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Forest Carbon Modeling in Poplar and Black Locust Short Rotation Coppice Plantation in Hungary

Budi Mulyana[1,2,*], András Polgár[1], Andrea Vityi[1]

[1] Faculty of Forestry, University of Sopron, Sopron, Hungary
[2] Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta, Indonesia
[*] Corresponding Author. E-mail address: budimulyana@ugm.ac.id

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ABSTRACT

Forest carbon dynamic modeling for estimating the carbon stock in short rotation coppice bioenergy plantation in Hungary will be vital for better comprehending the role of black locust (*Robinia pseudoacacia*) and poplar (*Populus* sp.) in carbon dioxide sequestration from the atmosphere. The research aims were 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. Modeling has been around for 45 years. In this research, the total carbon stock of black locust and poplar at the end of the simulation period was 64.13 and 131.08 $MgC.ha^{-1}$, respectively. The average carbon allocation above and below ground for black locust and poplar was 0.76, 19.76, 1.80, and 21.67 $MgC.ha^{-1}$, respectively. In conclusion, poplar outperformed black locust regarding carbon storage in the short rotation coppice bioenergy plantation. Below ground carbon allocation was much higher than above ground. Therefore, more attention should be paid on below ground allocation through environmentally friendly soil management.

1. Introduction

Climate change mitigation through reducing greenhouse gasses (GHG) emissions and removing sequestering carbon from the atmosphere to the biosphere is vital to prevent global warming. Global climate change actions emphasize reducing carbon emissions and enhancing carbon sequestration (Huang et al. 2020). Reducing carbon emissions, strategies decrease deforestation (Gatti et al. 2021) and promote energy transition from fossil fuel to renewable energy, such as wind, solar photovoltaic, and biomass (Creutzig et al. 2014). Furthermore, the carbon emission in the atmosphere can be sequestered through afforestation and reforestation actions (He et al. 2015; Ogunbode 2021). At the same time, the transition of energy from fossil fuel to biomass through bioenergy plantations is essential for reducing GHG and ensuring renewable energy sustainability (Pereira and Costa 2017).

Developing bioenergy plantations is one of the promising solutions in the energy transition to achieve a carbon neutrality scheme. In the carbon neutrality strategy, establishing fast-growing species such as hybrid poplar on unproductive land without harvesting scenarios for certain rotation could sequester the carbon emissions from the atmosphere and store them in the tree's biomass (Ménard et al. 2023). Furthermore, to minimize carbon loss, the harvested wood should be converted into a span of products or substituted the fossil fuel with wood biomass to generate energy through the combustion process (Giuntoli et al. 2020; Ménard et al. 2023). Developing bioenergy plantations in the agricultural and forest landscape can contribute to climate change mitigation actions (Calvin et al. 2021; Creutzig et al. 2015). The European Union (EU) has set an ambitious target to reduce GHG emissions to 55% by 2030 compared to 1990 levels and achieve carbon neutrality by 2050 (European Commission 2020), in which the rise of renewable energy will play a decisive role, and energy consumption share up to 20% from renewable energy sources (Pereira and Costa 2017). The primary renewable energy sources in the EU are bioenergy, around 60% of the total renewable energy (Scarlat 2019), followed by wind energy (14.56%), hydroelectric power (12.71%), solar energy (7.02%), liquid biofuels (6.63%), biogas (6.28%), heat pumps (6.61%), municipal waste (3.93%), geothermal energy (2.4%), and ocean wave energy (0.02%) (Stachowicz and Stolarski 2023).

Short rotation coppice (SRC) bioenergy plantations in Hungary have been developed in rural development projects to support renewable energy and enhance the carbon stock. According to the National Food Chain Safety Office of Hungary (2016), the total area of black locust and poplar (hybrid and native) was 80.44% (13,921 ha) of the total areas of afforestation and reforestation projects. Ecologically and economically, the development of the SRC bioenergy plantation in Hungary has had positive impacts (Schiberna et al. 2021).

Estimating and modeling the carbon dynamic from SRC bioenergy plantation are useful to understand better 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; b). Furthermore, the main objectives of this research were to estimate the potential carbon stock of the SRC bioenergy plantation, and to describe the carbon allocation in above and below ground SRC bioenergy plantations.

2. Materials and Methods

2.1. Short Rotation Coppice System in Bioenergy Plantation

The SRC system is a silviculture method for fast-growing species to produce fiber and bioenergy in a short period. Schiberna et al. (2021) explained that characteristics of SRC were using fast-growing species, high density planting, harvested at around 2-8 years, and can be maintained until 20 years using the coppicing system. Poplar (*Populus* spp.) and willow (*Salix* spp.) were the fast-growing species cultivated in short rotation and utilized as supply for bioenergy (electricity and heat) (Hauk et al. 2014). Furthermore, Hauk et al. (2014) reviewed 37 studies on short rotation coppice and found that 43% was economically feasible, and the profitability was affected by the biomass price and yield. In the Mediterranean conditions, the poplar short rotation coppice system can be achieved when the optimum yield was 56.52 $Mg.ha^{-1}.yr^{-1}$, biomass price was 40 $Euro.Mg^{-1}$, and the cultivation period was 12 years (4 rotations of 3 years each) (Fuertes et al. 2021). In this research, we used the terminology of the SRC system because the rotation is short (3 years), and the regeneration method uses the sprouting/coppicing system.

According to Czupy et al. (2012), the characteristics of SRC in Hungary can be described as follows: the rotation is 1–3 years and can be harvested many times, the species of SRC have a thin diameter around 1–5(10) cm, harvesting technology is using mobile chipper with the cutting height of 15–25 cm above the ground, sprout easily from the stump after harvesting. Furthermore, Schiberna et al. (2021) described the SRC as a woody plantation with fast-growing species, planted in high density and harvested in short rotation (2–8 years) for a 15–25 years lifecycle. Moreover, the yield of SRC depends on the proper clones, site quality, and management practices (Štochlová et al. 2019).

2.2. Model Parameterization

Forest carbon modeling is a tool to estimate the carbon stock in a certain period and is helpful for stakeholders as consideration on climate change mitigation policies and actions. Forest carbon modeling can be developed based on photosynthesis processes (Gennaretti et al. 2017) and empirical growth data (Kim et al. 2015). Furthermore, forest carbon modeling using empirical growth data has been used widely because this approach is more user-friendly than photosynthesis process data (Kim et al. 2015).

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. The consideration for choosing a 45 year simulation period is that the plantation management of poplar and black locust in Hungary can be done with a short rotation to supply bioenergy material or a long rotation (45 years) to support the industrial needs. Thus, by choosing a simulation period of 45 years, the plantation manager can consider whether to use their land for short or long rotation wood production. 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 (**Fig. 1**).

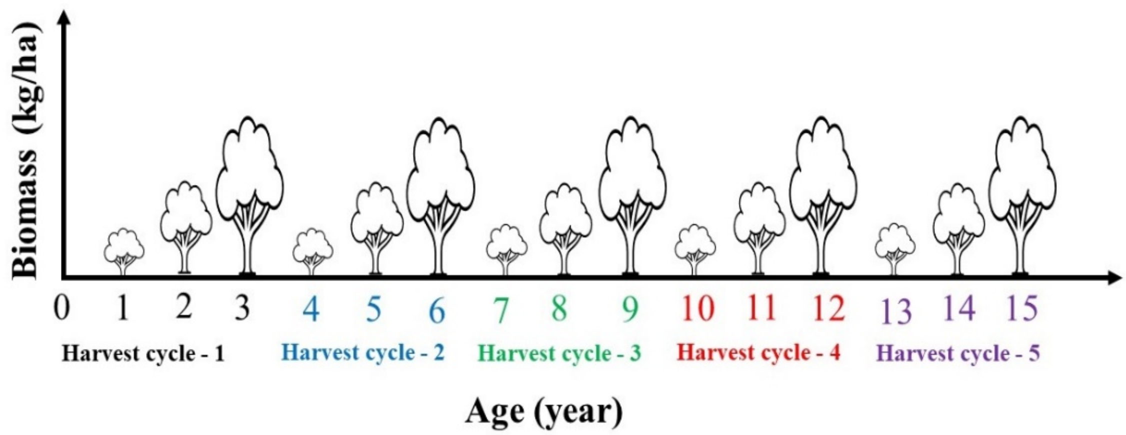

Fig. 1. Illustration of short rotation coppice management.

The development of the CO2FIX model for SRC bioenergy plantation in Hungary was focused on black locust and poplar species. As a prominent and dominant species for SRC bioenergy plantation, research to find promising cultivars of poplar and black locust has been done by researchers. In the early development of CO2FIX software for forest carbon modeling, this software has been applied in 16 forest types (Masera et al. 2003). Furthermore, for three decades, the CO2FIX software has been applied in 27 countries and various forest types (Mulyana et al. 2023b). The parameters of carbon dynamic simulation were divided into biomass, soil, products, and bioenergy cohorts (Masera et al. 2003; Schelhaas et al. 2004b). The parameters for developing the carbon dynamic in SRC bioenergy plantation using the CO2FIX model V 3.2 are summarized in **Table 1**.

Data was collected through field observations, expert interviews, and literature reviews. The growth rate of poplar and black locust was taken from previous researches conducted in several experimental sites in Hungary. Meanwhile, the climatology data was taken from the results of measurements by the Hungarian Meteorological Agency. Furthermore, the results of the CO2FIX simulation were discussed with the experts, and the actual condition of poplar and black locust growth was checked at the experimental site of the Forest Research Institute of the University of Sopron.

2.3. Simulation of Carbon Dynamic using CO2FIX Model

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; b). 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). Globally, the CO2FIX software has been applied in forest plantations and agroforestry systems to estimate the forest carbon dynamics (Mulyana et al. 2023b). In this study, CO2FIX was used to simulate forest carbon dynamics at SRC black locust and poplar bioenergy plantations.

According to Masera et al. (2003) and Schelhaas et al. (2004b), total carbon stock at time-$_t$ is the summation of carbon stock in the living biomass, soil organic matter, and wood products. Equation 1 calculates the changes in carbon stocks.

$$CT_t = Cb_t + Cs_t + Cp_t \quad (1)$$

where CT_t is total carbon at time-$_t$ (Mg C.h^{-1}), Cb_t is carbon stock in living biomass (stem, branches, leaves, and roots) at time-$_t$ (Mg C.h^{-1}), Cs_t is carbon stock in soil organic matter (Mg C.h^{-1}) at time-$_t$, and Cp_t is carbon stock in wood products (MgC.h^{-1}) 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. 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 Equation 2.

$$A = CT_t = Cbio_t \quad (2)$$

where A is the total atmospheric effect, and $Cbio_t$ is avoided emissions from bioenergy use at the time ($_t$).

Table 1. Model parameterization to develop CO2FIX modeling

Parameters	Unit	Value		References
		Black locust	**Poplar**	
Growth rate	ton/ha/year	3.12	35.71	Rédei et al. (2010, 2011); Schiberna et al. (2021)
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)
• Above ground		49	47	
• Below ground		45	46	
Climatic condition				Orszagos Meteorologiai Szolgalat (2022)
• Degree days (above zero)	°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.

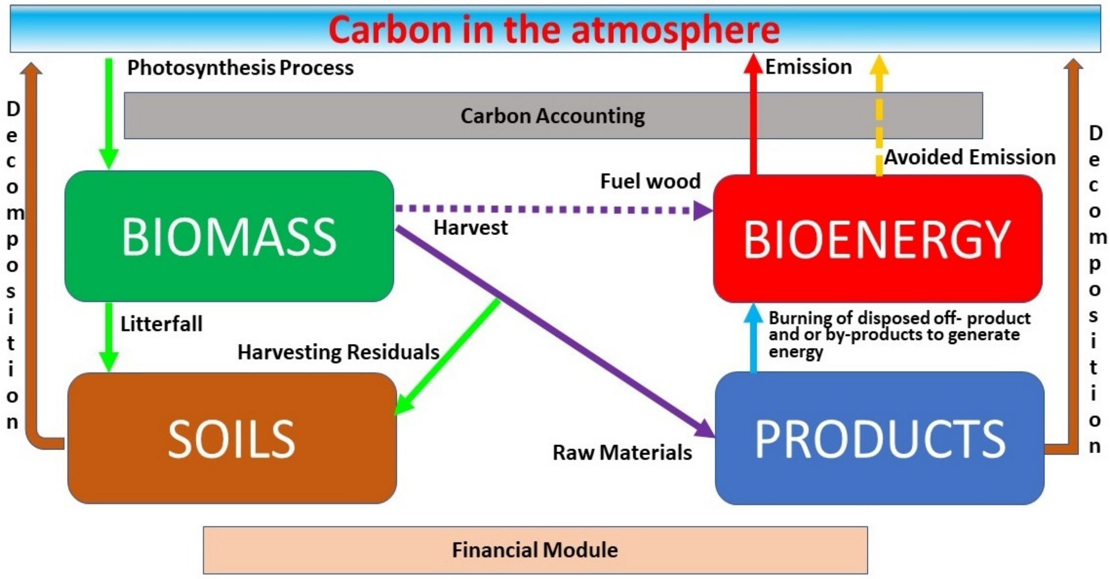

Fig. 2. Carbon dynamics in CO2FIX modeling adopted from Schelhaas et al. (2004b).

3. Results and Discussion

3.1. Overview of Poplar and Black Locust Plantations for Bioenergy

The short rotation coppice system has received attention in European countries, including Hungary, as a potential renewable energy source and tool to reduce greenhouse gas emissions to support climate change mitigation. In Hungary, the most prominent species as SRC for bioenergy plantation are black locust (*R. pseudoacacia*) and poplar (*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. 3**).

(a) (b)

Fig. 3. Coppice system of (a) black locust and (b) poplar.

In Hungary, one-third of black locust stands were utilized for industry (mining, construction, and furniture), while two-thirds were for energy and fiber purposes 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 et al. 2014, 2019).

Furthermore, poplar cultivation uses native and hybrid poplar species. The native poplars in Hungary are white poplars (*Populus alba* L) and grey poplars (*Populus x canescens)* (Rédei et al. 2012a; b). Moreover, the promising hybrid poplar for biomass production are white poplar clones (H-337 and H-384 (*P. alba x P. grandidentata*)) (Rédei et al. 2010), leuce poplar clones (H-425-4 (*Populus alba x Populus alba*), H 758 (*Populus alba* L. *Mosonmagyaróvár*), and H 427-3 (*Populus alba x Populus grandidentata*)) (Rédei et al. 2019). Thus, the management practices of black locust and poplar also varied, depending on the site characteristics (**Table 2**).

Table 2. Short rotation coppice system of black locust and poplar in Hungary

Characteristics	Unit	Black locust	Poplar
Spacing	m^2	1.5 × 0.3	3 × 0.6
		1.5 × 0.5	2.0 × 2.0
		1.5 × 1.0	1.5 × 0.5
Density	tree. ha^{-1}	10,000–22,222	2,500–13,333
Yield	ton. ha^{-1}. $year^{-1}$	6.7–8.0	4–12
Harvesting cycle	year	2–8	4
Rotation	year	15–25	15

Sources: Redei (1999) and Schiberna et al. (2021).

Wood is considered for bioenergy heating value, moisture content (Pereira and Costa 2017), ash content, and volatile matters (Marosvölgyi et al. 1999). 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 3**.

Table 3. Properties of black locust and poplar for bioenergy sources

Properties	Unit	Value		References
		Black locust	Poplar	
Wood density	g/cm^3	0.60	0.33	Klašnja et al. (2013)
Carbon content	% DM	52.60	53.46	Stachowicz and Stolarski (2023)
Heating value	MJ/kg	17.39–21.19	15.14–18.56	Klašnja et al. (2013); Marosvölgyi et al. (1999)
Ash content	% DM	1.67–2.08	1.67–4.81	Marosvölgyi et al. (1999); Stachowicz and Stolarski (2023)
Moisture content	% DM	38.89–41.52	47.30–56.52	Marosvölgyi et al. (1999); Stachowicz and Stolarski (2023)
Volatile matter	% DM	77.86	77.83	Stachowicz and Stolarski (2023)

Note: DM is a dry mass.

Referring to **Table 3**, the density 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 (IPCC 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. 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 (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).

3.2. Potential Carbon Stock in Short Rotation Coppice Bioenergy Plantation

In the previous section, in terms of thermal properties, black locust has shown better wood properties than poplar. However, from the perspective of carbon storage, the growth and carbon content of poplar was higher than that of black locust. Furthermore, the total carbon stock of poplar was better than that of black locust in a simulation period of 45 years (**Fig. 4**).

According to **Fig. 4**, the total carbon of black locust and poplar at the end of the simulation period were 64.13 and 131.08 MgC.ha^{-1}, respectively. For black locust and poplar, the dominant carbon stock was stored in the soil compartment, followed by biomass and product compartments. At the end of the simulation period (45 years), the carbon stock in black locust and poplar soil compartments was 28.46 and 33.02 MgC.ha^{-1}, respectively. Moreover, 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. The total carbon in the biomass compartment at the black locust and poplar harvesting cycle were 3.85 and 4.13 MgC.ha^{-1}, respectively.

The percentage of carbon in bioenergy to total carbon stock in black locust and poplar was 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.

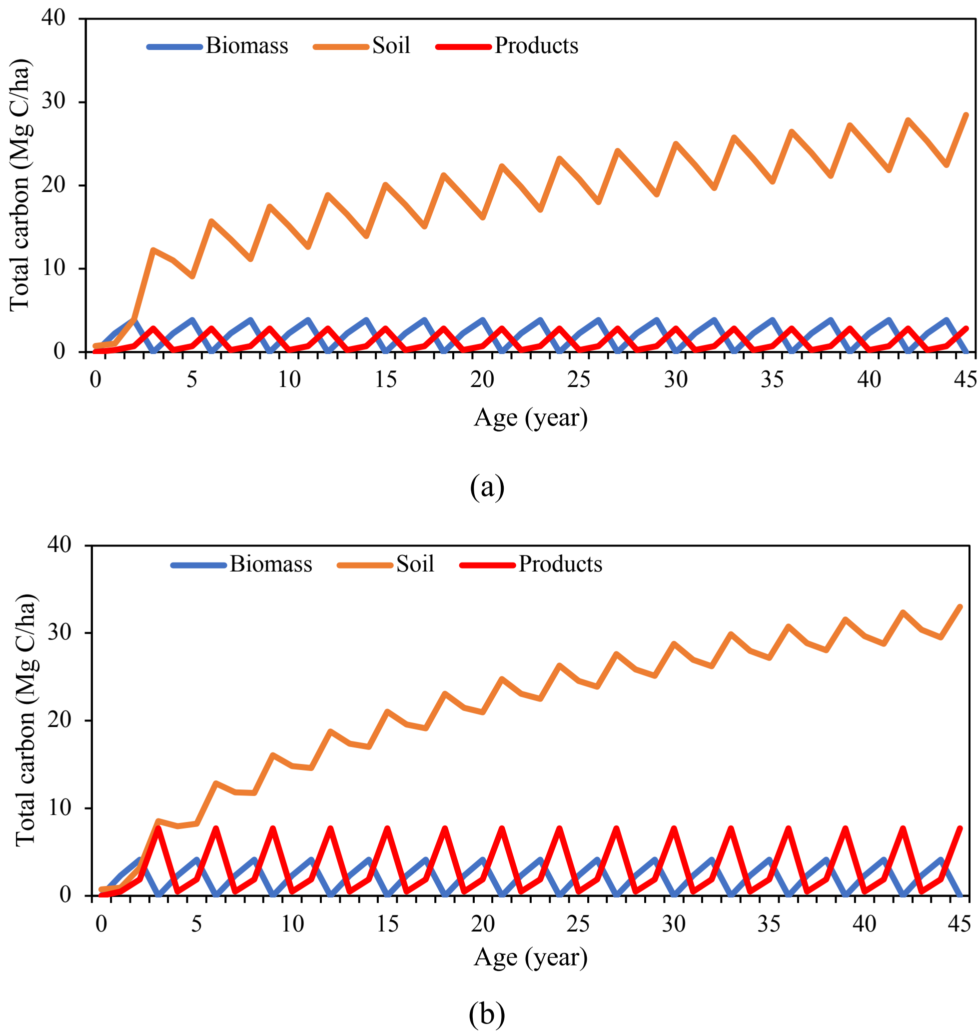

Fig. 4. Carbon dynamic in short rotation coppice (a) black locust and (b) poplar.

3.3. *Carbon Allocation in Short Rotation Coppice Bioenergy Plantation*

In this research, the carbon stock was stored above and below ground (**Fig. 5**). Carbon allocation in the poplar short rotation coppice system varies. The average carbon allocation above and below ground for black locust and poplar was 0.76, 19.76, 1.80, and 21.67 $MgC.ha^{-1}$, respectively. According to research by Oliveira et al. (2018) 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).

The contribution of below ground carbon stock in bioenergy plantations is vital to total carbon stock because the above ground carbon is removed periodically (Berhongaray et al. 2019). Below ground 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 below ground carbon pool that water availability, nitrogen fertilizer input, tillage practices have affected the content of soil organic carbon. The CO2FIX model produces litter in the biomass module through turnover, mortality, and logging slash (Schelhaas et al. 2004b). 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.

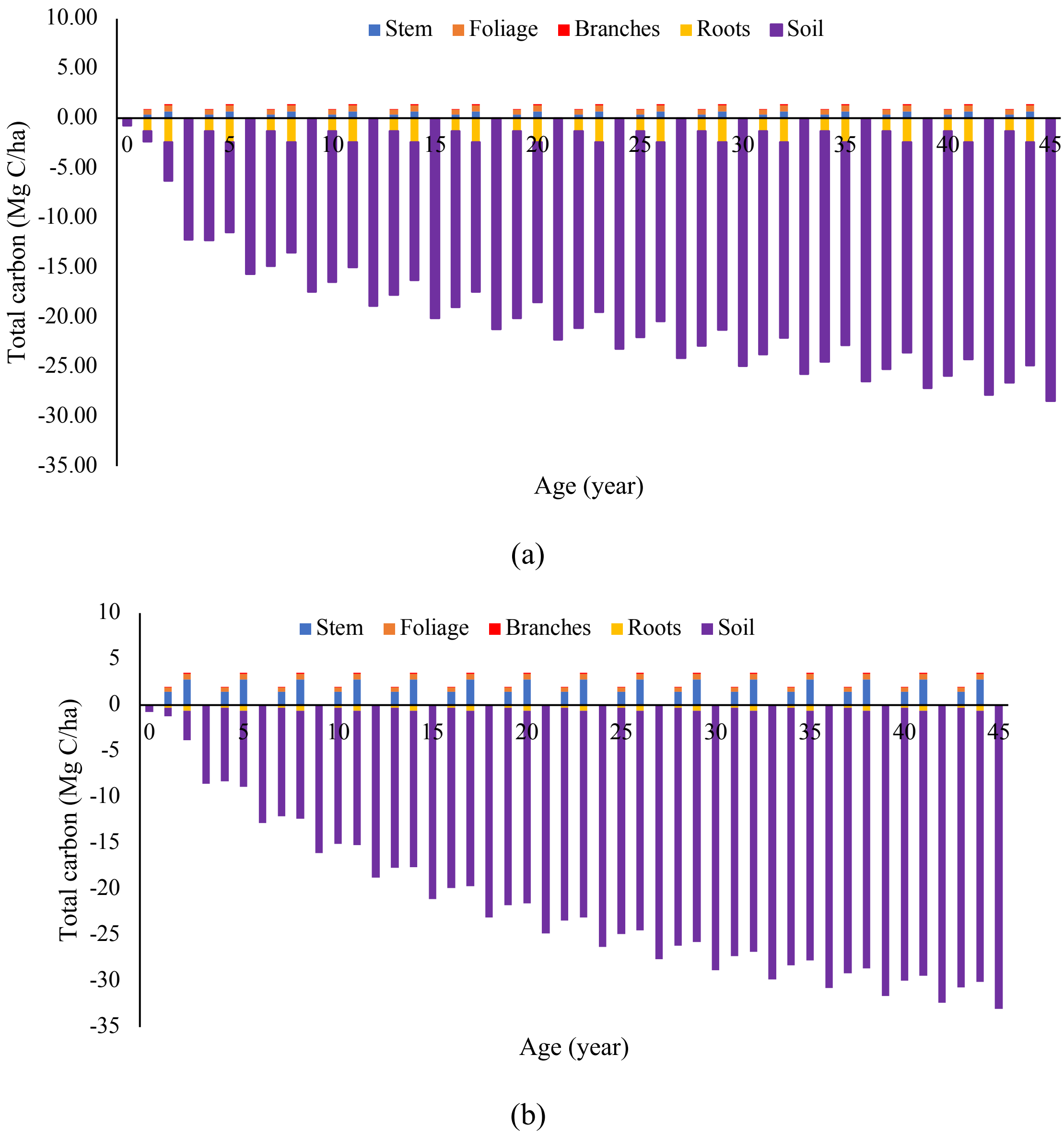

Fig. 5. Above and below ground carbon dynamics in short rotation coppice (a) black locust and (b) poplar.

4. Conclusions

SRC of poplar and black locust to provide bioenergy materials have shown promising results in mitigating climate change actions. SRC of poplar and black locust plantations were promising bioenergy plantations storing carbon in above and below ground compartments. Compared to black locust carbon stock, the poplar plantation has shown higher values for carbon stock above and below ground. In this research, the total carbon stock of black locust and poplar at the end of the simulation period (45 years) was 64.13 and 131.08 MgC.ha^{-1}, respectively. The average carbon allocation above and below ground for black locust and poplar was 0.76, 19.76, 1.80, and 21.67 MgC.ha^{-1}, respectively. In conclusion, poplar outperformed black locust regarding carbon storage in the SRC bioenergy plantation. For both poplar and black locust, the proportion of carbon stock in the soil compartment was higher than in biomass and products compartments. Based on our research findings, in the future, the stakeholders should pay more attention in managing below ground carbon through environmentally friendly soil management. The importance of this research was also emphasized by the fact that the EU's rural development policy has long recognized the importance of investing in nature as a source of economic development.

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