University of Sopron
Roth Gyula Doctoral School of Forestry and Game
Management Sciences

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

By:
Budi Mulyana

Supervisors:
Dr. Andrea Vityi
Dr. András Polgár

Sopron
2024

1. Introduction

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 (Nicolescu et al., 2018; Rédei et al., 2011), wood and wildlife conservation (Toyoshima et al., 2013), as well as wood with environmental services to absorb forest carbon (Mulyana et al., 2023b, 2023a, 2024; Nölte et al., 2018). 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 (Kovács & Vityi, 2022; Marosvölgyi & Vityi, 2019).

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; Jego et al., 2017; Lupi et al., 2015). 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., 2016), Germany (Faasch & 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.), poplar (*Populus* sp.), and elm (*Ulmus pumilla*) (Yuzhakova et al. 2012). Black locust (*Robinia pseudoacacia*) and poplar (*Populus* sp.) are the prominent species in forests of West and Central European countries. Black locust and poplar 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 poplar, from bioenergy plantations with short rotation coppice systems is a promising solution to support energy transition (Marosvölgyi & Vityi, 2019; Németh et al., 2018) . 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 dynamic 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., 2023a).

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.

1.1. Research objective

In this research, we propose some research questions as follows

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

2. Literature review

Literature review has been elaborated in the scientific documents (dissertation, journal articles, and conference proceedings). The literature review section divided into forest operations (plantation management, short-rotation coppice systems, forest plantations for industrial purposes), forest carbon cycle (forest carbon pools, forest carbon modelling), environmental management (life cycle assessment).

3. Research methodology

3.1. Data collection

CO2FIX software 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, 2004b). In the CO2FIX software, carbon dynamics are divided into three modules: biomass, soil, and products. Each module required data, such as growth rate, current annual increment, relative growth of tree components, percentage carbon content, wood product allocations, and climatology data.

Data on black locust growth was derived from the local black locust yield table developed by Rédei et al. (2014) from 105 sampling plots in the Nyírség region, Hungary. Whereas the growth of poplar was collected from a local poplar yield table constructed from 90 sampling plots in the sandy ridges between the rivers 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).

Data for life cycle inventory was collected from a literature review and database. Fuel and lubricants, fertilizers, and pesticide consumption were required as input data during the rotation. The most significant obstacle in the LCA process is the availability of inventory data, which practitioners and researchers address by employing proxy data (Kouchaki-Penchah et al., 2016). Furthermore, Kouchaki-Penchah et al. (2016) explained that the proxy data may be obtained from literature, such as the Ecoinvent database, ETH-ESU 96 database in Simapro 8 software, reports, and reviewed papers.

3.2. Data analysis

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 to use by end users 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.

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).

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. 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 N, P_2O_5, 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).

4. New Scientific result

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, Pannonia, 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. 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.
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, Pannonia, 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, Pannonia, 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, Pannonia, 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.

5. References

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6. Publication list

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**)
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