Original Article

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Biomass dry matter yield of willow and *Miscanthus* in low-input cropping on heavy clay soils in Ukraine

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Abstract: In Ukraine, 6.5 million hectares of agricultural land characterized by heavy clay soil could be available for sustainable bioenergy crop cultivation because they are considered marginal for food crop cultivation. This study investigated the biomass dry matter yield (DMY) of willow (*Salix triandra* L. and *Salix viminalis* L.) and *Miscanthus* (*Miscanthus* × *giganteus* Greef et Deuter) at two experimental sites with heavy clay in Ukraine. To promote plant rooting and adaptation in the first year of cultivation under low-input conditions, tillage, moisture-retaining agents, foliar fertilization, planting density and row spacing were varied. Willow obtained notable DMY on hard clay soils (clay >50%). The variety 'Tora' revealed the best DMY performance, indicated by the highest increment (4.1–4.6 m) in the first year of the second cycle. The highest biomass DMY (28.8 Mg ha^{-1}) was obtained at a planting density of 15 000 plants ha^{-1} and a row spacing of 0.75 × 1.50 m. However, neither willow nor *Miscanthus* allow for a feasible biomass production at clay contents above 64%, because the young roots are damaged and deprived of nutrients as the soil dries out. For *Miscanthus*, plowing provided better soil loosening and easier sprouting of rhizomes compared with mini-till. The application of moisture-retaining agent Aquasorb (200 kg ha^{-1}) supported *Miscanthus* plants with moisture in the first year of vegetation, but it did not maintain soil moisture in the long term. Therefore, growing willow and *Miscanthus* on soils with clay contents above 64% is not feasible because the soil texture and tendency to crack significantly reduce the DMY. © 2022 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: bioenergy; biomass yield; combustion; low-input practices; marginal land; moisture-retaining agent; plant survival

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Introduction

For a sustainable implementation of a bioeconomy, the cultivation of perennial bioenergy crops such as *Miscanthus* (*Miscanthus* × *giganteus* Greef et Deuter), willow (*Salix* spp.), black pine (*Pinus nigra* L.) and black locust (*Robinia pseudoacacia* L.) is considered an important strategy, provided that marginal agricultural land is used.[1–3] Besides shallow soil, unfavorable soil texture (UST) conditions play a fundamental role in limiting crop production on marginal agricultural land across Europe.[4] Regarding the performance of *Miscanthus* and willow on UST, positive indications can be found in the literature.[4] However, the number of datasets is low (for Miscanthus: 15, for willow: 19),[4] so more detailed information is needed for regions that are particularly characterized by UST, such as Ukraine.

Ukraine has a variety of soil conditions owing to the wide geographical range and the richness of its soil-forming materials. Along with fertile chernozem, gray forest soil, meadow-swamp and other nutrient rich soil types, there are large areas of lands that have low fertility or are not suitable for growing crops because of other reasons.[5] Heavy clay soils represent one such crop growth-limiting soil condition. Of the 15 million hectares of degraded lands in the Urkraine, about 38% are classified as marginal agricultural land owing to the high clay content, including land mudded due to anthropogenic activities, and 14% are considered waterlogged land. Heavy clay soils are classed as marginal agricultural land[2,6] because of the challenging conditions for plant growth owing to the poor structure and aeration, and they tend to be flooded, causing cracks when they dry. In addition, this type of soil imposes many requirements on agronomic operations and often makes effective cultivation impossible.[6] On the other hand, certain agronomic practices may be useful in growing energy crops on such soils.[7]

Willow is one of these energy crops that may be suitable for biomass production on heavy clay soil under conditions of the Continental climate zones (Fig. 1(a)), as was found by Stolarski *et al.*[8] The production and utilization of willow biomass for bioenergy purposes such as combustion are characterized by low input requirements and therefore low emissions to the environment and a relatively high calorific value compared with other energy crops. Grown on the same area for 20–25 years, energy willow plantations diversify the rural landscape, help reach net negative greenhouse gas emissions, attract cadmium (Cd) and other heavy metals, reduce erosion, improve soil carbon content, and show high productivity compared with other tree species, while the obtained wood biomass helps to reduce pressure on natural forests.[9–15] The most favorable conditions for the growth of willow are to be found on well-drained soils with various mechanical compositions.[16,17] The performance of willow on heavy clay soils in Ukraine has not been studied enough. Along with willow, *Miscanthus*, which also develops a root system that can withstand several biophysical constraints in the soil,[2,18,19] might be promising for cultivation on heavy

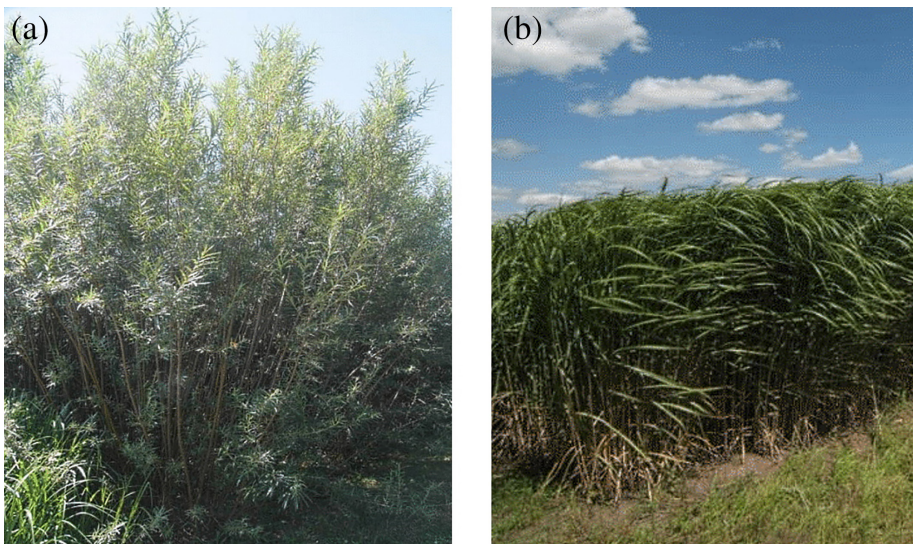

Figure 1. Impressions of (a) willow (*Salix viminalis* var. Ternopilska) and (b) *Miscanthus* (*Miscanthus* × *giganteus* Greef et Deuter) grown on hard clay soils (clay content >50%) in Yaltushkiv Experimental Breeding Station, Ukraine.

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clay soil (Fig. 1(b)). Hence, the goal of this study was to investigate the biomass dry matter yield of willow and *Miscanthus* grown under varying low-input agricultural practices on clay soils in the Forest-Steppe zone of Ukraine.

Materials and methods

The study was conducted at two locations in Ukraine: at the Experimental Field of the Institute of Bioenergy Crops and Sugar Beet National Academy of Agrarian Sciences (IBCSB NAAS), 50° 01′ 31.9″ N, 30° 10′ 16.7″ E (willow), characterized by an annual average temperature of 9.8°C (Fig. 2) and an annual average precipitation su of 437 mm (Fig. 3), and the Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS (Uladivske, Kalynivka district Vinnytsia region, 49° 33′ 15.7″ N, 28° 23′ 13.2″ E) (willow and *Miscanthus*), characterized by a long-term annual average temperature of 9.5°C (Fig. 2) and a long-term annual precipitation of 547 mm (Fig. 3). In total, three experiments were conducted as described in the following sections.

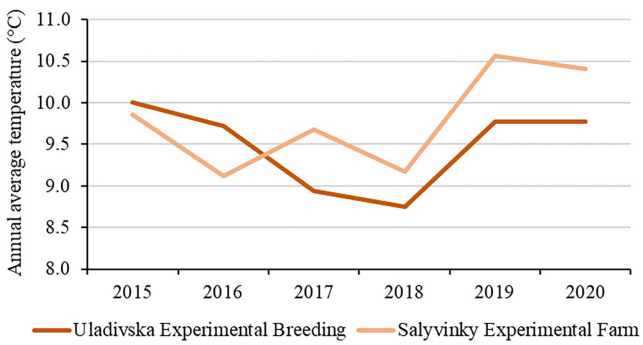

Figure 2. Annual average temperature at the two locations during the observation period.

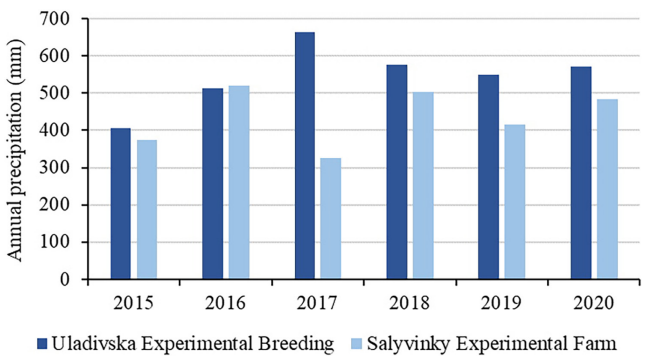

Figure 3. Annual precipitation at the two locations during the observation period.

First experiment

The first experiment was established in spring 2015 at the experimental field of the IBCSB NAAS. Willow cuttings 20 cm long of two different varieties (*Salix viminalis* and *Salix triandra*) were planted at two different row widths on plots of 20 m^2 each in a randomized block design with three replicates (Table 1). The planting density was also varied, because it is known to be an important factor in increasing the biomass productivity of willow by optimizing light, water and nutrient use efficiency of the plant stands[20–22] (Table 1).

The soil of the experimental field was deep mid-loamy chernozem with low organic matter content. The soil conditions were: pH 6.6; 53.2% clay; 2.6% organic matter; 280 mg kg^{-1} easily hydrolysed nitrogen; 180 mg kg^{-1} mobile phosphorus; 160 mg kg^{-1} mobile potassium. The study was conducted in willow plantations of the second rotation cycle. The experiment was established in spring 2015. The first harvest was in February 2018 (a 3 year cycle), and the second in December 2020 (a 3 year cycle). A control plot on soil with normal clay content (37.8%) was established with willow varieties Tora, Ternopilska, Marzencinski, Wilhelm and Inger at a planting density of 15 000 plants ha^{-1} and narrow row width. Before planting, deep plowing was performed to loosen the soil and provide favorable conditions for root development.

Second experiment

The second experiment (willow cultivation on hard clay soil) was established at Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS in 2016 on soil with high clay content (64%). Willow cuttings 20 cm long were planted on plots of an area of 20 m^2 in a randomized block design with three replicates and two experimental factors (Table 2).

The soil of the experimental field was deep meadow chernozem. The soil conditions were: pH 6.9; 64.0% clay; 5.3% organic matter; 210 mg kg^{-1} easily hydrolysed nitrogen; 86 mg kg^{-1} mobile phosphorus; 125 mg kg^{-1} mobile potassium. The soil was plowed to a depth of 30 cm. Fertilizers had not been applied. Mechanical weeding was

Table 1. Overview of experimental factors and treatments carried out in this study.

Variety	Row width	Planting density
Ternopilska	Narrow (0.75 × 1.50 m)	12 000 plants ha^{-1}
Tora	Wide (0.75 × 2.50 m)	15 000 plants ha^{-1}
		18 000 plants ha^{-1}

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carried out in the first year of cultivation. The plots were harvested by hand.

Third experiment

The third experiment was a trial on the efficiency of growing *Miscanthus* × *giganteus* on the land where the willow trial described above (2016) failed. This trial was established in 2019 at Uladivske–Liulyntsi Experimental Breeding Station of IBCSB NAAS on plots of an area of 20 m^2 in a randomized block design with three replicates and three experimental factors (Table 3).

Planting density was calculated by counting the number of plants on the whole plot and expressed as the number of plants per 1 ha. The soil was plowed to a depth of 30 cm. Fertilizers were not applied. Mechanical weeding was carried out in the first year of cultivation. The plots were harvested by hand. For biometric measurements, a sample of 10 plants was used from each plot. The measurements included plant height, the diameter of the shoots (at 1.3 m above ground) and the number of shoots of the first order. Biomass yield was determined by weighing fresh biomass (harvested by hand) from each plot and calculated per ha. The dry matter yield (DMY) was determined by drying at 105°C to a constant weight.

Statistical analysis

For the statistical analyses of experiment 1, a linear mixed model was performed to account for the design and the treatment effects 'variety', 'row width' and 'planting density'. For the trait 'Number of shoots', these effects were merged into 'treatment'. The procedure PROC MIXED in the SAS® Proprietary Software 9.3 TS level 1M0 (SAS Institute Inc., Cary, NC, USA) was performed for the traits: 'DMY' and 'Number of shoots'. The level of significance was determined at $P < 0.05$. For letter display, the macro %MULT[23] was applied. For experiments 2 and 3, an analysis of variance was performed to determine the factors influencing the experiment: 'variety' (factor A), 'row width' (factor B) and 'planting density' (factor C). The level of significance was determined at $P < 0.05$.

Table 2. Overview of experimental factors and treatments carried out in the field trial with willow established at Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS in 2016.

Variety	Planting time
Panfilska (*Salix triandra* L.)	January
Ternopilska (*Salix viminalis* L.)	March
	April

Results and discussion

In experiment 1, the DMY of willow ranged between 8.1 and 34.7 Mg ha^{-1} with an average of 19.7 Mg ha^{-1} (Fig. 4, Table A1), without any significant two- or threefold interactions (Table A2). These DMY levels are somewhat higher than those reported in studies carried out in northern Europe, where the DMYs ranged from 4.9 to 15.4 Mg ha^{-1} in the UK,[24–26] about 7.7 ± 4.5 Mg ha^{-1} in Sweden[27] and from 3.1 to 8.6 Mg ha^{-1} in Denmark.[28] These differences can be attributed to different climatic conditions, as the UK and Sweden are located in the Atlantic zone, which is characterized by lower temperatures than the Continental zone, where Ukraine is located.[5] Other studies report rather similar results with average annual DMYs of 6.4–20.0 Mg ha^{-1} in a three-year cycle.[10,29,30] Studies from the USA and Canada report willow DMYs ranging from 3.5 to 13.6 Mg ha^{-1} depending on genotype and location.[31,32] Research conducted in Poland confirmed that even high-yielding willow varieties perform much worse on marginal agricultural land characterized by low fertility compared with favorable soil.[33] However, when selecting varieties for agricultural land, it is recommended to choose those varieties that are the least demanding of nutrients and can survive without fertilizers and chemical plant protection on poor soils.[34,35]

When growing willow on heavy soils, the most critical time is the rooting period.[36] Therefore, in the first rotation

Table 3. Overview of experimental factors and treatments carried out in the field trial with *Miscanthus* established at Uladivske–Liulyntsi Experimental Breeding Station of IBCSB NAAS in 2019.

Tillage	Moisture-retaining agent (hydrogel)	Foliar fertilization in the tillering phase
Mini-till, disking to a depth of 5–15 cm. No seedbed preparation	Control	Control
Plowing, seedbed preparation to a depth of 6–8 cm using combined tools	Hydrogel Aquasorb 200 kg ha^{-1}	Foliar fertilization using Quantum-Humate (1 L ha^{-1})
		Quantum-Humate (1 L ha^{-1}) + active harvest macro (1.5 L ha^{-1})

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cycle (2015–2017) of the first experiment, the plantations were cared for well, which allowed quite a high rate of rooting and survival to be obtained. The survival rate of Tora ranged from 88 to 93% and that of Ternopilska from 89 to 95%. The average number of shoots per plant in Tora ranged from 2.2 to 2.3 and in Ternopilska from 4.1 to 5.0 (calculated based on data provided in Table A1). Interestingly, this index did not change during the whole study period, and it was not significantly affected by planting density and design.

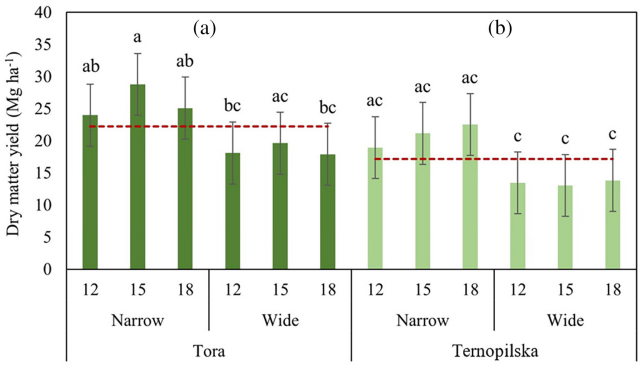

Figure 4. Results from the first experiment of growing willow on heavy clay soil at IBCSB NAAS, 2020: the dry matter yield as affected by variety (Tora, Ternopilska), row width (narrow, wide) and planting density (12 000, 15 000 and 18 000 plants ha^{-1}), and per variety across treatments. Error bars show standard errors. Different lower case letters denote significant ($P < 0.05$) differences between treatments across varieties. Different upper case letters denote significant ($P < 0.05$) differences between varieties across treatments. The red dotted line indicates the average DMY per variety.

Across all treatments, Tora showed the highest plants during the first three years. At the same time, both varieties demonstrated greater growth heights at a row width of 1.5 m. Indicators of the average diameter of shoots in all treatments correlated with plant height and, accordingly, were higher in Tora.

In February 2018, three-year old willow plantations were harvested. After that, the most intensive regrowth in terms of all biometric indicators was observed in Tora. The highest plants of the Tora variety (4.6 m) were obtained at narrow row width and a planting density of 12 000 plants ha^{-1} (Table 4). Increased plant densities of 15 000 and 18 000 plants ha^{-1} under the same row width resulted in smaller plant heights, 4.5 and 4.1 m, respectively (Table 4). The average height of Tora plants cultivated at wide row widths ranged from 4.2 to 4.5 m (Table 4), depending on the plant density. However, no significant differences were detected between row widths in this regard (Table 4).

The Ternopilska variety demonstrated the smallest regrowth (3.0 m) at a wide row width and a plant density of 15 000 plants ha^{-1} (Table 4). This variety demonstrated the best height results (3.5 m) at narrow row widths and a plant density of 12 000 plants ha^{-1} (Table 4).

In the second year of the second rotation cycle, the increment was lower than in the first year. The tendency toward decreased plant height along with increasing planting density remained. There was a significant difference in the plant height over varieties and row width. In the second year of growing, the height of Tora at narrow row widths and a planting density of 12 000 plants ha^{-1} was 6.1 m, with an annual increment of 1.5 m, which was the largest of all treatments. For plant densities of 15 000 and 18 000 plants ha^{-1}, the plant heights were 5.6 and 5.1 m, respectively, and

Table 4. Annual increment (m) of willow in the second rotation cycle as affected by planting density and row width, experimental field of the IBCSB NAAS.

Variety/year	Planting density (thousand plants ha^{-1})					
	Narrow row width			Wide row width		
	12	15	18	12	15	18
Tora						
2018	4.61 ± 0.78	4.45 ± 0.73	4.09 ± 0.68	4.45 ± 0.77	4.22 ± 0.71	4.21 ± 0.69
2019	1.48 ± 0.21	1.12 ± 0.15	1.03 ± 0.14	1.15 ± 0.16	1.02 ± 0.13	0.80 ± 0.10
2020	1.25 ± 0.17	1.04 ± 0.14	0.89 ± 0.12	1.10 ± 0.14	0.93 ± 0.12	0.75 ± 0.10
Ternopilska						
2018	3.54 ± 0.64	3.50 ± 0.60	3.41 ± 0.59	3.23 ± 0.56	2.97 ± 0.50	3.19 ± 0.55
2019	1.22 ± 0.18	1.05 ± 0.15	0.92 ± 0.13	1.07 ± 0.15	1.04 ± 0.14	0.65 ± 0.09
2020	1.08 ± 0.15	0.91 ± 0.13	0.84 ± 0.11	0.97 ± 0.13	0.85 ± 0.11	0.58 ± 0.08

$LSD_{0.05}$: 2018, 0.21; 2019, 0.14; 2020, 0.10.

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the increment was almost at the same level – it differed within error and ranged between 1.0 and 1.2 m.

In Ternopilska, the plant height was larger at a plant density of 12 000 plants ha^{-1} at both row widths, 4.8 and 4.3 m, respectively. At wide row widths, the average plant height was 5.0–5.6 m in Tora and 3.8–4.3 m in Ternopilska, which was much less than at narrow row widths.

In the third year of the second rotation cycle, the trends of the previous 2 years persisted, and growth intensity decreased by an average of 9.7% in Tora and 12.1% in Ternopilska compared with the previous year. Accordingly, plant height was most influenced by varietal characteristics (69.9%), followed by planting density (13.0%) and row width (9.3%).

Increased planting density had a negative effect on the number of shoots per plant. The highest number of shoots (6.9–7.8) in the first year of growth was in Ternopilska variety at narrow row widths, while the lowest (4.5–5.4) was in Tora at wide row widths.

At narrow row widths, Tora formed 6.6 shoots per plant at a plant density of 12 000 plants ha^{-1}, 5.4 shoots at a plant density of 15 000 plants ha^{-1} and 5.2 shoots at a density of 18 000 plants ha^{-1}. At wide row widths, Tora also produced the largest number of shoots (5.4) at a lower plant density. The number decreased at plant densities of 15 000 and 18 000 plants ha^{-1} (4.8 and 4.5, respectively).

In the second year of the second rotation cycle, the number of shoots per plant increased slightly; there was a small number of young shoots. The largest number of shoots in the second year (7.0–8.0) was observed in Ternopilska variety at narrow row widths, while the lowest (4.8–5.7) was in Tora at wide row widths. At narrow row widths, Tora formed 5.4–6.9 shoots per plant, depending on the planting density.

In the third year, the average number of shoots was 5.5 in Tora and 7.0 in Ternopilska (Fig. 5). It was found that the number of shoots per plant was most influenced by varietal characteristics (40.9%) followed by the initial plant density (34.3%). The factor of row width had a 10.7% impact, and the influence of other factors was not significant. The planting density in the first year of the second rotation cycle had a negligible effect on the diameter of the highest shoot in both willow varieties. There was only a slight decrease in the diameter of the shoots with increasing density; however, a significant difference in diameter was observed between varieties (Table 5).

The smallest diameter of the shoots was observed in Ternopilska at wide row widths and a planting density of 15 000 and 18 000 plants ha^{-1}, while the largest was in Tora at both row widths.

In the second year of the second rotation cycle, the effect of planting density on the diameter of shoots increased, as

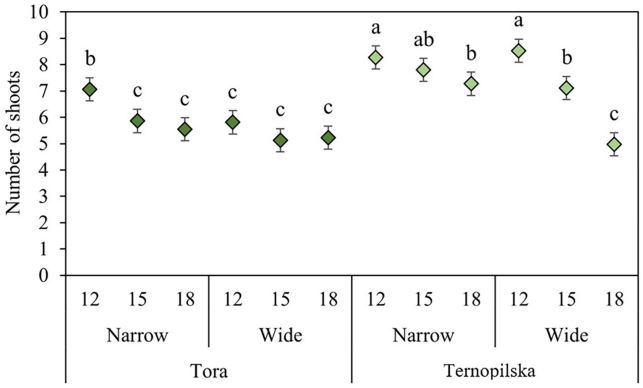

Figure 5. Results from the first experiment at IBCSB NAAS, 2020: the number of shoots per plant as affected by variety (Tora, Ternopilska), row width (narrow, wide) and planting density (12 000, 15 000 and 18 000 k plants ha^{-1}). Numbers per variety across treatments are not shown because of a significant ($P < 0.01$) threefold interaction (variety × row width × plant density). The error bars show standard errors. Different letters denote significant ($P < 0.05$) differences between treatments.

was indicated by significant differences in diameters over the treatments. The diameter of the highest shoot decreased with increasing planting density.

The largest diameter of shoots (36.8 mm) in Tora was recorded at the lowest planting density (12 000 plants ha^{-1}) and narrow row widths. The smallest diameter (20.3 mm) was obtained in Ternopilska at a planting density of 18 000 plants ha^{-1} and wide row widths.

It was also found that wide row widths led to a larger diameter of the shoot compared with narrow row widths. In addition, the shoot diameter decreased along with increased planting density. In the third year of vegetation, the same patterns were observed as in the second year.

In the first year of the second rotation cycle (2018), the biomass increment was intensive, similar to the second year of the first rotation cycle. At the same time, the highest values of biomass accumulation in both varieties were at narrow row widths. Thus, the accumulation of biomass in the first year of the second rotation cycle was most significantly influenced by the varietal factor (50.6%) and row width (27.5%).

In the second year of the second rotation cycle, similar values of biomass accumulation were obtained. The highest values showed Tora (41.7 Mg ha^{-1}) at narrow row widths and a planting density of 15 000 plants ha^{-1} and Ternopilska (30.5 Mg ha^{-1}) at a planting density of 12 000 plants ha^{-1} and the same row width.

It was also found that the annual increment in biomass decreased along with increasing plant density, while in the

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second year, the most important factor of influence was variety (63.7%). The yield of dry biomass in the third year of the second rotation cycle averaged 22.3 Mg ha^{-1} in Tora and 17.2 Mg ha^{-1} in Ternopilska (Fig. 3).

Trends in the formation of fresh biomass affected the DMY. The best row width for both varieties appeared to be narrow row width. In Tora, the planting density of 15 000 plants ha^{-1} was more efficient, ensuring an accumulated DMY of 28.8 Mg ha^{-1}, while in Ternopilska, the highest DMY (22.5 Mg ha^{-1}) was obtained at a planting density of 18 000 plants ha^{-1}. This indicates the larger DMY accumulation at this density, despite the better results of the fresh biomass yield in previous years at a planting density of 12 000 plants ha^{-1}.

Growing willow on marginal agricultural land imposes certain limitations on plant growth and DMY. The data presented in Table 6 demonstrate the differences in the biomass yield value and biomass yield structure when willow is grown on fertile soil (control).

A comparison of six-year-old willow plantations with narrow row width and a planting density of 15 000 plants ha^{-1} showed that Swedish varieties Tora, Inger and Wilhelm could be successfully cultivated in Ukraine. At the same time, limitations imposed by high clay content which significantly reduced the biomass yield. For example, the Tora variety demonstrated a 34% higher biom yield when cultivated on fertile soil. In the trial on hard clay soil, the best time for planting willow appeared in November or March, before the beginning of vegetation. However, November is somewhat risky because in some years, the soil is frozen. The performance of willow on hard clay soil in the second experiment is shown in Table 7.

In the first year of cultivation, the average survival rate of *Salix triandra* Panfilska was 47% and *Salix viminalis* Ternopilska 40%. In the following years, the willow stands became thinner and thinner, giving a small increment. At the end of the vegetation season of 2018, only 14.3% of Panfilska and 12.4% of Ternopilska plants survived. The two-year increment (2016–2018) was 0.44 m in Panfilska and 0.52 m in Ternopilska. Consequently, establishing plantations of willow on hard clay soil (64%) turned out to be a rather negative experience, especially in conditions of moisture deficit. The soil moisture content in April was good in 2017 and 2018, and sufficient in 2019 and 2020. In June, the moisture content was scarce in 2017 and sufficient in 2018–2020 (Table 8).

Table 5. The average diameter (mm) of the highest shoot as affected by the planting density and row width, experimental field of the IBCSB NAAS, 2018–2020.

Row width	Planting density (thousand plants ha^{-1})	Tora			Ternopilska		
		2018	2019	2020	2018	2019	2020
Narrow	12	25.5±3.3	36.8±4.7	40.2±5.2	18.6±2.6	28.7±3.9	33.1±4.4
	15	24.7±3.0	32.5±3.8	39.7±5.0	17.6±2.3	25.8±3.4	30.0±3.9
	18	24.0±3.1	30.2±3.8	37.1±4.8	16.1±2.2	21.2±2.8	26.7±3.4
Wide	12	24.4±3.2	34.3±4.2	39.3±4.8	16.2±2.2	24.3±3.1	27.0±3.9
	15	23.7±3.1	31.5±3.6	37.0±4.5	15.8±2.1	21.8±2.7	25.3±3.1
	18	22.9±2.9	29.0±3.4	35.4±4.4	14.9±2.0	20.3±2.6	24.1±3.0

$LSD_{0.05}$: 2018, 2.80; 2019, 3.29; 2020, 3.47.

Table 6. Yield structure of the six-year old willow plantation of the second rotation cycle, fertile soil (control), experimental field of the IBCSB NAAS, 2020.

Variety	The number of shoots	Average height of shoots (m)	Average diameter of shoots (cut at 1.3 m) (cm)	Fresh biomass per plant (kg)	Biomass yield (Mg ha^{-1})		Average annual increase in dry matter (Mg ha^{-1})
					Fresh	Dry	
Tora	6.8	7.9	4.7	6.3	77.1	38.6	12.9
Ternopilska	8.5	6.9	3.3	4.5	57.1	28.6	9.5
Marzencinski	2.60	7.0	3.1	3.3	41.2	20,6	6.9
Wilhelm	1.40	7.8	4.0	5.1	63.7	31.8	10.6
Inger	1.60	7.7	3.7	6.1	76.2	38.1	12.7
$LSD_{0.05}$	0.10	0.13	0.17	0.23	2.7	1.5	0.81

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Table 7. Performance of willow (Panfilska and Ternopilska), grown at Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS, 2016–2018.

Month of planting	Variety	Survival (%)		Shoots per plant		Plant height (m)	
		2016	2018	2016	2018	2016	2018
November	Panfilska	50.0	15.6	3.0	4.0	1.00	1.30
	Ternopilska	40.0	12.4	2.0	3.0	0.75	1.35
March	Panfilska	55.0	16.0	2.0	3.0	0.70	1.40
	Ternopilska	50.0	14.5	3.0	3.0	0.80	1.40
April	Panfilska	36.0	11.3	5.6	6.0	1.18	1.50
	Ternopilska	30.0	10.2	5.0	5.0	1.10	1.45
$LSD_{0.05}$		5.0	1.1	0.6	0.8	0.10	0.18

Table 8. Moisture content (mm) in soil, Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS, 2015–2020.

Year	Month	Treatment	Moisture content (mm) of the main soil layers	
			0–20 cm	20–100 cm
2017	April	No hydrogel	52	243
	June	No hydrogel	10	44
	September	No hydrogel	1	23
2018	April	No hydrogel	42	205
	June	No hydrogel	37	137
	September	No hydrogel	34	112
2019	April	No hydrogel	29	166
		Hydrogel Aquasorb	32	169
	June	No hydrogel	24	101
		Hydrogel Aquasorb	27	104
	September	No hydrogel	11	83
		Hydrogel Aquasorb	14	86
2020	April	No hydrogel	26	140
		Hydrogel Aquasorb	29	143
	June	No hydrogel	20	94
		Hydrogel Aquasorb	23	97
	September	No hydrogel	7	48
		Hydrogel Aquasorb	10	51

Depletion of moisture from the rooting layer in hard clay soils leads to the formation of cracks in the soil, as was observed in 2017. As a result, many plants died.

To investigate a possible solution to the problem, the third experiment – a trial on *Miscanthus* – was designed with application of a moisture-retaining agent (hydrogel)



Figure 6. Hydrogel particles on *Miscanthus* rhizomes, Uladivske–Liulyntsi Experimental Breeding Station IBCSB NASS, 2019.

on hard clay soil. Figure 6 shows *Miscanthus* rhizomes with stuck particles of hydrogel. The data on field sprouting and the survival of *Miscanthus* rhizomes are shown in Table 9. Plowing provided better soil loosening and consequently better contact of soil with rhizomes, which resulted in a higher rate of rhizomes sprouting – by 9.6% compared with mini-till. The application of the moisture-retaining agent Aquasorb (200 kg ha^{-1}) proved to be an effective method to support *Miscanthus* plants. For example, plant survival was 11.1% higher in 2019 and 8.1% higher in 2020 for the hydrogel treatments compared with the control. Nevertheless, even hydrogel was not enough to preserve soil moisture stocks in hard clay soil and support plants (Fig. 7). Plants of *Miscanthus* are very sensitive to the moisture content in the rooting soil layer (0–20 cm).

In the second year, only those *Miscanthus* plants survived whose roots have been in contact with the hydrogel (Fig. 6).

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Table 9. Field sprouting and survival of *Miscanthus* rhizomes, Uladivske–Liulyntsi Experimental Breeding Station IBCSB NAAS, 2019–2020.

Tillage	Treatment	Foliar fertilization	Field sprouting of rhizomes (%)	Survival (%)	
			2019	2019	2020
Mini-till	No hydrogel	No fertilization	53.1	34.5	16.8
		Quantum-Humate (1 L ha^{-1})	53.0	35.6	17.0
		Quantum-Humate (1 L ha^{-1}) + active harvest macro (1.5 L ha^{-1})	53.0	37.8	17.9
	Hydrogel Aquasorb	No fertilization	65.2	40.0	23.4
		Quantum-Humate (1 L ha^{-1})	65.3	42.3	25.6
		Quantum-Humate (1 L ha^{-1}) + active harvest macro (1.5 L ha^{-1})	65.2	44.1	26.9
Plowing	No hydrogel	No fertilization	66.8	39.8	18.2
		Quantum-Humate (1 L ha^{-1})	66.7	42.2	19.0
		Quantum-Humate (1 L ha^{-1}) + active harvest macro (1.5 L ha^{-1})	66.8	43.9	20.6
	Hydrogel Aquasorb	No fertilization	70.7	56.2	25.6
		Quantum-Humate (1 L ha^{-1})	70.8	57.8	27.9
		Quantum-Humate (1 L ha^{-1}) + active harvest macro (1.5 L ha^{-1})	70.8	59.9	28.6
$LSD_{0.05}$			4.2	3.0	2.8



Figure 7. The formation of cracks in theg soil with high clay content (64%), Uladivske–Liulyntsi Experimental Breeding Station IBCSB NASS, 2019.

However, even in these plants, it was observed that the format cracks in the soil negatively affected rooting, which reduced the establishment success of *Miscanthus*.

Overall, the effects of marginal growth conditions on the biometric parameters of willow varieties presented here are in line with other studies.[29,37–40] It is also noteworthy that willow varieties generally have a better ratio of biometric parameters compared with wild forms of willow.[41,42] This study showed that willow produces the highest DMY when shoots are few in number but tall, and when the tallest shoot has a large diameter of more than 10 cm. Other studies found that biomass obtained from plants with fewer shoots has a larger ratio of wood to bark content.[35,43,44] Furthermore, some willow varieties demonstrated higher productivity on a clay soil compared with a sandy soil in another study from Denmark. Such results confirm the conclusions of this study that clay soils are better than sand soils for willow.[45] *Miscanthus*, however, seems to grow better on light soils than on clay soils, because as a C4-grass it uses moisture efficiently.[46,47]

Conclusions

In Ukraine, the main characteristics of abandoned land are low fertility caused by low organic matter content, acidity, high content of clay or low moisture capacity. On such areas, willow DMY can be stabilized or even increased through agricultural measures related to proper establishment and management of plantings. These measures include: (i) the selection of an appropriate willow variety; (ii) adequate soil preparation, (iii) adequate row width; and (iv) adequate planting density. In this study, willow achieved remarkable DMY on hard clay soils (clay >50%), as found in the forest-Steppe of Ukraine.

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Here, the willow variety 'Tora' showed the best biomass yield performance, as indicated by the highest increment (4.09–4.61 m) in the first year of the second cycle compared with the other tested cultivars. Furthermore, the highest DMY (28.8 Mg ha^{-1}) was obtained at a planting density of 15 000 plants per hectare combined with narrow row widths. *Miscanthus* performance on hard clay soils (clay >50%) needs further investigation. However, if the content of clay is higher than 64%, neither willow nor *Miscanthus* allow for a feasible biomass production. This is because the dense soil structure and the tendency to form cracks in the soil during droughts decrease the plant density, increment and DMY of both willow and *Miscanthus*. In the future, the productivity of willow could be increased by the development of new varieties. The same could be true for climatically and pedologically comparable regions around the world, where an expansion of the provision of bioenergy from the biomass of perennial industrial crops such as willow and *Miscanthus* is being considered.

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Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability statement

All datasets are included in this study.

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A. Appendix

Table A1. Raw data from experiment 1.

Treatment	Variety	Row width	Planting density (thousand plants ha^{-1})	Dry matter yield ($Mg\,ha^{-1}$)	Shoots per plant
1	Tora	Narrow	12	20.4	6.6
2	Tora	Narrow	15	21.2	5.4
3	Tora	Narrow	18	18.2	5.2
4	Tora	Wide	12	11.1	5.4
5	Tora	Wide	15	16.2	4.8
6	Tora	Wide	18	10.3	5.2
1	Tora	Narrow	12	27.6	7.7
2	Tora	Narrow	15	34.7	6.4
3	Tora	Narrow	18	31.6	6.0
4	Tora	Wide	12	25.1	6.3
5	Tora	Wide	15	26.9	5.6
6	Tora	Wide	18	28.2	5.7
1	Tora	Narrow	12	24	6.9
2	Tora	Narrow	15	30.5	5.8
3	Tora	Narrow	18	25.5	5.4
4	Tora	Wide	12	18.1	5.7
5	Tora	Wide	15	15.8	5.0
6	Tora	Wide	18	15.2	4.8
7	Ternopilska	Narrow	12	14.2	7.8
8	Ternopilska	Narrow	15	15.7	7.4
9	Ternopilska	Narrow	18	16.1	6.9
10	Ternopilska	Wide	12	11.1	7.9
11	Ternopilska	Wide	15	8.1	6.7
12	Ternopilska	Wide	18	10.3	4.5
7	Ternopilska	Narrow	12	22.8	9.0
8	Ternopilska	Narrow	15	25.5	8.5
9	Ternopilska	Narrow	18	27.9	7.9
10	Ternopilska	Wide	12	16	9.3
11	Ternopilska	Wide	15	18.3	7.8
12	Ternopilska	Wide	18	19.8	5.4
7	Ternopilska	Narrow	12	19.8	8.0
8	Ternopilska	Narrow	15	22.3	7.5
9	Ternopilska	Narrow	18	23.6	7.0
10	Ternopilska	Wide	12	13.3	8.4
11	Ternopilska	Wide	15	12.7	6.9
12	Ternopilska	Wide	18	11.4	5.0

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Table A2. Results of statistical analyses of fixed effects.

Effect	Dry matter yield	Number of shoots
Variety	*	(***)
Row width	**	(***)
Planting density	n.s.	(***)
Variety × row width	n.s.	n.s.
Variety × planting density	n.s.	(*)
Row width × planting density	n.s.	n.s.
Variety × row width × planting density	n.s.	**

Note: Brackets denote significant differences masked by significant threefold interaction.
Abbreviation: n.s., non-significant.
*= $P < 0.05$.
**= $P < 0.01$.
***= $P < 0.0001$.

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