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Evaluation of the Efficiency of Energy *Populus* (Poplar) Growing Technology as an Alternative Source of Energy

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ABSTRACT

After conducting research on energy *Populus* plants, it was discovered that biometric indicators and productivity were affected by both sowing density and nutritional background. The results showed that the tallest energy *Populus* shoots were observed in the group with a sowing density of 5600 pieces/ha, reaching heights of 11.1–11.6 m. The diameter of the central shoot in this variant was between 157 and 163 mm. The number of shoots was 1.8–2.5 pcs. on 1 plant and 21600–30000 pcs. on 1 hectare. The variant with a sowing density of 6700 units/ha yielded the most energy *Populus* biomass, specifically 178.3 tons of green mass and 100.9 tons of dry mass per hectare. Compared to the variant with a sowing density of 8300 units/ha, this represented an increase of 19.9 and 11.3 t/ha respectively, and an increase of 18.0 and 10.4 t/ha respectively, when compared to the variant with a sowing density of 5600 units/ha. The utilization of mineral fertilizers was shown to notably enhance productivity, as evidenced by an increase in green mass of 21.1–37.1 t/ha and an increase in dry mass of 11.2–20.6 t/ha across all trial variations. In the Precarpathian region, where sod podzolized soils are prevalent, the optimal sowing density of energy *Populus* biofuel was determined to be 6700 pcs./ha, with a yield of 110.990 kg/ha achieved through the application of mineral fertilizers. This approach generated an energy output of 1775.8 GJ/ha. In the case of a sowing density of 8300 units/ha and the use of mineral fertilizers, the energy output produced was 1576.9 GJ/ha, whereas sowing density of 5600 units/ha resulted in an energy output of 1591.0 GJ/ha. The introduction of mineral fertilizers led to an increase in energy output ranging from 12.3 to 22.6 GJ/ha for all experimental variants.

Keywords: dry biomass, biometric indicators, productivity, energy output, crop capacity, fertilizers.

INTRODUCTION

Since the beginning of the 21st century, humanity has been actively searching for the replacement of traditional energy sources with renewable ones. This need is largely determined by the depletion of global hydrocarbon reserves, disruption of the natural balance of ecosystems, global environmental problems, in particular, the increase in the concentration of greenhouse gases in the atmosphere, which leads to frequent natural disasters and sudden changes in the weather on the Earth's surface. Therefore, the development of such a new field of science as bioenergy, which can become an important element in reducing the deficit of fossil hydrocarbon raw materials and the basis of sustainable supply of the state with bioresources and its energy security, is becoming more and more urgent [Roik, 2010; Mulvaney et al., 2006; Hnap, 2018; Hryhoriv et al., 2022; Tsyuk et al., 2022].

In Ukraine, in the last decade, considerable attention has been paid to increasing the efficiency of the use of biofuels and bioenergy, which makes it possible to reduce the dependence of the domestic economy on imports of the energy carriers, reduce its energy consumption and ensure economic growth [Voloshchuk, 2020; Sikora et al., 2020; Hryhoriv et al., 2023a].

The dependence of the economy of Ukraine on the import of energy carriers necessitates the search for alternative sources for their production. Solving this problem in the near future is extremely urgent, given the fact that in 7–10 years global oil reserves are projected to be depleted by 60–65%, while natural gas reserves will only last for 50–60 years, oil reserves will only be available for 25–30 years, while coal will be available for the next 500–600 years. The constant increase in tariffs for gas and communal services further drives the search for, introduction of, as well as utilization of alternative and non-traditional energy sources [Lü et al., 2019; Voloshchuk, 2020; Hryhoriv et al., 2023b].

The current direction of bioenergy development in Ukraine is the creation of perennial plantations of bioenergy crops, in particular, energy *Populus*. However, there are a number of problems that require their solution. The productivity of bioenergy crops is contingent upon the specific climatic and soil conditions as well as the method of cultivation employed. Numerous scientific publications and literary sources have already established the impact of primary environmental conditions and growing technologies on agricultural crop yields. However, the effect of cultivation technology on the growth and development of energy *Populus* plants in the Precarpathian region has yet to be extensively studied and is not well-documented in scientific literature. As a result, this issue remains relevant and demands further attention in the current research.

The increase in energy consumption, rising energy prices and increasing emissions of detrimental substances into the atmosphere have made the development of bioenergy immensely urgent. A number of studies have been conducted and the positive aspects of the use of energy crop plantations have been proven [Makarchenko, 2012; Kravchuk, 2013; Lys et al., 2018; Fuchylo, 2018; Karpenko et al., 2022].

The search for new and alternative sources of energy has been propelled by a multitude of factors, one of which is ecological. A majority of energy plants have a robust vegetative growth that undergoes photosynthesis at a high rate, leading to a reduction of the surplus carbon dioxide in the atmosphere and mitigating the anthropogenic "greenhouse effect". Furthermore, when a crop is cultivated for a prolonged period in a particular area, the root system enriches the organic content of the soil, thus enhancing its fertility [Roik, 2011; Roik, 2013; Long et al., 2018; Szparaga et al., 2019; Rieznik et al., 2021; Karbivska et al., 2023].

MATERIAL AND METHODS

Research work was carried out on the experimental fields of the Precarpathian State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences and under laboratory conditions [Dospekhov, 1985; Roik, 2012].

The soil type of the experimental field is a combination of sod and podzol, with a humus horizon thickness of 40 cm. The granulometric composition of the soil is coarse-grained and medium-loamy, and the structure of the arable layer is lumpy-dusty, leading to soil floating and crust formation after rainfall. Agrochemical assessments reveal a pH-saline (potentiometric) value of 4.6, a sum of absorbed bases (Ca+Mg) of 11.4 mg-eq/100 g (as per Kappen), and a humus content (as per Tiurin) of 2.54%. Further, alkaline hydrolyzed nitrogen (as per Kornfield) is 79.0, mobile phosphorus (as per Kirsanov) is 48.0, and mobile potassium (as per Kirsanov) is 82.0 mg/kg of soil. The soil also contains mobile forms of microelements, with boron (as per Berger and Truog) at 1.00, molybdenum (as per Grieg) at 0.20, and manganese (as per Peive and Rinkis) at 48.0 mg/kg of soil.

The experimental design involves the assessment of various factors that may impact the crop growth, development, and yield, as outlined in Table 1.

The experiment was conducted four times to ensure the validity of results. The sowing area encompassed 150 m^2, while the accounting area spanned 125 m^2. The total area occupied by the experimental plots measured 0.36 ha. The planting scheme consisted of a singular row with a 3 m distance between each row.

Table 1. Scheme of the experiment

Crop	Option	Planting density Factor A	Mineral feeding Factor B
Energy *Populus* Max-4	1	8300 units ha^{-1} (planting step 40 cm)	Without fertilizers
	2		$N_{40}P_{300}K_{300} + N_{40}$
	3	6700 units ha^{-1} (planting step 50 cm)	Without fertilizers
	4		$N_{40}P_{300}K_{300} + N_{40}$
	5	5600 units ha^{-1} (planting step 60 cm)	Without fertilizers
	6		$N_{40}P_{300}K_{300} + N_{40}$

RESULTS AND DISCUSSION

On May 20th, the height of *Populus* shoots was in the range from 9.2 to 9.9 m. The diameter of the central shoot for this period was in the range from 88 to 124 mm. The number of shoots was 1.5–2.5 pcs.

According to the conducted phenological research, the greatest increase in vegetative mass was obtained in the period from June to September. The last biometric measurements were carried out on October 8th. The height of the plants during this period was between 10.6 and 11.6 m. The diameter of the central shoot was between 120 and 163 mm. The number of shoots did not change (Table 2).

Application of mineral fertilizers ($N_{40}P_{300}K_{300} + N_{40}$) provided plants with more available nutrients and contributed to an increase in shoot thickness up to 14 mm. The height of the plants under this option was greater by 0.7 m compared to the option without fertilizers.

When analyzing the increase in the biometric indicators of energetic *Populus* in the sixth year of vegetation, it should be noted that they were significantly higher than in previous years. Thus, in the third year of vegetation, the height of plants increased by an average of 1.8 m; in the fourth year of vegetation, the increase was an average of 2.4 m; in the fifth year of vegetation – by 1.0 m; in the sixth year of vegetation, the increase in *Populus* biometric indicators of energy was from 1.4 to 1.7 m. This also applies to the diameter of the shoots, where in the third year of vegetation the diameter of the central shoot increased by an average of 21 mm; in the fourth year of vegetation the increase was on average 30 mm; in the fifth year of vegetation – 35 mm, and in the sixth year of vegetation the increase was 39 mm.

The study results demonstrate that the highest yield of energy *Populus* biomass was achieved in the variant with a sowing density of 6700 units/ha. This resulted in 178.3 t/ha of green mass and 100.9 t/ha of dry mass, which was 19.9 t/ha and 11.3 t/ha more, respectively, when compared to the option with a sowing density of 8300 units/ha. Similarly, compared to the sowing density of 5600 units/ha, the 6700 units/ha variant had 18.0 t/ha and 10.4 t/ha more of green and dry mass, respectively. Additionally, the use of mineral fertilizers led to an increase in productivity across all variants of the experiment. Specifically, the introduction of mineral fertilizers resulted in a productivity increase of 21.1–37.1 t/ha of green

Table 2. Biometric indicators of energy Populus plants (2016–2021 vegetation year) depending on the density of planting and background nutrition

Option	Record date						Increase	
	20.05.2021			08.10.2021				
	Plant height, cm	The number of shoots in bushes, pc.	Diameter of the central shoot, mm	Plant height, cm	The number of shoots	Diameter of the central shoot, mm	Plant height, cm	Diameter of the central shoot, mm
1	9.3	1.5	88	10.8	1.5	120	1.5	32
2	9.4	2.3	93	11.0	2.3	127	1.6	34
3	9.2	1.6	104	10.6	1.6	139	1.4	35
4	9.7	2.2	115	11.3	2.2	153	1.6	38
5	9.5	1.8	120	11.1	1.8	157	1.6	37
6	9.9	2.5	124	11.6	2.5	163	1.7	39

mass and 11.2–20.6 t/ha of dry mass, as illustrated in Table 3.

Note: LSD05 t ha^{-1} (dry mass): Factor A – 2.34, Factor B – 1.91, Interaction of AB – 2.58.

It is worth mentioning that the application of mineral fertilizers furnished the energy willow plants with an ample quantity of essential nutrients. Consequently, this led to an increase in productivity in all conducted studies.

Upon conducting an analysis of the growth in yield during various growing seasons, it is vital to acknowledge that the sixth year of cultivating energy willow resulted in a noteworthy increase in the yearly yield of freshly cut wood. Specifically, the yield rose from 11.8 t/ha with a planting step of 60 cm and without fertilizer application, to 28.6 t/ha with a planting step of 50 cm and with the implementation of the full quantity of fertilizers (Table 4). This trend was also observed in the preceding growing years.

The variant of sowing density that yielded the highest energy *Populus* biofuel was 6700 units per hectare, along with the incorporation of mineral fertilizers. This particular variant resulted in a yield of 110.990 kilograms per hectare, as depicted in Table 5. The energy output for this option was

Table 3. Collection of energy Populus biomass (2016–2021 vegetation year) depending on the density of the plantation and the nutritional background

Option	Planting density Factor A	Mineral nutrition Factor B	Collection of green mass, t ha^{-1}	Collection of dry mass, t ha^{-1}	The content of absolutely dry matter in biomass, %
1	8300 units ha^{-1} (planting step 40 cm)	Without fertilizers	135.9	76.8	56.5
2		$N_{40}P_{300}K_{300} + N_{40}$	158.4	89.6	56.6
3	6700 units ha^{-1} (planting step 50 cm)	Without fertilizers	141.2	80.3	56.8
4		$N_{40}P_{300}K_{300} + N_{40}$	178.3	100.9	56.6
5	5600 units ha^{-1} (planting step 60 cm)	Without fertilizers	139.2	79.2	56.9
6		$N_{40}P_{300}K_{300} + N_{40}$	160.3	90.4	56.4

Note: LSD_{05} t ha^{-1} (dry mass): Factor A – 2.34, Factor B – 1.91, Interaction of AB – 2.58.

Table 4. Dynamics of energy Populus productivity by years of vegetation

Option	Planting density Factor A	Mineral nutrition Factor B	Years of research					
			2016	2017	2018	2019	2020	2021
			Collection of green mass, t ha^{-1} Collection of dry mass, t ha^{-1}					
1	8300 units ha^{-1} (planting step 40 cm)	Without fertilizers	21.3 12.2	52.2 29.4	70.5 39.8	90.5 51.0	112.2 63.4	135.9 76.8
2		$N_{40}P_{300}K_{300} + N_{40}$	23.0 12.4	54.0 30.6	92.9 52.6	112.9 63.9	134.1 75.9	158.4 89.6
3	6700 units ha^{-1} (planting step 50 cm)	Without fertilizers	23.9 13.3	55.5 30.8	74.9 41.4	99.7 55.3	118.1 67.0	141.2 80.3
4		$N_{40}P_{300}K_{300} + N_{40}$	25.6 14.2	57.0 31.7	97.0 53.9	125.0 69.5	149.7 84.7	178.3 100.9
5	5600 units ha^{-1} (planting step 60 cm)	Without fertilizers	25.1 13.7	49.2 27.5	66.2 37.0	90.2 50.4	114.6 65.2	139.2 79.2
6		$N_{40}P_{300}K_{300} + N_{40}$	27.7 15.2	52.8 29.6	91.8 51.5	118.8 66.6	139.3 78.6	160.3 90.4

Table 5. Output of energy and solid biofuel from the obtained energy Populus biomass (2016–2021 vegetation year) depending on the density of the plantation and the nutritional background

Option	Planting density	Mineral nutrition	Collection of dry mass, t ha^{-1}	Solid biofuel output, kg ha^{-1}	Energy output, GJ ha^{-1}
1.	8300 units ha^{-1} (planting step 40 cm)	Without fertilizers	76.8	84480	1351.6
2.		$N_{40}P_{300}K_{300} + N_{40}$	89.6	98560	1576.9
3.	6700 units ha^{-1} (planting step 50 cm)	Without fertilizers	80.3	88330	1413.2
4.		$N_{40}P_{300}K_{300} + N_{40}$	100.9	110990	1775.8
5.	5600 units ha^{-1} (planting step 60 cm)	Without fertilizers	79.2	87120	1393.9
6.		$N_{40}P_{300}K_{300} + N_{40}$	90.4	99440	1591.0

1775.8 GJ/ha, in the option with a density of planting of 8300 pcs./ha and the introduction of mineral fertilizers, 1576.9 GJ/ha, in the option with a sowing density of 5600 pcs./ha 1591.0 GJ/ha. The introduction of mineral fertilizers provides an increase in energy output in the range from 12.3 to 22.6 GJ/ha in all conducted studies.

Therefore, the application of mineral fertilizers ensures an increase in the yield of solid biofuel and the yield of energy from *Populus* in all variants of the experiment.

CONCLUSIONS

According to research results, the tallest energy *Populus* shoots were observed in the option with a sowing density of 5600 pieces/ha, reaching heights of 11.1–11.6 m. The tallest energy *Populus* shoots in 2016–2021 years of vegetation were observed in the option with a sowing density of 5600 pieces/ha, reaching heights of 11.1–11.6 m. The diameter of the central shoot in this variant was between 157 and 163 mm. The number of shoots is 1.8–2.5 pcs. on 1 plant and 21.6–30000 pcs. on 1 hectare.

The variant with a sowing density of 6700 units/ha yielded the most energy *Populus* biomass, specifically 178.3 tons of green mass and 100.9 tons of dry mass per hectare. Compared to the variant with a sowing density of 8300 units/ha, this represented an increase of 19.9 and 11.3 t/ha, respectively, and an increase of 18.0 and 10.4 t/ha, respectively, when compared to the variant with a sowing density of 5600 units/ha. The utilization of mineral fertilizers is shown to notably enhance productivity, as evidenced by an increase in green mass of 21.1–37.1 t/ha and an increase in dry mass of 11.2–20.6 t/ha across all trial variations.

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