. alba x P. grandidentata*) (Rédei et al. 2010), H-425-4 (*Populus alba x Populus alba*), H 758 (*Populus alba L. Mosonmagyaróvár*), H 427-3 (*Populus alba x Populus grandidentata*) (Rédei et al. 2019) or Pannónia (*Populus x euramericana cv. Pannónia*) and I-214 (*Populus x euramericana cv. I-214*) (Vágvölgyi, 2014). Thus, the management practices of black locust and poplar also varied, depending on the site characteristics (Table 4.1).

Table 4.1. Short rotation coppice system of black locust and poplar in Hungary

Characteristics	Unit	Black locust	Poplar
Spacing	m^2	1.5 x 0.3 m 1.5 x 0.5 m 1.5 x 1.0 m	3 x 0.6 m 2.0 x 2.0 m 1.5 x 0.5 m
Density	Tree/ha	10,000 - 22,222	2,500 – 13,333
Yield	Ton/ha. year	6.7 – 8.0	4 – 12
Harvesting cycle	Year	2 – 8	4
Rotation	Year	15 – 25	15

Source: Rédei (1999); Schiberna et al. (2021)

When utilizing wood for bioenergy purposes, its calorific value, moisture content (Pereira and Costa 2017), ash content, and volatile substances are considered decisive (Marosvölgyi et al. 1999; Vityi et al. 2003). Moisture content is related to the endothermal processes, influencing the calorific value, and volatile matters affect the combustion duration (Pereira and Costa 2017). Moreover, in biomass combustion, the solid remains of burning (ashes and unfavorable cinders) should also be measured (Marosvölgyi et al. 1999). The physical and thermal properties of the black locust and poplar woods as a source of fuelwood can be seen in Table 4.2.

Table 4.2. Properties of black locust and poplar for bioenergy sources

Properties	Unit	Value		References
		Black locust	Poplar	
Wood density	gr/cm^3	0.60	0.33	Klašnja et al. (2013)
Carbon content	% DM	52.60	53.46	Stolarski and Stachowicz (2023)
Heating value	MJ/kg	17.72–18.14	15.14–18.56	Marosvölgyi et al. (1999); Vityi et al. (2003); Kraszkiewicz (2013)
Ash content	% DM	1.67–2.08	1.67–4.81	Marosvölgyi et al. (1999); Vityi et al. (2003); Stolarski and Stachowicz (2023)
Moisture content	%	24.00-42.00	10.00–47.30	Marosvölgyi et al. (1999); Vityi et al. (2003); Kraszkiewicz (2013)
Volatile matter	% DM	77.86	77.83	Stolarski and Stachowicz (2023)

Note: DM is a dry mass,

Referring to Table 4.2, the density of black locust was higher than poplar. Higher wood density provided more biomass at the same growth rate and affected the carbon stock and harvesting yield. In the bioenergy market, the consumer buys fuelwood in units of mass. Moreover, in the carbon stock estimation, the dry mass of wood will be multiplied by the percentage of carbon content. For example, wood density has influenced tropical forest biomass on multiple scales, from individual trees to biome (Phillips et al. 2019). Thus, tree species with higher wood density will be advantageous in calculating the carbon content or bioenergy market.

The carbon content of wood is the amount of carbon fraction in dry wood. Generally, the carbon content of wood is 50% of the total dry mass (Intergovernmental Panel on Climate Change 2014). However, for detailed carbon stock estimation, laboratory work to measure the carbon content of wood is vital to provide a more precise estimation. In this modeling, especially in the biomass cohort, the amount of carbon content will affect the total carbon stock in biomass.

Heating value is an essential consideration when choosing materials for combustion. The heating value of wood varies among species and ages, but primarily depends on its moisture content (μ%). In this research, black locust has shown higher heating value than poplar. Heating values of 1- and 3-year-old poplars in Hungary were 15.147 and 17.390 MJ/kg (μ%= 29.37%) (Marosvölgyi et al. 1999). Furthermore, the fuelwood from black locust and poplar SRC bioenergy plantations is promising for co-firing supply for power plants (Pereira and Costa 2017).

4.2. Forest carbon dynamics in different plantation management scenarios

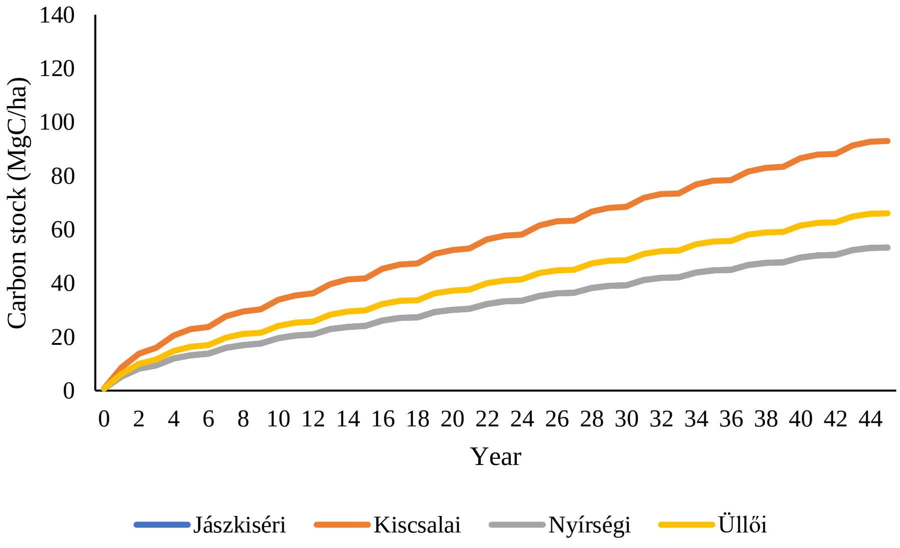
Forest carbon dynamic in short-rotation coppice system was developed based on yield data from Rédei et al (2010b, 2011) for hybrid black locust and Schiberna et al. (2021) for hybrid poplar. According to Rédei et al. (2010b, 2011), the available data for hybrid black locust are yield for cultivars Üllői, Jászkiséri, Nyírségi, Kiscsalai. Meanwhile, the cultivars for hybrid poplar are cultivars Agathe-F, I-214, Pannónia, and S 298-8 (Schiberna et al. 2021).

Hybrid black locust and poplar for short-rotation coppice system were cultivated in Helvécia. The spacing was 1.5 x 1.0 m and the density was 6,667 stems/ha. According to Schiberna et al. (2021), the experimental site of hybrid poplar has sandy soil texture and no additional water supply. Furthermore, the characteristics of hybrid black locust's experimental site in Helvécia were slightly humous sandy soil and without ground-water influence (Rédei et al. 2010b, 2011).

Forest carbon dynamics in long-rotation systems has been referred to Rédei et al. (2014) for white poplar's yield table and Rédei et al. (2012) for black locust's yield table. According to Rédei et al. (2014), the white poplar yield has been constructed from 50 permanent and 40 temporary plots which are located in the sandy ridges between the rivers Danube and Tisza. Furthermore, the Nyírség black locust yield table has been developed from 105 sampling plots in the North-Eastern part of Hungary.

4.2.1. Forest carbon dynamics in short-rotation coppice systems

The result of CO2FIX modeling for short-rotation coppice systems for a simulation period of 45 years has shown that the total carbon stock for the hybrid black locust plantation and hybrid poplar plantation varied. The total carbon of black locust and poplar at the end of the simulation period were around 53.28 – 119.74 MgC/ha, respectively. In detailed, the total carbon for hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Furthermore, the total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. According to Table 3.5, the yield of hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai are 3.0-, 2.4-, 2.4-, and 4.2-ton OD/ha/year. Furthermore, the bioenergy compartment has contributed significantly to the total carbon in CO2FIX modelling (Fig. 4.3.).



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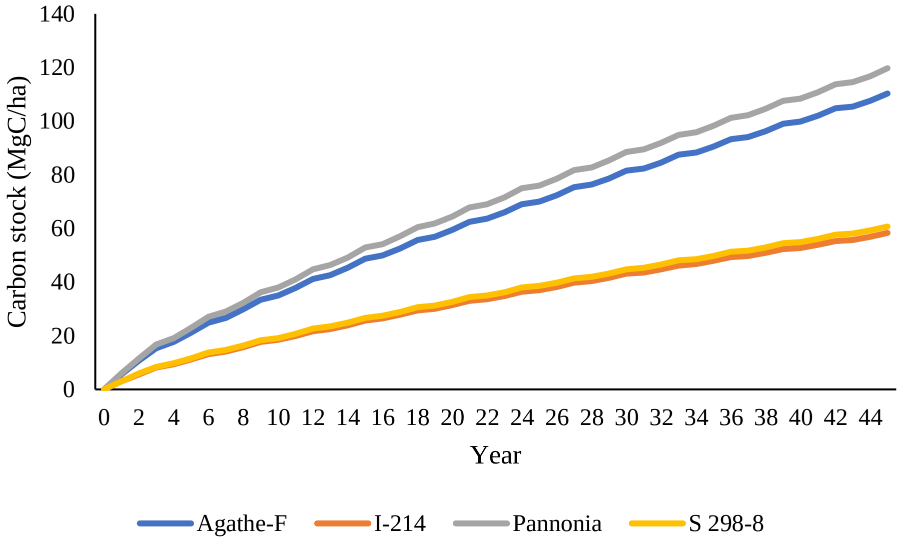


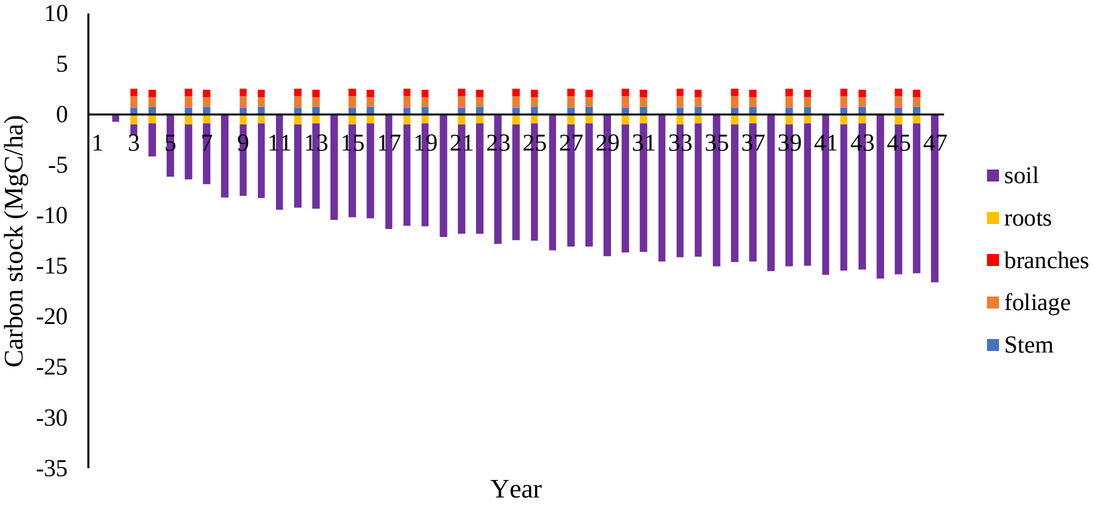
(b)

Fig. 4.3. Carbon dynamic in short rotation coppice: a). black locust, b). poplars

In single harvesting cycle (3 years), the total carbon in biomass compartment for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 4.54, 2.45, 4.91, and 2.54 MgC/ha, respectively. In comparison, the total carbon in hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai at 3 years are 4.41, 3.56, 3.56, and 6.2 MgC/ha, respectively. Meanwhile, the yield of hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 4.7-, 2.5-, 5.1-, and 2.6-ton OD/ha/year, in average respectively. Furthermore, yield of hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai at 3 years are 3.00-, 2.40-, 2.40-, and 4.2-ton OD/ha/year, respectively. The total carbon in biomass compartment during the simulation period are affected by the yield of hybrid black locust and poplars.

Results of CO2FIX modeling were also affected by other input data for biomass compartments, such as survival rate, wood density, and carbon content. Poplar and black locust survival rates were 90.3% and 60.8%, respectively (Stolarski and Stachowicz 2023). A higher survival rate affected the biomass accumulation for the next harvest cycle. In the CO2FIX modeling, the harvest cycle was five times for a 15-year rotation. The lower of the survival rate, the plant density will decrease. However, the wood density of black locust is higher than that of poplar, 727 kg/m^3 and 336 kg/m^3, respectively (Klašnja et al. 2013; Rédei et al. 2017). At the end of simulation period 45 years, the total carbon stock in biomass compartment for hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Moreover, the total carbon stock in biomass compartment for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively.

Regarding the carbon stock distribution (above and belowground) of hybrid black locust and poplar SRC, the dominant carbon stock was stored in the soil compartment, followed by biomass and product compartments. During the simulation period, aboveground biomass had fluctuated patten. At the end of harvesting cycle, the biomass was decreased to zero, and then increased gradually in the growth phase. Meanwhile, the belowground carbon has shown an accumulative pattern (Fig. 4.4. and 4.5.)



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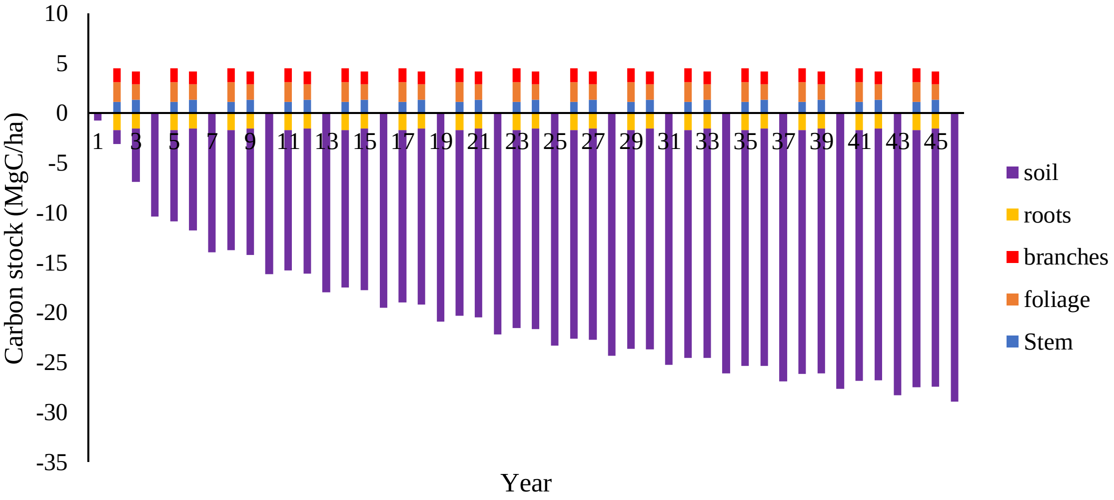

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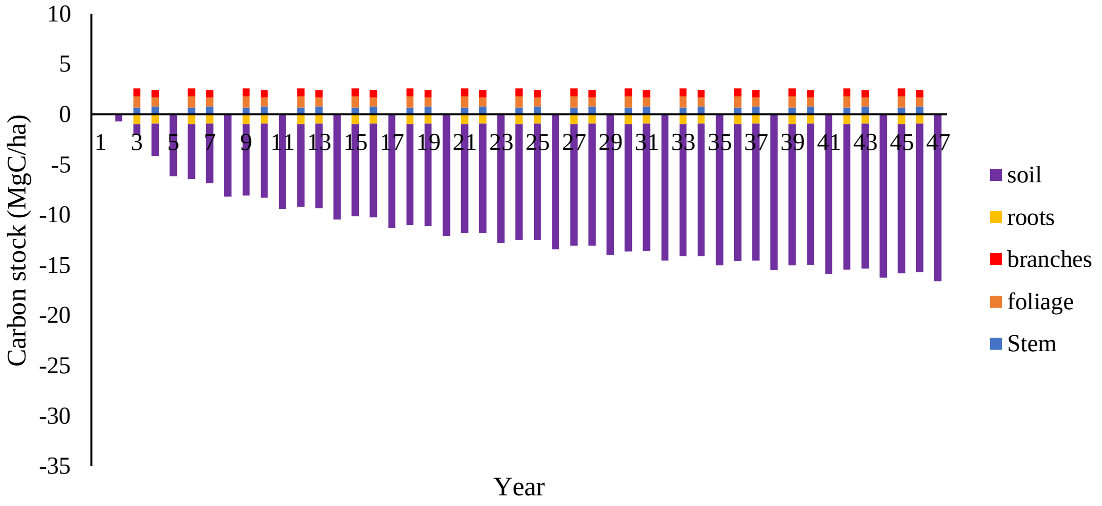

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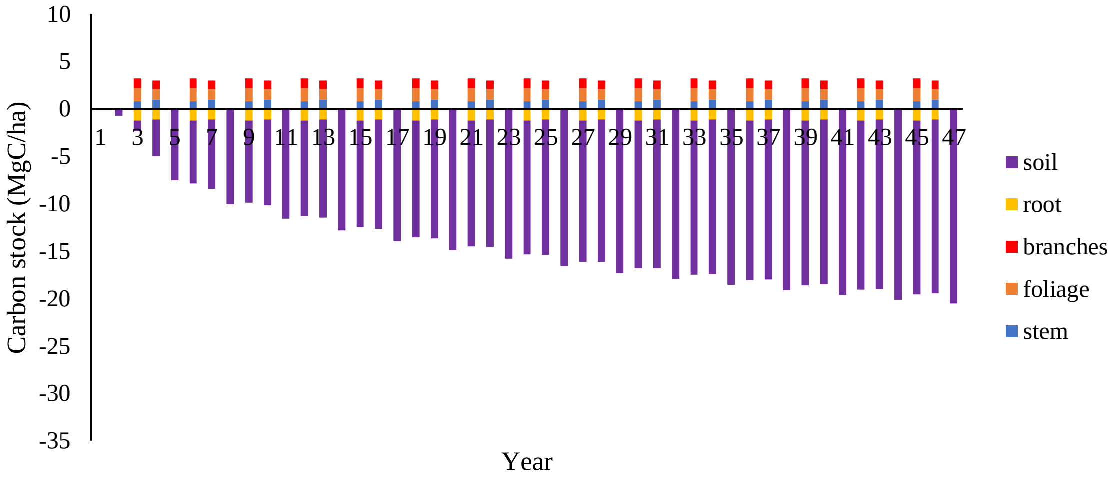
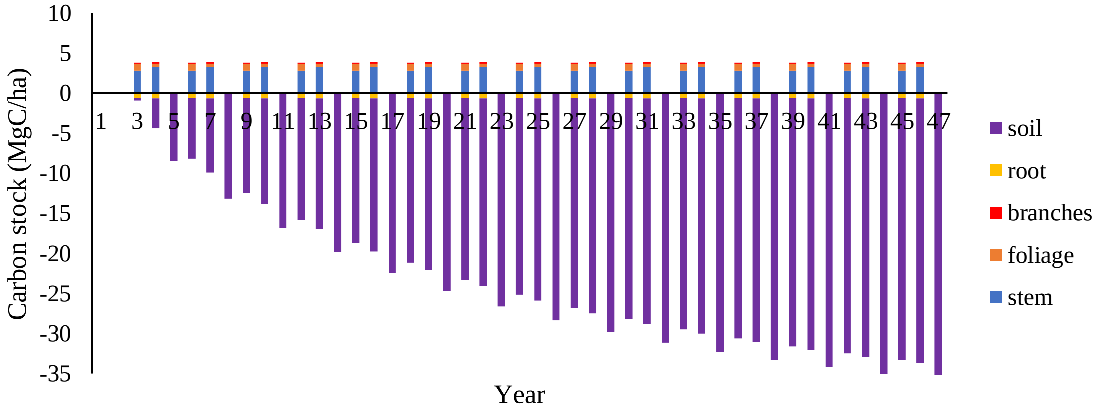


(d)

Fig. 4.4. Carbon distribution in hybrid black locust for cultivar a). Jászkiséri, b). Kiscsalai, c). Nyírségi, and d). Üllői



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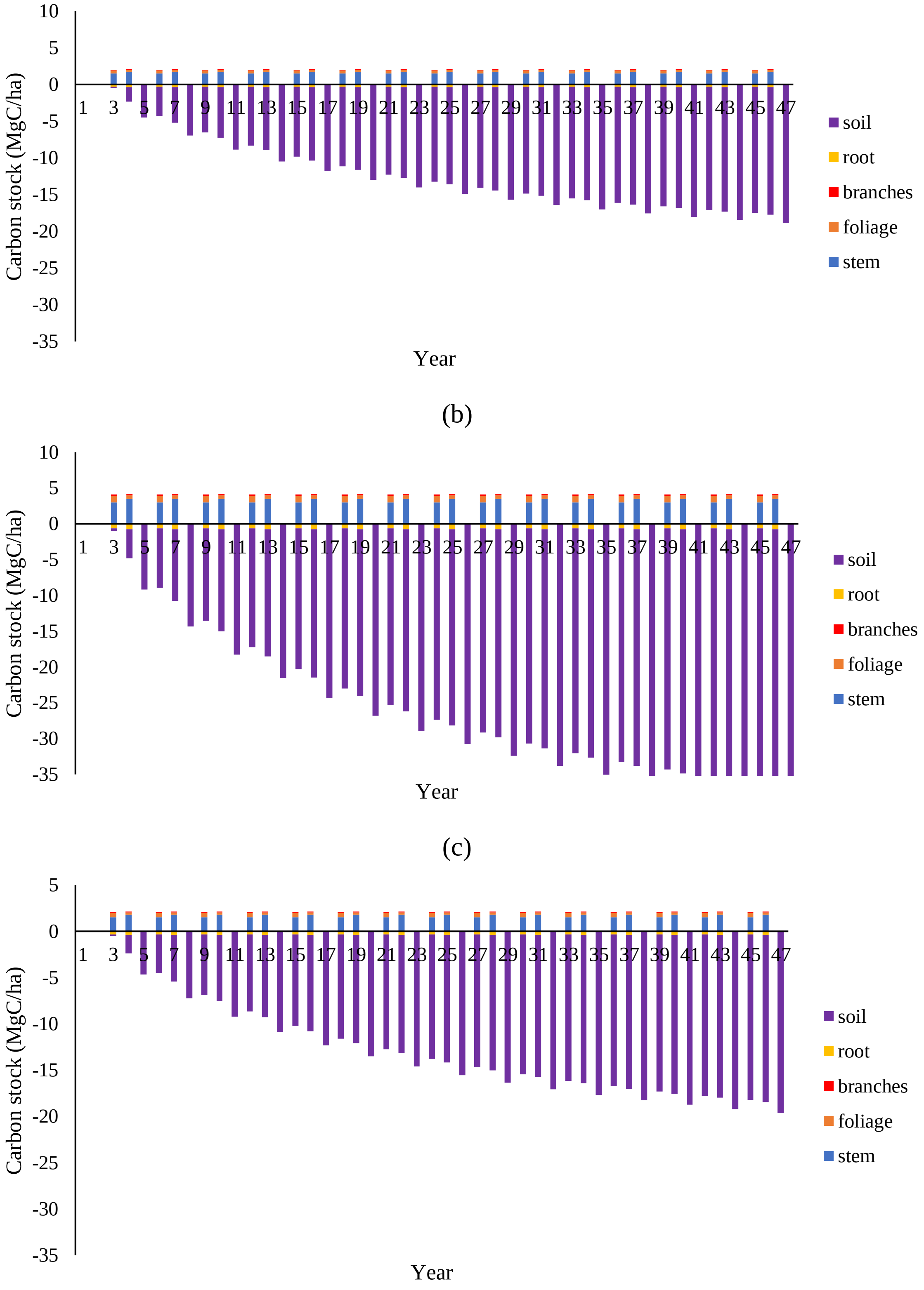


(b)

(c)

(d)

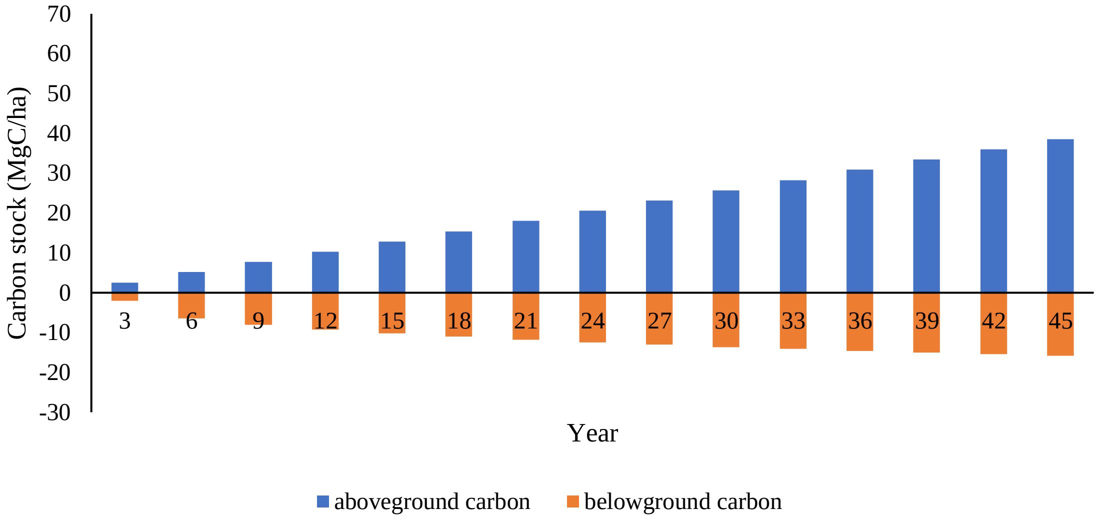
Fig. 4.5. Carbon distribution in hybrid poplar for cultivar a). Agathe-F, b). I-214, c). Pannónia, and d). S 298-8

According to Fig. 4.4 and 4.5., at the end of the simulation period (45 years), the soil carbon stock in hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai are 20.55, 16.62, 16.62, and 28.94 MgC/ha, respectively. The total carbon stock in soil compartment for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 35.81, 18.86, 38.91, and 19.63 MgC/ha, respectively. The carbon stock in biomass peaked at the end of the harvesting cycle (3, 6, 9, 12, 15 years). After the harvesting cycle in year 15, the stand will be replaced with new seedlings for black locust and cuttings for poplar.

The percentage of carbon in bioenergy to total carbon stock in black locust and poplar were 67.29 and 65.75%, respectively. The high amount of carbon stock in the bioenergy cohort is because the purpose of developing the SRC of black locust and poplar is bioenergy plantation. Total carbon in the bioenergy cohort does not represent a carbon stock but an estimation of the effect of using biomass to substitute fossil fuel (Schelhaas et al. 2004b). The harvested wood will be used as fuelwood in industries, meaning all parts of biomass black locust and poplar will be used for fuelwood only.

In this research, the carbon stock was stored above and below ground (Fig. 4.6. and 4.7.). Carbon distribution in the hybrid black locust and poplar short rotation coppice system varies along the simulation period. The accumulative carbon stock aboveground for hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 47.85, 38.55, 38.55, and 67.20 MgC /ha, respectively. However, the accumulative carbon stock in the belowground of hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 20.55, 16.62, 16.62, and 28.94 MgC /ha, respectively.

Meanwhile, the accumulative carbon stock aboveground for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 56.40, 30.00, 61.05, and 31.20 MgC/ha, respectively. Furthermore, the accumulative carbon stock belowground for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 35.81, 18.86, 38.91, and 19.63 MgC/ha, respectively. According to research by Oliveira et al. (2018b) in a poplar experimental site in Mediterranean conditions, the above-ground carbon allocation was four to seven times higher than below ground. In contrast, the root carbon in poplar at the experimental site in the United States was higher than in stem, branches, and foliage (Pregitzer et al. 1990).


Carbon stock (MgC/ha)
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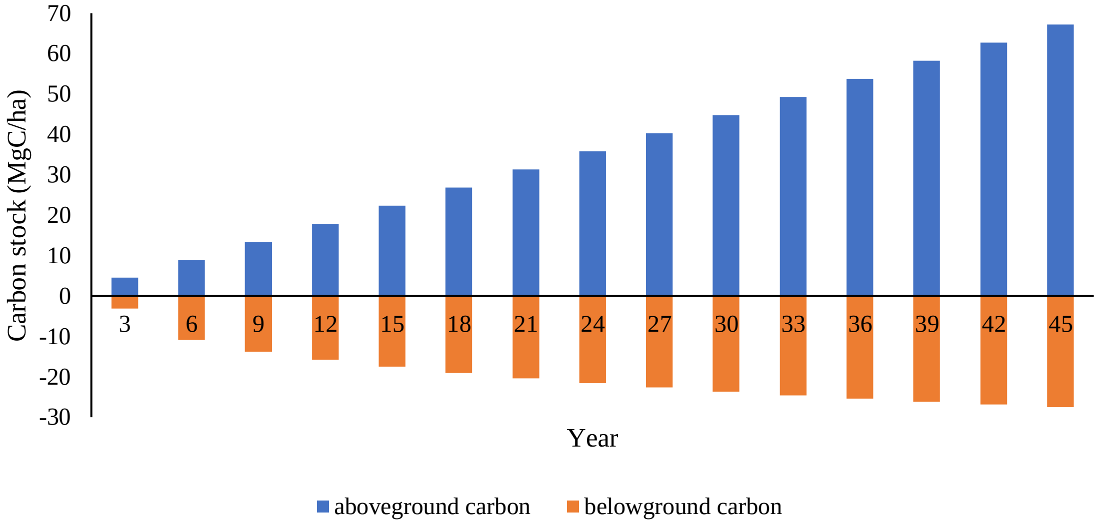
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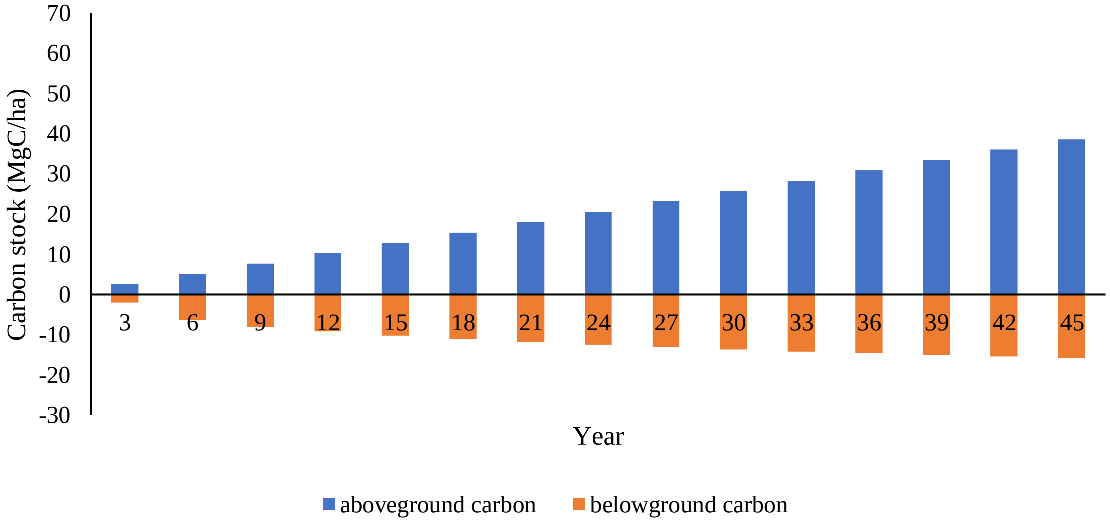
Carbon stock (MgC/ha)
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Year
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belowground carbon

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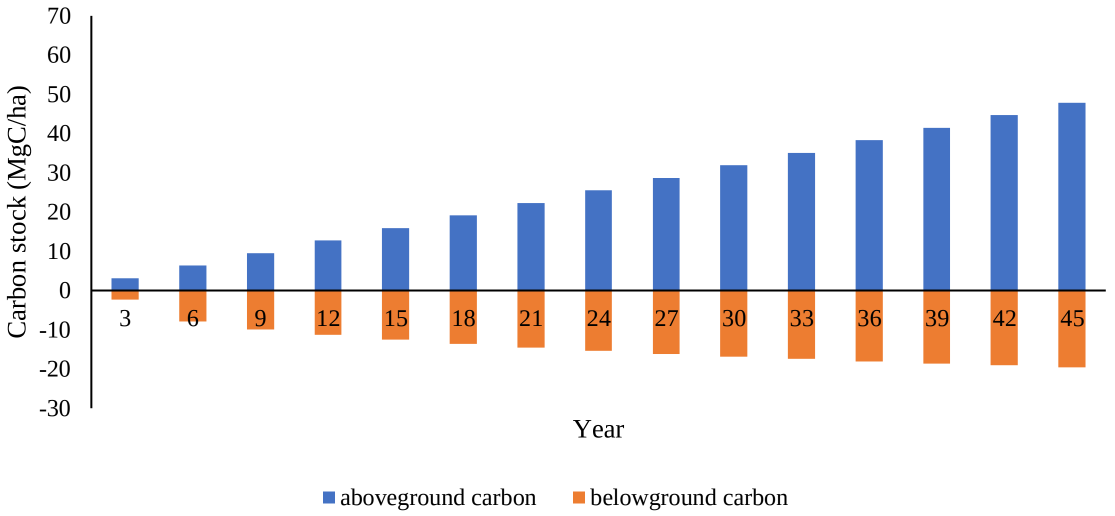

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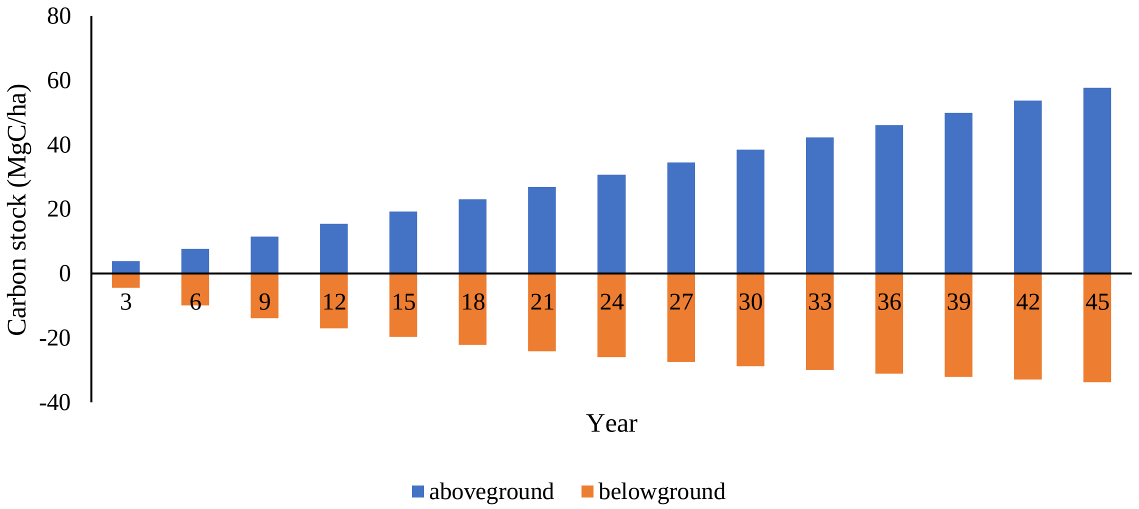
Figure 4.6. Cumulative carbon stock in above and belowground of hybrid black locust for cultivar a). Jászkiséri, b). Kiscsalai, c). Nyírségi, and d). Üllői



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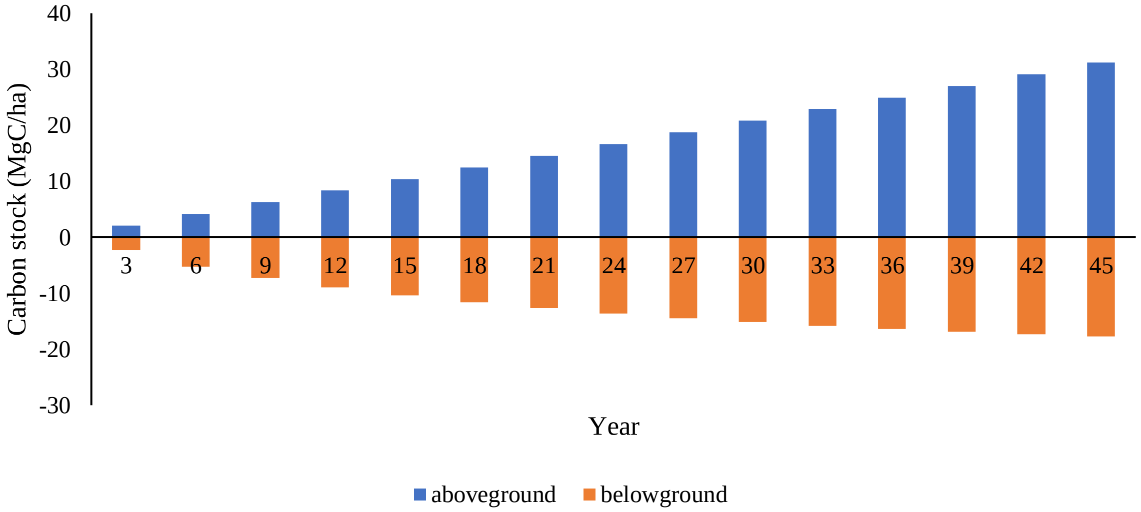

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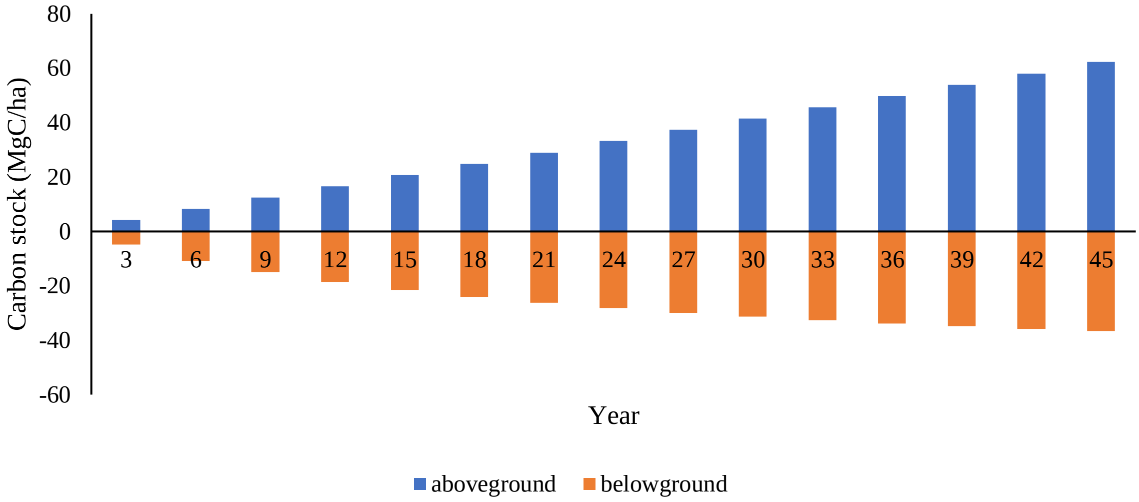

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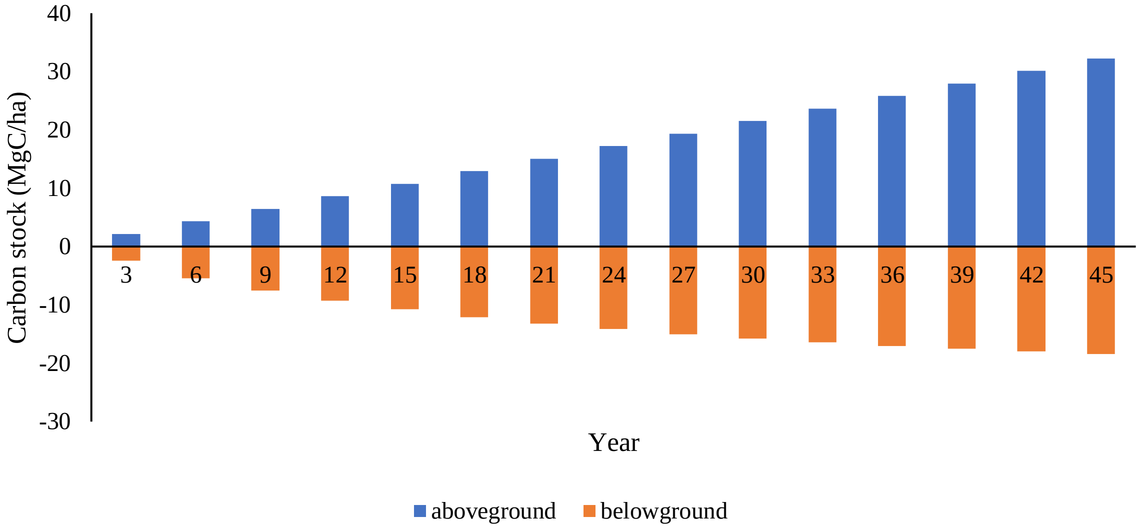


(d)

Figure 4.7. Cumulative carbon stock in above and belowground of hybrid poplar for cultivar a). Agathe-F, b). I-214, c). Pannónia, and d). S 298-8

The contribution of belowground carbon stock in bioenergy plantations is vital to total carbon stock because the aboveground carbon is removed periodically (Berhongaray et al. 2019). Belowground carbon accumulation was maximized by longer forest rotation (20–50 years) (Paul et al. 2002). Furthermore, Abbas et al. (2020) reviewed the soil carbon dynamic as part of the belowground carbon pool, stating that water availability, nitrogen fertilizer input, and tillage practices have affected the soil organic carbon content. The CO2FIX model produces litter in the biomass module through turnover, mortality, and logging slash (Schelhaas et al. 2004a, b). Black locust and poplar are deciduous species that will shed their leaves every year. According to Quinkenstein and Jochheim (2016), the leaf turnover of deciduous trees in temperate regions is around 1.0/year.

4.2.2. Forest carbon dynamics in forest plantation for industrial purposes

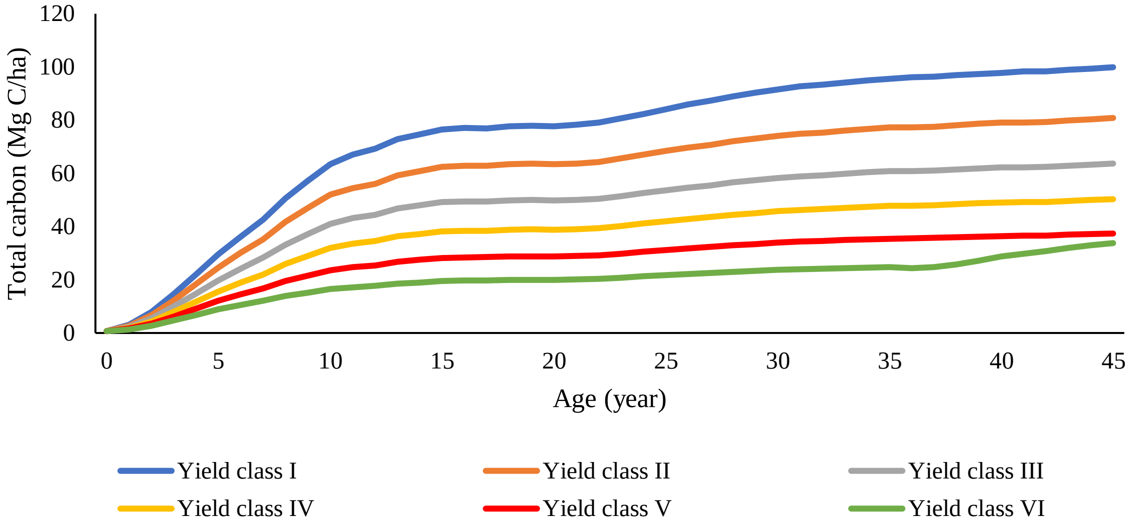
The result of carbon dynamic analysis of black locust and poplar forest plantation using the CO2FIX model showed that the total carbon at the end of rotation (45 years) in the yield class I was the highest, followed by yield classes II, III, IV, V, and VI (Table 4.3.). Apart from the total carbon at the end of rotation (45 years), the total carbon (biomass, soil, product) from the 1st year to the 44th year also showed that the total carbon in the yield class I was always higher than the other classes, either in black locust or poplar species. These findings also strengthen the evidence that the total carbon in the CO2FIX modeling is closely related to input data of the current annual increment (CAI) for each yield class. Based on the yield table of black locust (Rédei et al. 2014) and poplar (Rédei et al. 2012) in Hungary, the CAI of class yield is consistently higher than the CAI of other classes during the cultivation period.

Table 4.3. Total carbon at the end of rotation in different forest management scenarios

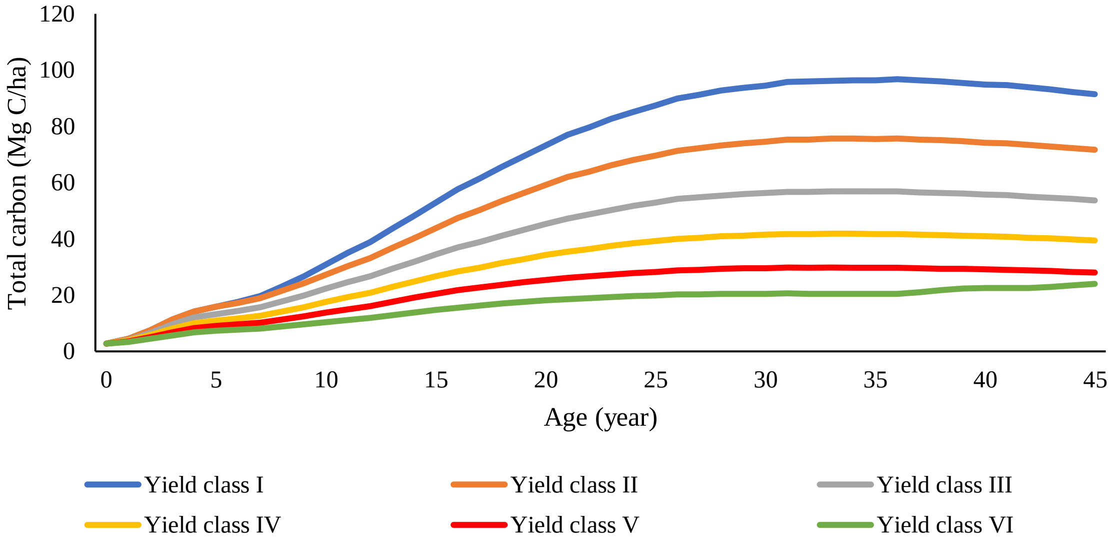
	Total carbon at the age of 45 years (MgC/ha)					
	Poplar			Black locust		
	Sawmill	Board	Pulp	Sawmill	Board	Pulp
Yield Class I	91.38	90.12	93.75	99.90	98.92	101.75
Yield Class II	71.70	70.69	73.58	80.84	81.13	83.50
Yield Class III	53.68	52.93	55.09	63.69	63.97	66.99
Yield Class IV	39.44	38.88	40.48	50.30	49.79	51.24
Yield Class V	28.07	27.67	28.81	37.39	37.01	38.09
Yield Class VI	24.01	23.75	24.50	33.79	33.54	34.27

Based on Table 4.3, the total carbon at the end of the rotation in the black locust plantation was higher than in poplar. The higher value of total carbon in black locust than in poplar was related to input data on growth and wood density. At the final harvesting, the black locust and poplar volumes were 527 and 565 m^3/ha (Rédei et al. 2012, 2014). However, the wood density of black locust is higher than poplar, 602 and 336 Kg/m^3, respectively (Klašnja et al. 2013). Furthermore, the percentage carbon content of black locust and poplar was 49.3% and 46.1%, respectively (Quinkenstein and Jochheim 2016; Ma et al. 2022). Therefore, black locust biomass and carbon stock were higher than poplar.

The carbon was stored in the seedling biomass and soil at the beginning of modeling. Furthermore, in the following years, the carbon increases in biomass due to plant growth. In contrast, the compartments of product and bioenergy did not store carbon because there were no wood production or harvesting activities. According to equations 1-3 and 13, the total carbon is summation from carbon stock in aboveground (biomass), belowground (soil), harvested wood products, and bioenergy (Fig. 4.8.)



(a)

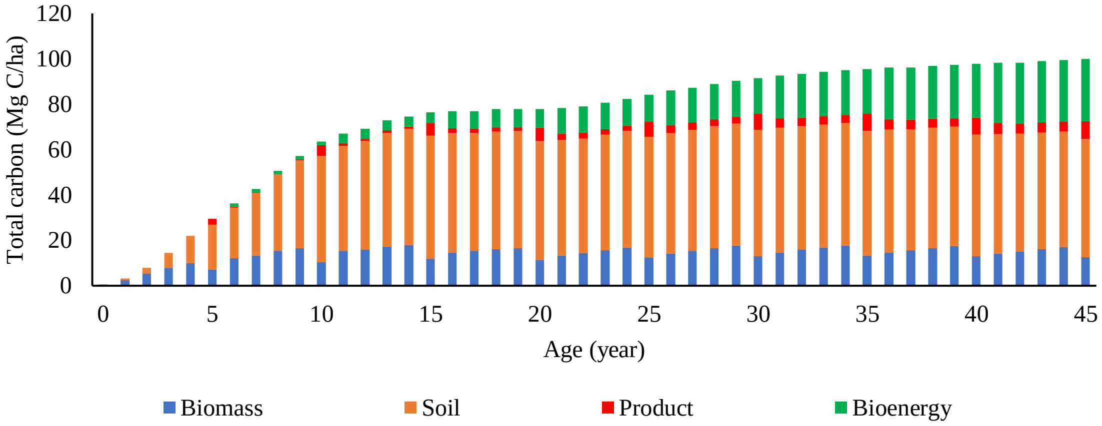


(b)

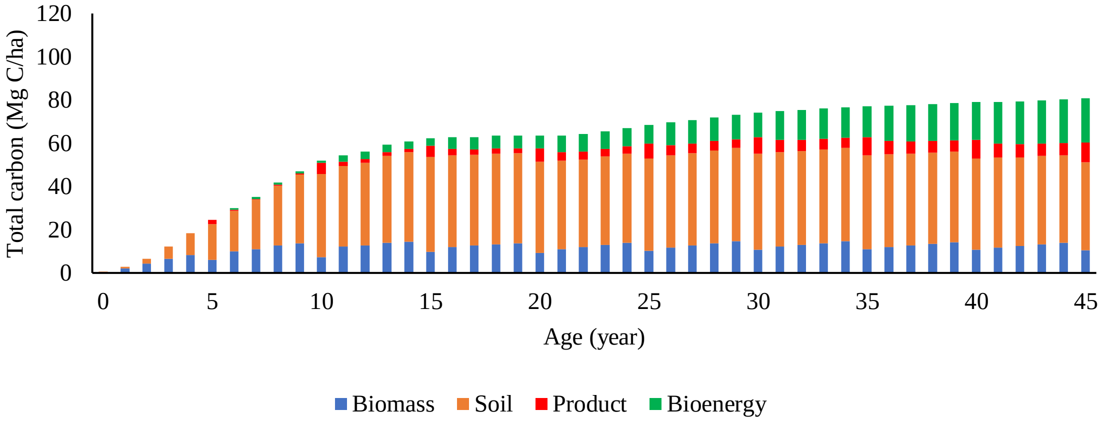
Fig. 4.8. Total carbon dynamic for long-rotation plantation of a). black locust, b). poplars

Total black locust and poplar carbon stock were stored in the biomass, soil, and product compartments (Fig. 4.9., and 4.10.). Meanwhile, the amount of carbon in energy represents the number of potential carbon stocks if the fuelwood substitutes for fossil fuels (Schelhaas et al. 2004a, b). Generally, the soil's carbon stock proportion was higher than that of biomass and products. In the first three years of rotation, the percentage of carbon stock in the biomass was higher than in the soil of both black locust and poplar. From the 4th year to the end of rotation (45 years), the allocation of carbon stock in the soil was higher than biomass and product.

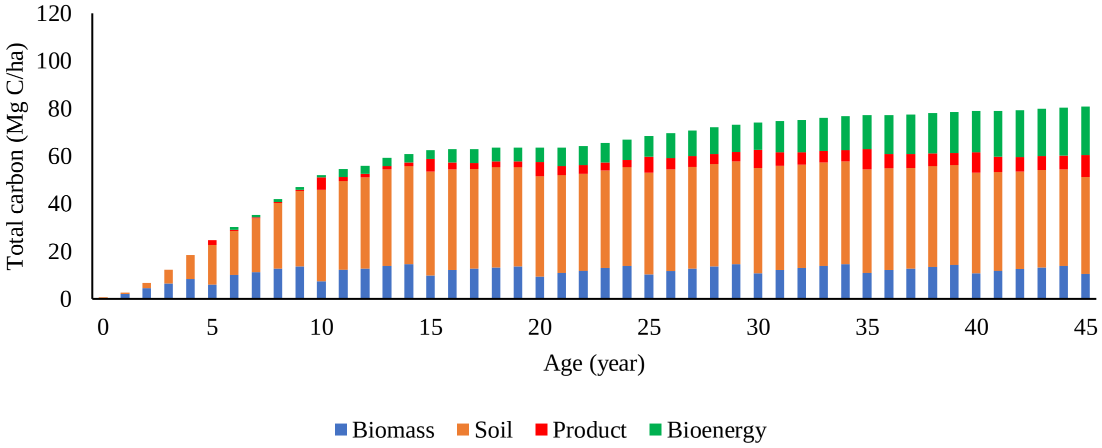
Furthermore, the carbon stock of products started in the 5th year when the thinning was carried out. The harvested wood products from thinning were stored in the products (sawn mill, board, or pulp products).



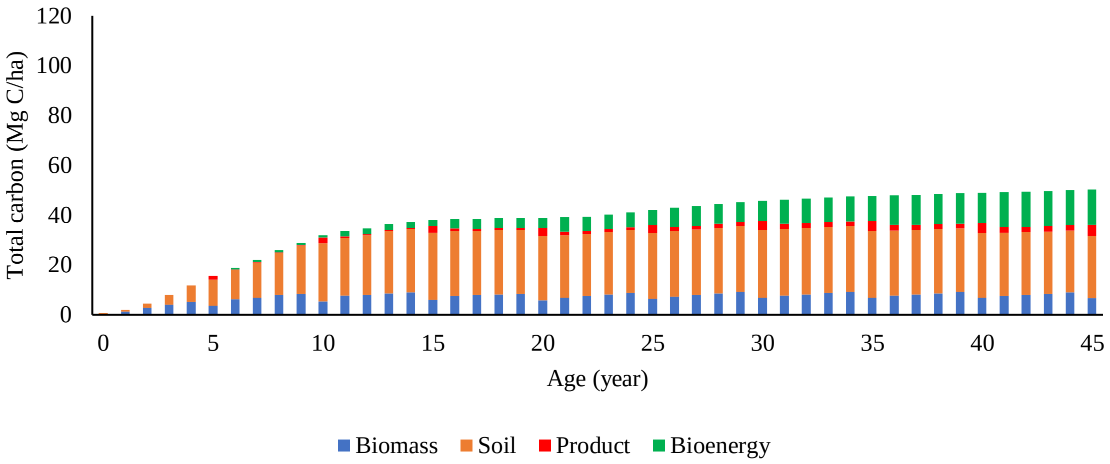
Yield class I



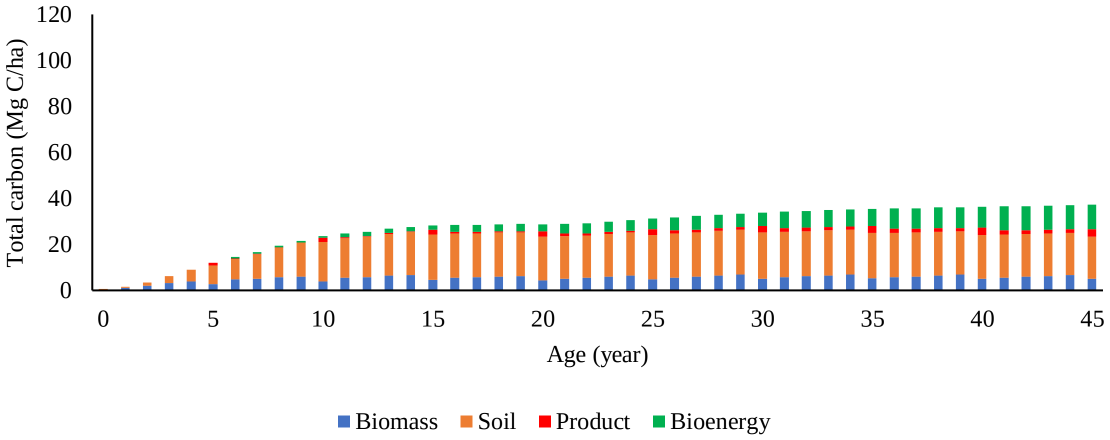
Yield class II



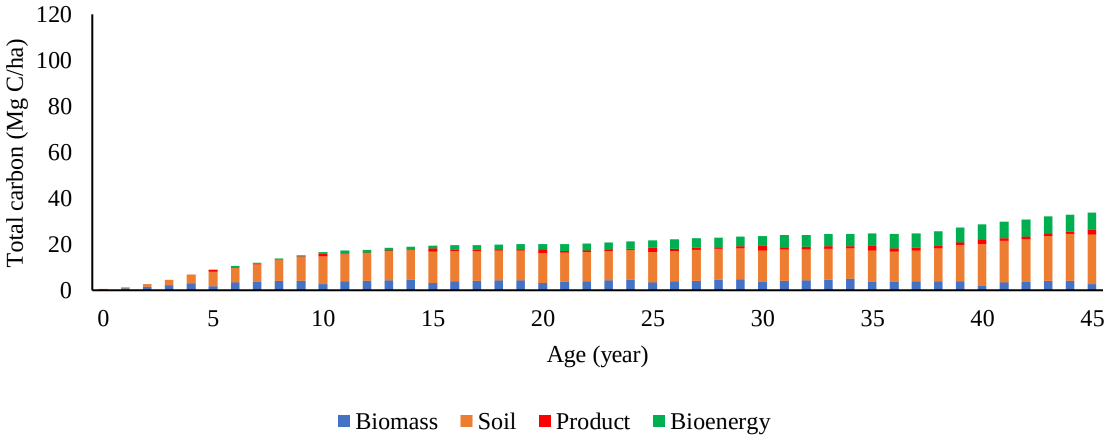
Yield class III



Yield class IV

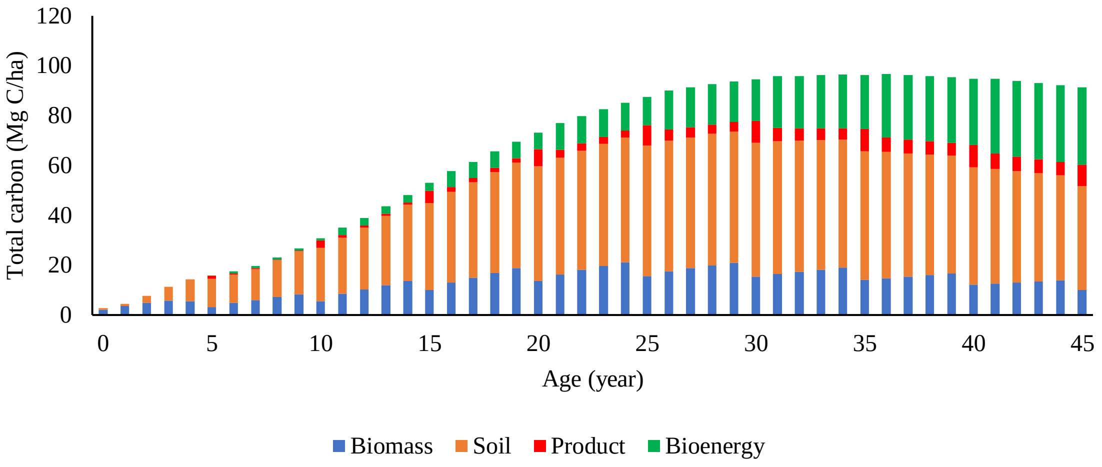


Yield class V

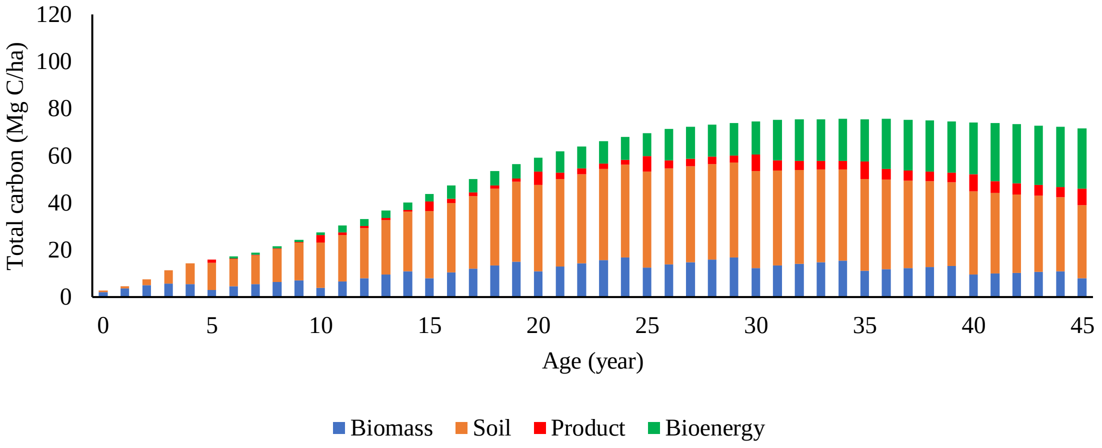


Yield class VI

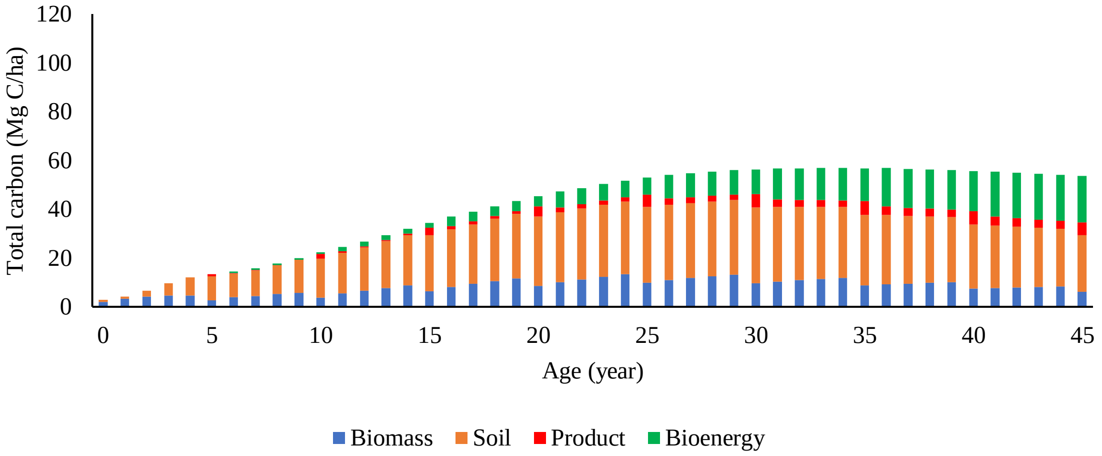
Fig. 4.9. Forest carbon dynamic for black locust in different yield classes



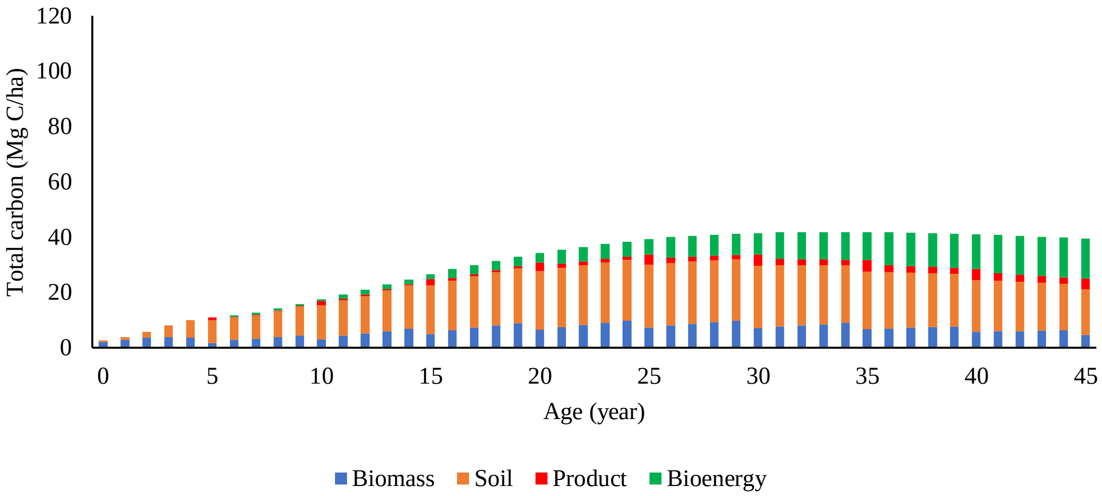
Yield class I



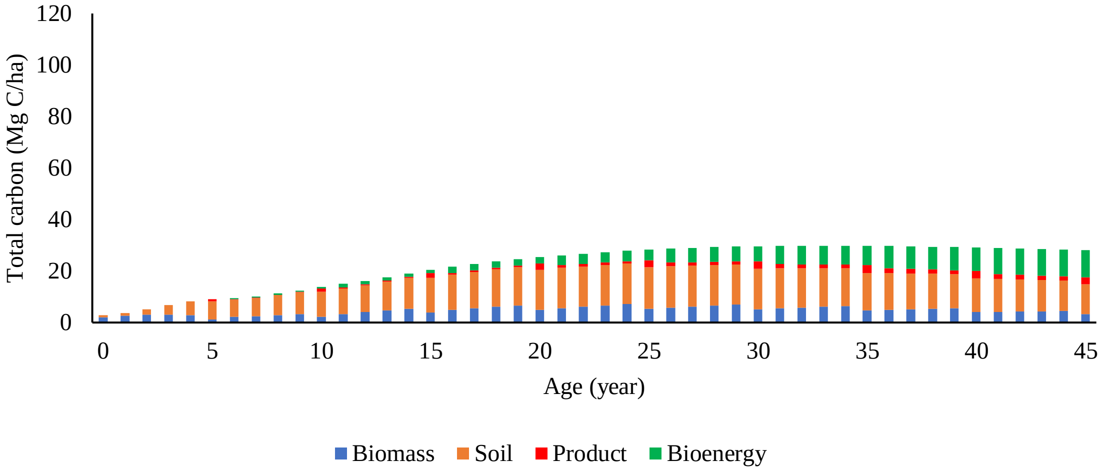
Yield class II



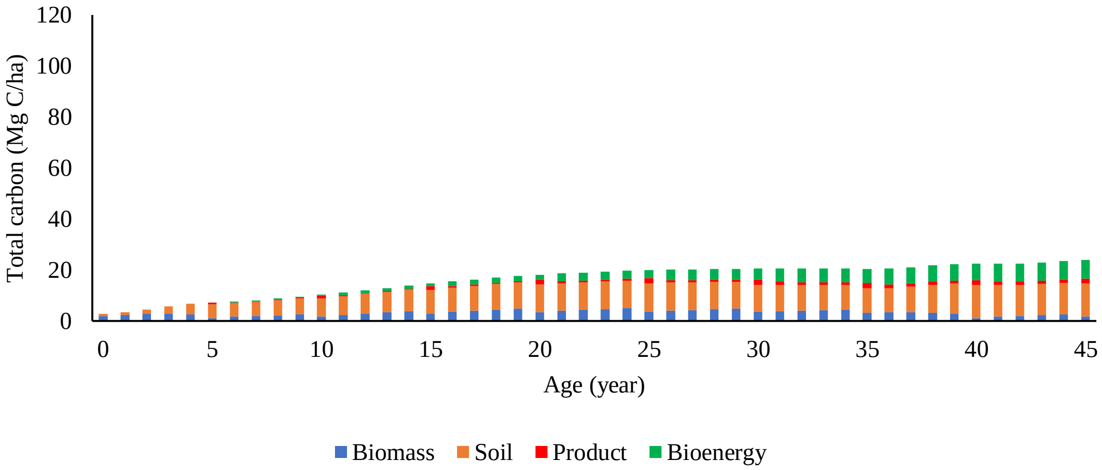
Yield class III



Yield class IV



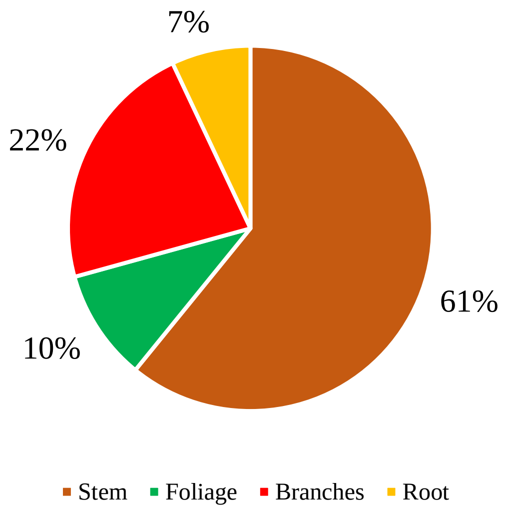
Yield class V



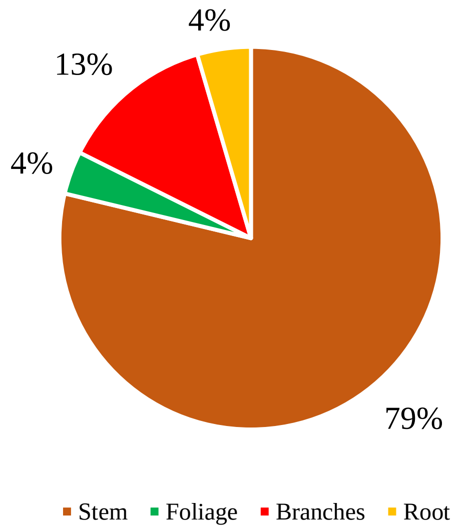
Yield class VI

Fig. 4.10. Forest carbon dynamic for poplars in different yield classes

In the process of photosynthesis, plants absorb carbon dioxide from the atmosphere and store the carbon in the organs of plants, such as foliage, stems, branches, and roots. At the end of the rotation in the black locust and poplar plantations, the highest carbon stock was stored in the stem, followed by branches, foliage, and root (Fig. 4.11.). Research findings also similar to biomass allocation in hybrid poplar in Canada, the carbon allocation in stem and branches were 64.8% and 17.4% of the total biomass (Truax et al. 2018). In black locust in China, at the age of 38 years, the carbon allocation in the stem was higher than in branches and foliage (Li and Liu 2014).



(a)

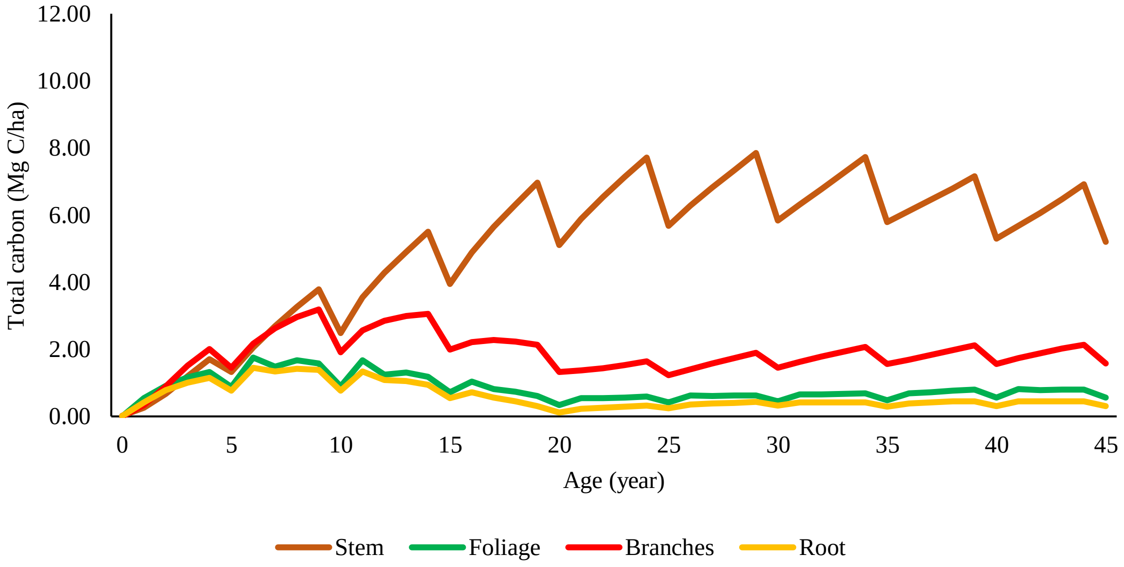


(b)

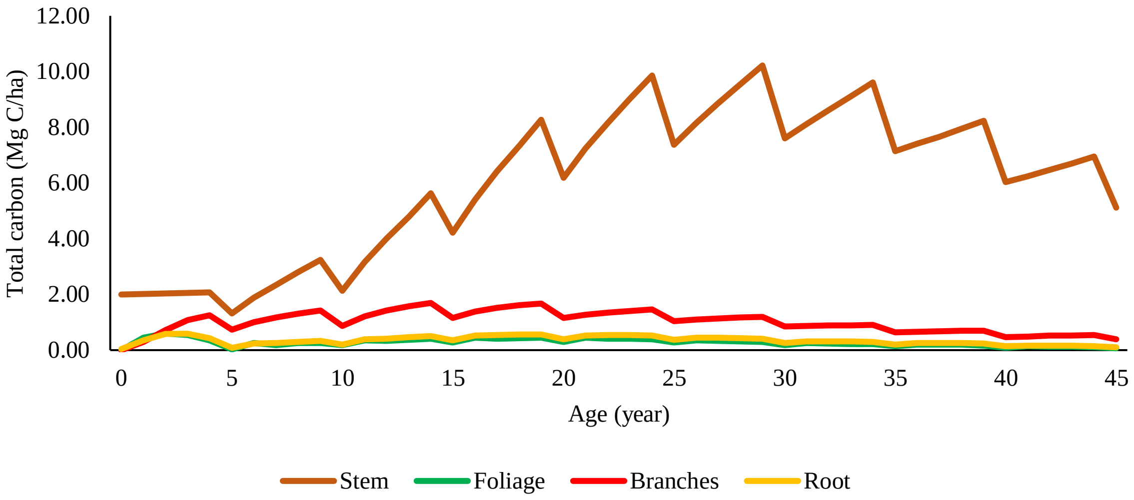
Fig. 4.11. Carbon allocation in tree's organs: a) black locust, b). poplars

Referring to Fig. 4.11., the carbon stock in the individual tree was predominantly stored in the stem organ and followed by branches, foliage, and roots. The phenomena of carbon stock dominance in stems are also found in the tree species in dry forests in Indonesia (Almulqu 2017), agroforestry system in India (Negash and Kanninen 2015), woodlot in Zambia (Kaonga and Bayliss-Smith 2012), bioenergy plantation in Indonesia (Mulyana et al. 2020a, b), and natural and pine in Chilean Patagonia (Stolpe et al. 2010).

During the simulation period of 45 years, the biomass dynamics in black locust for the first five years have shown the allocation in foliage, stem, branches, and roots were relatively similar, around 20 – 30 % (Fig. 4.12.). Furthermore, from 5th to 10th year, carbon allocation in stem and branches was relatively similar, while the carbon stock in foliage and roots begin to decline. After 15 years, the carbon allocation in the stem increases to around 50 – 75% of the total tree carbon stock. Meanwhile, the carbon allocation of foliage and roots was less than 10% of the total tree carbon stock. However, the growth of the poplar differed from that of the black locust, in which the carbon allocation in the stem was higher than branches, foliage, and roots. According to the Global Forest Resources Assessment of Hungary, the allocation of forest carbon aboveground (stem, branches, and leaves) was around four times that of the belowground (root) during the period 1990 – 2020 (FAO 2020).



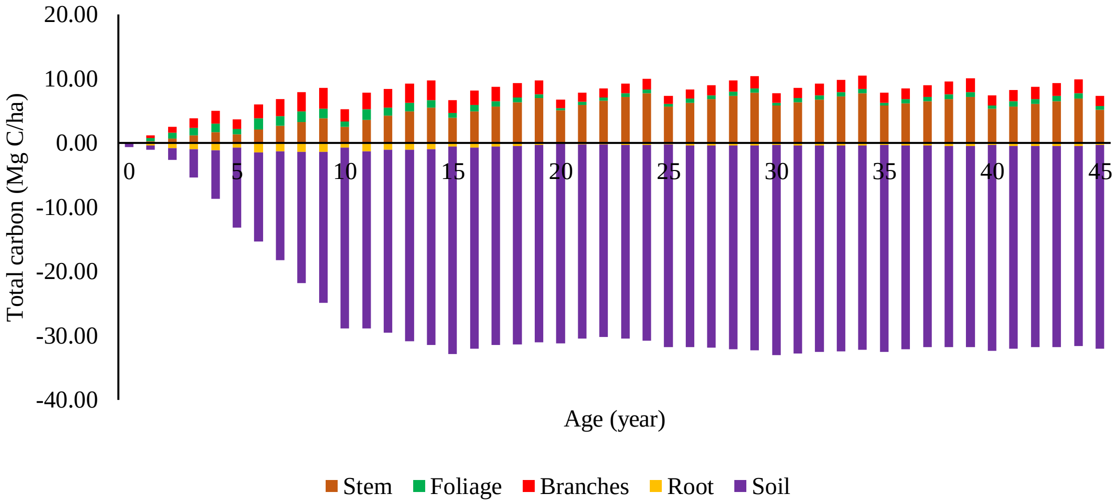
(a)



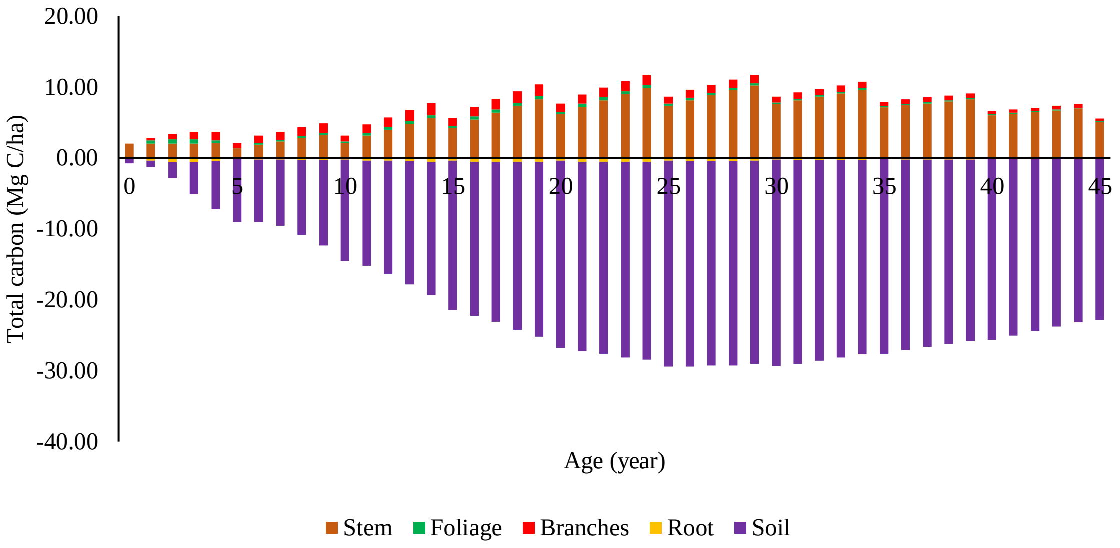
(b)

Fig. 4.12. Carbon dynamic in the biomass; a). black locust, b). poplars

Above and belowground carbon stock in black locust was higher than in the poplar plantation (Fig. 4.13.). During the 45-year simulation, the average value (yield class I – VI) of aboveground carbon stock in black locust and poplar were 7.76 and 7.29 MgC/ha, respectively. Belowground carbon stock (roots and soil) in bioenergy plantations will benefit significantly in the long rotation (Truax et al. 2018). It showed that the carbon stock belowground should be given more attention to preserving the forest carbon stock in lithospheres. Disturbance in soil has the potential to reduce the forest carbon stock.



(a)



(b)

Note: the minus values reflect that the carbon stock stored in belowground

Fig. 4.13. Carbon dynamic in above and belowground carbon a). black locust, b). poplars

Referring to Fig. 4.11., the carbon allocation in root at black locust and poplar were 7 and 4% of the total carbon stock. It means the aboveground carbon in Fig. 4.8. for black locust and poplar was 93 and 96 % of the total carbon stock. The most significant proportion of belowground carbon stock has come from soil carbon. In this research, the initial carbon stock in the soil layer was 0 MgC/ha. It followed Lemma et al. (2007), simulating the soil organic sequestration in tree plantation using CO2FIX. Furthermore, at the end of simulation period (45 years), the total above and belowground carbon for black locust and poplar varied, depending on the yield class (Table 4.4).

Table 4.4. Total above and belowground carbon for black locust and poplar in long rotation systems

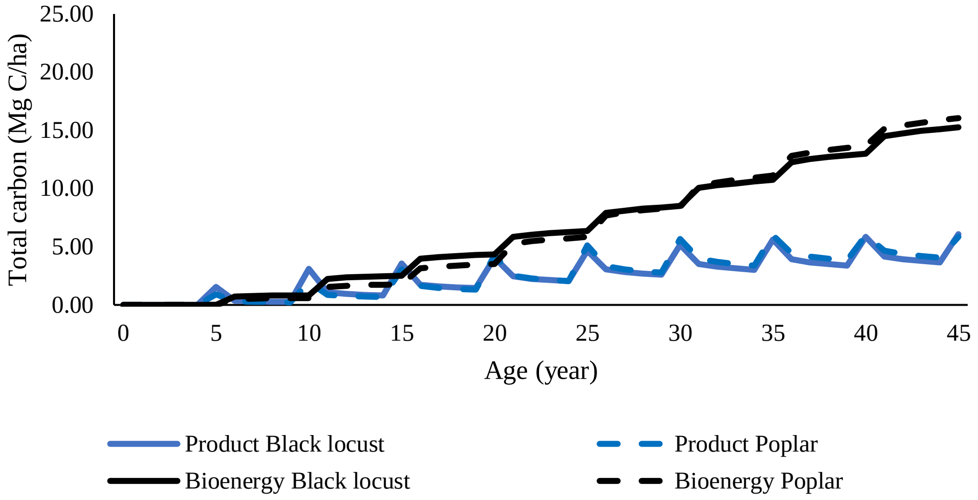
Species	Yield class	Total carbon (MgC/ha)	
		Aboveground	Belowground
Black locust	I	12.18	52.43
	II	10.09	41.20
	III	8.21	32.83
	IV	6.47	25.25
	V	4.83	18.65
	VI	2.28	21.91
Poplar	I	9.95	41.82
	II	7.91	31.74
	III	6.09	23.16
	IV	4.56	16.55
	V	3.26	13.18
	VI	1.59	11.57

According to research findings from Nabuurs and Schelhaas (2002), at 16 forest types in European countries, the long-term average carbon stock was predominantly stored belowground rather than aboveground. A similar finding was also found in India's agroforestry systems, in which the soil carbon stock was higher than the carbon stock in the tree biomass (Negash and Kanninen 2015). Kaonga and Bayliss-Smith (2012), simulating the above and belowground carbon stock using CO2FIX in the woodlot area in Zambia, showed that the simulated carbon stock belowground was higher than aboveground. Furthermore, based on field measurements of soil in the woodlot area at a depth of 0 – 200 m, the result showed that the carbon stock in the soil layer was higher than the simulated value (Kaonga and Bayliss-Smith 2012). CO2FIX simulation in a larch (*Larix gmelinni* var. *Principis-rupprechtii*) plantation in Weichang County, China, found that 70% of total carbon was stored in the soil compartment (Jia et al. 2016).

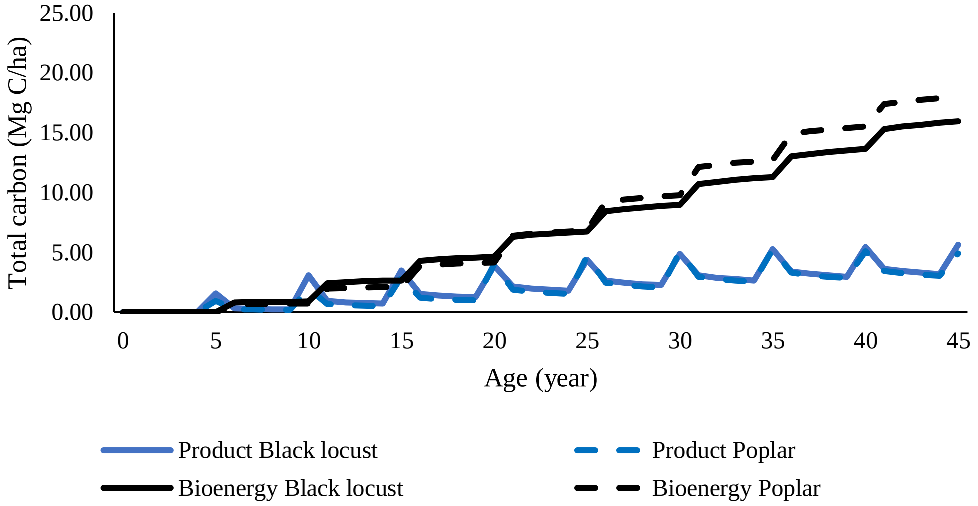
Dominant factors affecting the high value of soil carbon stock were the higher litter input and composition of fine woody litter (branches and coarse roots) (Lemma et al. 2007). According to Fig. 4.10., the belowground carbon stock in the black locust plantation was higher than in the poplar plantation. During the simulation period of 45 years, the average belowground carbon stock in black locust and poplar plantations was 35.47 and 21.16 MgC/ha, respectively. The higher value of carbon belowground stock of black locust compared to poplar was in line with the finding in Fig. 4.13. In Fig. 4.11., the composition of leaf biomass of black locust was 10% of total tree biomass, higher than poplar's 4%. Both black locust and poplar are deciduous species that shade their leaves during autumn and winter. Furthermore, the fallen leaves were the input source of soil organic carbon through decomposition.

Total carbon in the products compartment at the end of the simulation period for board, sawn mill, and pulp of black locust and poplar was similar (Fig. 4.14.). In the yield class I for black locust plantation, the total carbon in the board, sawn mill, and pulp products were 9.61, 7.86, and 4.68 MgC/ha, respectively. Meanwhile, the total carbon in the board, sawn mill, and pulp products at the exact class yield for the poplar plantation were 10.79, 8.53, and 4.43 Mg C/ha. Furthermore, the total carbon for yield class II-VI decreased gradually.

Carbon in the product compartment began to appear in the 5th year when the first thinning activity was carried out. Even though the trees have been harvested in the thinning activity, the carbon stock is still stored as carbon in the harvested wood products and wood residue. In this study, we assumed that the wood from thinning would be used as the harvested wood product (70%) and fuelwood (30%). There will be a decrease in carbon stock at thinning wood products due to the wood deterioration process and combustion of fuelwood. However, the carbon stock will increase again during the second thinning in the 10th year. Thinning activities in black locust and poplar were carried out every five years.



(a)



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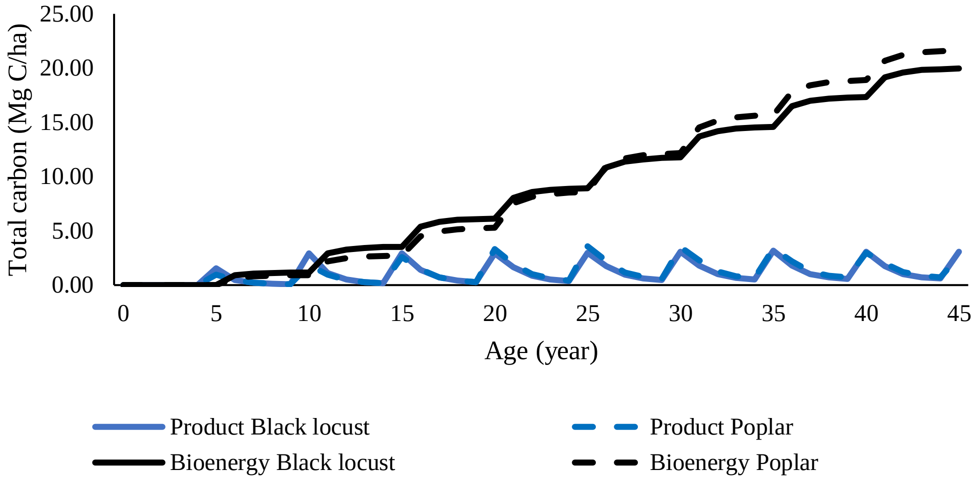


(c)

Fig. 4.14. Carbon dynamic in product and bioenergy compartments for: a). board, b). sawn mill, c). pulp

According to Fig. 4.14., the total carbon in the bioenergy compartment between black locust and poplar was relatively similar. In the bioenergy compartment, the total carbon in black locust was higher in the first half of the rotation than in poplar. However, from the middle to the end of the rotation, the carbon stock in the bioenergy compartment was higher in the poplar.

4.3. Environmental impact assessment of forest operations in different plantation management scenarios.

Since the agricultural revolution, the utilization of machines and chemicals (fertilizer and pesticide) has spread worldwide. The consumption of fossil fuels has increased due to the replacement of human labor by combustion engines in the 1900s (Dijkman et al. 2018). However, in 1962, Rachel Carson, author of the influential book Silent Spring, revealed the negative impacts of pesticide utilization on non-targeted animals and humans. Furthermore, environmental problems resulting from using machines and chemicals in agricultural production, such as eutrophication and greenhouse gas emissions, have become serious issues that receive serious attention.

LCA in agriculture and food production was divided into six stages: production and transportation to the farm, cultivation, processing, distribution, consumption, and waste management (Dijkman et al. 2018). Furthermore, Dijkman et al. (2018) explained that due to the complexity of the agriculture production study of the cradle-to-gate farm, agricultural production has used fertilizer, pesticides, and machinery to produce the products. Plantation management in short and long-rotation is similar to agricultural production, which uses agrichemicals (fertilizer and pesticide) and fuel consumption to produce wood. Thus, we have designed the system boundary as cradle-to-gate in this research.

4.3.1. Life cycle assessment in short rotation coppice systems

The forest typology and the purpose of forest product utilization influence forest management. Referring to Barbati et al. (2007), the European forest types have been categorized into 14 groups and forest plantation was included in these groups. In this research, the forest plantation was divided into two groups: short-rotation coppice (SRC) management systems to provide bioenergy and long-rotation management systems to supply wood for industrial purposes.

In this research, the rotation of SRC management systems, either black locust or poplar, was 15 years, with the cutting cycles every three years. Furthermore, the silviculture activities for SRC are plantation establishment (site preparation and seed planting), tree growth maintenance, and harvesting (Dimitriou and Rutz 2015). Timeline of black locust and poplar plantations with SRC management systems was plantation establishment (year-1), tree growth maintenance (year-1, 4, 5, 7, 8, 10, 11, 13, and 14), harvesting (year-3, 6, 9, 12, and 15), and plantation liquidation after final harvesting to remove the old trees and replace them with the new ones (Fig. 4.15.).

Fertilizer application was applied to enrich the soil properties after the harvesting (Stolarski and Stachowicz 2023). However, the utilization of fertilizer caused a negative impact on surface water (Dijkman et al. 2018). The fertilizer results in emissions to air, such as ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxides (NO_x), which contribute to acidification, climate change, and eutrophication (Dijkman et al. 2018). Furthermore, the impact of fertilizer on water bodies is eutrophication through the emissions of nitrate (NO_3^-) and phosphate (PO_4^3) (Dijkman et al. 2018).

Pesticides (fungicide, insecticide, and herbicide) cause a toxic impact on untargeted species during the application and accumulated in the parts of products as well as contributing to ecotoxicity and human toxicity (Dijkman et al. 2018). In the Sphera LCA for Experts Education License version 9.2.1.68 Education database, there was no process for pesticide production. However, because the consumption of pesticides was less than 2 kg/ha, the avoidance of pesticides calculation does not significantly affect the total environmental impacts.

Fuel and lubricants are sources of emissions that affect the environment. Fuel is consumed to operate the machinery in on-farm operations such as ploughing, applying fertilizer and pesticide, harvesting, and transporting the seedlings' products (Dijkman et al. 2018). In this research, the consumption of fuel and lubricants each year along the rotation is relatively stable.

In general, the stand management of SRC in different fast-growing species is relatively similar. For instance, stand management of poplar plantation in Italy is site preparation, planting, and harvesting (González-García et al. 2012a). Furthermore, the stand management of willow plantations in Northern Ireland and Sweden is site preparation, establishment/planting, harvesting/cutting, and replacement (González-García et al. 2012b; Livingstone et al. 2022). Even though the names of stand management are different, the inputs are similar: seed, fertilizer, pesticides, fuel, and lubricants.

Although there are similarities in stand management, the cutting cycle and rotation are different. In Our research, the cutting cycle is three years, and the rotation is 15 years (5 times harvesting). In contrast, SRC poplar plantation in Italy was harvested every 2 or 5 years, and the rotation is ten years (González-García et al. 2012a). Meanwhile, the cutting cycle of SRC willow plantations in Ireland and Sweden is 2.8 and 4 years. The rotation of SRC willow plantation is relatively similar, around 20 to 25 years (González-García et al. 2012b; Livingstone et al. 2022).

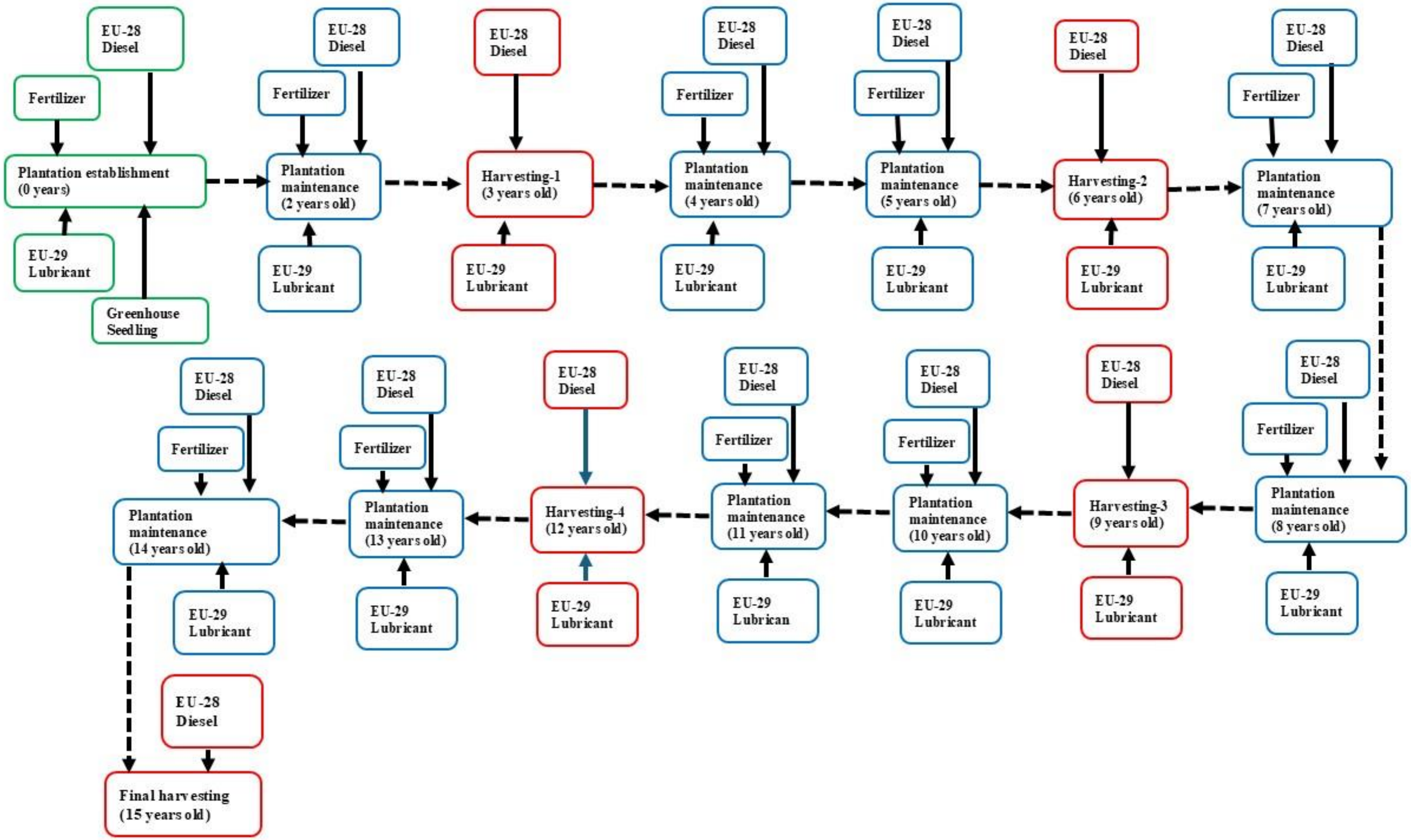


Fig. 4.15. Life cycle assessment of short-rotation coppice systems for black locust and poplars

According to Fig. 4.15. The standing management of short-rotation coppice systems management was divided into three stages.

- Plantation establishment (year 1)
- Growth management (years 2, 4, 5, 7, 8, 10, 11, 13, and 14)
- Harvesting (year 3, 6, 9, 12, and 15).

In the plantation establishment, the input is seed of black locust or poplar’s cutting, fertilizer, and pesticides. Due to the mechanization of planting and maintenance, the machines need fuel and lubricant as energy sources. Furthermore, in the growth maintenance phase, the input is fertilizer and the energy source (fuel and lubricant). Moreover, the input is fuel and lubricant for harvesting machinery in harvesting activities.

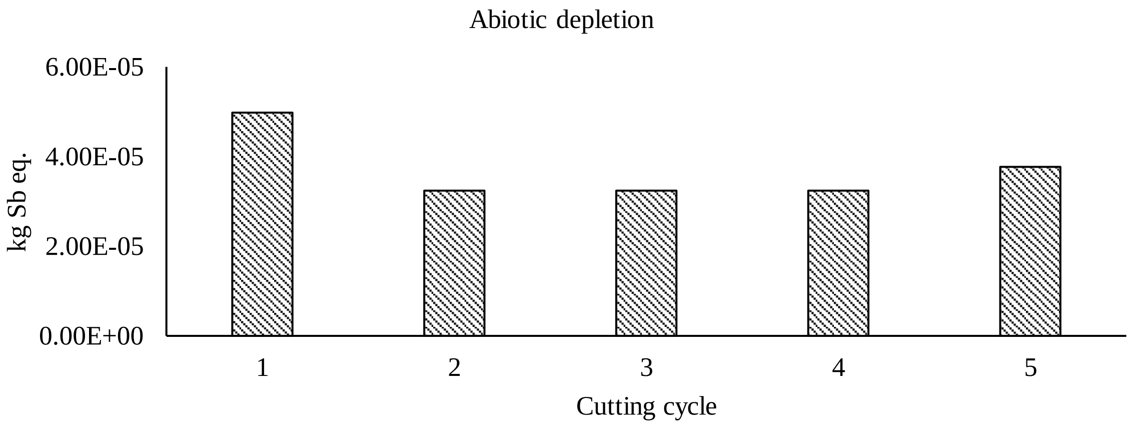
Overall, the result of the life cycle assessment analysis of our research is lower than other SRC in Italy, Northern Ireland, and Sweden (Table 4.5). Poplar plantations in Italy were cultivated for 10 years, meanwhile in Sweden and Ireland more than 20 years.

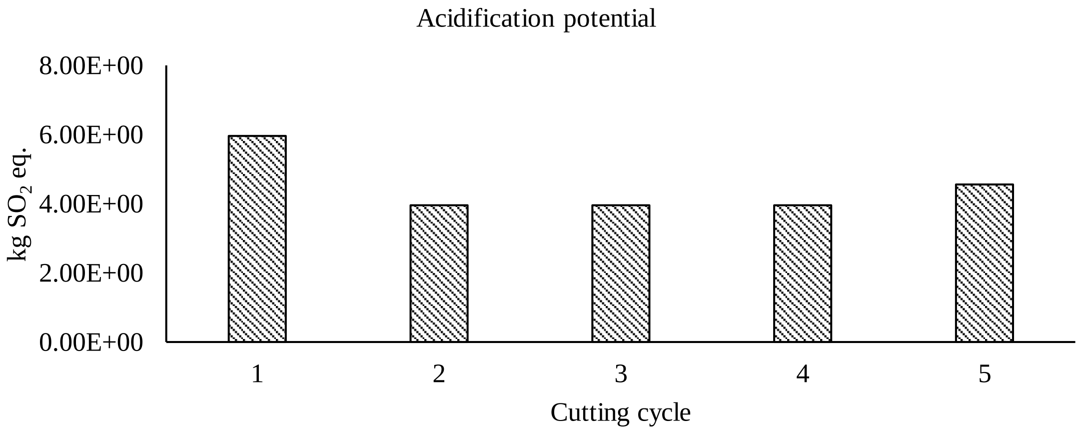
Table 4.5. Environmental impacts of short-rotation coppice system

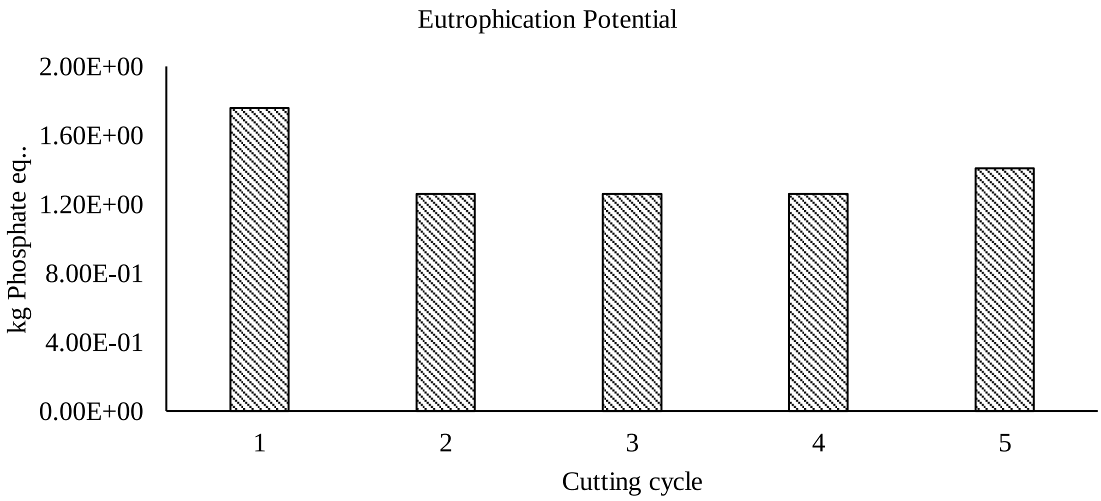
	Our research	Livingstone et al. (2022)	González-García et al. (2012a)		González-García et al. (2012b)
Location	Hungary	Northern Ireland	Italy	Italy	Sweden
Species	Poplar and black locust	Willow	Poplar	Poplar	Willow
LCA analysis software	Sphera LCA for Experts Education License version 9.2.1.68	SIMAPRO v.9	SIMAPRO v.7.10	SIMAPRO v.7.10	SIMAPRO v.7.10
Database	USLCI	Ecoinvent	n.a	n.a	Ecoinvent
Rotation	15 years	25 years	10 years	10 years	21 years
First cutting	3 years	2.8 years	2 years (VSRC)	5 years (SRC)	4 years
Number of harvesting	5 times	8 times	5 times	2 times	5 times
Purpose	Bioenergy	Bioenergy	Bioenergy	Bioenergy	Bioenergy
Tree density	6,700 trees/ha	15,000 trees/ha	5,560 trees/ha	5,560 trees/ha	10,000 – 13,000 trees/ha
System boundaries	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
Stand management	a). plantation establishment, b). growth management c). harvesting and liquidation	a). site preparation, b). planting c). harvesting	a). site preparation b). planting c). harvesting	a). site preparation b). planting c). harvesting	a). Establishment b). Cutting c). Replacement
Functional unit	Per unit area (ha)	Per unit area (ha)	Per unit area (ha)	Per unit area (ha)	Per unit area (ha)
CML2001					
- GWP100 (kg CO_2 eq)	5.96E+03	19.5E+03	-374.7E+03	-433.8E+03	-323.7E+03
- Eutrophication potential (kgPO_4^3/ha)	7.8	26.6	32.89	25.89	159.5
- Acidification potential (kg SO_2 eq)	21.6	41.3	140.08	108.87	73.3
- Abiotic depletion (kg Sb eq)	0.000171	-	36.18	36.62	52.5
- Ozone layer depletion (kg CFC-11 eq)	3.87 E-13	-	7.13E-04	7.41E-04	1.02
	484	-	4.028	4.346	5,236

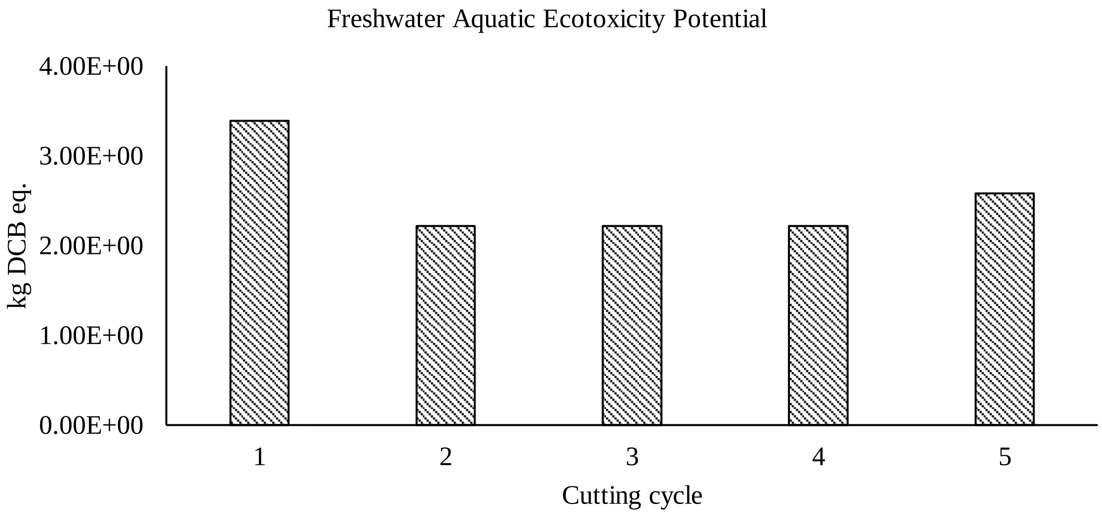
	Our research	Livingstone et al. (2022)	González-García et al. (2012a)		González-García et al. (2012b)
- Human toxicity (kg 1,4-DB eq)	11.8	-	678	653	1,062
- Freshwater aquatic ecotoxicity (kg 1,4-DB eq)	3.43E+04	-	1.48E+06	1.40E+06	2.6E+03
- Marine aquatic ecotoxicity (kg 1,4-DB eq)	4.676	-	14.22	11.80	24.8
- Terrestrial ecotoxicity (kg 1,4-DB eq)	1.82	-	0.88	0.91	1.2
- Photochemical oxidation (kg C_2H_4 eq)					
- cumulative energy demand (GJ eq)	-	-	85.56	85.78	8,777
- Gross energy production (GJ eq)	-	-	3.2E+03	3.7E+03	2.8E+06

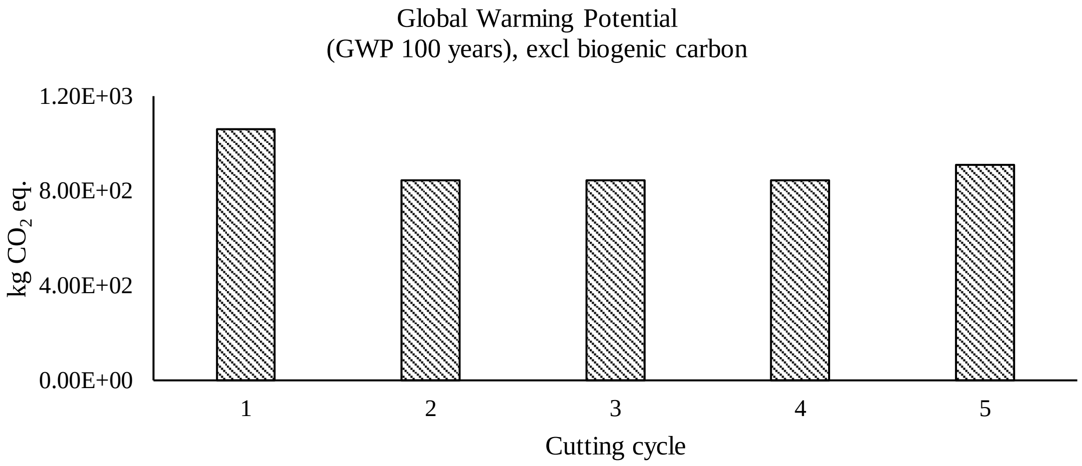
In detail, we divided the LCA analysis into five cycles; each cycle is three years (Fig. 4.16). The first cycle consists of plantation establishment, growth maintenance, and harvesting. Furthermore, cycles 2, 3, and 4 activities are growth maintenance (2 times) and harvesting. The last cycle is growth maintenance (2 times), harvesting, and plantation liquidation.

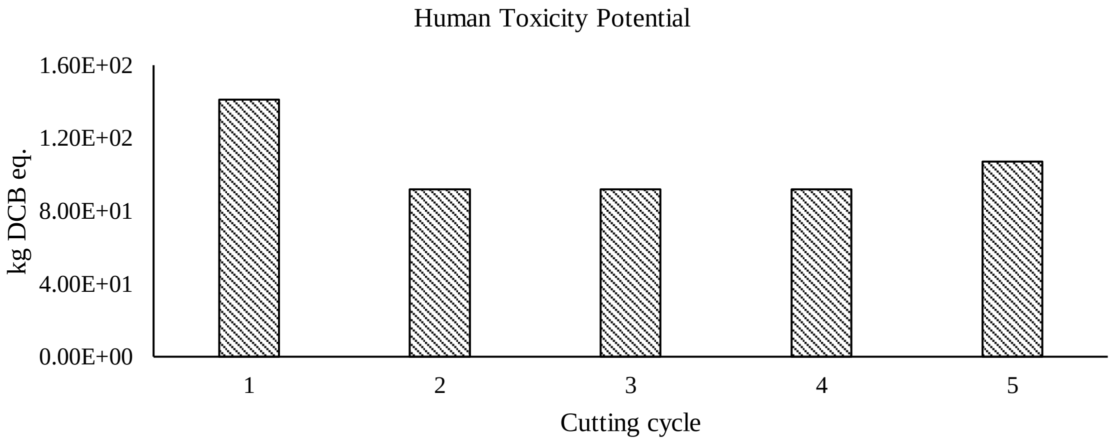

Abiotic depletion

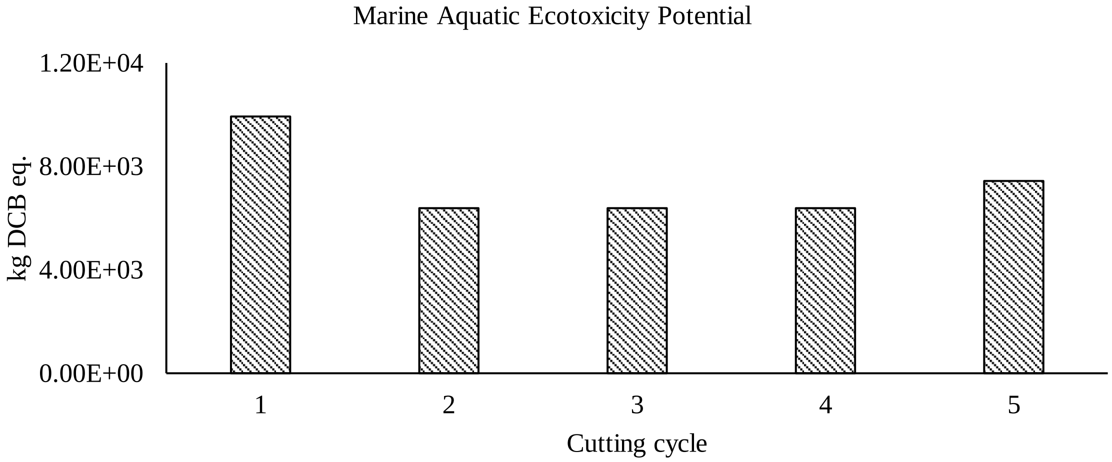

Acidification potential

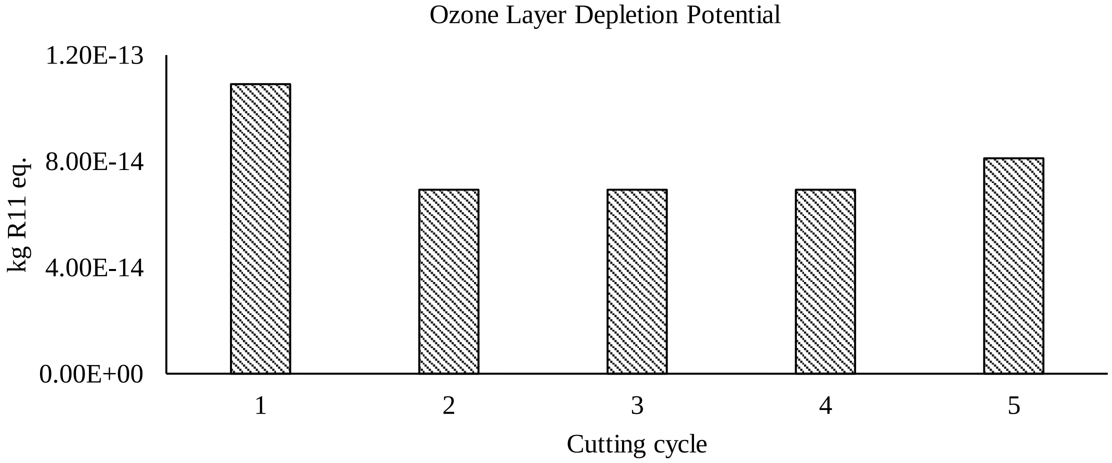

Eutrophication Potential

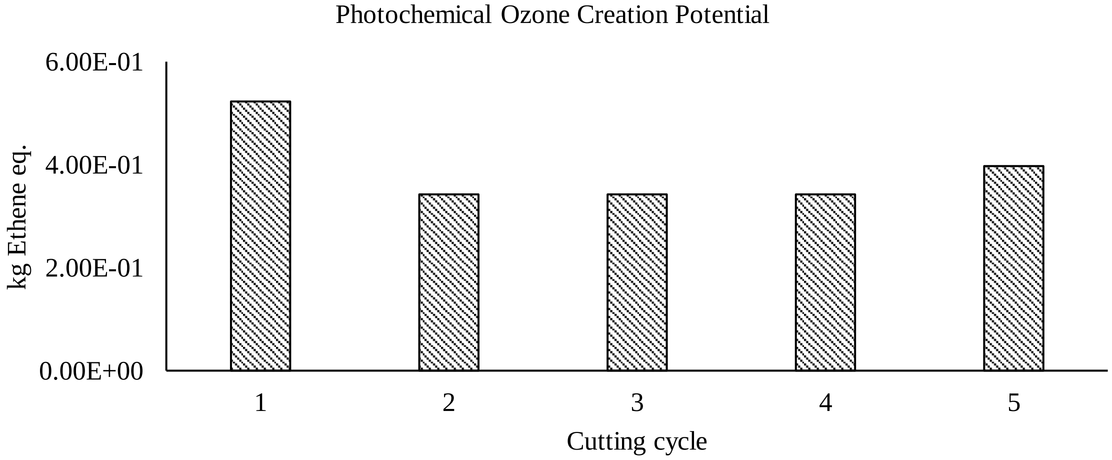

Freshwater Aquatic Ecotoxicity Potential
kg DCB eq.
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
1
2
3
4
5
Cutting cycle


Global Warming Potential
(GWP 100 years), excl biogenic carbon
kg CO$_2$ eq.
1.20E+03
8.00E+02
4.00E+02
0.00E+00
1
2
3
4
5
Cutting cycle


Human Toxicity Potential
kg DCB eq.
1.60E+02
1.20E+02
8.00E+01
4.00E+01
0.00E+00
1
2
3
4
5
Cutting cycle


Marine Aquatic Ecotoxicity Potential
1.20E+04
8.00E+03
4.00E+03
0.00E+00
kg DCB eq.
1
2
3
4
5
Cutting cycle


Ozone Layer Depletion Potential
1.20E-13
8.00E-14
4.00E-14
0.00E+00
kg R11 eq.
1
2
3
4
5
Cutting cycle


Photochemical Ozone Creation Potential
6.00E-01
4.00E-01
2.00E-01
0.00E+00
kg Ethene eq.
1
2
3
4
5
Cutting cycle

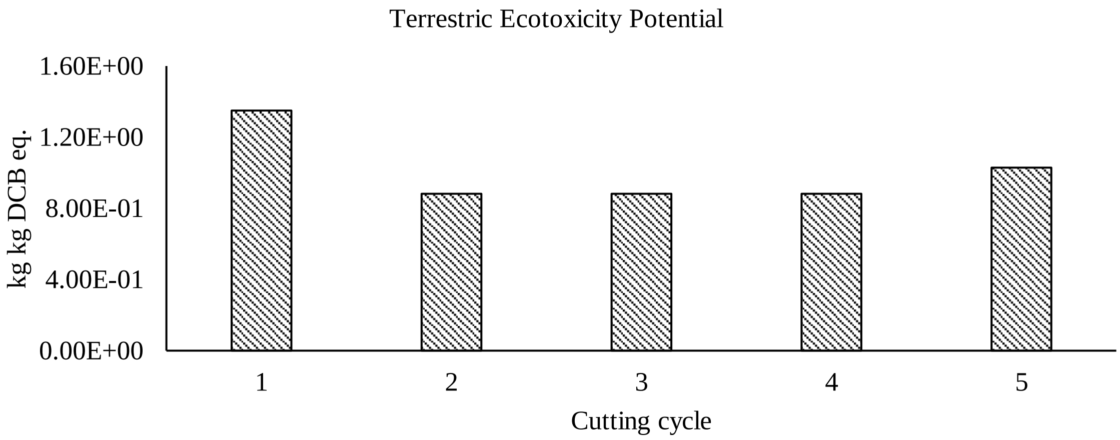


Fig. 4.16. Environmental impacts during SRC rotation (15 years) in the CML 2001 method

According to Fig. 4.16, the hotspot activity resulting in the highest environmental impact is in the first cycle. The input is more complicated in the first cycle than in the others. Although the background data on process seedlings and electricity generation does not contribute to environmental impacts in the first cycle, fertilizer, fuel, and lubricant consumption is higher than in the other cycles. Due to the limitations of the Sphera LCA for Experts Education License version 9.2.1.68 database, the impact of pesticide consumption could not be calculated in this research.

Regarding the carbon footprint perspective, the value of global warming potential (GWP 100 years) can be used to reference carbon emissions from a process. In this research, the process is producing wood for bioenergy from the SRC management system. Although the GWP has been recognized for decades, some people are unaware that GWP is a different name for the carbon footprint (Finkbeiner 2009).

LCA analysis in the Sphera LCA for Experts Education License version 9.2.1.68 version can be conducted using many methods, such as CML 2001, Environmental Footprint (EF) 3.0, IPCC AR5, and ReCiPe 2016. The total carbon footprint for SRC, either black locust or poplar, in 15 years rotation for CML 2001, EF 3.0, IPCC AR5, and ReCiPe 2016 midpoint are 4.5E+03, 4.7E+03, 4.5E+03, and 3.5E+03 kg CO_2 eq., respectively.

In detail, we analyzed the carbon footprint contribution by cutting the cycle. The carbon footprint from the CML 2001 method for the first, second, third, fourth, and final cycles are 1.06E+03, 0.84E+03, 0.84E+03, 0.84E+03, and 0.91E+03 kg CO_2 eq., respectively. Based on the input data and LCA plan (Fig. 4.15.), the primary carbon footprint sources are fertilizer, fuel, and lubricant consumption. Combustion for machinery used in the cultivation process has released carbon emissions into the atmosphere (González-García et al. 2012a, b). Furthermore, according to González-García et al. (2012b), the carbon footprint of poplar with inorganic fertilizer was more significant than that of poplar plantation management without inorganic fertilizer.

4.3.2. Life cycle assessment in forest plantation for industrial purposes

Forest management of forest plantations for industrial purposes differs from that of SRC plantations. Although the silvicultural activities are relatively similar, such as plantation establishment, growth maintenance, and harvesting, the number of harvestings is different. In SRC plantation, the trees can be harvested many times during the rotation, but in forest plantation for industrial purposes, the harvesting is only conducted at the end of the rotation.

In similar LCA experiments on silvicultural activities for poplar plantation for industrial purposes that used forest establishment, growth maintenance, and harvesting have been applied in Iran (Hafezi et al. 2021) and Italy (Lovarelli et al. 2018; Chiarabaglio et al. 2020; Cantamessa et al. 2022). The input in the life cycle assessment is also relatively similar: energy (electricity, fuel, and lubricant) and agrochemicals (fertilizer and pesticide).

Fertilizer in long-rotation plantations for industrial purposes is applied in the first year (plantation establishment). Pesticides are also applied in the first year to inhibit the growth of herbs that disturb the black locust or poplar seedling. Furthermore, the contribution of fertilizer and pesticides to environmental impacts in long-rotation plantations for industrial purposes is not as immense as fuel and lubricants' contribution. This happened because of the consumption of agrochemicals (fertilizer and pesticides), which is only one in a whole process. In contrast, energy (fuel and lubricant) consumption starts at the establishment of the plantation in the first year and continues until the final harvesting at the end of the rotation.

Furthermore, growth maintenance in long-rotation plantations for industrial purposes is a thinning activity. Thinning is conducted every five years to reduce the tree density. Moreover, in LCA plan for thinning is like harvesting. The difference between thinning and harvesting is the consumption of fuel and lubricants. In thinning, the harvesting system is selective cutting, which allows the good trees to survive until the end of the rotation. Meanwhile, all the trees will be harvested in the final harvesting stage. Thus, the consumption of fuel and lubricants in harvesting will be higher than in thinning activities (Fig.4.17.).

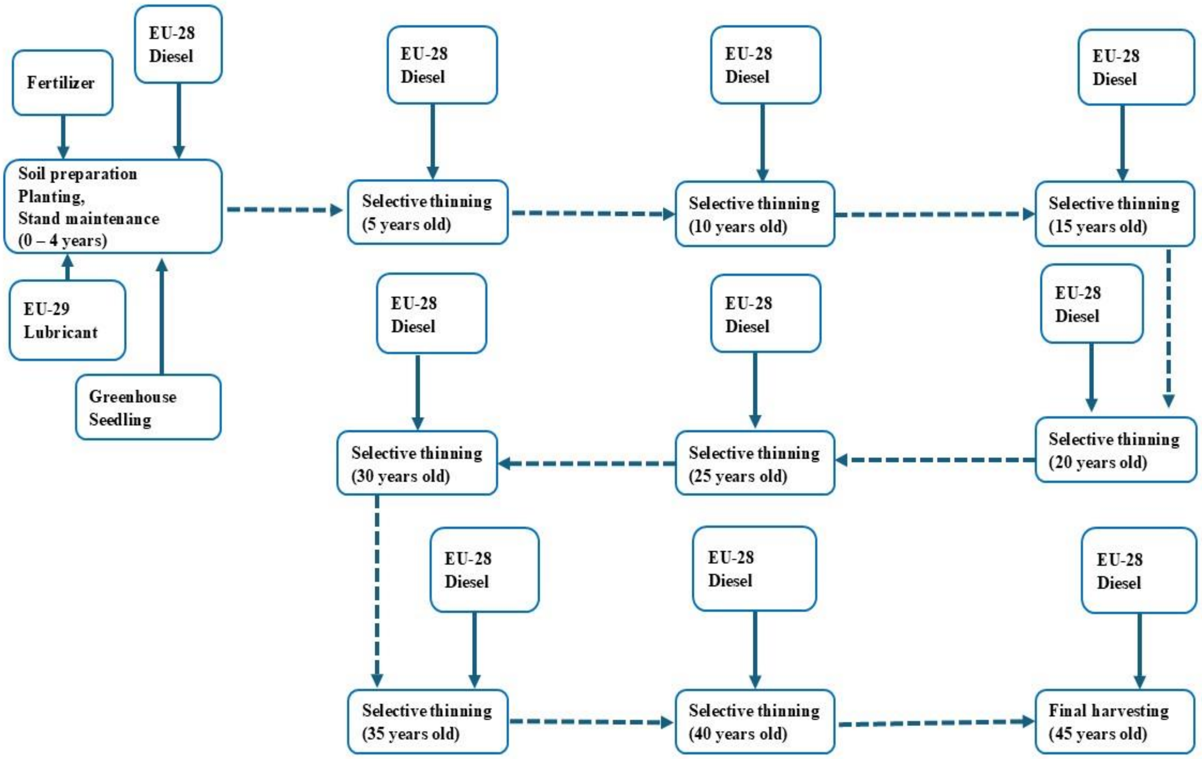


Fig. 4.17. Life cycle assessment of long-rotation systems for black locust and poplars

According to Fig. 4.17., the stand management of plantation for industrial purposes was divided into three stages, namely plant establishment and stand maintenance (year 0-4), thinning (year 5, 10, 15, 20, 25, 30, 35, and 40), and harvesting (year 45). The inputs for whole processes in black locust and poplar plantations are fuel, lubricant, fertilizer, and pesticide. Furthermore, Chiarabaglio et al. (2020) and Cantamessa et al. (2022) also reported similar inputs (fuel, lubricant, fertilizer, and pesticides) in the poplar plantation in Italy for industrial purposes.

Although the functional unit between our research and poplar plantation management to supply medium-density fiber (MDF) wood in Iran differed, the input in wood production was similar (Hafezi et al. 2021). Lovarelli et al. (2018) described in poplar plantation for timber production in Italy that the inputs for planting, growth maintenance, and harvesting are fuel, lubricant, organic and mineral fertilizer, and pesticides. Thus, even though the functional unit or the utilization of wood (timber, MDF, and veneer), the inputs for poplar plantation are the same.

The life cycle assessment analysis in Sphera LCA for Experts Education License version 9.2.1.68 is varied. Methods for estimating the environmental impacts include CML 2001, Environmental Footprint (EF) 3.0, IPCC AR5, and ReCiPe 2016. For the purpose of result comparison with other research on poplar plantations with similar functional units and system boundaries, we found articles from Chiarabaglio et al. (2020) and Cantamessa et al. (2022), in which they used IPCC AR5 and ReCiPe 2016 method (Table 4.6).

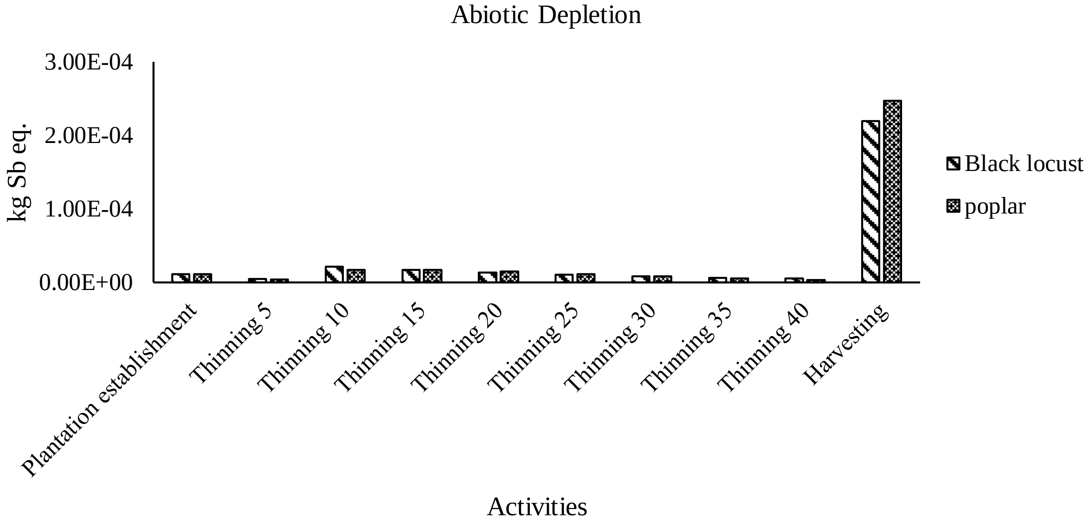
According to Table 4.6, the carbon footprint of poplar in our research is lower than others. The value of carbon footprint (IPCC AR5 method) in this research, Chiarabaglio et al. (2020) and Cantamessa et al. (2022) are 4.3E10+03, 10.5E+03, and 7.3E+03 kg CO_2 eq (I-214 clones) 7.2E+03 kg CO_2 eq (MSA clones), respectively. The results explain that the value of the environmental impact will differ from one site to another or from one clone to another.

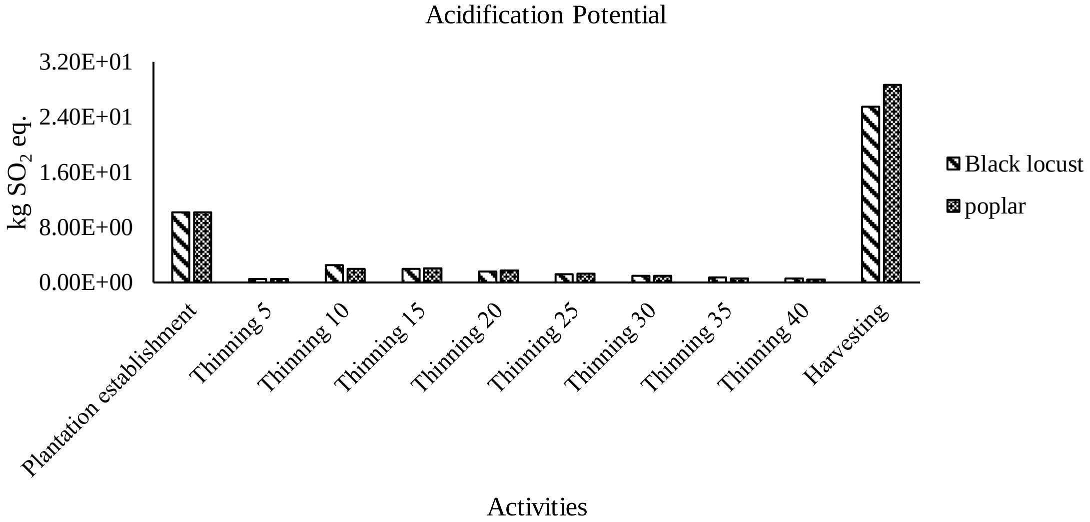
In the ReCiPe 2016 midpoint method, our result also showed lower impacts than poplar plantations in Italy. However, the result of environmental impact categories should be considered as a potential impact that can affect environmental and human health. In the future, the stakeholders can develop new processes or technologies to reduce the potential impact. In the ReCiPe 2016 methodology, there were 18 midpoint and 3 endpoint impact categories (Huijbregts et al. 2017). The result fluctuation is normal because it is affected by different forest management practices, soil, and climatic conditions (González-García et al. 2014).

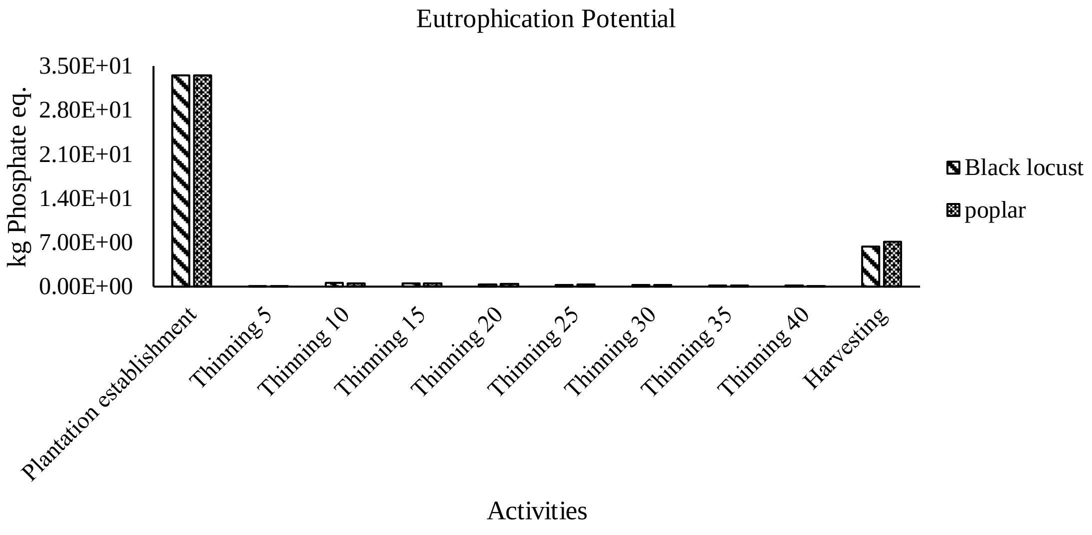
Table 4.6. Environmental impacts of plantation for industrial purposes

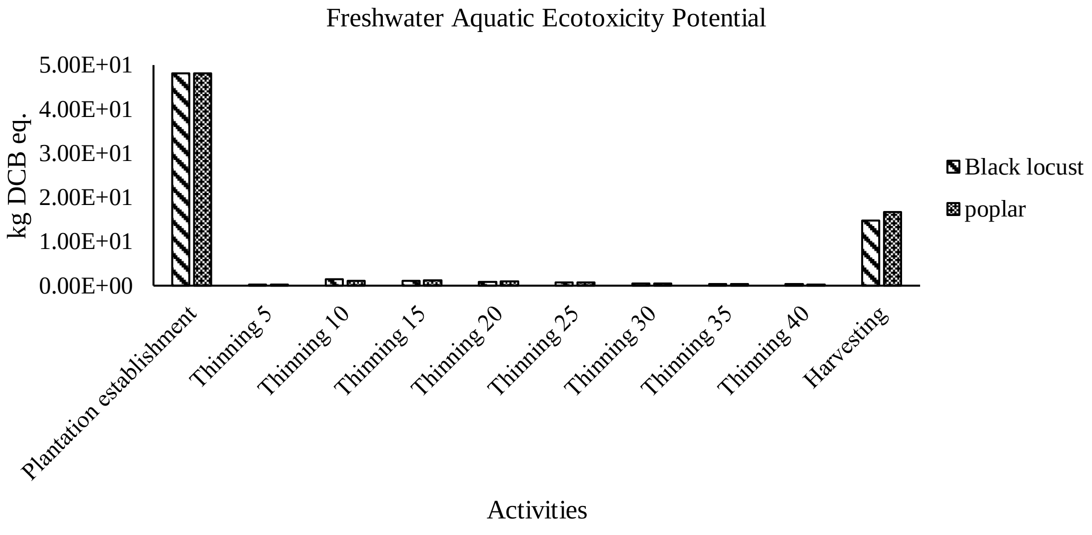
	Our research		Cantamessa et al. (2022)	Chiarabaglio et al. (2020)
Location	Hungary	Hungary	Italy	Italy
Species	Poplar	Black locust	Poplar	Poplar
LCA analysis software	Sphera LCA for Experts Education License version 9.2.1.68	Sphera LCA for Experts Education License version 9.2.1.68	SIMAPRO v.8.0	SIMAPRO v.8.0
Database	USLCI	USLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI
Rotation	45 years	45 years	10 years	10 years
Purpose	Industrial	Industrial	Industrial (veneer)	Industrial
Soil	Sandy loamy	Sandy loamy	Sandy loamy	Sandy loamy
Tree density	400 trees/ha	400 trees/ha	250 – 300 trees/ha	250 – 300 trees/ha
System boundaries	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
Stand management	a). plantation establishment b). growth management c). harvesting	a). plantation establishment b). growth management c). harvesting	a). soil preparation and planting b). cultivation c). harvesting	a). soil preparation and planting b). cultivation c). harvesting
Functional unit	Per unit area (ha)	Per unit area (ha)	Per unit area (ha)	Per unit area (ha)
GWP100 (IPCC AR5)	4.3E10+03 kg CO_2 eq	4.0E10+03 kg CO_2 eq	10.5E+03 kg CO_2 eq	7.3E+03 kg CO_2 eq (I-214 clones) 7.2E+03 kg CO_2 eq (MSA clones)
ReCiPe midpoint				n.a
- Terrestrial acidification	36.2 kgSO_2 eq	34.3 kgSO_2 eq	48.3 kgSO_2 eq	
- Terrestrial ecotoxicity	1,260 kg 1,4-DCB	1,235 kg 1,4-DCB	18,503 kg 1,4-DCB	
- Freshwater ecotoxicity	4.708 kg 1,4-DCB	4.655 kg 1,4-DCB	165 kg 1,4-DCB	
- Marine ecotoxicity	21,756 kg 1,4-DCB	21,432 kg 1,4-DCB	205 kg 1,4-DCB	
- Human toxicity	350.9 kg 1,4-DCB	345.0 kg 1,4-DCB	6,254 kg 1,4-DCB	
- Water consumption	- m^3	- m^3	17,460 m^3	
- Stratospheric ozone depletion	0.0009 kg CFC11 eq	0.0008 kg CFC11 eq	0.016 kg CFC11 eq	
- Land use	190.2 m^2a crop eq	177.6 m^2a crop eq	140.4 m^2a crop eq	
- Fossil resources scarcity	1,287.3 kg oil eq	1,201.3 kg oil eq	3,431.3 kg oil eq	
Yield	425 m^3/ha	378 m^3/ha	158 m^3/ha	n.a

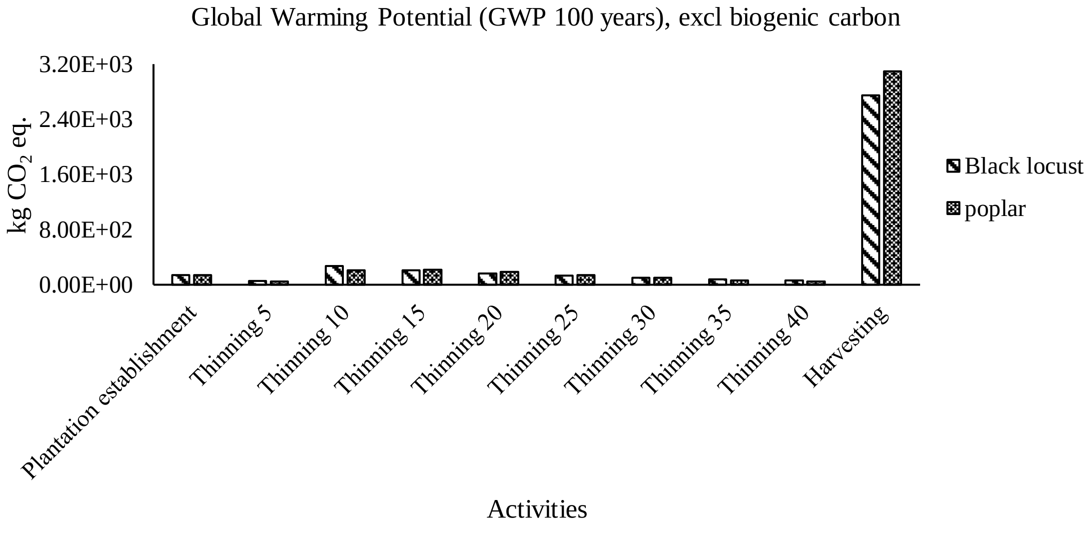
Furthermore, in this research, we conducted a detailed analysis of each environmental impact using the CML 2001 method (Fig. 4.18.). The CML 2001 method is more detailed and scientific and is accepted in many European countries (Klöpffer 2006). In the CML 2001 method, environmental impacts were categorized as abiotic depletion (ADP), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestric ecotoxicity potential (TETP).

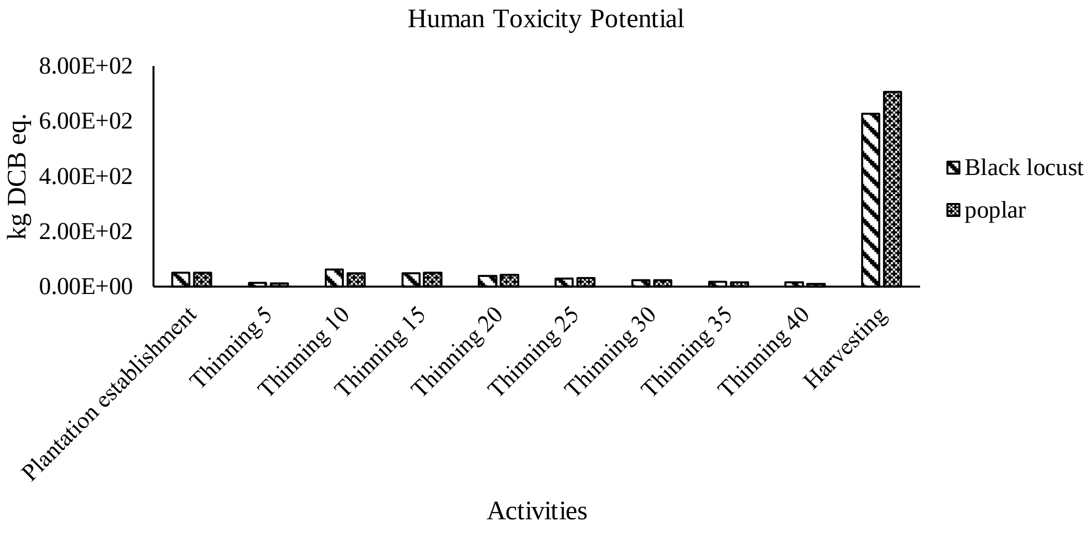


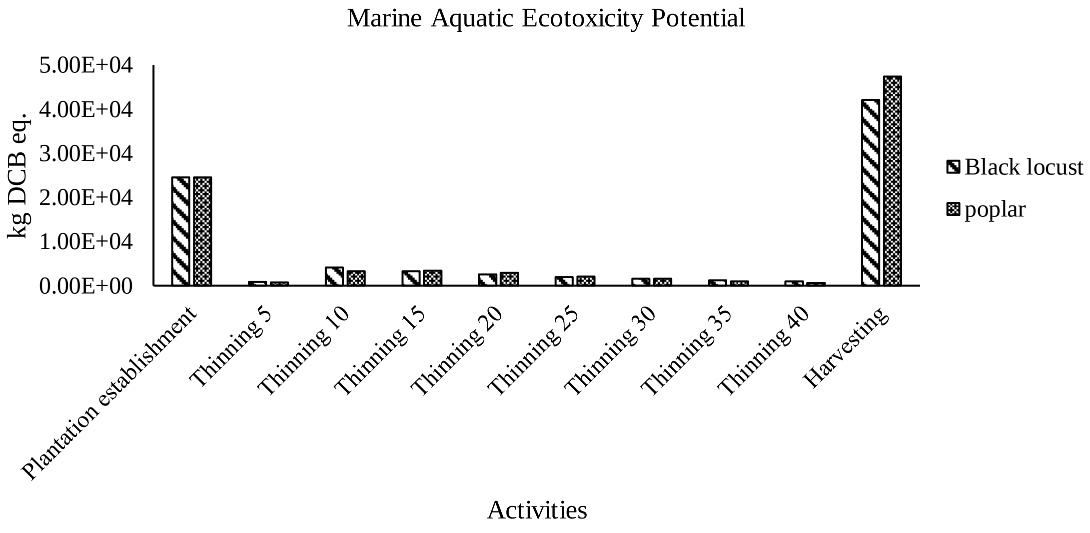


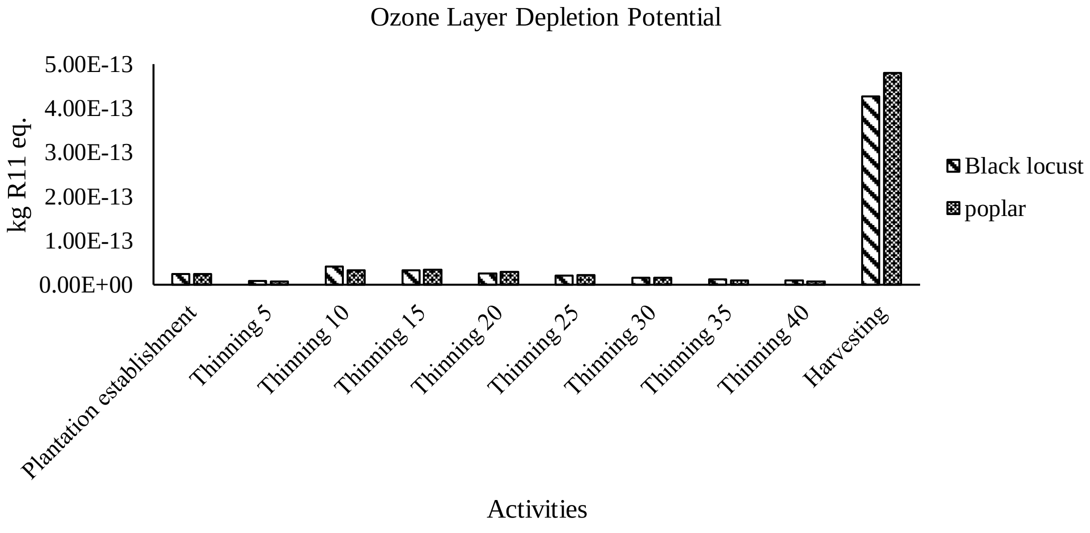

Eutrophication Potential
kg Phosphate eq.
3.50E+01
2.80E+01
2.10E+01
1.40E+01
7.00E+00
0.00E+00
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar

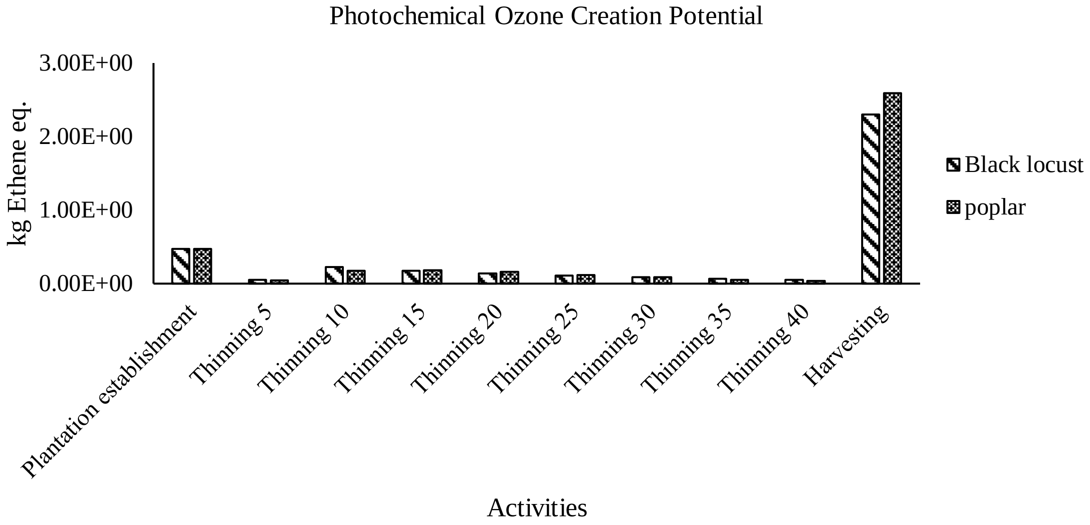

Freshwater Aquatic Ecotoxicity Potential
kg DCB eq.
5.00E+01
4.00E+01
3.00E+01
2.00E+01
1.00E+01
0.00E+00
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar


Global Warming Potential (GWP 100 years), excl biogenic carbon
kg CO_2 eq.
3.20E+03
2.40E+03
1.60E+03
8.00E+02
0.00E+00
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar


Human Toxicity Potential
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
kg DCB eq.
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar


Marine Aquatic Ecotoxicity Potential
5.00E+04
4.00E+04
3.00E+04
2.00E+04
1.00E+04
0.00E+00
kg DCB eq.
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar


Ozone Layer Depletion Potential
5.00E-13
4.00E-13
3.00E-13
2.00E-13
1.00E-13
0.00E+00
kg R11 eq.
Plantation establishment
Thinning 5
Thinning 10
Thinning 15
Thinning 20
Thinning 25
Thinning 30
Thinning 35
Thinning 40
Harvesting
Activities
Black locust
poplar



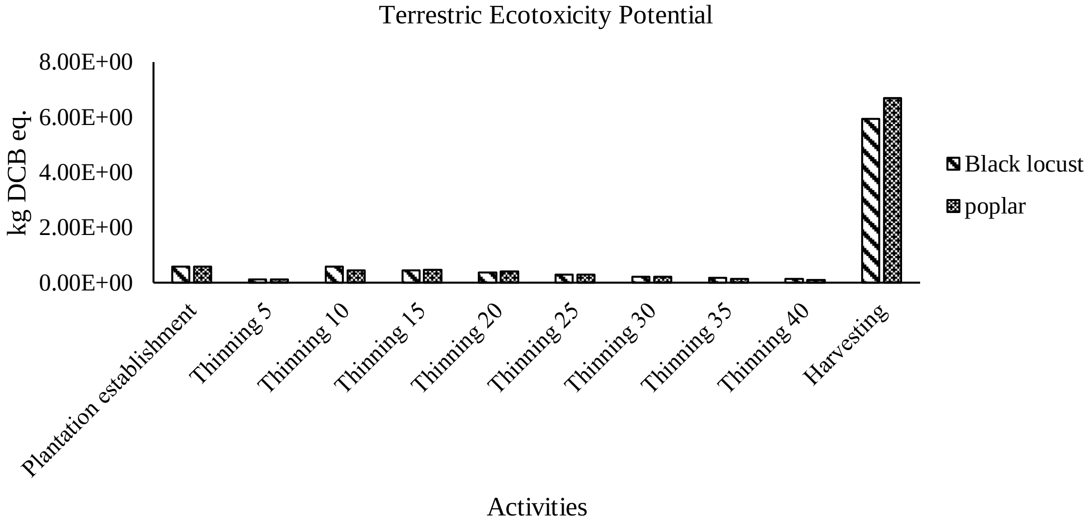


Fig. 4.18. Environmental impacts during long rotation plantation (45 years) in the CML 2001 method

According to Fig. 4.18, the hotspots of environmental impacts are plantation establishment and harvesting activities. In the plantation establishment, the inputs are fertilizer, pesticides, fuel, and lubricants. The effects of fertilizer on the environment are eutrophication and freshwater aquatic ecotoxicity potential. The value of EP and FAETP of the long-rotation plantation was 33.5 kg Phosphate eq. and 48.1 kg dichlorobenzene equivalent (DCB eq.), respectively. The application of inorganic fertilizer in cultivation has caused the excessive of nutrients (nitrogen and phosphorus) in the waters (freshwater and marine) (Balasuriya et al. 2022). Furthermore, Balasuriya et al. (2022) explained that excessive nutrients accelerate the growth of toxic algae, which reduces sunlight in the deep-water layers.

In the harvesting operation, the inputs are fuel and lubricant. Consuming fuel and lubricant in the harvesting operation has caused some environmental impacts. This research will focus on emissions from greenhouse gas carbon dioxide. The carbon footprint in the harvesting activity for black locust and poplar are 2.7E+03 and 3.1E+03 kg CO_2 eq., respectively. The carbon footprint contribution from harvesting activity to the total carbon footprint of black locust and poplar are 70 and 73%. A similar finding was also revealed by (González-García et al. 2014) from some forest operations in European countries (France, Germany, Italy, Portugal, and Sweden), that harvesting operations were identified as hotspots due to their notable contribution to total carbon footprint.

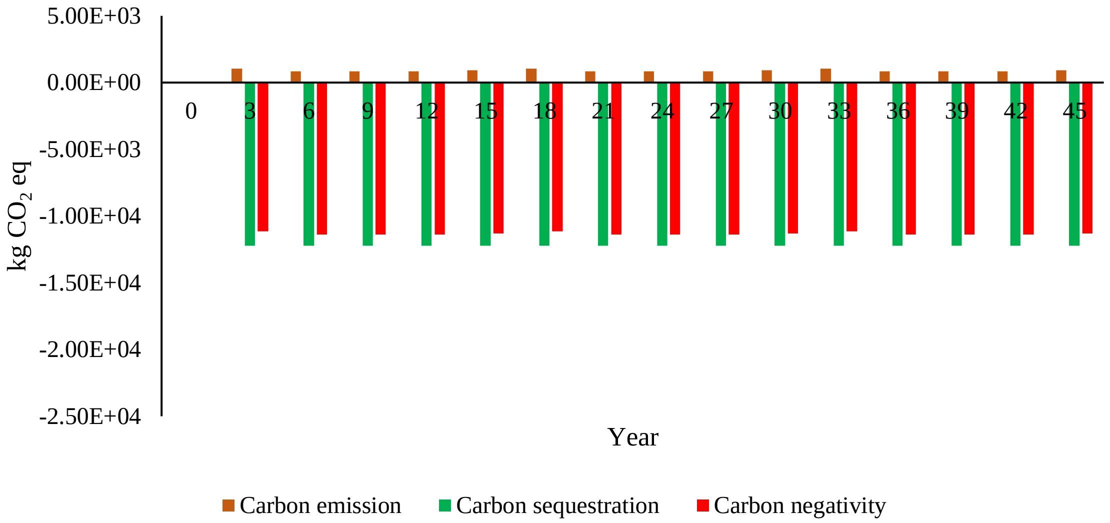
The magnitude of harvesting operations in producing carbon footprint has attracted researchers to elaborate on each activity's contribution to harvesting operation. For example, Polgár et al. (2018) have compared the carbon footprint of different harvesting technologies for small, medium, and large energy plantations in Hungary. They found that transportation activity has contributed dominantly to the total carbon footprint of harvesting operations.

4.4. Carbon balance in different plantation management scenarios

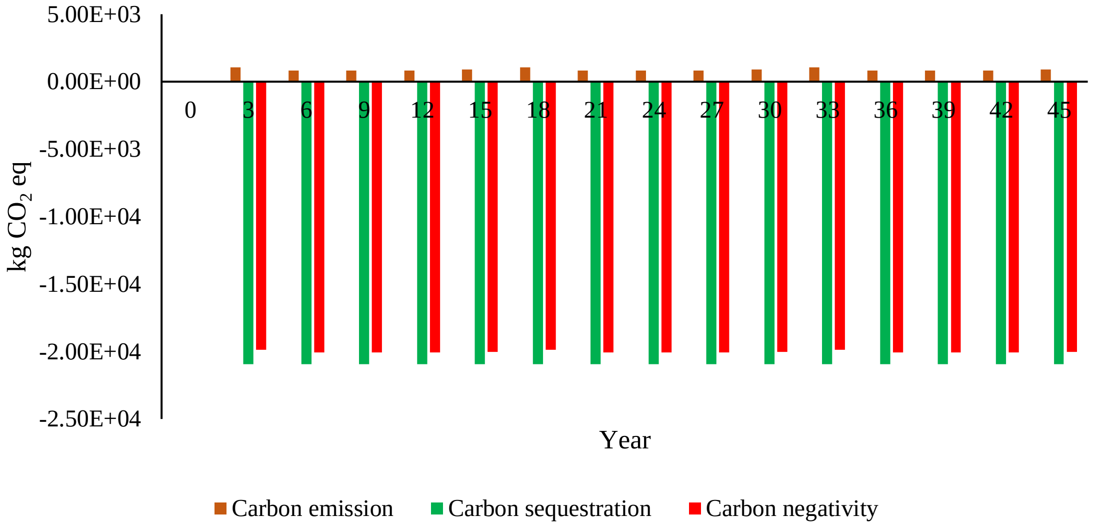
4.4.1. Carbon balance in short rotation coppice systems

Carbon dynamics in the forest is a complex system. The carbon is sequestered into plants through photosynthesis and released in the atmosphere by combustion or biodegradation (Bosner et al. 2012). Bosner et al. (2012) explained the complexity of carbon dynamics, which can be seen from the life cycle of forest products, production chains, and the relationship between products, by-products, and waste. In this research, the life cycle of forest products is short for wood for bioenergy and long for wood for industrial purposes.

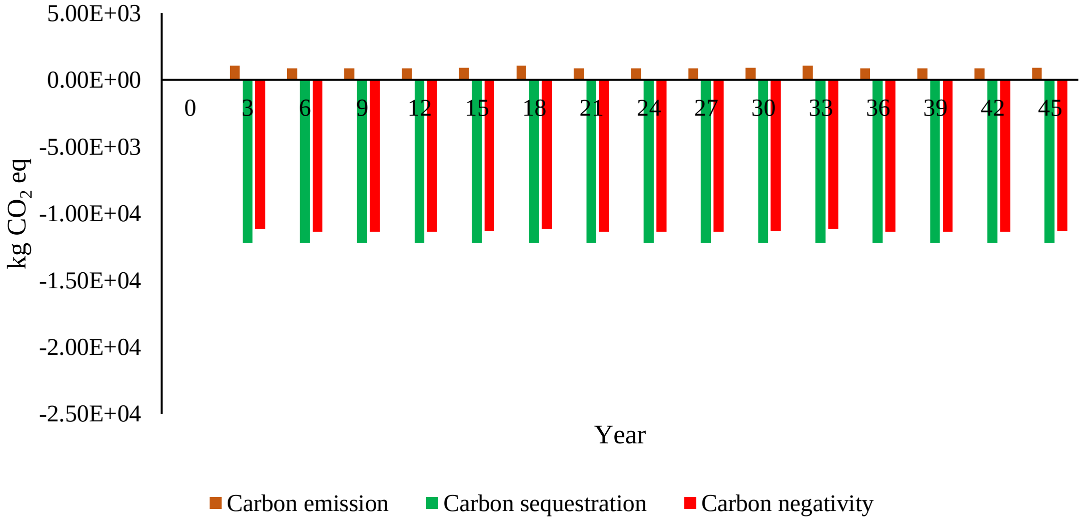
In the short-rotation coppice management systems, either hybrid black locust or poplar plantations, carbon sequestration is higher than carbon emission (Fig. 4.19). Carbon emission occurs yearly but looks higher in the third, sixth, eighth, eleventh, and fifteenth years or each harvesting period.


5.00E+03
0.00E+00
-5.00E+03
-1.00E+04
-1.50E+04
-2.00E+04
-2.50E+04
kg CO2 eq
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
Year
Carbon emission
Carbon sequestration
Carbon negativity

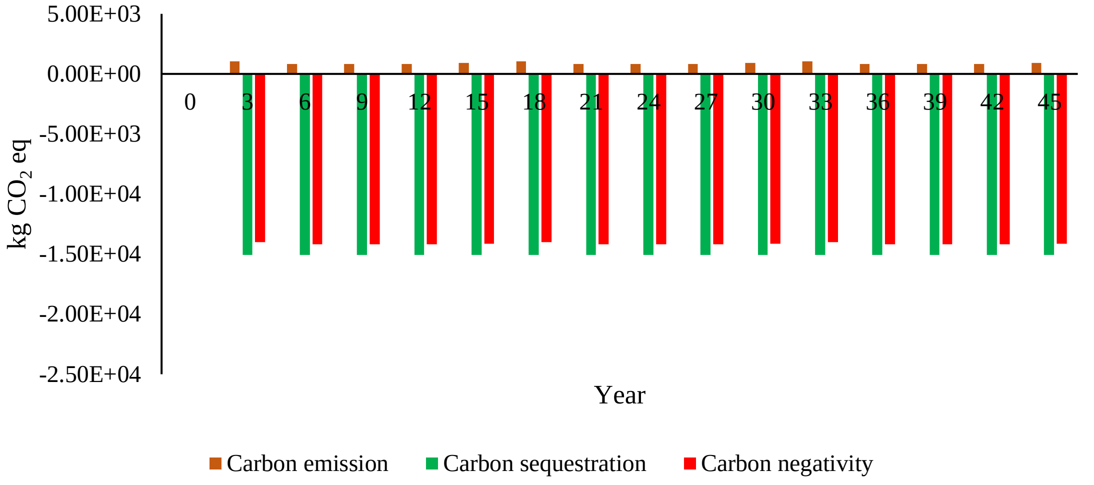
(a)


5.00E+03
0.00E+00
-5.00E+03
-1.00E+04
-1.50E+04
-2.00E+04
-2.50E+04
kg CO2 eq
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
Year
Carbon emission
Carbon sequestration
Carbon negativity

(b)

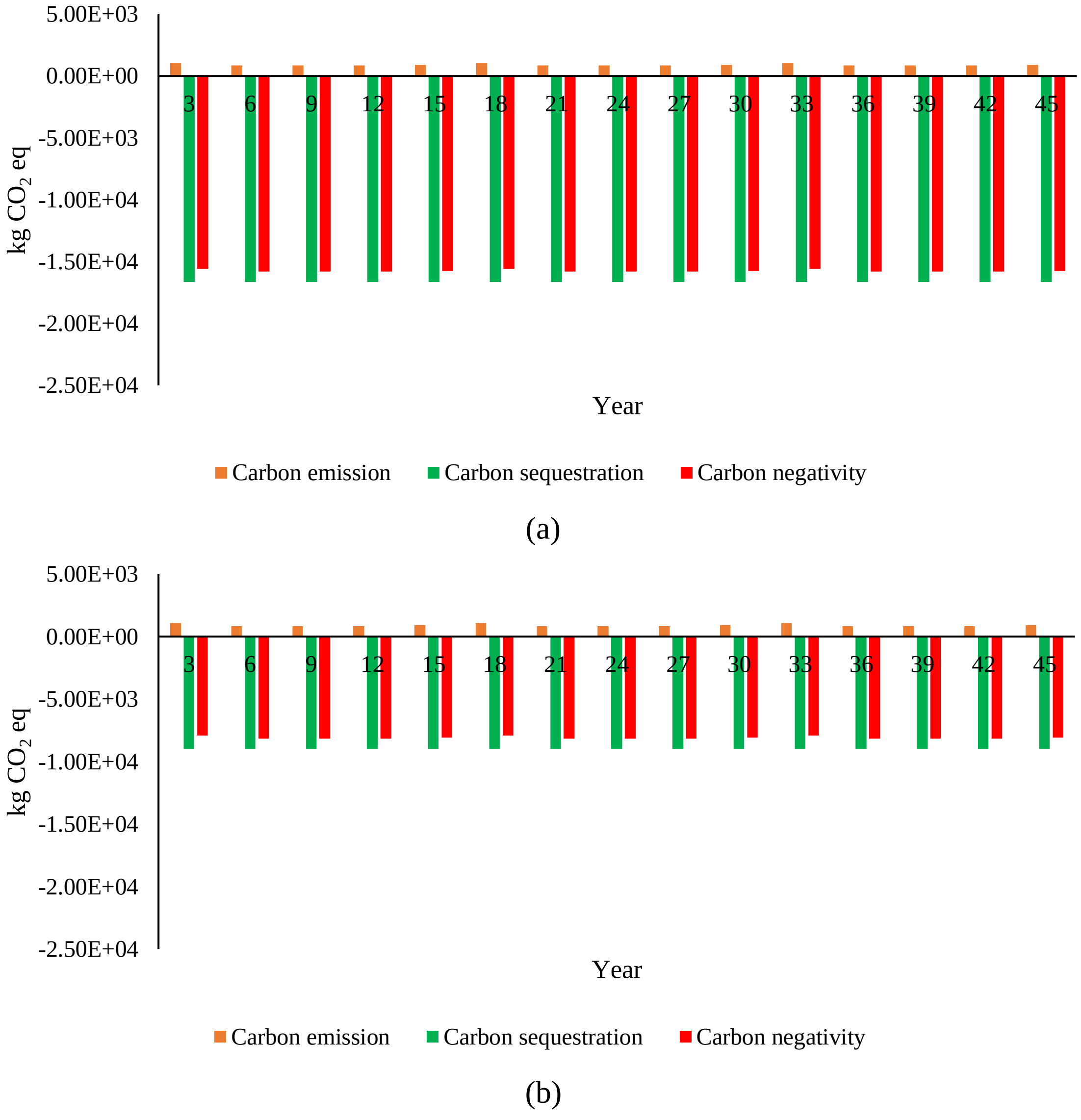

5.00E+03
0.00E+00
-5.00E+03
-1.00E+04
-1.50E+04
-2.00E+04
-2.50E+04
kg CO2 eq
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
Year
Carbon emission
Carbon sequestration
Carbon negativity

(c)



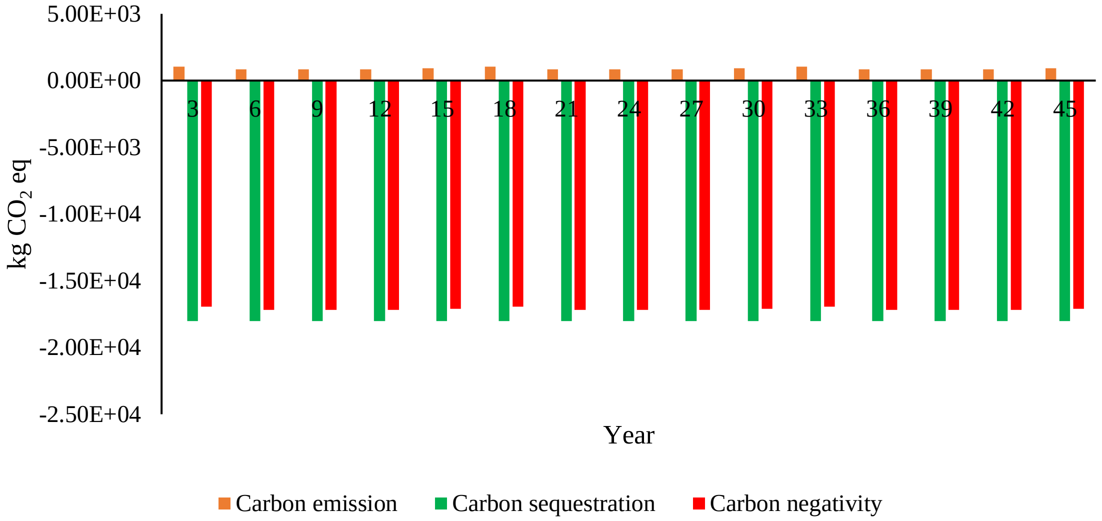
(d)

Fig. 4.19. Carbon balance of black locust in short-rotation coppice systems for cultivar a). Jászkiséri, b). Kiscsalai, c). Nyírségi, and d). Üllői

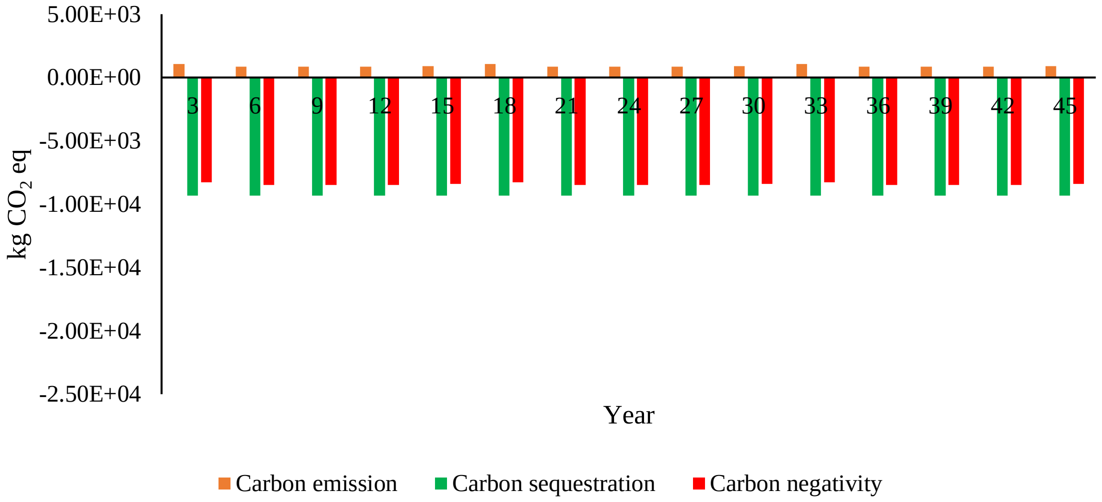


(a)

(b)



(c)



(d)

Fig. 4.20. Carbon balance of hybrid poplar in short-rotation coppice systems for cultivar a). Agathe-F, b). I-214, c). Pannónia, and d). S 298-8

According to Fig. 4.19 and 4.20., minus values represent the amount of CO_2 emission absorbed by trees (black locust or poplar) and then processed in photosynthesis. Furthermore, the result of photosynthesis is carbon that is stored in the tree's biomass. However, the positive values are the amount of CO_2 emission released from forest operations (fuels of machinery and the utilization of pesticides and fertilizer) and harvested biomass. In SRC management systems, the amount of carbon stored in a tree's biomass for three years will be removed as harvested wood. For this reason, the bioenergy from wood biomass is called carbon neutral.

The benefits of SRC plantations are that they not only produce wood for biomass but also provide some ecosystem services, such as preventing soil erosion, improving water quality, enhancing biodiversity, and mitigating climate change beside their ability to absorb CO_2

emissions from the atmosphere. According to Fig. 4.19 and 4.20., our research shows that the black locust and poplar plantation with SRC management systems have proven to absorb the CO_2 emission from the atmosphere and store the carbon in the body parts of trees as biomass. Although the forest operations have released some environmental impact - especially carbon emission from the utilization of fuel, lubricant, pesticide, and fertilizer -the amount of carbon absorption was higher than the carbon emission.

In black locust SRC management systems for cultivar Jászkiséri, Kiscsalai, Nyírségi, and Üllői, the amount of carbon sequestration for the first and second years are 1.22E+04, 1.31E+04; 2.09E+04, 2.28E+04; 1.22E+04, 1.31E+04; and 1.50E+04, 1.62E+04 kg CO_2 eq/ha, respectively. Furthermore, in the third year, the harvested biomass for cultivar a). Jászkiséri, b). Kiscsalai, c). Nyírségi, and d). Üllői are 7.69, 13.39, 7.69, and 9.53 dry tons/ha or equal to 3.56, 6.2, 3.56, and 4.41 MgC/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 hybrid black locust SRC management system has removed 3.56 – 6.20-ton C/ha or equal to 13.0E+03 – 22.6E+03 kg CO_2 eq. per harvesting. The total carbon balance for 45 years was 195.0E+03 - 339.0E+03 kg CO_2 eq.

Furthermore, the carbon sequestration in the hybrid poplar SRC management system for cultivar Agathe-F, I-214, Pannónia, and S 298-8 are similar to that of black locust. Carbon sequestration in the first and second years for cultivar Agathe-F, I-214, Pannónia, and S 298-8 are 1.60E+04, 1.67E+04; 8.5E+03, 9.0E+03; 1.74E+04, 1.80E+04; and 8.8E+03, 9.3E+03 kg CO_2 eq, respectively. Meanwhile, the harvesting has removed 2.45 - 4.91-ton C/ha or equal to 9.0E+03 – 18.0E+03 kg CO_2 eq. per harvesting. Regarding carbon sequestration, the black locust cultivar Kiscsalai in SRC management system is better than the other cultivars.

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 from the atmosphere.

4.4.2. Carbon balance in forest plantation for industrial purposes

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 was the dominant contributor 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. It happened because of the large number of trees that should be harvested in the final harvesting compared to the thinning activities.

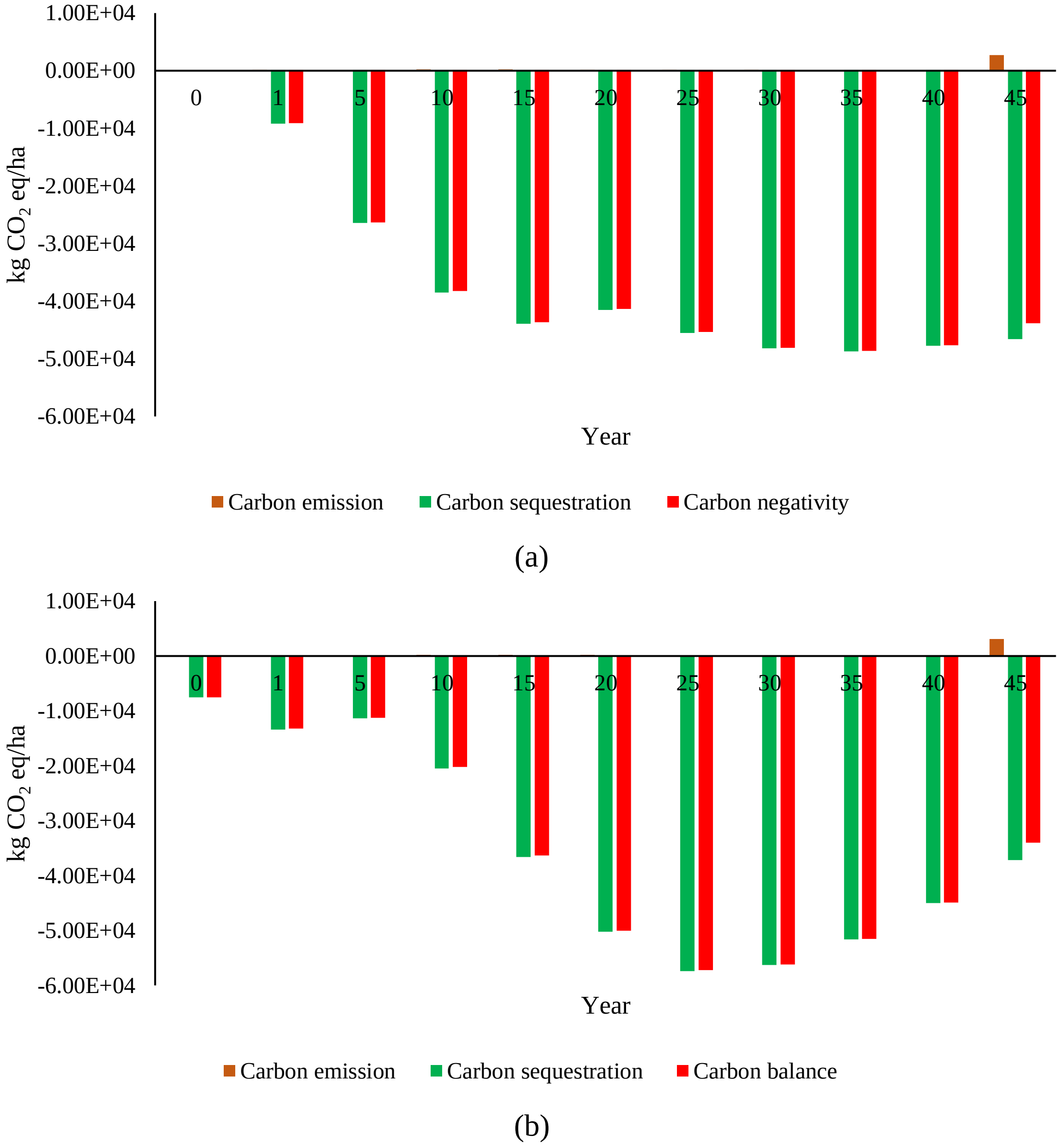


Fig.4.21. Carbon balance for long rotation plantation of a). black locust, b). poplars

According to Fig. 4.21., poplar plantations have a better carbon balance than black locust plantations. Black locust and poplar plantations have been proven to sequester CO_2 from the atmosphere and store carbon. Carbon management can be conducted by avoiding deforestation, managing existing forests, restoring forests, and improving wood utilization (Verkerk et al. 2022). 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 (Király and Borovics 2024).

The carbon balance decreases significantly at the end of the rotation, when 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 in other silvicultural activities (forest planting, tree maintenance, and thinning). Harvesting is affecting the forest carbon sinks and can be an instrument for emission reduction (Hyyrynen et al. 2023). Furthermore, Hyyrynen et al. (2023) explained that when the forest is harvested, the carbon is removed from the forest and moved to the 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, the pattern or carbon balance of black locust and poplar are different. In the black locust plantation, the carbon balance started stable at the year of 15. The carbon balance in the 15 years was 4.36E+04 kg CO_2 eq. and 4.38E+04 kg CO_2 eq. at the end of rotation. The higher carbon balance were 4.81E+04 and 4.87E+04 kg CO_2 eq. in the years 30 and 35.

In contrast, the poplar plantation pattern is similar to a bell shape. Starting at 0.7E+04 kg CO_2 eq. at the beginning of the rotation, reaching the peak in year 25 (5.7E+04 kg CO2 eq.). In the following year, the carbon balance decreased gradually. At the end of the rotation, the carbon balance was 3.4E+04 kg CO_2 eq.

V. CONCLUSION AND RECOMMENDATION

This study has revealed that forest plantations (short- and long-rotation) have shown their ability to sequester carbon from the atmosphere and store it as biomass above and below. Although forest operations use machinery and agrochemicals that release the emission, the carbon footprint is lower than that of trees, which can store carbon emissions. The research findings should be considered by stakeholders who are concerned about climate change mitigation policies and actions, and establishing forest plantations is a promising strategy to reduce carbon emissions.

5.1. Conclusion

This research has assessed the forest carbon dynamics, carbon emissions, and carbon balance in different management strategies. The conclusions are:

- *Question 1: how much carbon stock is in the simulation period in short-rotation coppice systems?*

  Developing bioenergy forest plantations to support energy security and renewable energy transition positively impacts climate change mitigation. In the examined scenarios for short-rotation coppice plantations of poplar and black locust, poplar has shown higher value on carbon stock above and below ground than black locust. At the end of the simulation period of 45 years, the total carbon stock of poplar and black locust are around 53.28 – 119.74 MgC/ha, respectively. The total carbon for hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. The total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. The distribution of carbon stock below ground is higher than above ground and should be considered in sustainable land management. However, this study has limitations in calculating root biomass after coppicing. In the future, research on measuring root biomass after coppicing can be conducted to get a more precise carbon stock estimation.
- *Question 2: How much carbon stock is in forest plantation for industrial purposes during the simulation period?*

  Forest plantation for timber production is commonly applied in many regions. For forest planning purposes, the site index is one of the important factors determining the yield of the plantation. The average total carbon stock of the examined poplar plantation for industrial purposes (sawmill, board, and pulp) for yield class I, II, III, IV, V, and VI are 91.73, 71.99, 53.90, 39.60, 28.18, and 24.09 MgC/ha, respectively. Furthermore, the average total carbon stock of black locust plantation for yield class I, II, III, IV, V, and VI are 100.19, 81.82, 64.88, 50.44, 37.50, and 33.87 MgC/ha, respectively. In detailed, in the long-term forest plantation for industrial purposes, the highest total carbon dynamic in the simulation period of 45 years was the forest management scenario for black locust species in the class yield I to supply pulp industry (101.75 MgC/ha). In contrast, the lowest total carbon dynamic was the forest management scenario for poplar plantations in the class yield VI to supply board industry (23.75 MgC/ha). Based on class yield, the total carbon dynamic of either black locust or poplar plantation was total carbon in class yield I > class yield II > class yield III > class yield IV > class yield V > class yield VI. Furthermore, the total carbon in black locust plantations was higher than in poplar plantations. Regarding timber utilization, total carbon for pulp purposes produced the highest total carbon, followed by sawn mill and board purposes. Assessment of the site index is essential as a consideration of stakeholders to optimize the timber production and carbon stock. Future research can be conducted to do detailed research on biomass allocation in a tree's body parts (leaves, branches, stems, and roots) continuously from seedling until harvesting.

- *Question 3: How much carbon emission is produced in short-rotation coppice systems?*

  The total carbon footprint of the studied poplar and black locust plantations in the short-rotation coppice management system over the 45 years is 17.7E+03 kg CO_2 eq. The source of carbon emissions comes from the application of agrochemicals (pesticide and fertilizer) and fuel consumption for machines. The highest contribution comes from the first and end cycles, at 3.2E+03 and 2.7E+03 kg CO_2 eq, respectively. Furthermore, cycles 2, 3, and 4 contribute 2.5E+03 kg CO_2 eq for each cycle. The limitation of the life cycle assessment approach is detailed data. Furthermore, collecting and compiling databases in the forestry sector should be started and standardized to get more precise analysis.

- *Question 4: How much carbon emission is produced in forest plantations for industrial purposes?*

  The total carbon footprint of the studied long-rotation management system for black locust and poplar is 4.0E+03 and 4.4E+03 kg CO_2 eq, respectively. The source of carbon emissions comes from the application of agrochemicals (pesticide and fertilizer) and fuel consumption for machines. Harvesting activities account for around 70% of the total CO_2 emissions at the end of rotation. In the forestry sector, the data availability for the life cycle assessment approach is still limited. Furthermore, developing databases in the forestry sector is important to assist the stakeholders in examining some forest management scenarios or products using a life cycle assessment approach.

- *Question 5: Which plantation management scenarios in short-rotation coppice systems provide benefit in carbon balance?*

  Carbon balance is a framework for assessing a process or product that supports climate change mitigation. Carbon balance in the short-rotation coppice management system shows that carbon sequestration from the atmosphere is higher than carbon emissions released to the atmosphere. The total carbon balance in hybrid black locust plantations for 45 years for the cultivar Jászkiséri, Kiscsalai, Nyírségi, and Üllői were 2.0E+05, 3.4E+05, 2.0E+05, and 2.4E+05 kg CO_2 eq, respectively. Furthermore, total carbon balance in hybrid poplar cultivar Agathe-F, I-214, Pannónia, and S 298-8 for 45 years were 2.5E+05, 1.4E+05, 2.7E+05, and 1.4E+05 kg CO_2 eq, respectively. Based on the findings, from the perspective of forest carbon, planting poplar and black locust in short-rotation coppice systems does not differ significantly.
- *Question 6: Which plantation management scenarios in forest plantations for industrial purposes provide benefits in carbon balance?*

  Carbon balance of long-rotation shows that carbon sequestration from the atmosphere is higher than carbon emissions released into the atmosphere. The total carbon balance for black locust and poplar long-rotation plantations included in this research were 2.3E+06 and 2.2E+06 kg CO_2 eq., respectively. According to research findings, the total carbon balance of black locust was higher than poplar in long-term plantations.

5.2. Recommendation

Based on our findings, our recommendations are

- The accumulation of total carbon in below-ground carbon in hybrid black locust and poplar SRC plantations has shown an increase gradually from the beginning of simulation until the end. Also, in the long-term system examined, soil proved to be the largest carbon poop of all cohorts. The implication is the stakeholders should pay more attention to managing below-ground carbon through environmentally friendly soil management.
- Carbon stock in the aboveground for hybrid black locust and poplar in SRC in single harvesting cycle was lower than the belowground. However, the accumulation of aboveground carbon during the simulation period has increased. In practical, the land manager can use this finding to develop a green campaign on bioenergy sources from short-rotation coppice systems. Furthermore, in scientific research, increasing the resprouting capacity of hybrid black locust and poplar will impact on the increasing of aboveground carbon stock.

- According to the carbon balance, the long-rotation management system provides better carbon balance compared to the short-rotation coppice management system. However, in site index VI, in which the soil quality is low, carbon sequestration of the long-rotation management system is more or less like the short-rotation coppice management system. Furthermore, in carbon balance perspective, a short-rotation coppice management system can be developed on marginal land. Meanwhile, the long-rotation management system is suitable for arable land.
- According to Hungarian law, Decree No. 45 of 2007 (VI.11.) FVM, there are 13 species for energy plantation in Hungary. Further research on carbon dynamics and life cycle assessment should be conducted for species White willow (*Salix alba*), Basket weaving willow (*Salix viminalis*), Gummy alder (*Alnus glutinosa*), Tall ash (*Fraxinus excelsior*), Narrow-leaved ash (*Fraxinus angustifolia*), Red oak (*Quercus rubra*), Black walnut (*Juglans nigra*), and Early maple (*Acer platanoides*) plantations.
- The result of life cycle assessment showed that carbon footprint in short and long-rotation plantation have been contributed mostly from the application of fertilizer and fuel. In the future, alternative energy inputs (fuel and fertilizer) can be elaborated to result in lower environmental impacts.

SUMMARY

The impacts of climate change are already being felt clearly. 2023 is recorded as the hottest year in history since the industrial revolution. Then, in early 2024, the temperature felt colder than usual. Furthermore, some climate change mitigation actions should be more intensive, and close cooperation among stakeholders is also necessary. The forestry sector can be essential in supporting renewable energy policies, particularly bioenergy, from using biomass with multipurpose tree management. The development of forest plantations also will support the energy transition and climate change mitigation in Hungary. Short-rotation coppice plantations are suitable for supporting bioenergy sources, while long-rotation forest plantations supply wood for industries and sequester atmospheric carbon emissions during the rotation. This research attempts to address the following research objectives:

- To estimate the forest carbon dynamics in short rotation coppice systems
- To estimate the forest carbon dynamics in forest plantation for industrial purposes
- To quantify the carbon footprint through life cycle assessment in short rotation coppice systems
- To quantify the carbon footprint through life cycle assessment in forest plantations for industrial purposes.
- To determine the carbon balance in short rotation coppice systems.
- To determine the carbon balance in forest plantations for industrial purposes.

This research examined forest carbon dynamics to determine carbon stock and life cycle assessment to calculate carbon emissions. We used some software to model the forest carbon dynamics and life cycle assessment. Software CO2FIX estimates the carbon dynamics for short and long-rotation plantation management with a simulation period of 45 years. Furthermore, we used manual calculations and Sphera LCA for Experts Education License version 9.2.1.68 software to estimate carbon emissions using a life cycle assessment approach. The carbon balance was calculated by reducing carbon sequestration and carbon emissions.

The research findings show that the total carbon of hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai at the end of simulation period (45 years) are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Furthermore, the total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. For black locust and poplar, the dominant carbon stock was stored in the soil compartment, followed by biomass and product compartments. The accumulative carbon stock above ground for hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 47.85, 38.55, 38.55, and 67.20 MgC

/ha, respectively. However, the accumulative carbon stock in the belowground of hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 20.55, 16.62, 16.62, and 28.94 MgC /ha, respectively. Meanwhile, the accumulative carbon stock aboveground for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 56.40, 30.00, 61.05, and 31.20 MgC/ha, respectively. Furthermore, the accumulative carbon stock belowground for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 35.81, 18.86, 38.91, and 19.63 MgC/ha, respectively.

Total carbon at the end of the rotation in the black locust plantation was higher than in poplar. The higher value of total carbon in black locust than in poplar was related to input data on growth and wood density. Total black locust and poplar carbon stock were stored in the biomass, soil, and product compartments. During the simulation period of 45 years, the biomass dynamics in black locust for the first five years have shown the allocation in foliage, stem, branches, and roots were relatively similar, around 20 – 30 %. During the 45-year simulation, the aboveground carbon stock in black locust and poplar in long rotation system were 2.28 – 12.18 and 3.26 – 9.95 MgC/ha, respectively. Moreover, the belowground carbon stock in black locust and poplar plantations were 21.91 – 52.43 and 11.57 – 41.82 MgC/ha, respectively.

Regarding LCA analysis in the short-rotation coppice management system, the hotspot activity resulting in the highest environmental impact is in the first cycle. Regarding the carbon footprint perspective, the value of global warming potential (GWP 100 years) can be used to reference carbon emissions from a process. The total carbon footprint for SRC, either black locust or poplar, in 15 years rotation for CML 2001, EF 3.0, IPCC AR5, and ReCiPe 2016 midpoint are 4.5E+03, 4.7E+03, 4.5E+03, and 3.5E+03 kg CO_2 eq., respectively. The carbon footprint from the CML 2001 method for the first, second, third, fourth, and final cycles are 1.06E+03, 0.84E+03, 0.84E+03, 0.84E+03, and 0.91E+03 kg CO_2 eq., respectively.

Stand management of plantation for industrial purposes was divided into three stages, namely plant establishment (year 1), thinning (year 5, 10, 15, 20, 25, 30, 35, and 40), and harvesting (year 45). The hotspots of environmental impacts are plantation establishment and harvesting activities. In plantation establishment, the environmental impact categories are eutrophication potential (33.5 kg Phosphate eq.) and freshwater aquatic ecotoxicity potential (48.1 kg DCB eq.). The carbon footprint in the harvesting activity for black locust and poplar are 2.7E+03 and 3.1E+03 kg CO_2 eq., respectively.

In black locust SRC management systems for cultivar Jászkiséri, Kiscsalai, Nyírségi, and Üllői, the amount of carbon sequestration for the first and second years are 1.22E+04, 1.31E+04; 2.09E+04, 2.28E+04; 1.22E+04, 1.31E+04; and 1.50E+04, 1.62E+04 kg CO_2 eq/ha, respectively. Furthermore, in the third year, the harvested biomass for cultivar a). Jászkiséri, b). Kiscsalai, c). Nyírségi, and d). Üllői are 7.69, 13.39, 7.69, and 9.53 dry tons/ha or equal to 3.56, 6.2, 3.56, and 4.41 MgC/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 hybrid black locust SRC management system has removed the 3.56 – 6.20-ton C/ha or equal to 13.0E+03 – 22.6E+03 kg CO_2 eq. per harvesting. The total carbon balance for 45 years were 1.95E+05 – 3.39E+05 kg CO_2 eq.

Furthermore, the carbon sequestration in the hybrid poplar SRC management system for cultivar Agathe-F, I-214, Pannónia, and S 298-8 are similar to that of black locust. Carbon sequestration in the first and second years for cultivar Agathe-F, I-214, Pannónia, and S 298-8 are 1.60E+04, 1.67E+04; 8.5E+03, 9.0E+03; 1.74E+04, 1.80E+04; and 8.8E+03, 9.3E+03 kg CO_2 eq, respectively. Meanwhile, the harvesting has removed 2.45 - 4.91-ton C/ha or equal to 9.0E+03 – 18.0E+03 kg CO_2 eq. per harvesting. Regarding carbon sequestration, the black locust cultivar Kiscsalai in SRC management system is better than the other cultivars.

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, the pattern or carbon balance of black locust and poplar are different. In the black locust plantation, the carbon balance started stable at the year of 15. The carbon balance in the 15 years was 4.3E+04 kg CO_2 eq. and 4.3E+04 kg CO_2 eq. at the end of rotation. The highest carbon balance was 4.8E+04 kg CO_2 eq. at the years of 30 and 35. In contrast, the poplar plantation pattern is similar to a bell shape. Starting at 0.7E+04 kg CO_2 eq. at the beginning of the rotation, reaching the peak in year 25 (5.7E+04 kg CO_2 eq.). In the following year, the carbon balance decreased gradually. At the end of the rotation, the carbon balance was 3.4E+04 kg CO_2 eq.

In conclusion, the black locust and poplar plantations in short- and long-rotation management systems have shown their ability to sequester the atmosphere's carbon emissions and store them as carbon stock above and belowground. In contrast, the carbon emission produced through forest operations for black locust and poplar plantations in short- and long-rotation management systems is lower than the ability of forest plantations to absorb carbon emission. Furthermore, the carbon balance of black locust and poplar plantations has shown negative values. It means that the carbon stock of black locust and poplar plantations is more extensive than the released carbon emission.

According to our bibliometric analysis of the research on forest carbon dynamics and environmental assessment in the forestry sector in Hungary, we believe that our findings are essential to fill the gap in these research areas. Furthermore, based on our research findings, developing tree plantations (black locust and poplar) in short- and long-rotation management systems is vital to Hungary's climate change mitigation policies and actions. Tree plantations have shown their ability to store carbon stock and release negligible carbon emissions throughout tree operations. Moreover, sustainable land management is also crucial in maintaining belowground carbon stock.

NEW SCIENTIFIC RESULTS

In this research, we conducted a bibliometric analysis to understand better the research on forest carbon dynamics and environmental assessment in the forestry sectors in Hungary. The findings showed limited research topics on forest carbon dynamics and environmental assessment of forestry sectors in Hungary (Mulyana et al. 2023b). Furthermore, we believe that our research will benefit and support the development of research on forest environmental services such as carbon storage pools.

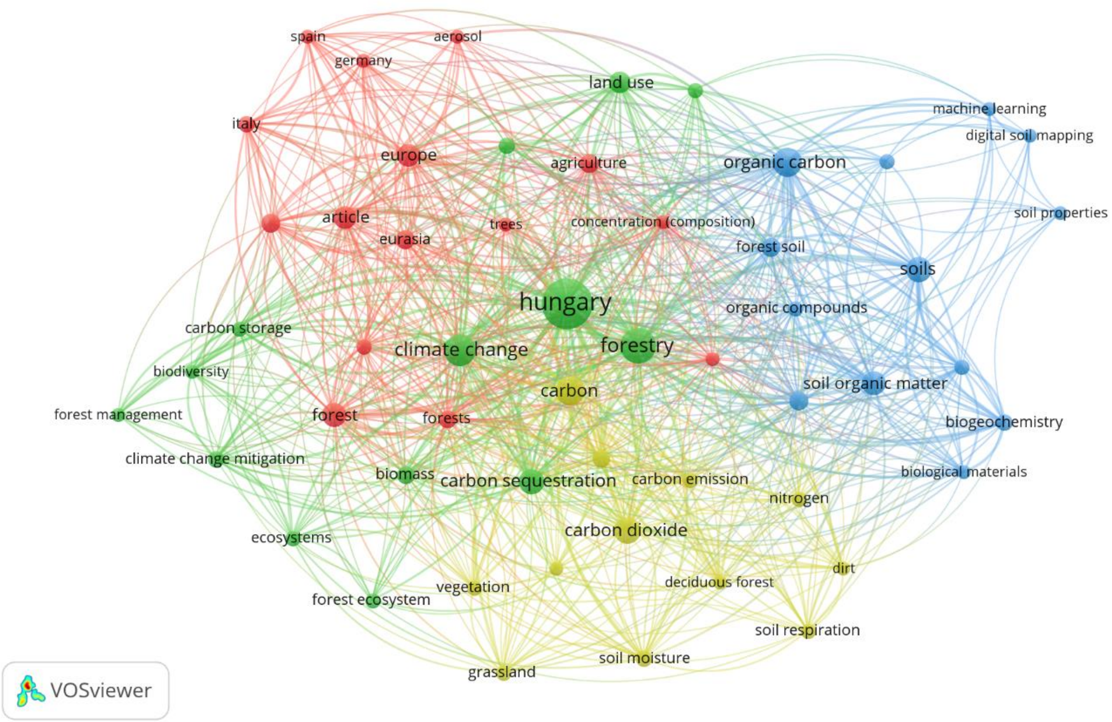


Fig. 5.1. Co-occurrence analysis of research on forest carbon in Hungary (data retrieved from Scopus database on 19 April 2024)

In this study, we combine the research topics of forest carbon estimation and potential carbon emissions from forestry operations. Based on bibliometric analysis, generally the researchers focus on a single topic, forest carbon stock estimation or potential carbon emissions, and none of them combine the two topics in single research. Integrating carbon absorption and carbon emission in single research is helpful to get better understanding the forest carbon dynamics. In this study, we have successfully presented research findings that poplar and black locust plantations, either short or long-rotation, are able to absorb more carbon emission than they produce. Based on our research findings, there is an opportunity to conduct the similar research for other species in Hungary.

A. Forest carbon dynamics in short and long-rotation systems

Our research has provided strong evidence of the ability of black locust and poplar plantations with short- and long-rotation management systems to absorb carbon emissions from the atmosphere and store carbon above and belowground. The total carbon stock (biomass, product, soil, and bioenergy compartments) at the end of simulation period (45 years) for hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Furthermore, the total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. Stakeholders can also consider our research findings on their policies or technical assistance to support climate change mitigation actions that hybrid black locust and poplar in short-rotation coppice systems has the ability to absorb the carbon emission from atmosphere and store in the above and belowground.

A similar finding also found in the black locust and poplar plantation in long-rotation system. The total carbon in black locust and poplar plantation in long-rotation system has shown that the total carbon in yield class I is higher than yield class II, III, IV, V, and VI. It was strong evidence that the total carbon in CO2FIX modeling is closely related to input data of growth rate. For instance, the total carbon at the end of simulation period 45 years to supply the sawmill industry for yield class I, II, III, IV, V, and VI were 91.38, 71.70, 53.68, 39.44, 28.07, and 24.01 MgC/ha, respectively.

Scientifically, based on Fig. 5.1. the research topic on forest carbon dynamics in Hungary is relatively rare. According to our bibliometric analysis, the research articles on carbo of poplar or black locust in Hungary were 10 documents (data retrieved on 21 March 2023). Now, we repeat the same keywords and found 13 documents in Scopus database (data retrieved on 4 November 2024). In the future, our research can be continued with other species or forest management systems. To validate forest carbon dynamics, long-term experimental sites are also essential to calibrate our findings. The effect of climate change is actual, and the effect of climate change on forest carbon dynamics should be observed periodically.

B. Carbon footprint in short and long-rotation systems

The life cycle assessment method in the forestry sector is relatively new. The impact categories from LCA cover a wide range of environmental impacts (soil, air, water, and human). Based on Fig. 5.1. and Mulyana et al. (2023b), scholars researching LCA in Hungarian forests are still rare. One of the prominent researchers in Hungary on LCA in the forestry sector is Dr. András Polgar. He is researching LCA on different harvesting systems in SRC energy plantations and harvested wood products. Our study enriches research on LCA in Hungarian forests by comparing the carbon footprint in different management strategies (short- and long-rotation plantation management).

Based on our findings, the carbon footprint in short- and long-rotation plantation management systems is still lower than the forest's ability to absorb carbon emission and store carbon in the tree’s organs. The carbon footprint of poplar plantations in short and long-rotation for 45 years rotation is 17.7E+03 and 4.4E+03 kg CO_2 eq, respectively. Meanwhile, the carbon footprint for black locust plantations in short and long-rotation for 45 years rotation is 17.7E+03 and 4.0E+03 kg CO_2 eq, respectively.

The findings will also convince the stakeholders that the climate change mitigation actions in Hungary, such as reforestation and afforestation projects, are important and should be continued consistently. The ability of poplar plantations in absorbing carbon emissions from atmospheric in short and long-rotation are 4,492 and 22,479 times higher than carbon emissions. Meanwhile, the ability of poplar plantations in absorbing carbon emissions from atmospheric in short and long-rotation are 4,096 and 31,000 times higher than carbon emissions. Although forest operations released carbon emission during the 45-years rotation, the contribution of carbon sequestration from the atmosphere and then stored in biomass is also huge.

C. Carbon budget in short and long-rotation systems.

Generally, studies on carbon stock and carbon footprint are carried out separately. However, in our study, we used two approaches, carbon stock and carbon footprint, and then calculated the carbon balance. Our study provides evidence that planting black locust or poplar with long-rotation plantation management systems will better benefit carbon balance than SRC plantation management systems. The total carbon balance in black locust and poplar plantations in short-rotation coppice management systems for 45 years were 1.95E+05 – 3.39E+05 kg CO_2 eq. Furthermore, the total carbon balance for black locust and poplar long-rotation plantations were 2.3E+06 and 2.2E+06 kg CO_2 eq., respectively.

From the perspective of carbon balance, our findings can help stakeholders develop a decision support system in choosing the appropriate plantation management system. Especially for SRC plantation management systems, our finding also shows the mechanism of carbon neutrality of bioenergy from forest biomass is almost valid. It means that the energy transition from fossil fuels to biomass energy will reduce the carbon emissions in the atmospheric zone.

THESES

The most important scientific results of the PhD research are the following ones:

1. Our research has provided strong evidence of the ability of black locust and poplar plantations with short-rotation management systems to absorb carbon emissions from the atmosphere and store carbon above and belowground. The total carbon stock (biomass, product, soil, and bioenergy compartments) at the end of simulation period (45 years) for hybrid black locust Üllői, Jászkiséri, Nyírségi, Kiscsalai are 66.00, 53.28, 53.28, and 92.97 MgC/ha, respectively. Furthermore, the total carbon for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 are 110.30, 58.34, 119.74, and 60.71 MgC/ha, respectively. In biomass compartment, the carbon reached the peak before harvested (year 3, 6, 9, 12, and 15). Meanwhile, the carbon stock in soil compartment has shown increase regularly during the simulation period.
2. The total carbon in black locust and poplar plantation in long-rotation system has shown that the total carbon in yield class I is higher than yield class II, III, IV, V, and VI. It was strong evidence that the total carbon in CO2FIX modeling is closely related to input data of growth rate. The total carbon of poplar and black locust plantation at the end of simulation period 45 years to supply the sawmill, board, and pulp industry for yield class I, II, III, IV, V, and VI as follow:

	Total carbon at the age of 45 years (MgC/ha)					
	Poplar			**Black locust**		
	Sawmill	**Board**	**Pulp**	**Sawmill**	**Board**	**Pulp**
Yield Class I	91.38	90.12	93.75	99.90	98.92	101.75
Yield Class II	71.70	70.69	73.58	80.84	81.13	83.50
Yield Class III	53.68	52.93	55.09	63.69	63.97	66.99
Yield Class IV	39.44	38.88	40.48	50.30	49.79	51.24
Yield Class V	28.07	27.67	28.81	37.39	37.01	38.09
Yield Class VI	24.01	23.75	24.50	33.79	33.54	34.27

3. The accumulative of aboveground carbon of hybrid black locust and poplar in short-rotation coppice system is higher than the accumulative belowground carbon. The accumulative carbon stock above ground for hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 47.85, 38.55, 38.55, and 67.20 MgC /ha, respectively. However, the accumulative carbon stock in the belowground of hybrid black locust Üllői, Jászkiséri, Nyírségi, and Kiscsalai were 20.55, 16.62, 16.62, and 28.94 MgC /ha, respectively. Meanwhile, the accumulative carbon stock aboveground for hybrid poplar Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 56.40, 30.00, 61.05, and 31.20 MgC/ha, respectively. Furthermore, the accumulative carbon stock belowground for hybrid poplar

Agathe-F, I-214, Pannónia, and S 298-8 at end of simulation period 45 years are 35.81, 18.86, 38.91, and 19.63 MgC/ha, respectively.

4. In the long rotation system during the 45-year simulation, the accumulative of aboveground carbon of black locust and poplar are lower than the accumulative belowground carbon. The aboveground carbon stock in black locust and poplar were 2.28 – 12.18 and 3.26 – 9.95 MgC/ha, respectively. Moreover, the belowground carbon stock in black locust and poplar plantations were 21.91 – 52.43 and 11.57 – 41.82 MgC/ha, respectively.
5. Based on our findings, the carbon footprint in short- and long-rotation plantation management systems is still lower than the forest's ability to absorb carbon emission and store carbon in the tree’s organs. The findings will also convince the stakeholders that the climate change mitigation actions in Hungary, such as reforestation and afforestation projects, are important and should be continued consistently. The total carbon footprint from short-rotation forest plantation is 17.7E+03 kg CO_2 eq. Meanwhile, the total carbon footprint for black locust and poplar plantations in long-rotation management systems are 4.0E+03 and 4.3E+03 kg CO_2 eq.
6. Regarding LCA analysis in the short-rotation coppice management systems, the hotspot activity resulting in the highest environmental impact is in the first cycle. For all potential environmental impacts (abiotic depletion, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity potential, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, ozone layer depletion creation potential, and terrestrial ecotoxicity potential) in the first cycle is higher around 1.2 – 1.6 times from second, third, fourth, and fifth cycles.
7. Carbon balance of black locust and poplar plantation in short rotation coppice systems shows negative values. The negative values indicate the carbon absorption is higher than the carbon emission that is released during the forest operations. In black locust SRC management systems for cultivar Jászkiséri, Kiscsalai, Nyírségi, and Üllői, from planting to harvesting (3 years) has absorbed 3.84E+04, 6.65E+04, 3.84E+04, and 4.74E+04 kg CO_2 eq., respectively, from the atmosphere and released the carbon emission 1.06E10+3 kg CO_2 eq. to the atmosphere. Meanwhile, for hybrid poplar plantation for cultivar Agathe-F, I-214, Pannónia, and S 298-8, the amount of carbon absorption were 4.94E+04, 2.65E+04, 5.30E+04, and 2.74E+04 kg CO_2 eq., respectively, and released carbon emission 1.06E+03 kg CO_2 eq. Due to the short-rotation coppice system is harvested 5 times during the rotation period, the carbon negativity also will be higher than single harvesting period.

8. In the black locust and poplar plantations in long-rotation management systems, the average total carbon absorption for black locust and poplar (yield class I-VI) at the end of simulation period (45 years) were 2.81E+04 and 2.08E+04 kg CO_2 eq., respectively. Meanwhile, the total carbon emission that released from planting, thinning, and harvesting operations in 45 years rotation for black locust and poplar were 3.97E+03 and 4.25E+03 kg CO_2 eq., respectively. In the long rotation also has shown that the carbon sequestration was higher than the carbon emission.

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REFERENCES

Abbas F, Hammad HM, Ishaq W, et al (2020) A review of soil carbon dynamics resulting from agricultural practices. J Environ Manage 268:110319. https://doi.org/10.1016/j.jenvman.2020.110319

Ábri T, Keserű Z, Borovics A, et al (2022) Comparison of Juvenile, Drought Tolerant Black Locust (*Robinia pseudoacacia* L.) Clones with Regard to Plant Physiology and Growth Characteristics in Eastern Hungary: Early Evaluation. Forests 13:292. https://doi.org/10.3390/f13020292

Afas N Al, Marron N, Van Dongen S, et al (2008) Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). For Ecol Manage 255:1883–1891. https://doi.org/10.1016/j.foreco.2007.12.010

Ajit, Dhyani SK, Handa AK, et al (2017) Estimating carbon sequestration potential of existing agroforestry systems in India. Agroforestry Systems 91:1101–1118. https://doi.org/10.1007/s10457-016-9986-z

Ajit, Dhyani SK, Ramnewaj, et al (2013) Modeling analysis of potential carbon sequestration under existing agroforestry systems in three districts of Indo-gangetic plains in India. Agroforestry Systems 87:1129–1146. https://doi.org/10.1007/s10457-013-9625-x

Akmalluddin F, Sulistyawati E, Sutrisno (2019) Potential Biomass Production Estimation of Wood Energy Species in Post Mining Reclamation Area Using CO2FIX Model. In: IOP Conference Series: Earth and Environmental Science 394. Institute of Physics Publishing, p 012038

Alig RJ, Adams DM, McCarl BA, Ince PJ (2000) Economic potential of short-rotation woody crops on agricultural land for pulp fiber production in the United States. For Prod J 50:67–74

Almulqu AA (2017) Dynamic growth model simulation for carbon stock management in dry forest. Biosyst Divers 25:249–254. https://doi.org/10.15421/011738

Álvarez S, Rubio A (2013) Carbon Baseline in a Mixed Pine-Oak Forest in the Juarez Mountain Range (Oaxaca, Mexico) Using the CO2FIX V.3.2 Model. Revista Chapingo, Serie Ciencias Forestales y del Ambiente 19:125–137. https://doi.org/10.5154/r.rchscfa.2012.01.005

Alvarez S, Rubio A (2016) Wood Use and Forest Management for Carbon Sequestration in Community Forestry in Sierra Juárez, Mexico. Small-scale Forestry 15:357–374. https://doi.org/10.1007/s11842-016-9325-2

Amaducci S, Facciotto G, Bergante S, et al (2017) Biomass production and energy balance of herbaceous and woody crops on marginal soils in the Po Valley. GCB Bioenergy 9:31–45. https://doi.org/10.1111/gcbb.12341

Amichev BY, Hangs RD, Rees KCJ Van (2010) A novel approach to simulate growth of multi-stem willow in bioenergy production systems with a simple process-based model (3PG). Biomass Bioenergy 35:473–488. https://doi.org/10.1016/j.biombioe.2010.09.007

Athanassiadis D, Lidestav G, Wästerlund I (1999) Fuel, Hydraulic Oil and Lubricant Consumption in Swedish Mechanized Harvesting Operations, 1996. Journal of Forest Engineering 10:59–66

Aylott MJ, Casella E, Tubby I, et al (2008) Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. New Phytologist

Bacenetti J, Bergante S, Facciotto G, Fiala M (2016a) Woody biofuel production from short rotation coppice in Italy: Environmental-impact assessment of different species and crop management. Biomass Bioenergy 94:209–219. https://doi.org/10.1016/j.biombioe.2016.09.002

Bacenetti J, Fusi A, Negri M, et al (2014) Environmental assessment of two different crop systems in terms of biomethane potential production. Science of the Total Environment 466–467:1066–1077. https://doi.org/10.1016/j.scitotenv.2013.07.109

Bacenetti J, Pessina D, Fiala M (2016b) Environmental assessment of different harvesting solutions for Short Rotation Coppice plantations. Science of the Total Environment 541:210–217. https://doi.org/10.1016/j.scitotenv.2015.09.095

Balasuriya BTG, Ghose A, Gheewala SH, Prapaspongsa T (2022) Assessment of eutrophication potential from fertiliser application in agricultural systems in Thailand. Science of the Total Environment 833:154993. https://doi.org/10.1016/j.scitotenv.2022.154993

Barbara G (2018) Energetikai faültetvények környezeti hatásainak vizsgálata (Assessment of Environmental Impacts in Energy Plantation). University of Sopron, Hungary

Barbati A, Corona P, Marchetti M (2007) A forest typology for monitoring sustainable forest management: The case of European Forest Types. Plant Biosyst 141:93–103. https://doi.org/10.1080/11263500601153842

Barro R, Fern MJ, Ciria P (2020) Production and composition of biomass from short rotation coppice in marginal land: A 9-year study. Biomass Bioenergy 134:105478. https://doi.org/10.1016/j.biombioe.2020.105478

Baumannt H, Rydberg T (1994) Life cycle assessment A comparison of three methods for impact analysis and evaluation. J Clean Prod 2:13–20

Baumgartner RJ (2019) Sustainable development goals and the forest sector-A complex relationship. Forests 10:152. https://doi.org/10.3390/f10020152

Bergante S, Manzone M, Facciotto G (2016) Biomass and Bioenergy Alternative planting method for short rotation coppice with poplar and willow. Biomass Bioenergy 87:39–45. https://doi.org/10.1016/j.biombioe.2016.02.016

Berhongaray G, Cotrufo FM, Janssens IA, Ceulemans R (2019) Below-ground carbon inputs contribute more than above-ground inputs to soil carbon accrual in a bioenergy poplar plantation. Plant Soil 434:363–378. https://doi.org/10.1007/s11104-018-3850-z

Biró K, Szalmáné Csete M (2023) Revealing the concept of sustainability in life cycle assessment. Ecocycles 9:49–58. https://doi.org/10.19040/ecocycles.v9i2.277

Bjørn A, Laurent A, Owsianiak M, Olsen SI (2018a) Goal Definition. In: Hauschild M, Rosenbaum R, Olsen S (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 67–74

Bjørn A, Moltesen A, Laurent A, et al (2018b) Life Cycle Inventory Analysis. In: Hauschild M, Rosenbaum R, Olsen S (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 117–165

Bordoloi R, Das B, Tripathi OP, et al (2022) Satellite based integrated approaches to modelling spatial carbon stock and carbon sequestration potential of different land uses of Northeast India. Environmental and Sustainability Indicators 13:100166. https://doi.org/10.1016/j.indic.2021.100166

Bosner A, Porsinsky T, Stankic I (2012) Forestry and Life Cycle Assessment. In: Okia CA (ed) Global Perspective on Sustainable Forest Management. InTech, Croatia, pp 139–160

Cantamessa S, Rosso L, Giorcelli A, Chiarabaglio PM (2022) The Environmental Impact of Poplar Stand Management: A Life Cycle Assessment Study of Different Scenarios. Forests 13:464. https://doi.org/10.3390/f13030464

Chang H, Han HS, Anderson N, et al (2023) The Cost of Forest Thinning Operations in the Western United States: A Systematic Literature Review and New Thinning Cost Model. J For 121:193–206. https://doi.org/10.1093/jofore/fvac037

Charnley S (2006) Industrial plantation forestry: Do local communities benefit? Journal of Sustainable Forestry 21:35–57. https://doi.org/10.1300/J091v21n04_04

Chavan SB, Newaj R, Rizvi RH, et al (2021) Reduction of global warming potential vis-à-vis greenhouse gases through traditional agroforestry systems in Rajasthan, India. Environ Dev Sustain 23:4573–4593. https://doi.org/10.1007/s10668-020-00788-w

Chiarabaglio PM, Deidda A, Bergante S, et al (2020) Life Cycle Assessment (LCA): New poplar clones allow an environmentally sustainable cultivation. Annals of Silvicultural Research 45:72–82. https://doi.org/10.12899/asr-2017

Ciuvăţ AL, Vasile Abrudan I, Blujdea V, et al (2013) Biomass Equations and Carbon Content of Young Black Locust (*Robinia pseudoacacia* L.) Trees from Plantations and Coppices on Sandy Soils in South-Western Romanian Plain. Not Bot Horti Agrobot Cluj Napoca 41:590–592

Cronkleton P, Guariguata MR, Albornoz MA (2012) Forest Ecology and Management Multiple use forestry planning : Timber and Brazil nut management in the community forests of Northern Bolivia. For Ecol Manage 268:49–56. https://doi.org/10.1016/j.foreco.2011.04.035

D'Amato AW, Bradford JB, Fraver S, Palik BJ (2011) Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. For Ecol Manage 262:803–816. https://doi.org/10.1016/j.foreco.2011.05.014

Das B, Sarkar PK, Kumari N, et al (2019) Biophysical performance of different multipurpose trees species in Jharkhand, India. Curr Sci 116:82–88. https://doi.org/10.18520/cs/v116/i1/82-88

De Francesco F, Magagnotti N, Kováč B, et al (2022) Integrated Harvesting of Medium Rotation Hybrid Poplar Plantations: Systems Compared. Forests 13:1873. https://doi.org/10.3390/f13111873

de Jong BH, Masera O, Olguín M, Martínez R (2007) Greenhouse gas mitigation potential of combining forest management and bioenergy substitution: A case study from Central Highlands of Michoacan, Mexico. For Ecol Manage 242:398–411. https://doi.org/10.1016/j.foreco.2007.01.057

Deák Z, Ferencz Á (2017) Financial Feasibility of Short Rotation Energy Crops in Hungary: a Case Study. Annals of the Polish Association of Agricultural and Agribusiness Economists XIX:41–45. https://doi.org/10.5604/01.3001.0010.3213

Dijkman TJ, Basset-Mens C, Antón A, Núñez M (2018) LCA of Food and Agriculture. In: Hauschild M, Rosenbaum R, Olsen S (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 723–754

Dimitriou I, Rutz D (2015) Sustainable Short Rotation Coppice: A Handbook. WIP Renewable Energies, Munich

Directorate-General for Energy European Commission (2012) The Report on Greenhouse Gas Emissions from the Cultivation of Agricultural Crops Used as Raw Materials for Biofuels Production

Dixon RK, Brown S, Houghton RA, et al (1994) Carbon pools and flux of global forest ecosystems. Science (1979) 263:185–190. https://doi.org/10.1126/science.263.5144.185

Durojaye O, Laseinde T, Oluwafemi I (2020) A Descriptive Review of Carbon Footprint. In: Ahram T, Karwowski W, Pickl S, Taiar R (eds) Advances in Intelligent Systems and Computing. Springer Verlag, Munich, pp 960–968

Eisenbies MH, Volk TA, DeSouza D, et al (2021) An assessment of the harvesting and fuel performance of a single-pass cut-and-chip harvester in commercial-scale short-rotation poplar crops as influenced by crop and weather conditions. Biomass Bioenergy 149:106075. https://doi.org/10.1016/j.biombioe.2021.106075

Eisenbies MH, Volk TA, Espinoza J, et al (2017) Biomass, spacing and planting design influence cut-and-chip harvesting in hybrid poplar. Biomass Bioenergy 106:182–190. https://doi.org/10.1016/j.biombioe.2017.09.003

El Haouzali H, Marchal R, Bléron L, et al (2020) Some properties of plywood produced from 10 cultivars of poplar. International Wood Products Journal 11:101–106. https://doi.org/10.1080/20426445.2020.1735729

Eufrade-Junior H de J, Guerra SPS, Sansígolo CA, Ballarin AW (2018) Management of Eucalyptus short-rotation coppice and its outcome on fuel quality. Renew Energy 121:309–314. https://doi.org/10.1016/j.renene.2018.01.033

European Commission. Joint Research Centre. Institute for Environment and Sustainability (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps., First Edition. Publications Office of the European Union, Luxembourg

European Environment Agency (2019) EMEP/EEA air pollutant emission inventory guidebook 2019, technical guidance to prepare national emission inventories

Evans J (2004) Plantation Silviculture | Forest Plantations. In: Encyclopedia of Forest Sciences. Elsevier, pp 822–828

Faasch RJ, Patenaude G (2012) The economics of short rotation coppice in Germany. Biomass Bioenergy 45:27–40. https://doi.org/10.1016/j.biombioe.2012.04.012

Fahey RT, Alveshere BC, Burton JI, et al (2018) Shifting conceptions of complexity in forest management and silviculture. For Ecol Manage 421:59–71. https://doi.org/10.1016/j.foreco.2018.01.011

FAO (2020) Global forest resources assessment 2020, Report Hungary. Rome

Farooq TH, Shakoor A, Wu X, et al (2021) Perspectives of plantation forests in the sustainable forest development of China. IForest 14:166–174. https://doi.org/10.3832/ifor3551-014

Fazio S, Monti A (2011) Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass Bioenergy 35:4868–4878. https://doi.org/10.1016/j.biombioe.2011.10.014

Ferreira MC, Santos RC dos, Castro RVO, et al (2017) Biomass and Energy Production at Short Rotation Eucalyptus Clonal Plantations Deployed in Rio Grande Do Norte1. Revista Árvore 41:1–7. https://doi.org/10.1590/1806-90882017000500004

Fiala M, Bacenetti J (2012) Model for the economic, energy and environmental evaluation in biomass productions. Journal of Agricultural Engineering 43:5. https://doi.org/10.4081/jae.2012.e5

Finkbeiner M (2009) Carbon footprinting-opportunities and threats. International Journal of Life Cycle Assessment 14:91–94. https://doi.org/10.1007/s11367-009-0064-x

Food and Agriculture Organization of the United Nations (2020a) The State of the World’s Forests 2020. Forest, biodiversity, and people. Food and Agriculture Organization of the United Nations (FAO) and United Nations Environmental Programme (UNEP), Rome

Food and Agriculture Organization of the United Nations (2006) Global planted forest thematic study. Rome

Food and Agriculture Organization of the United Nations (2020b) Global Forest Resources Assessment 2020. Food and Agriculture Organization of the United Nations, Rome

Food and Agriculture Organization of the United Nations (2019) Global forest products facts and figures 2018. Rome

Fortier J, Truax B, Gagnon D, Lambert F (2013a) Mature hybrid poplar riparian buffers along farm streams produce high yields in response to soil fertility assessed using three methods. Sustainability (Switzerland) 5:1893–1916. https://doi.org/10.3390/su5051893

Fortier J, Truax B, Gagnon D, Lambert F (2013b) Root biomass and soil carbon distribution in hybrid poplar riparian buffers, herbaceous riparian buffers and natural riparian woodlots on farmland. Springerplus 2:539. https://doi.org/10.1186/2193-1801-2-539

Fortier J, Truax B, Gagnon D, Lambert F (2015) Biomass carbon, nitrogen and phosphorus stocks in hybrid poplar buffers, herbaceous buffers and natural woodlots in the riparian zone on agricultural land. J Environ Manage 154:333–345. https://doi.org/10.1016/j.jenvman.2015.02.039

Fortier J, Truax B, Gagnon D, Lambert F (2016) Potential for hybrid poplar riparian buffers to provide ecosystem services in three watersheds with contrasting agricultural land use. Forests 7:37. https://doi.org/10.3390/f7020037

Fortier J, Truax B, Gagnon D, Lambert F (2020) Soil nutrient availability and microclimate are influenced more by genotype than by planting stock type in hybrid poplar bioenergy buffers on farmland. Ecol Eng 157:105995. https://doi.org/10.1016/j.ecoleng.2020.105995

Fox TR (2000) Sustained productivity in intensively managed forest plantations. For Ecol Manage 138:187–202

Gabathuler H (1997) The CML Story How Environmental Sciences Entered the Debate on LCA. Int J Life Cycle Assess 2:187–194

Gabira MM, Girona MM, DesRochers A, et al (2023) The impact of planting density on forest monospecific plantations: An overview. For Ecol Manage 534:120882. https://doi.org/10.1016/j.foreco.2023.120882

Gaboury S, Boucher JF, Villeneuve C, et al (2009) Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec’s closed-crown boreal forest. For Ecol Manage 257:483–494. https://doi.org/10.1016/j.foreco.2008.09.037

Gauthier MM, Barrette M, Tremblay S (2015) Commercial thinning to meet wood production objectives and develop structural heterogeneity: A case study in the spruce-fir forest, Quebec, Canada. Forests 6:510–532. https://doi.org/10.3390/f6020510

Ghazoul J (2013) Deforestation and Land Clearing. In: Encyclopedia of Biodiversity. Elsevier, pp 447–456

Goedkoop M, Heijungs R, De Schryver A, et al (2009) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level

González-García S, Bacenetti J, Murphy RJ, Fiala M (2012a) Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. J Clean Prod 26:56–66. https://doi.org/10.1016/j.jclepro.2011.12.020

González-García S, Mola-Yudego B, Dimitriou I, et al (2012b) Environmental assessment of energy production based on long term commercial willow plantations in Sweden. Science of the Total Environment 421–422:210–219. https://doi.org/10.1016/j.scitotenv.2012.01.041

González-García S, Moreira MT, Dias AC, Mola-Yudego B (2014) Cradle-to-gate Life Cycle Assessment of forest operations in Europe: Environmental and energy profiles. J Clean Prod 66:188–198. https://doi.org/10.1016/j.jclepro.2013.11.067

González-García S, Moreira MT, Feijoo G, Murphy RJ (2012c) Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar). Biomass Bioenergy 39:378–388. https://doi.org/10.1016/j.biombioe.2012.01.028

Groot RS De, Alkemade R, Braat L, et al (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 7:260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

Guest G, Cherubini F, Strømman AH (2013) The role of forest residues in the accounting for the global warming potential of bioenergy. GCB Bioenergy 5:459–466. https://doi.org/10.1111/gcbb.12014

Hafezi SM, Zarea- Hosseinabadi H, Huijbregts MAJ, Steinmann ZJN (2021) The importance of biogenic carbon storage in the greenhouse gas footprint of medium density fiberboard from poplar wood and bagasse. Cleaner Environmental Systems 3:100066. https://doi.org/10.1016/j.cesys.2021.100066

Hart QJ, Tittmann PW, Bandaru V, Jenkins BM (2015) Modeling poplar growth as a short rotation woody crop for biofuels in the Pacific Northwest. Biomass Bioenergy 79:12–27. https://doi.org/10.1016/j.biombioe.2015.05.004

Hauk S, Knoke T, Wittkopf S (2014) Economic evaluation of short rotation coppice systems for energy from biomass - a review. Renewable and Sustainable Energy Reviews 29:435–448. https://doi.org/10.1016/j.rser.2013.08.103

He D, Chen K, Zhang T, et al (2021) Regional CO_2 budget and abatement countermeasures for forest scenic spots: A case study of the Shenyang national forest park. Sustainability (Switzerland) 13:861. https://doi.org/10.3390/su13020861

Heinimann HR (2012) Life Cycle Assessment (LCA) in Forestry-State and Perspectives. Croatian Journal of Forest Engineering 33:357–372

Holtsmark B (2015) Quantifying the global warming potential of CO_2 emissions from wood fuels. GCB Bioenergy 7:195–206. https://doi.org/10.1111/gcbb.12110

Huber JA, Matiu M, Hülsbergen KJ (2018) First-rotation growth and stand structure dynamics of tree species in organic and conventional short-rotation agroforestry systems. Heliyon 4:1–24. https://doi.org/10.1016/j.heliyon.2018.e00645

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. International Journal of Life Cycle Assessment 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

Hyyrynen M, Ollikainen M, Seppälä J (2023) European forest sinks and climate targets: past trends, main drivers, and future forecasts. Eur J For Res 142:1207–1224. https://doi.org/10.1007/s10342-023-01587-4

Intergovernmental Panel on Climate Change (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva

Intergovernmental Panel on Climate Change (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva

International Energy Agency (2022) Hungary 2022 Energy Policy Review

International Standarization Organization (2006a) ISO 14044 Environmental management-Life cycle assessment-Requirements and guidelines

International Standarization Organization (2006b) ISO 14040 Environmental management-Life cycle assessment-Principles and framework. Geneva

Islam S, Ponnambalam SG, Lam HL (2016) Review on life cycle inventory: methods, examples and applications. J Clean Prod 136:266–278. https://doi.org/10.1016/j.jclepro.2016.05.144

Jabareen Y (2008) A new conceptual framework for sustainable development. Environ Dev Sustain 10:179–192. https://doi.org/10.1007/s10668-006-9058-z

Jego G, Thibodeau F, Morissette R, et al (2017) Estimating the yield potential of short-rotation willow in Canada using the 3PG model. Canadian Journal of Forest Research 47:636–647. https://doi.org/10.1139/cjfr-2016-0353

Jia YL, Li QR, Xu ZQ, Sang WG (2016) Carbon cycle of larch plantation based on CO2FIX model. Chinese Journal of Plant Ecology 40:405–415. https://doi.org/10.17521/cjpe.2015.0208

Jiao W, Wang W, Peng C, et al (2022) Improving a Process-Based Model to Simulate Forest Carbon Allocation under Varied Stand Density. Forests 13:1212. https://doi.org/10.3390/f13081212

Jin I (2023) Probability of Achieving NDC and Implications for Climate Policy: CO-STIRPAT Approach. Journal of Economic Analysis 2:82–97. https://doi.org/10.58567/jea02040005

Johansson T, Hjelm B (2012) Stump and root biomass of poplar stands. Forests 3:166–178. https://doi.org/10.3390/f3020166

Johnston CR, Walsh LR, McCracken AR (2022) Effect of two vs. three year harvest intervals on yields of Short Rotation Coppice (SRC) willow. Biomass Bioenergy 156:106303. https://doi.org/10.1016/j.biombioe.2021.106303

Kaipainen T, Liski J, Pussinen A, Karjalainen T (2004) Managing carbon sinks by changing rotation length in European forests. Environ Sci Policy 7:205–219. https://doi.org/10.1016/j.envsci.2004.03.001

Kallio MH, Kanninen M, Krisnawati H (2012) Smallholder teak plantations in two villages in Central Java: Silvicultural activity and stand performance. Forests Trees and Livelihoods 21:158–175. https://doi.org/10.1080/14728028.2012.734127

Kanninen M (2010) Plantation forests: global perspectives. In: Bauhaus J, Van Der Meer P, Kanninen M (eds) Ecosystem goods and services from plantation forest. Earthscan, London, pp 1–15

Kaonga ML, Bayliss-Smith TP (2012) Simulation of carbon pool changes in woodlots in eastern Zambia using the CO2FIX model. Agroforestry Systems 86:213–223. https://doi.org/10.1007/s10457-011-9429-9

Kåresdotter E, Bergqvist L, Flores-Carmenate G, et al (2022) Modeling the Carbon Sequestration Potential of Multifunctional Agroforestry-Based Phytoremediation (MAP) Systems in Chinandega, Nicaragua. Sustainability (Switzerland) 14:4932. https://doi.org/10.3390/su14094932

Kilpeläinen A, Alam A, Strandman H, Kellomäki S (2011) Life cycle assessment tool for estimating net CO2 exchange of forest production. GCB Bioenergy 3:461–471. https://doi.org/10.1111/j.1757-1707.2011.01101.x

Kim H, Kim YH, Kim R, Park H (2015) Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. Forest Sci Technol 11:212–222. https://doi.org/10.1080/21580103.2014.987325

Király É, Börcsök Z, Kocsis Z, et al (2022) Carbon Sequestration in Harvested Wood Products in Hungary an Estimation Based on the IPCC 2019 Refinement. Forests 13:1809. https://doi.org/10.3390/f13111809

Király É, Borovics A (2024) Carbon sequestration of Hungarian forests by management system and protection status. Trees, Forests and People 15:100511. https://doi.org/10.1016/j.tfp.2024.100511

Kiss M, Cseh V, Tanács E (2015) Carbon sequestration of different types of floodplain forests in the Maros river valley (Hungary). In: Luc M, Somorowska U, Szmanda J (eds) Springer Geography, Landscape Analysis. Springer, pp 159–171

Klašnja B, Orlović S, Galić Z (2013) Comparison of Different Wood Species as Raw Materials for Bioenergy. South-East European Forestry 4:81–88

Klein D, Wolf C, Schulz C, Weber-Blaschke G (2015) 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. International Journal of Life Cycle Assessment 20:556–575. https://doi.org/10.1007/s11367-015-0847-1

Klöpffer W (2006) The role of SETAC in the development of LCA. International Journal of Life Cycle Assessment 11:116–122. https://doi.org/10.1065/lca2006.04.019

Koprivica R, Veljković B, Gavrilović M, et al (2021) Opremljenost I Angazovanost Mehanizacije Na Porodicnom Poljoprivrednom Gazdinstvu (equipment and engagement of mechanization on the family agricultural farm). Poljoprivredna tehnika 46:74–83. https://doi.org/10.5937/poljteh2104074k

Kouchaki-Penchah H, Sharifi M, Mousazadeh H, Zarea-Hosseinabadi H (2016) Life cycle assessment of medium-density fiberboard manufacturing process in Islamic Republic of Iran. J Clean Prod 112:351–358. https://doi.org/10.1016/j.jclepro.2015.07.049

Kovács K, Vityi A (2022) Soil and Atmospheric Microclimate Research in Poplar Forestry Intercropping System in Hungary. Acta Silvatica et Lignaria Hungarica 18:9–24. https://doi.org/10.37045/aslh-2022-0001

Kraszkiewicz A (2013) Evaluation of the Possibility of Energy Use Black locust (*Robinia pseudoacacia* L.) Dendromass Acquired in Forest Stands Growing on Clay Soils. Journal Central European Agriculture 14(1): 388-399.

Krzyżaniak M, Stolarski MJ, Warmiński K, et al (2023) Life Cycle Assessment of Poplar Biomass for High Value Products and Energy. Energies (Basel) 16:7287. https://doi.org/10.3390/en16217287

Kuka E, Cirule D, Andersone I, et al (2019) Life cycle inventory for currently produced pine roundwood. J Clean Prod 235:613–625. https://doi.org/10.1016/j.jclepro.2019.07.004

Kunickaya O, Tanyukevich V, Khmeleva D, et al (2020) Cultivation of the targeted forest plantations. Journal of Environmental Treatment Techniques 8:1385–1393. https://doi.org/10.47277/JETT/8(4)1393

Kurz WA, Dymond CC, White TM, et al (2009) CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol Modell 220:480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018

Langhof M, Schmiedgen A (2023) 13 years of biomass production from three poplar clones in a temperate short-rotation alley cropping agroforestry system. Biomass Bioenergy 175:106853. https://doi.org/10.1016/j.biombioe.2023.106853

Laureysens I, Pellis A, Willems J, Ceulemans R (2005) Growth and production of a short rotation coppice culture of poplar. III. Second rotation results. Biomass Bioenergy 29:10–21. https://doi.org/10.1016/j.biombioe.2005.02.005

Lemma B, Kleja DB, Olsson M, Nilsson I (2007) Factors controlling soil organic carbon sequestration under exotic tree plantations: A case study using the CO2Fix model in southwestern Ethiopia. For Ecol Manage 252:124–131. https://doi.org/10.1016/j.foreco.2007.06.029

Li T, Liu G (2014) Age-related changes of carbon accumulation and allocation in plants and soil of black locust forest on Loess Plateau in Ansai County, Shaanxi Province of China. Chin Geogr Sci 24:414–422. https://doi.org/10.1007/s11769-014-0704-3

Liu W, Zhang Z, Xie X, et al (2017) Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. Sci Rep 7:39857. https://doi.org/10.1038/srep39857

Livingstone D, Smyth BM, Lyons G, et al (2022) Life cycle assessment of a short-rotation coppice willow riparian buffer strip for farm nutrient mitigation and renewable energy production. Renewable and Sustainable Energy Reviews 158:112154. https://doi.org/10.1016/j.rser.2022.112154

Lovarelli D, Fusi A, Pretolani R, Bacenetti J (2018) Delving the environmental impact of roundwood production from poplar plantations. Science of the Total Environment 645:646–654. https://doi.org/10.1016/j.scitotenv.2018.06.386

Lupi C, Larocque G, Desrochers A, et al (2015) Evaluating sampling designs and deriving biomass equations for young plantations of poplar and willow clones Andr e. Biomass Bioenergy 83:196–205. https://doi.org/10.1016/j.biombioe.2015.09.019

Ma X, Wu L, Zhu Y, et al (2022) Simulation of Vegetation Carbon Sink of Arbor Forest and Carbon Mitigation of Forestry Bioenergy in China. Int J Environ Res Public Health 19:13507. https://doi.org/10.3390/ijerph192013507

Ma XZ, Wang Z (2011) Estimation of provincial forest carbon sink capacities in Chinese Mainland. Chinese Science Bulletin 56:883–889. https://doi.org/10.1007/s11434-011-4402-6

Mao Z, Derrien D, Didion M, et al (2019) Modeling soil organic carbon dynamics in temperate forests with Yasso07. Biogeosciences 16:1955–1973. https://doi.org/10.5194/bg-16-1955-2019

Marchi E, Chung W, Visser R, et al (2018) Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. Science of the Total Environment 634:1385–1397. https://doi.org/10.1016/j.scitotenv.2018.04.084

Marinov KI, Gochev Z, Stoilov S (2013) Technological opportunities survey of forest short rotation plantations in Bulgaria for energy biomass production. Part II : – Technology stages of creation and cultivation of wood biomass plantations. Innovation in Woodworking Industry and Engineering Design 1:161–173

Markewitz D (2006) Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. For Ecol Manage 236:153–161. https://doi.org/10.1016/j.foreco.2006.08.343

Marosvölgyi B, Halupa L, Wesztergom I (1999) Poplars as biological energy sources in Hungary. Biomass Bioenergy 16:245–247

Marosvolgyi B, Vityi A (2019) Use of Fast Growing Tree Species in a Crop Rotation (Gyorsannövő Fafajok Használata Vetésforgóban)

Martínez-Blanco J, Inaba A, Finkbeiner M (2015) Scoping organizational LCA—challenges and solutions. International Journal of Life Cycle Assessment 20:829–841. https://doi.org/10.1007/s11367-015-0883-x

Masera OR, Garza-Caligaris JF, Kanninen M, et al (2003) Modeling carbon sequestration in afforestation, agroforestry and forest management projects: The CO2FIX V.2 approach. Ecol Modell 164:177–199. https://doi.org/10.1016/S0304-3800(02)00419-2

Masiero M, Secco L, Pettenella D, Brotto L (2015) Standards and guidelines for forest plantation management: A global comparative study. For Policy Econ 53:29–44. https://doi.org/10.1016/j.forpol.2014.12.008

Matyka M, Radzikowski P (2020) Productivity and biometric characteristics of 11 varieties of willow cultivated on marginal soil. Agriculture (Switzerland) 10:616. https://doi.org/10.3390/agriculture10120616

McMahon SM, Parker GG, Miller DR (2010) Evidence for a recent increase in forest growth. In: Proceedings of the National Academy of Sciences of the United States of America. pp 3611–3615

Merry K, Bettinger P, Grebner D, et al (2017) Assessment of potential agricultural and short-rotation forest bioenergy crop establishment sites in Jackson County, Florida, USA. Biomass Bioenergy 105:453–463. https://doi.org/10.1016/j.biombioe.2017.08.004

Miina J, Pukkala T, Hotanen JP, Salo K (2010) Optimizing the joint production of timber and bilberries. For Ecol Manage 259:2065–2071. https://doi.org/10.1016/j.foreco.2010.02.017

Ministry For Innovation And Technology Hungary (2021) National Clean Development Strategy 2020 - 2050. Budapest

Mitchel C, Ford-Robertson J, Watters M (1991) Production from energy forest plantations. In: Grassi G, Collina A, Zibetta H (eds) Biomass for Energy, Industry and Environment, Sixth European Biomass Conference. Elsevier, London, pp 150–156

Monti A, Fazio S, Venturi G (2009) Cradle-to-farm gate life cycle assessment in perennial energy crops. European Journal of Agronomy 31:77–84. https://doi.org/10.1016/j.eja.2009.04.001

Mulyana B, Polgár A, Vityi A (2023a) Three Decades of Forest Carbon Dynamics Modeling Using CO2FIX: A Bibliometric Analysis. EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy 10:2105–2119

Mulyana B, Polgár A, Vityi A (2023b) Research trends in the environmental assessment of poplar plantations in Hungary: A bibliometric analysis. Ecocycles 9:23–32. https://doi.org/10.19040/ecocycles.v9i3.339

Mulyana B, Polgár A, Vityi A (2024) Forest Carbon Modeling in Poplar and Black Locust Short Rotation Coppice Plantation in Hungary. Jurnal Sylva Lestari 12:324–337. https://doi.org/10.23960/jsl.v12i2.883

Mulyana B, Purwanto RH (2020) Potensi Simpanan Karbon Ranting-Daun Kayu Putih Di KPH Yogyakarta. Gorontalo Journal of Forestry Research 3:23–30

Mulyana B, Purwanto RH, Rohman, Reorita R (2021) Allometric model to estimate biomass of leave-twigs cajuput (*Melaleuca cajuput*) at KPH Yogyakarta, Indonesia. In: IOP Conference Series: Earth and Environmental Science. p 012084

Mulyana B, Soeprijadi D, Hadi Purwanto R (2020a) Development of bioenergy plantation in Indonesia: Yield regulation and above-ground carbon storage in Gliricidia (*Gliricidia sepium*) plantation. In: E3S Web of Conferences. p 08009

Mulyana B, Soeprijadi D, Purwanto RH (2020b) Allometric Model Of Wood Biomass And Carbon for Gliricidia (*Gliricidia Sepium* (Jacq.) Kunth Ex Walp.) At Bioenergy Plantation In Indonesia. For Ideas 26:153–164

Nabuurs GJ, Mohren GM (1995) Modelling analysis of potential carbon sequestration in selected forest types. Canadian Journal of Forest Research 25:1157–1172. https://doi.org/10.1139/x95-128

Nabuurs GJ, Schelhaas MJ (2002) Carbon profiles of typical forest types across Europe assessed with CO2FIX. Ecol Indic 1:213–223

Nair PKR (2012) Carbon sequestration studies in agroforestry systems: a reality-check. Agroforestry Systems 86:243–253. https://doi.org/10.1007/s10457-011-9434-z

National Food Chain Safety Office (2016) Forest resources and forest management in Hungary 2015. Budapest

National Land Center Forestry Department (2024) Hungarian National Forest Inventory

Negash M, Kanninen M (2015) Modeling biomass and soil carbon sequestration of indigenous agroforestry systems using CO2FIX approach. Agric Ecosyst Environ 203:147–155. https://doi.org/10.1016/j.agee.2015.02.004

Neitzel H (1997) LCA and Ecolabelling Application of Life Cycle Assessment in Environmental Labelling. International Journal of Life Cycle Assessment 2:241–249

Németh R, Fehér S, Komán S (2018) Utilization of Fast Growing Plantation Timber as Bioenergy in Hungary. In: IOP Conference Series: Earth and Environmental Science 159. Institute of Physics Publishing, p 012029

Newell JP, Vos RO (2012) Accounting for forest carbon pool dynamics in product carbon footprints: Challenges and opportunities. Environ Impact Assess Rev 37:23–36. https://doi.org/10.1016/j.eiar.2012.03.005

Nicolescu VN, Hernea C, Bakti B, et al (2018) Black locust (*Robinia pseudoacacia* L.) as a multi-purpose tree species in Hungary and Romania: a review. J For Res (Harbin) 29:1449–1463. https://doi.org/10.1007/s11676-018-0626-5

Nicolescu VN, Rédei K, Mason WL, et al (2020) Ecology, growth and management of black locust (*Robinia pseudoacacia* L.), a non-native species integrated into European forests. J For Res (Harbin) 31:1081–1101. https://doi.org/10.1007/s11676-020-01116-8

Nölte A, Meilby H, Yousefpour R (2018) Multi-purpose forest management in the tropics: Incorporating values of carbon, biodiversity and timber in managing *Tectona grandis* (teak) plantations in Costa Rica. For Ecol Manage 422:345–357. https://doi.org/10.1016/j.foreco.2018.04.036

Nordfjell T, Athanassiadis D, Talbot B (2003) Fuel Consumption In Forwarders. International Journal of Forest Engineering 14:11–20. https://doi.org/10.1080/14942119.2003.10702474

Nuberg IK, Gunn B, Tavune M, et al (2015) Evaluation of short-rotation coppicing fuelwood production systems for Papua New Guinea. Biomass Bioenergy 78:126–139. https://doi.org/10.1016/j.biombioe.2015.04.010

Oliveira N, del Río M, Forrester DI, et al (2018a) Mixed short rotation plantations of *Populus alba* and *Robinia pseudoacacia* for biomass yield. For Ecol Manage 410:48–55. https://doi.org/10.1016/j.foreco.2017.12.034

Oliveira N, Rodríguez-soalleiro R, Pérez-cruzado C, et al (2018b) Above- and below-ground carbon accumulation and biomass allocation in poplar short rotation plantations under Mediterranean conditions. For Ecol Manage 428:57–65. https://doi.org/10.1016/j.foreco.2018.06.031

Oneil E, Puettmann ME (2017) A life-cycle assessment of forest resources of the pacific Northwest, USA. For Prod J 67:316–330. https://doi.org/10.13073/FPJ-D-17-00011

Országos Meteorológiai Szolgálat (2021) Climate of Hungary. https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/altalanos_eghajlati_jellemzes/altalanos_leiras/. Accessed 9 Dec 2021

Országos Meteorológiai Szolgálat(2022) Climate Data series 1901-2022. https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/eghajlati_adatsorok/Szombathely/adatok/napi_adatok/index.php. Accessed 23 Oct 2022

Pagdee A, Kim YS, Daugherty PJ (2006) What makes community forest management successful: A meta-study from community forests throughout the world. Soc Nat Resour 19:33–52. https://doi.org/10.1080/08941920500323260

Pandey D, Agrawal M, Pandey JS (2011) Carbon footprint: Current methods of estimation. Environ Monit Assess 178:135–160. https://doi.org/10.1007/s10661-010-1678-y

Pannacci E, Bartolini S, Covarelli G (2009) Evaluation of four poplar clones in a short rotation forestry in central Italy. Italian Journal of Agronomy 4:191–198. https://doi.org/10.4081/ija.2009.4.191

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. For Ecol Manage 168:241–257

Pecenka R, Hoffmann T (2015) Harvest technology for short rotation coppices and costs of harvest, transport and storage. Agronomy Research 13:361–371

Pennington DW, Potting J, Finnveden G, et al (2004) Life cycle assessment Part 2: Current impact assessment practice. Environ Int 30:721–739. https://doi.org/10.1016/j.envint.2003.12.009

Pereira S, Costa M (2017) Short rotation coppice for bioenergy: From biomass characterization to establishment – A review. Renewable and Sustainable Energy Reviews 74:1170–1180. https://doi.org/10.1016/j.rser.2017.03.006

Pereira S, Costa M, Carvalho M da G, Rodrigues A (2016) Potential of poplar short rotation coppice cultivation for bioenergy in Southern Portugal. Energy Convers Manag 125:242–253. https://doi.org/10.1016/j.enconman.2016.03.068

Phillips OL, Sullivan MJP, Baker TR, et al (2019) Species Matter: Wood Density Influences Tropical Forest Biomass at Multiple Scales. Surv Geophys 40:913–935. https://doi.org/10.1007/s10712-019-09540-0

Polgár A (2023) Carbon footprint and sustainability assessment of wood utilisation in Hungary. Environ Dev Sustain. https://doi.org/10.1007/s10668-023-03571-9

Polgár A, Horváth A, Mátyás KS, et al (2018) Carbon footprint of different harvesting work systems in short rotation energy plantations. Acta Silvatica et Lignaria Hungarica 14:113–126. https://doi.org/10.2478/aslh-2018-0008

Polgár A, Kovács Z, Fodor VE, Bidló A (2019) Environmental Life-Cycle Assessment of Arable Crop Production Technologies Compared to Different Harvesting Work Systems in Short Rotation Energy Plantations. Acta Silvatica et Lignaria Hungarica 15:55–68. https://doi.org/10.2478/aslh-2019-0005

Prada M, Bravo F, Berdasco L, et al (2016) Carbon sequestration for different management alternatives in sweet chestnut coppice in northern Spain. J Clean Prod 135:1161–1169. https://doi.org/10.1016/j.jclepro.2016.07.041

Pregitzer KS, Dickmann DI, Hendrick R, Nguyen P V (1990) Whole-tree carbon and nitrogen partitioning in young hybrid poplars. Tree Physiol 7:79–93

Proto AR, Bacenetti J, Macrì G, Zimbalatti G (2017) Roundwood and bioenergy production from forestry: Environmental impact assessment considering different logging systems. J Clean Prod 165:1485–1498. https://doi.org/10.1016/j.jclepro.2017.07.227

Puettmann M, Sahoo K, Wilson K, Oneil E (2020) Life cycle assessment of biochar produced from forest residues using portable systems. J Clean Prod 250:119564. https://doi.org/10.1016/j.jclepro.2019.119564

Purwanto RH, Mulyana B, Madya Septiana R, Permadi DB (2022) Allometric equation for the biomass and carbon stock of cajuput (*Melaleuca cajuputi* Powell) stand in Wanagama Forest, Yogyakarta, Indonesia. For Ideas 28:380–392

Quinkenstein A, Jochheim H (2016) Assessing the carbon sequestration potential of poplar and black locust short rotation coppices on mine reclamation sites in Eastern Germany - Model development and application. J Environ Manage 168:53–66. https://doi.org/10.1016/j.jenvman.2015.11.044

Rabbi MF, Kovács S (2024) Quantifying global warming potential variations from greenhouse gas emission sources in forest ecosystems. Carbon Research 3:70. https://doi.org/10.1007/s44246-024-00156-7

Radzikowski P, Matyka M, Berbeć AK (2020) Biodiversity of weeds and arthropods in five different perennial industrial crops in eastern Poland. Agriculture (Switzerland) 10:636. https://doi.org/10.3390/agriculture10120636

Rédei K (1999) Black locust (*Robinia pseudoacacia* L.) energy plantations in Hungary. Silva Gandavensis 64:37–43. https://doi.org/https://doi.org/10.21825/sg.v64i0.827

Rédei K (2000) Early performance of promising white poplar (*Populus alba*) clones in sandy ridges between the rivers Danube and Tisza in Hungary. Forestry 73:407–413

Rédei K, Csiha I, Keseru Z (2011) Black locust (*Robinia pseudoacacia* L.) short-rotation crops under marginal site conditions. Acta Silvatica et Lignaria Hungarica 7:125–132

Rédei K, Csiha I, Keseru Z, et al (2014) Growth and Yield of Black Locust (*Robinia pseudoacacia* L.) Stands in Nyírség Growing Region (North-East Hungary). South-east European forestry 5. https://doi.org/10.15177/seefor.14-04

Rédei K, Gál J, Keseru Z, Antal B (2017) Above-ground biomass of black locust (*Robinia pseudoacacia* L.) trees and stands. Acta Silvatica et Lignaria Hungarica 13:113–124. https://doi.org/10.1515/aslh-2017-0008

Rédei K, Keseru G, Szulcsan Z (2010a) Early Evaluation of Promising White Poplar (*Populus alba* L.) Clones in Hungary. Acta Silvatica et Lignaria Hungarica 6:9–16

Rédei K, Keserű Z, Rásó J (2012) Clonal approaches to growing Leuce poplars and their hybrids in Hungary. Hungarian Agricultural Research 3:14–17

Rédei K, Keserű Z, Rásó J (2012) Practice-Oriented Yield Table for White Poplar Stands Growing under Sandy Soil Conditions in Hungary. South-east European forestry 3:33–40. https://doi.org/10.15177/seefor.12-04

Rédei K, Osváth-Bujtás Z, Keserű Zs (2007) The Silviculture of Black locust (*Robinia pseudoacacia* L.) in Hungary: a review. South-East European forestry 13:101–107. https://doi.org/10.31421/ijhs/13/3/763

Rédei K, Takács M, Kiss T, Keserű Z (2019) Promising Leuce poplar clones in sandy ridges between the rivers Danube and Tisza in Hungary: a case study. Acta Agraria Debreceniensis 111–113. https://doi.org/10.34101/actaagrar/1/2380

Rédei K, Veperdi I (2009) The role of black locust in establishment of short rotation energy plantation in Hungary. Int J Hortic Sci 15:41–44

Rédei K, Veperdi I, Meilby H (2006) Stand structure and growth of mixed white poplar (*Populus alba* L.) and black locust (*Robinia pseudoacacia* L.) plantations in Hungary. Acta Silvatica et Lignaria Hungarica 2:23–32

Rédei K, Veperdi I, Tomé M, et al (2010b) Black Locust (*Robinia pseudoacacia* L.) Short-Rotation Energy Crops in Hungary: A Review. Silva Lusit 18:217–223

Rodrigues AM, Costa MMG, Nunes LJR (2021) Short rotation woody coppices for biomass production: An integrated analysis of the potential as an energy alternative. Current Sustainable Renewable Energy Reports 8:70–89. https://doi.org/10.1007/s40518-020-00171-3/Published

Rodríguez-Loinaz G, Amezaga I, Onaindia M (2013) Use of native species to improve carbon sequestration and contribute towards solving the environmental problems of the timberlands in Biscay, northern Spain. J Environ Manage 120:18–26. https://doi.org/10.1016/j.jenvman.2013.01.032

Rose DW, DeBell DS (1978) Economic Assessment of Intensive Culture of Short-Rotation Hardwood Crops. J For 76:706–711

Rosenbaum RK, Hauschild MZ, Boulay AM, et al (2018) Life cycle impact assessment. In: Hauschild M, Rosenbaum R, Olsen S (eds) Life Cycle Assessment: Theory and Practice. Springer International Publishing, pp 167–270

Rugani B, Golkowska K, Vázquez-Rowe I, et al (2015) Simulation of environmental impact scores within the life cycle of mixed wood chips from alternative short rotation coppice systems in Flanders (Belgium). Appl Energy 156:449–464. https://doi.org/10.1016/j.apenergy.2015.07.032

Sabatti M, Fabbrini F, Harfouche A, et al (2014) Evaluation of biomass production potential and heating value of hybrid poplar genotypes in a short-rotation culture in Italy. Ind Crops Prod 61:62–73. https://doi.org/10.1016/j.indcrop.2014.06.043

Sahoo K, Bergman R, Alanya-Rosenbaum S, et al (2019) Life cycle assessment of forest-based products: A review. Sustainability (Switzerland) 11:4722. https://doi.org/10.3390/su11174722

Sahoo K, Bergman R, Runge T (2021) Life-cycle assessment of redwood lumber products in the US. International Journal of Life Cycle Assessment 26:1702–1720. https://doi.org/10.1007/s11367-021-01937-7

Sarkar PK, Sarkar P, Kumar A, et al (2021) Carbon Storage Potential of a Waterlogged Agroforestry System of Tripura, India. Water Air Soil Pollut 232:151. https://doi.org/10.1007/s11270-021-05098-z

Schelhaas MJ, Van Esch PW, Groen TA, et al (2004a) CO2FIX V 3.1-Manual

Schelhaas MJ, Van Esch PW, Groen TA, et al (2004b) CO2FIX V 3.1 - description of a model for quantifying carbon sequestration in forest ecosystem and wood products. Wageningen

Schiberna E, Borovics A, Benke A (2021) Economic modelling of poplar short rotation coppice plantations in hungary. Forests 12:. https://doi.org/10.3390/f12050623

Schmid S, Thürig E, Kaufmann E, et al (2006) Effect of forest management on future carbon pools and fluxes: A model comparison. For Ecol Manage 237:65–82. https://doi.org/10.1016/j.foreco.2006.09.028

Schmidt HJ (2009) Carbon footprinting, labelling and life cycle assessment. International Journal of Life Cycle Assessment 14:S6–S9. https://doi.org/10.1007/s11367-009-0071-y

Schweier J, Magagnotti N, Labelle ER, Athanassiadis D (2019) Sustainability Impact Assessment of Forest Operations: a Review. Current Forestry Reports 5:101–113. https://doi.org/10.1007/s40725-019-00091-6

Sims REH, Maiava TG, Bullock BT (2001) Short rotation coppice tree species selection for woody biomass production in New Zealand. Biomass Bioenergy 20:329–335

Siry JP, Cubbage FW, Ahmed MR (2005) Sustainable forest management: Global trends and opportunities. For Policy Econ 7:551–561. https://doi.org/10.1016/j.forpol.2003.09.003

Sobocki S, Adamczyk F, Tylek P, et al (2023) A Seedling Collection Unit of a Mobile Automatic Device for Forest Tree Planting—An Extended Operating Concept. Forests 14:2420. https://doi.org/10.3390/f14122420

Spinelli R, Magagnotti N, De Francesco F, et al (2022) Cut-to-Length Harvesting Options for the Integrated Harvesting of the European Industrial Poplar Plantations. Forests 13:1478. https://doi.org/10.3390/f13091478

Spinelli R, Visser R, Björheden R, Röser D (2019) Recovering Energy Biomass in Conventional Forest Operations: a Review of Integrated Harvesting Systems. Current Forestry Reports 5:90–100. https://doi.org/10.1007/s40725-019-00089-0

Štochlová P, Novotná K, Costa M, Rodrigues A (2019) Biomass production of poplar short rotation coppice over five and six rotations and its aptitude as a fuel. Biomass Bioenergy 122:183–192. https://doi.org/10.1016/j.biombioe.2019.01.011

Stolarski MJ, Śnieg M, Krzyżaniak M, et al (2018) Short rotation coppices, grasses and other herbaceous crops: Biomass properties versus 26 genotypes and harvest time. Ind Crops Prod 119:22–32. https://doi.org/10.1016/j.indcrop.2018.03.064

Stolarski MJ, Stachowicz P (2023) Black locust, poplar or willow? Yield and energy value in three consecutive four-year harvest rotations. Ind Crops Prod 193:116197. https://doi.org/10.1016/j.indcrop.2022.116197

Stolpe NB, Dubé F, Zagal E (2010) Calibration of CO2FIX to native forest, pine plantation, and pasture on a volcanic soil of the Chilean Patagonia. Acta Agric Scand B Soil Plant Sci 60:235–244. https://doi.org/10.1080/09064710902865722

Szalay D, Kertész S, and Vágvölgyi A (2019) Changes in the legal and support background of woody energy plantations. Analecta Technica Szegedinensia 13(1): 72-81.

Tahvanainen V, Miina J, Pukkala T, Kurttila M (2018) Optimizing the joint production of timber and marketed mushrooms in Picea abies stands in eastern Finland. J For Econ 32:34–41. https://doi.org/10.1016/j.jfe.2018.04.002

Tenorio C, Moya R, Arias-aguilar D, Brice E (2016) Biomass yield and energy potential of short-rotation energy plantations of Gmelina arborea one year old in Costa Rica. Ind Crops Prod 82:63–73. https://doi.org/10.1016/j.indcrop.2015.12.005

The International Organization for Standardizations (2006) International Standard 14044, Environmental Management- Life Cycle Assessment — Requirements and Guidelines. Geneva

Toyoshima Y, Yamaura Y, Mitsuda Y, et al (2013) Reconciling wood production with bird conservation: A regional analysis using bird distribution models and forestry scenarios in Tokachi district, northern Japan. For Ecol Manage 307:54–62. https://doi.org/10.1016/j.foreco.2013.07.006

Truax B, Fortier J, Gagnon D, Lambert F (2018) Planting density and site effects on stem dimensions, stand productivity, biomass partitioning, carbon stocks and soil nutrient supply in hybrid poplar plantations. Forests 9:1–21. https://doi.org/10.3390/f9060293

Truax B, Gagnon D, Lambert F, Fortier J (2015) Multiple-use zoning model for private forest owners in agricultural landscapes: A case study. Forests 6:3614–3664. https://doi.org/10.3390/f6103614

UNFCCC (2022) Greenhouse Gas Emissions Calculator. https://unfccc.int/documents/271269?gad_source=1&gclid=EAIaIQobChMImav9y42PhQMVp1tBAh2-QQIfEAAYAiAAEgJn_fD_BwE. Accessed 25 Mar 2024

Vágvölgyi A (2014) Fás Szárú Energetikai Ültetvények Helyzete Magyarországon Napjainkig; Üzemeltetésük, Hasznosításuk Alternatívái. PhD dissertation. 195 p. University of Sopron, Hungary.

Vanbeveren SPP, Schweier J, Berhongaray G, Ceulemans R (2015) Operational short rotation woody crop plantations: Manual or mechanised harvesting? Biomass Bioenergy 72:8–18. https://doi.org/10.1016/j.biombioe.2014.11.019

Vanbeveren SPP, Spinelli R, Eisenbies M, et al (2017) Mechanised harvesting of short-rotation coppices. Renewable and Sustainable Energy Reviews 76:90–104. https://doi.org/10.1016/j.rser.2017.02.059

Veli P (1983) Short-rotation forestry. The Finnish Forest Research Institute, Vantaa

Verkerk H, Delacote P, Hurmekoski E, et al (2022) Forest-based climate change mitigation and adaptation in Europe

Verlinden MS, Broeckx LS, and Ceulemans R. 2015. First vs. second rotation of poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics. Biomass and Bioenergy 73: 174-185.

Vítková M, Müllerová J, Sádlo J, et al (2017) Black locust (*Robinia pseudoacacia*) beloved and despised: A story of an invasive tree in Central Europe. For Ecol Manage 384:287–302. https://doi.org/10.1016/j.foreco.2016.10.057

Vityi, A ; Marosvölgyi, B ; Ivelics, R ; Szűcs-Szabó, L (2003) Increasing the raw material basis of bio-briquette production by using new materials. Hungarian Agricultural Engineering 2003/16, pp. 84-85.

Wackernagel M, Rees W (1996) Our Ecological Footprint, Reducing Human Impact on the Earth. New Society Publisher, Gabriola Island

Weih M (2004) Intensive short rotation forestry in boreal climates: present and future perspectives. Canadian Journal of Forest Research 34:1369–1378. https://doi.org/10.1139/x04-090

Werner C, Haas E, Grote R, et al (2012) Biomass production potential from Populus short rotation systems in Romania. GCB Bioenergy 4:642–653. https://doi.org/10.1111/j.1757-1707.2012.01180.x

Willebrand E, Ledin S, Verwijst T (1993) Willow Coppice Systems In Short Rotation Forestry: Effects of Plant Spacing, Rotation Length And Clonal Composition On Biomass Production. Biomass Bioenergy 4:323–331

Winter R, Pölz W, Süssenbacher E, et al (2010) Typical Greenhouse Gas Emissions from Cultivation of Agricultural Raw Materials for Use as Biofuel and Bioliquid. Vienna

Xiaodong Y, Junfang Z (2007) Establishing and validating individual-based carbon budget model FORCHHN of forest ecosystem in China. Acta Ecologica Sinica 27:2684–2694

Xie J, Zhang G, Li Y, et al (2023) A Bibliometric Analysis of Forest Gap Research during 1980–2021. Sustainability 15:1994. https://doi.org/10.3390/su15031994

Yadav PN, Dev Prakash O, Springate-Baginski O, Soussan J (2003) Forest Management and Utilization Under Community Forestry. Journal of forest and livelihood 3:37–50

Yuzhakova T, Rédey Á, Lakó J, et al (2012) Biomass potential in Hungary. Fresenius Environ Bull 21:2356–2361

Zbieć M, Franc-Dąbrowska J, Drejerska N (2022) Wood Waste Management in Europe through the Lens of the Circular Bioeconomy. Energies (Basel) 15:4352. https://doi.org/10.3390/en15124352

Zhang L, Sun Y, Song T, Xu J (2019) Harvested wood products as a carbon sink in China, 1900-2016. Int J Environ Res Public Health 16:445. https://doi.org/10.3390/ijerph16030445

Zhang X, Yang H, Chen J (2018) Life-cycle carbon budget of China’s harvested wood products in 1900–2015. For Policy Econ 92:181–192. https://doi.org/10.1016/j.forpol.2018.05.005

Zhang X, Zhang W, Xu D (2020) Life cycle assessment of complex forestry enterprise: A case study of a forest-fiberboard integrated enterprise. Sustainability (Switzerland) 12:4147. https://doi.org/10.3390/su12104147

Zhou S, Runge T, Karlen SD, et al (2017) Chemical Pulping Advantages of Zip-lignin Hybrid Poplar. ChemSusChem 10:3565–3573. https://doi.org/10.1002/cssc.201701317

Zhou W, Gao L (2016) The impact of carbon trade on the management of short-rotation forest plantations. For Policy Econ 62:30–35. https://doi.org/10.1016/j.forpol.2015.10.008