Research paper

Modelling of forest carbon dynamics in different forest management scenarios: A case study on poplar and black locust plantations in Hungary

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

Mulyana, B., Polgár, A., Vityi, A. 2024. Modelling of forest carbon dynamics in different forest management scenarios: A case study on poplar and black locust plantations in Hungary. – Forestry Studies | Metsanduslikud Uurimused 80, 77–89, ISSN 1406-9954. Journal homepage: http://mi.emu.ee/forestry.studies

Abstract. Long-term forest carbon modelling 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*) and poplars (*Populus* sp.) are prominent and dominant species in reforestation and afforestation projects. The research aimed to estimate the carbon dynamics of black locust and white poplar long rotation plantations in some forest management scenarios. Thirty-six forest management scenarios were developed from two species, six yield classes, and tree wood utilization. CO2FIX modelling projected carbon dynamics for 45 years of rotation. Our findings have shown that class yield I resulted in the highest carbon stock compared to class yields II–VI. Black locust plantations have stored carbon to a larger extent than white poplar plantations. In terms of wood utilization, harvested black locust or white poplar wood contributed the most extensive carbon stock if used for pulp. In conclusion, from 36 forest management scenarios, the best scenario was black locust plantation in class yield I and the aim for pulp that stored the carbon at the end of rotation was 101.75 Mg C/ha. In all forest management scenarios, the soil carbon stock was higher than carbon in biomass, products, and bioenergy. Thus, conserving the soil as the dominant carbon pool is vital for future policy recommendations.

Key words: carbon accounting, carbon stock, climate change mitigation, CO2FIX model, forest plantation.

Authors' addresses: [1]Faculty of Forestry, University of Sopron, Sopron H-9400, Hungary; [2]Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia; *e-mail: budimulyana@ugm.ac.id

Introduction

Black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* sp.) are the prominent species in the forests of West and Central European countries. Black locust and poplar were the most planted broadleaf species in the world after *Eucalyptus* spp. (Nicolescu *et al.*, 2020). Ecologically, black locust and poplars are important for soil stabilization, revegetation for mining reclamation, and carbon sequestration (Nicolescu *et al.*, 2020). Furthermore, the development of perennial industrial plantations, such as black locust, poplars, and willows, in marginal land will provide environmental and

DOI: 10.2478/fsmu-2024-0005

economic benefits (Amaducci *et al.*, 2017; Matyka & 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).

In Hungary, based on data from the National Food Chain Safety Office (2016), the total area of black locust and poplars (hybrid and native) was 13,921 ha (80.44%) of the total 17,305 ha of reforestation and afforestation areas in Hungary. Ecologically, Hungary's landscape with sandy loam or loamy soils, shallow groundwater, and annual precipitation around 600 mm is suitable for the cultivation of black locust or poplars in long-rotation or short-rotation coppice (SRC) systems (Schiberna *et al.*, 2021). Black locust as a prominent species in reforestation and afforestation projects has shown its eminency as a fast-growing plant, nitrogen-fixing, site-tolerant, high yield providing, and having good quality wood (Rédei *et al.*, 2017a, 2011). Furthermore, the timber production from black locust, hybrid poplars, and native poplars was 1,793, 1,113, and 225 thousand m^3 per year (National Food Chain Safety Office, 2013). The harvested black locust and poplar plantation in long rotations are sent to industries to be processed for pulp wood, veneer log, and board. Whereas the products from industrial SRC plantations are utilized for bioenergy purposes (Schiberna *et al.*, 2021). The rotation length of black locust depends on the type of wood product, site index, and regeneration pathway (Nicolescu *et al.*, 2018). According to the table yield of black locust (Rédei *et al.*, 2014) and white poplar (Rédei *et al.*, 2012), the rotation was 45 years in different site indexes.

The development of forest plantations supports energy transition and climate change mitigation in Hungary. The government of Hungary sets the energy target from carbon-neutral and renewable energy sources at least 21% of the total energy consumption by 2030 (International Energy Agency, 2022). Furthermore, based on the data of the International Energy Agency (2022), Hungary's energy production was 10.8 Mtoe which originates from nuclear energy (38.9%), bioenergy (25.8%), natural gas (12.2%), oil (9.6%), coal (8.6%), solar energy (2.1%), geothermal energy (1.4%), wind energy (0.5%), and hydroenergy (0.2%). The utilization of fast-growing species, such as black locust and poplars, from bioenergy plantations with a short rotation coppice system is a promising solution to support energy transition (Marosvölgyi & Vityi, 2019; Németh *et al.*, 2018). Furthermore, the development of industrial plantations is important 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 the wood industries and sequester carbon emissions from the atmosphere during the rotation. The National Clean Development Strategy (NCDS) of Hungary has used the projections and modelling to reduce the greenhouse gas emissions through business as usual (BAU), late action (LA) climate neutrality, and early action (EA) climate neutrality scenarios by 2050 (Ministry for Innovation and Technology, 2021). Furthermore, the Ministry for Innovation and Technology (2021) explained that one of the efforts to achieve net zero emissions by 2050 is increasing the CO_2 absorption by forests and maintaining the potential carbon sink in the forest. Estimating forest carbon dynamics in Hungary is important for stakeholders as providing decision tools for climate change mitigation policies (Mulyana *et al.*, 2023a). Therefore the objective of this research was to calculate the potential carbon stock in forest plantation in Hungary through the CO2FIX model in different forest management scenarios.

Materials and Methods

Model parameterization

The CO2FIX software was developed in the CASFOR-II project from 1999 to 2004. The latest update of the 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 the current annual increment, climatology data, and wood product allocations (Table 1).

Table 1. Model parameterization.

No	Parameters	References	
		Black locust	Poplar
1	Growth	Rédei *et al.* (2014)	Rédei *et al.* (2012)
2	Biomass allocation	Rédei *et al.* (2017a)	Jiao *et al.* (2022)
3	Survival rate	Quinkenstein & Jochheim (2016)	Al Afas *et al.* (2008)
4	Wood product allocation	Quinkenstein & Jochheim (2016)	Zbieć *et al.* (2022); Zhang *et al.* (2019, 2018)
5	Percentage carbon content	Quinkenstein & Jochheim (2016)	Ma *et al.* (2022)
6	Soil and root turnover rate	Quinkenstein & Jochheim (2016)	Ajit *et al.* (2013)
7	Relative growth of tree components	Lemma *et al.* (2007); Rédei *et al.* (2017b)	Ajit *et al.* (2013); Nabuurs & Mohren (1995)
8	Foliage, branches, root turnover rate	Quinkenstein & Jochheim (2016)	Nabuurs & Mohren (1995); Quinkenstein & 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)

Data on the 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 white poplar was collected from a local white 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 white poplar growth were measured until the end of their rotation in 45 years. Thus, this research estimates the forest carbon dynamic for one rotation period (45 years). From yield table data, the data of annual increment 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).

In the soil module, the primary data was litter production and climatology data. The CO2FIX model has used YASSO modelling to estimate the soil carbon dynamics. YASSO modelling is considered in predicting the soil organic dynamics 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 (Lemma *et al.*, 2007; Schelhaas *et al.*, 2004a).

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). Furthermore, Schelhaas *et al.* (2004a) explained that carbon is still stored in the products until the products are not used anymore and sent to the mill site dump or landfill or burned as fuelwood.

Model development

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

The yield 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.*, 2014, 2012). Furthermore, Rédei *et al.* (2014, 2012) developed a yield class classification for black locust and white poplar species in Hungary based on the expected height value of white poplar and black locust at the reference age of 25 years. According to Rédei *et al.* (2012, 2014), the yield classes were developed based on height parameters of dominant and co-dominant trees at reference age (25 years). The expected height at the reference age of 25 years (H25) for yield classes I, II, III, IV, V, and VI are 24.2, 21.6, 19.0, 16.4, 13.8, and 11.2 m, respectively (Rédei *et al.*, 2012).

Harvested wood products in Hungary in the period of 1964–2020 has 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 modelling, product allocation of the production line is divided into sawmill, board, pulp, and firewood (Schelhaas *et al.*, 2004a). Therefore, in this research, wood utilization is grouped into sawmill, board, and pulp. Meanwhile, firewood allocation is not related to the carbon stock but the value of carbon emissions replacing fossil fuels to generate energy.

This research used wood product allocation based on the CO2FIX product module. In the product module, the product allocation depends on the production line data, end products, and recycling life span (Schelhaas *et al.*, 2004a). In the production line, the required data is fraction of raw material allocation and process losses. Meanwhile, in the end products, the fraction is allocated to long, medium, and short term. Furthermore, in the recycling life span, the life span is defined as half-life. Half-life means that in a specific time, 50% of product carbon is left.

Results and Discussion

Overview of forest carbon dynamics

The result of carbon dynamic analysis of black locust and white 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 2). 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 white poplar species. These findings also strengthen the evidence that the total carbon in CO2FIX modelling is closely related to the 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 white poplar (Rédei *et al.*, 2012) in Hungary, the CAI of yield class I is consistently higher than the CAI of other classes during the cultivation period.

Table 2. Total carbon at the end of rotation in different forest management scenarios.

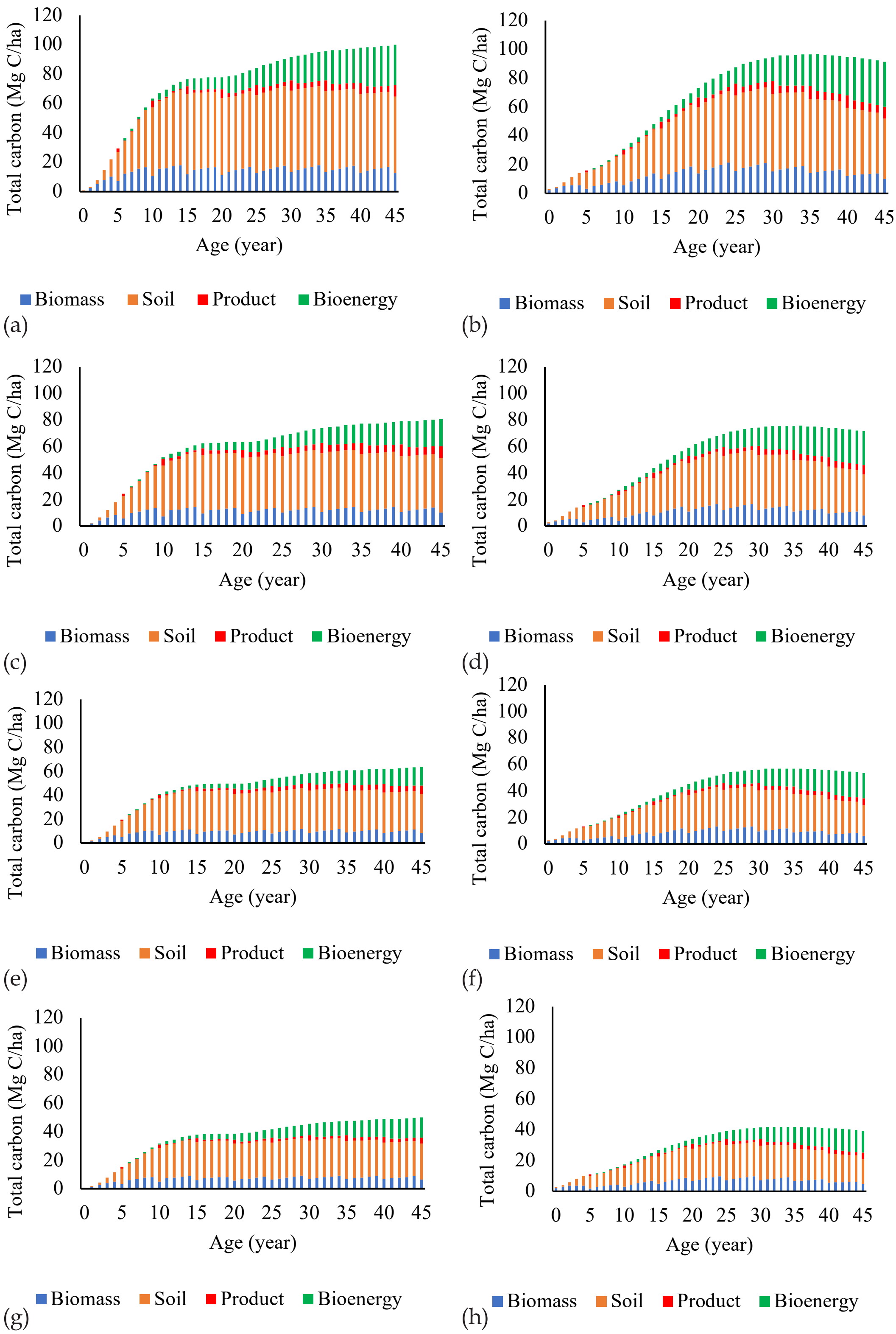
	Total carbon at the age of 45 years (Mg C/ha)					
	White poplar			Black locust		
	Sawmill	Board	Pulp	Sawmill	Board	Pulp
Yield class I	91.38	90.12	93.75	99.90	98.92	101.75
Yield class II	71.70	70.69	73.58	80.84	81.13	83.50
Yield class III	53.68	52.93	55.09	63.69	63.97	66.99
Yield class IV	39.44	38.88	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 2, the total carbon at the end of the rotation in the black locust plantation was higher than in white poplar. The high value of total carbon in black locust than white poplar was related to the input data on growth and wood density. At the final harvesting, the black locust and white poplar volumes were 527 and 565 m^3/ha (Rédei *et al.*, 2014, 2012). 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% (Ma *et al.*, 2022; Quinkenstein & Jochheim 2016). Therefore, black locust biomass and carbon stock were higher than in poplar.

The total black locust and white poplar carbon stock were stored in the biomass, soil, and product compartments (Figure 1). Meanwhile, the carbon amount of bioenergy represents the number of potential carbon stocks if the fuelwood substitutes for fossil fuels (Schelhaas *et al.*, 2004a). Generally, the proportion of carbon stock in the soil was higher than in biomass and product. In the first three years of rotation, the percentage of carbon stock in the biomass was higher than in the black locust and white poplar soil. 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).

Carbon dynamics in biomass

In the process of photosynthesis, plants absorb carbon dioxide from the atmosphere and store it in their organs, such as foliage, stem, branches, and roots. At the end of the rotation in the black locust and white poplar plantations, the highest carbon stock was stored in the stem, followed by branches, foliage, and root (Figure 2). Research findings similar to biomass allocation are in hybrid poplar in Canada; carbon allocation in stem and branches were 64.8% and 17.4% of the total biomass (Truax *et al.*, 2018). For black locust in China, at the age of 38 years, the carbon allocation


Total carbon (Mg C/ha)
Age (year)
Biomass
Soil
Product
Bioenergy
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

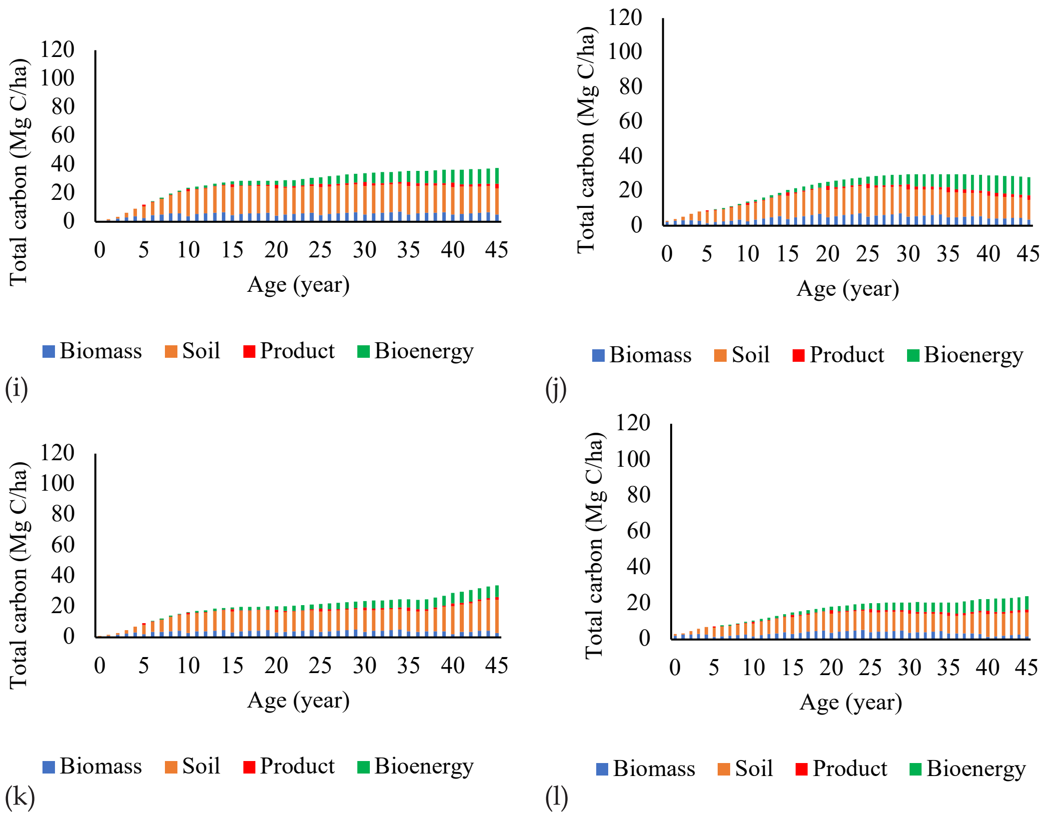
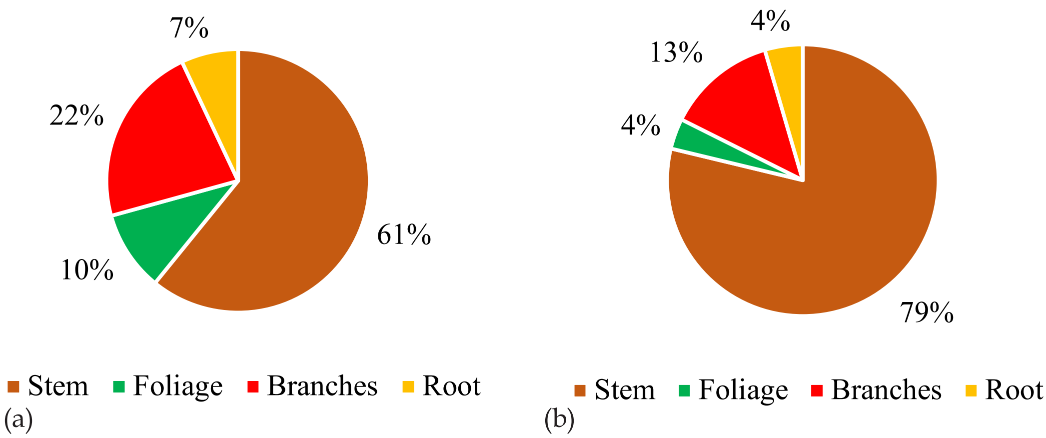


Figure 1. Forest carbon dynamics for black locust (left) and white poplar (right) in different yield classes (started from yield class I on the upper side and yield class VI on the lower side).

in stem was higher than in branches and foliage (Li & Liu, 2014).

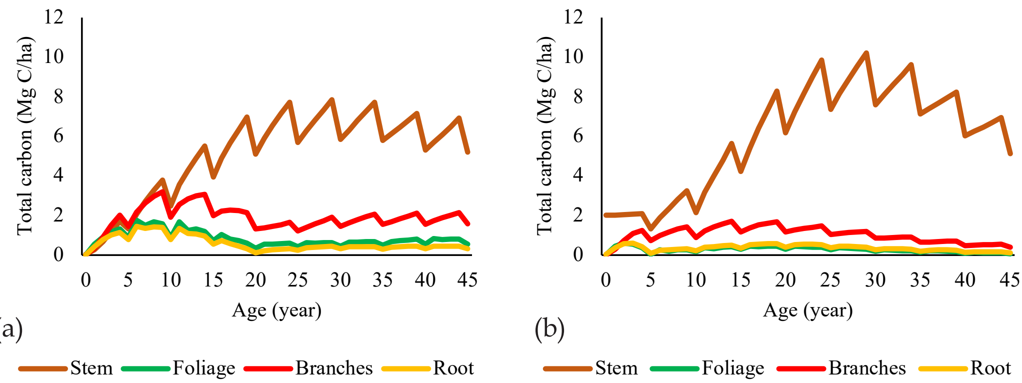
Referring to Figure 2, the carbon stock in the individual tree was predominantly stored in the stem organ and followed by branches, foliage, and roots. The phenomena of carbon stock dominance in stems are also found in the tree species in dry forests in Indonesia (Almulqu, 2017), agroforestry system in India (Negash & Kanninen, 2015), woodlot in Zambia (Kaonga & Bayliss-Smith, 2012), bioenergy plantation in Indonesia (Mulyana *et al.*, 2020a, 2020b), and natural regeneration 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 that the allocation in foliage, stem, branches, and roots were relatively similar around 20–30% (Figure 3). Furthermore, from the 5th to 10th year, carbon allocation in stem and branches was relatively similar, while the carbon stock in foliage and roots began to decline. After 15 years, the carbon allocation in the stem increases around 50–75% of the total tree carbon stock. Meanwhile, the carbon allocation of foliage and roots were less than 10% of the total tree carbon stock. However, the growth of white poplar differed from that of black locust in that the carbon allocation in stem was higher than in branches, foliage, and root. According to the Global Forest Resources Assessment of Hungary, the allocation of forest carbon above ground (stem, branches, leaves) was around four times that of below ground (root) during the period of 1990–2020 (FAO, 2020).



Note: based on the average value of yield classes I–VI.

Figure 2. Carbon allocation in tree's organs: (a) black locust, (b) white poplar.



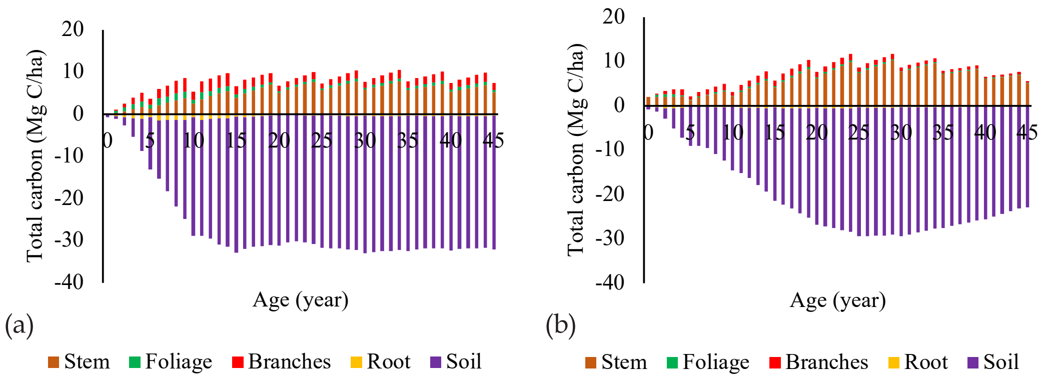
Note: based on the average value of yield classes I–VI.

Figure 3. Carbon dynamics in the biomass; (a) black locust, (b) white poplar.

Carbon dynamics in soil

Above- and below-ground carbon stock in black locust was higher than in the white poplar plantation (Figure 4). During the 45-year simulation, the average value of above-ground carbon stock in black locust and white poplar were 7.76 and 7.29 Mg C/ha, respectively. Moreover, the ratio between below- and above-ground carbon stock in black locust was 5.15, and in white poplar plantation it was 2.85. Below-ground carbon stock (roots and soil) in bioenergy plantations will benefit greatly in the long rotation (Truax *et al.*, 2018). It showed that the carbon stock below ground should get more attention with regard to preserving the forest carbon stock in lithospheres. Disturbance in soil has the potential to reduce the forest carbon stock.

In reference to Figure 2, the carbon allocation in the roots of black locust and white poplar were 7% and 4% of the total carbon stock. This means that the above-ground carbon in Figure 4 for black locust and white poplar was 93% and 96% of the total carbon stock. The most significant proportion of below-ground carbon stock has come from soil carbon. In this research, the initial carbon stock in the soil layer was



Note: the minus values reflect the carbon stock stored below ground. The figure is based on the average value of yield classes I–VI.

Figure 4. Carbon dynamics in above- and below-ground carbon; (a) black locust, (b) white poplar.

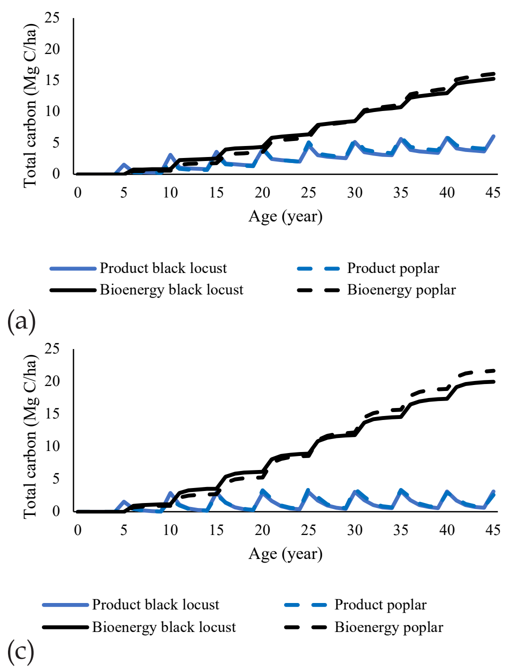
0 Mg C/ha. This followed Lemma *et al.* (2007), simulating the soil organic sequestration in tree plantation using CO2FIX.

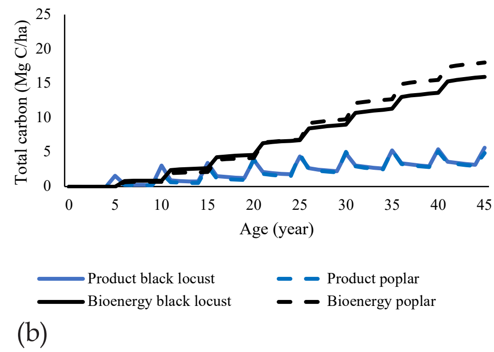
According to research findings from Nabuurs & Schelhaas (2002), for 16 forest types in European countries, the long-term average carbon stock was predominantly stored below ground rather than above ground. A similar finding was also found in India's agroforestry systems, in which the soil carbon stock was higher than the carbon stock in the tree biomass (Negash & Kanninen, 2015). Kaonga & Bayliss-Smith (2012) simulated the above- and below-ground carbon stock using CO-2FIX in the woodlot area in Zambia and showed that the simulated carbon stock below ground was higher than above ground. Furthermore, based on the field measurements of soil in the woodlot area at a depth of 0–200 cm, the results showed that the carbon stock in the soil layer was higher than the simulated value (Kaonga & Bayliss-Smith, 2012). The CO2FIX simulation in a larch (*Larix gmelinii* var. *principis-rupprechtii* (Mayr) Pilg.) plantation in Weichang County, China, found that 70% of the 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 Figure 4, the below-ground carbon stock in the black locust plantation was higher than in the white poplar plantation. During the simulation period of 45 years, the average below-ground carbon stock in black locust and white poplar plantations was 35.47 and 21.16 Mg C/ha, respectively. The high value of carbon below-ground stock of black locust compared to white poplar was in line with the finding in Figure 2. In Figure 2, the composition of the leaf biomass of black locust was 10% of the total tree biomass, which is higher than the 4% of white poplar. Both black locust and white poplar are deciduous species that shed their leaves during autumn and winter. Furthermore, the fallen leaves were the input source of soil organic carbon through decomposition.

Carbon dynamics in product and bioenergy

The total carbon in the products compartment at the end of the simulation period for board, sawn mill, and pulp of black locust and white poplar was similar (Figure 5). In the yield class I for black locust plantation, the total carbon in the board, sawn mill, and pulp products was 9.61, 7.86, and 4.68 Mg C/ha, respectively. Meanwhile,





Note: based on the average value of yield classes I–VI.

Figure 5. Carbon dynamic in product and bioenergy compartments for: (a) board, (b) sawn mill, (c) pulp.

the total carbon in the board, sawn mill, and pulp products at the exact class yield for the white poplar plantation were 10.79, 8.53, and 4.43 Mg C/ha. Furthermore, the total carbon for yield classes 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 will be used as harvested wood product (70%) and fuelwood (30%). There is 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 white poplar were carried out every 5 years.

According to Figure 5, the total carbon in the bioenergy compartment between black locust and white 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 white poplar. However, from the middle to the end of the rotation, carbon stock in the bioenergy compartment in white poplar was higher than in black locust.

Conclusions

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 for the pulp industry. In contrast, the lowest total carbon dynamic was the forest management scenario for white poplar plantations in the class yield VI to supply for the board industry. Based on class yield, the total carbon dynamic of either black locust or white poplar plantation was the 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 white poplar plantations. Regarding timber utilization, the total carbon for pulp purposes produced the highest total carbon, followed by sawn mill and board purposes.

Carbon stock below ground, especially in the soil, is greater than above ground, both in black locust and white poplar forest plantations. Soil management should pay attention to the potential carbon stock below ground. It should promote increasing the soil organic carbon through maintaining the carbon inputs, such as litter from foliage, branches, and harvested wood residue.

In this research, we realized that there are limitations in data collection. Long-term monitoring of permanent plots will be very useful to develop and validate the CO2FIX model for black locust and white poplar or other species. Due to the authors' limited knowledge, carbon stock in the soil compartment before planting (year 0) was assumed to be 0. Research on soil carbon stock in forest plantations should be carried out to fill in the lack of information on the initial soil carbon stock. Thus, carbon dynamic modelling can be developed more accurately. However, the research findings can be considered by stakeholders in making climate change mitigation policies.

Acknowledgements. The authors thank the Tempus Public Foundation for providing the Stipendium Hungaricum Scholarship, the government of Indonesia for financial support, and reviewers for valuable comments and feedback.

References

Ábri, T., Keserű, Z., Borovics, A., Rédei, K., Csajbók, J. 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(2), 292. https://doi.org/10.3390/f13020292.

Ajit, Dhyani, S.K., Ramnewaj, Handa, A.K., Prasad, R., Alam, B., Rizvi, R.H., Gupta, G., Pandey, K.K., Jain, A., Uma. 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.

Al Afas, N., Marron, N., Van Dongen, S., Laureysens, I., Ceulemans, R. 2008. Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). – Forest Ecology and Management, 255(5–6), 1883–1891. https://doi.org/10.1016/j.foreco.2007.12.010.

Almulqu, A.A. 2017. Dynamic growth model simulation for carbon stock management in dry forest. – Biosystems Diversity, 25(3), 249–254. https://doi.org/10.15421/011738.

Amaducci, S., Facciotto, G., Bergante, S., Perego, A., Serra, P., Ferrarini, A., Chimento, C. 2017. Biomass production and energy balance of herbaceous and woody crops on marginal soils in the Po Valley. – Global Change Biology Bioenergy, 9(1), 31–45. https://doi.org/10.1111/gcbb.12341.

de Jong, B.H., 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. – Forest Ecology and Management, 242(2–3), 398–411. https://doi.org/10.1016/j.foreco.2007.01.057.

FAO. 2020. Global Forest Resources Assessment 2020 Report, Hungary. Rome, Italy, FAO. 57 pp.

International Energy Agency (IEA). 2022. Hungary 2022. Energy Policy Review. Paris, France, IEA Publications. 173 pp.

Jia, Y.-L., Li, Q.-R., Xu, Z.-Q., Sang, W.-G. 2016. Carbon cycle of larch plantation based on CO2FIX model. – Chinese Journal of Plant Ecology, 40(4), 405–415. https://doi.org/10.17521/cjpe.2015.0208.

Jiao, W., Wang, W., Peng, C., Lei, X., Ruan, H., Li, H., Yang, Y., Grabarnik, P., Shanin, V. 2022. Improving a process-based model to simulate forest carbon allocation under varied stand density. – Forests, 13(8), 1212. https://doi.org/10.3390/f13081212.

Kaonga, M.L., Bayliss-Smith, T.P. 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.

Király, É., Börcsök, Z., Kocsis, Z., Németh, G., Polgár, A., Borovics, A. 2022. Carbon sequestration in harvested wood products in Hungary an estimation based on the IPCC 2019 refinement. – Forests, 13(11), 1809. https://doi.org/10.3390/f13111809.

Klašnja, B., Orlović, S., Galić, Z. 2013. Comparison of different wood species as raw materials for bioenergy. – South-East European Forestry, 4(2), 81–88. https://doi.org/10.15177/seefor.13-08.

Lemma, B., Kleja, D.B., 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. – Forest Ecology and Management, 252(1–3), 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. – Chinese Geographical Science, 24(4), 414–422. https://doi.org/10.1007/s11769-014-0704-3.

Ma, X., Wu, L., Zhu, Y., Wu, J., Qin, Y. 2022. Simulation of vegetation carbon sink of arbor forest and carbon mitigation of forestry bioenergy in China. – International Journal of Environmental Research and Public Health, 19(20), 13507. https://doi.org/10.3390/ijerph192013507.

Mao, Z., Derrien, D., Didion, M., Liski, J., Eglin, T., Nicolas, M., Jonard, M., Saint-André, L. 2019. Modeling soil organic carbon dynamics in temperate forests with Yasso07. – Biogeosciences, 16(9), 1955–1973. https://doi.org/10.5194/bg-16-1955-2019.

Marosvölgyi, B., Vityi, A. 2019. Use of fast growing tree species in a crop rotation. (Gyorsannövő fafajok használata vetésforgóban). Factsheet No. 35. Lugo, Spain, AFINET (Agroforestry Innovation Networks). 2 pp. (In Hungarian and English).

Matyka, M., Radzikowski, P. 2020. Productivity and biometric characteristics of 11 varieties of willow cultivated on marginal soil. – Agriculture, 10(12), 616. https://doi.org/10.3390/agriculture10120616.

Ministry for Innovation and Technology. 2021. National Clean Development Strategy 2020 – 2050. Budapest, Hungary, Ministry for Innovation and Technology. 119 pp.

Mulyana, B., Polgár, A., Vityi, A. 2023a. Research trends in the environmental assessment of poplar plantations in Hungary: A bibliometric analysis. – Ecocycles, 9(3), 23–32. https://doi.org/10.19040/ecocycles.v9i3.339.

Mulyana, B., Polgár, A., Vityi, A., 2023b. Three decades of forest carbon dynamics modeling using CO2FIX: A bibliometric analysis. – EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 10(4), 2105–2119.

Mulyana, B., Soeprijadi, D., Purwanto, R.H. 2020a. Development of bioenergy plantation in Indonesia: yield regulation and above-ground carbon storage in gliricidia (*Gliricidia sepium*) plantation. – E3S Web of Conferences, 202, 08009.

Mulyana, B., Soeprijadi, D., Purwanto, R.H. 2020b. Allometric model of wood biomass and carbon for gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) at bioenergy plantation in Indonesia. – Forestry Ideas, 26(1(59)), 153–164.

Nabuurs, G.J., Mohren, G.M.J. 1995. Modelling analysis of potential carbon sequestration in selected forest types. – Canadian Journal of Forest Research, 25(7), 1157–1172. https://doi.org/10.1139/x95-128.

Nabuurs, G.J., Schelhaas, M.J. 2002. Carbon profiles of typical forest types across Europe assessed with CO2FIX. – Ecological Indicators, 1(3), 213–223. https://doi.org/10.1016/S1470-160X(02)00007-9.

National Food Chain Safety Office. 2013. Forest resources and forest management in Hungary 2012. Budapest, National Food Chain Safety Office. 4 pp.

National Food Chain Safety Office. 2016. Forest resources and forest management in Hungary 2015. Budapest, National Food Chain Safety Office. 2 pp.

Negash, M., Kanninen, M. 2015. Modeling biomass and soil carbon sequestration of indigenous agroforestry systems using CO2FIX approach. – Agriculture, Ecosystems & Environment, 203, 147–155. https://doi.org/10.1016/j.agee.2015.02.004.

Németh, R., Fehér, S., Komán, S. 2018. Utilization of fast growing plantation timber as bioenergy in Hungary. – IOP Conference Series: Earth and Environmental Science, 159, 012029. https://doi.org/10.1088/1755-1315/159/1/012029.

Nicolescu, V.-N., Hernea, C., Bakti, B., Keserű, Z., Antal, B., Rédei, K. 2018. Black locust (*Robinia pseudoacacia* L.) as a multi-purpose tree species in Hungary and Romania: a review. – Journal of Forestry Research, 29, 1449–1463. https://doi.org/10.1007/s11676-018-0626-5.

Nicolescu, V.-N., Rédei, K., Mason, W.L., Vor, T., Pöetzelsberger, E., Bastien, J.-C., Brus, R., Benčať, T., Đodan, M., Cvjetkovic, B., Andrašev, S., La Porta, N., Lavnyy, V., Mandžukovski, D., Petkova, K., Roženbergar, D., Wąsik, R., Mohren, G.M.J., Monteverdi, M.C., Musch, B., Klisz, M., Perić, S., Keça, L., Bartlett, D., Hernea, C., Pástor, M. 2020. Ecology, growth and management of black locust (*Robinia pseudoacacia* L.), a non-native species integrated into European forests. – Journal of Forestry Research, 31, 1081–1101. https://doi.org/10.1007/s11676-020-01116-8.

Országos Meteorológiai Szolgálat. 2021. Climate of Hungary – general characteristics. [WWW Document]. – URL https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/altalanos_eghajlati_jellemzes/altalanos_leiras/. [Accessed 12 September 2021].

Prada, M., Bravo, F., Berdasco, L., Canga, E., Martínez-Alonso, C. 2016. Carbon sequestration for different management alternatives in sweet chestnut coppice in northern Spain. – Journal of Cleaner Production, 135, 1161–1169. https://doi.org/10.1016/j.jclepro.2016.07.041.

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. – Journal of Environmental Management, 168, 53–66. https://doi.org/10.1016/j.jenvman.2015.11.044.

Radzikowski, P., Matyka, M., Berbeć, A.K. 2020. Biodiversity of weeds and arthropods in five different perennial industrial crops in eastern Poland. – Agriculture, 10(12), 636. https://doi.org/10.3390/agriculture10120636.

Rédei, K., Csiha, I., Keserű, Z. 2011. Black locust (*Robinia pseudoacacia* L.) short-rotation crops under marginal site conditions. – Acta Silvatica et Lignaria Hungarica, 7(1), 125–131. https://doi.org/10.37045/aslh-2011-0010.

Rédei, K., Csiha, I., Keserű, Z., Rásó, J., Kamandiné Végh, Á., Antal, B. 2014. Growth and yield of black locust (*Robinia pseudoacacia* L.) stands in Nyírség growing region (North-East Hungary). – South-East European Forestry, 5(1), 13–22. https://doi.org/10.15177/seefor.14-04.

Rédei, K., Gál, J., Keserű, Z., Antal, B. 2017a. Above-ground biomass of black locust (*Robinia pseudoacacia* L.) trees and stands. – Acta Silvatica et Lignaria Hungarica, 13(2), 113–124. https://doi.org/10.1515/aslh-2017-0008.

Rédei, K., Csiha, I., Rásó, J., Keserű, Z. 2017b. Selection of promising black locust (*Robinia pseudoacacia* L.) cultivars in Hungary. – Journal of Forest Science, 63(8), 339–343. https://doi.org/10.17221/23/2017-JFS.

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(1), 33–40. https://doi.org/10.15177/seefor.12-04.

Schelhaas, M.J., van Esch, P.W., Groen, T.A., de Jong, B.H.J., Kanninen, M., Liski, J., Masera, O., Mohren, G.M.J., Nabuurs, G.J., Palosuo, T., Pedroni, L., Vallejo, A., Vilén, T. 2004a. CO2FIX V 3.1 - Manual. Wageningen, The Netherlands, Alterra. 49 pp.

Schelhaas, M.J., van Esch, P.W., Groen, T.A., de Jong, B.H.J., Kanninen, M., Liski, J., Masera, O., Mohren, G.M.J., Nabuurs, G.J., Palosuo, T., Pedroni, L., Vallejo, A., Vilén, T. 2004b. CO2FIX V 3.1 - A modelling framework for quantifying carbon sequestration in forest ecosystem. ALTERRA-rapport 1068. Wageningen, The Netherlands, Alterra. 122 pp.

Schiberna, E., Borovics, A., Benke, A. 2021. Economic modelling of poplar short rotation coppice plantations in Hungary. – Forests, 12(5), 623. https://doi.org/10.3390/f12050623.

Stolpe, N.B., Dubé, F., Zagal, E. 2010. Calibration of CO2FIX to native forest, pine plantation, and pasture on a volcanic soil of the Chilean Patagonia. – Acta Agriculturae Scandinavica, Section B – Soil & Plant Science, 60(3), 235–244. https://doi.org/10.1080/09064710902865722.

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(6), 293. https://doi.org/10.3390/f9060293.

Vítková, M., Müllerová, J., Sádlo, J., Pergl, J., Pyšek, P. 2017. Black locust (*Robinia pseudoacacia*) beloved and despised: A story of an invasive tree in Central Europe. – Forest Ecology and Management, 384, 287–302. https://doi.org/10.1016/j.foreco.2016.10.057.

Zbieć, M., Franc-Dąbrowska, J., Drejerska, N. 2022. Wood waste management in Europe through the lens of the circular bioeconomy. – Energies, 15(12), 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. – International Journal of Environmental Research and Public Health, 16(3), 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. – Forest Policy and Economics, 92, 181–192. https://doi.org/10.1016/j.forpol.2018.05.005.