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Adaptive properties of plants and yield of energy crops under different growing conditions: A case study from Ukraine

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ABSTRACT

In Ukraine, balancing agricultural efficiency, food security, and energy development is crucial. Energy crops offer a sustainable raw material due to their adaptability and high biomass yields, supporting biofuel production and value-added products like bioplastics and paper. However, the war has severely degraded agricultural land, necessitating reclamation efforts to restore productivity and enhance bioenergy potential. A five-year field study (2019–2023) in Ukraine's forest-steppe and steppe zones assessed energy crop yields on marginal lands. Research methods included field studies, gravimetric biomass analysis, data visualization, and statistical analysis (ANOVA, LSD at 5% significance). Findings showed that drooping sorghum and perennial sorghum exhibited the highest drought resistance, while switchgrass and drooping sorghum demonstrated the best frost resistance. Drooping sorghum also had the greatest lodging resistance, whereas switchgrass and perennial sorghum were more prone to lodging, particularly in the forest-steppe, suggesting a correlation with precipitation levels. The vegetation period varied by region, influenced by plant biology and environmental factors. In the Steppe, it lasted 170.6–192.0 days, with drooping sorghum having the longest cycle. In the forest-steppe, it ranged from 170.3 to 181.3 days, with switchgrass exhibiting the longest duration. Biomass yields were higher in the steppe (7.8–11.2 t/ha) than in the forest-steppe (7.4–10.4 t/ha). Over four years, switchgrass and perennial sorghum achieved the highest total biomass yields: 56.0 t/ha and 53.6 t/ha in the steppe, and 51.9 t/ha and 51.7 t/ha in the forest-steppe, respectively. Drooping sorghum produced 46.1 t/ha (steppe) and 39.9 t/ha (forest-steppe), while big bluestem had the lowest yield (39.1 t/ha and 36.9 t/ha). Switchgrass and perennial sorghum proved to be the most productive and adaptable energy crops. Their stable biomass production makes them promising candidates for biofuel manufacturing. Future research will explore strategies to enhance yields, particularly through spring foliar fertilization on marginal lands.

Keywords: yield, biomass, energy crops, adaptability, growing conditions, phytomass output.

INTRODUCTION

Currently, a pressing issue is the development of efficient and environmentally safe agro-technologies for growing energy crops, which are among the most promising sources of bio-based raw materials. These crops play a crucial role in biofuel production as well as in the manufacturing of value-added products. To enhance biomass production efficiency and achieve maximum energy crop productivity, it is essential to use agricultural land rationally, especially marginal lands. The reclamation of such lands is an integral part of sustainable natural resource management and environmental protection (Wu et al., 2024).

In Ukraine, a significant portion of agricultural land has been severely degraded due to ongoing military actions, including explosions, fires, and soil contamination with heavy metals and unexploded ordnance. This large-scale destruction has led to a decrease in arable land availability, necessitating the urgent development of effective land restoration strategies and alternative approaches for biomass production. The rehabilitation of these disturbed lands for energy crop cultivation not only contributes to environmental sustainability but also aligns with the goal of increasing biofuel feedstock availability (Kozlenko et al., 2023). Therefore, studying the efficiency of traditional and less common energy crops on marginal lands in Ukraine's Forest-Steppe and Steppe zones over a five-year period is highly relevant.

Among energy crops, species from the Poaceae family have demonstrated the highest adaptability and productivity on disturbed lands. These include switchgrass (*Panicum virgatum* L.), Indiangrass (*Sorghastrum nutans* (L.) Nash), big bluestem (*Andropogon gerardii* Vitman), and Columbus grass (*Sorghum almum* Parodi) (Quader & Ahmed, 2017; Mitchell & Vogel, 2004). Assessing the aboveground phytomass productivity potential of these energy crops presents a valuable opportunity for maximizing the energy yield from such agroecosystems.

Background

The use of biomass from energy crops plays a crucial role in the development of renewable energy sources. These crops serve as high-quality plant raw materials for biofuels, contributing to the reduction of Ukraine's energy dependence. Additionally, the cultivation of energy crops presents opportunities for regional economic development, fostering job creation and stimulating local economies (Kulyk & Padalka, 2020; Knapp et al., 1998; Pryshliak et al., 2021).

Several studies have examined the agroecological characteristics and energy potential of various energy crops. Research has focused on optimizing agronomic management strategies, including new cultivation techniques for switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus* spp.), and sorghum (*Sorghum* spp.) (Mauro et al., 2024).

In addition to these well-studied crops, other species such as giant reed (*Arundo donax*) and sugar sorghum (*Sorghum saccharatum*) have also attracted scientific interest (Spencer & Ksander, 2006; Rossa et al., 1998; Saltonstall et al., 2010; Pryshliak et al., 2021). However, the morphological and biological traits of these species, as well as their biomass yield potential in relation to biofuel production, remain insufficiently explored.

Grassy energy crops from the Poaceae family exhibit significant variability in their growth characteristics, including differences in vegetative period duration, developmental intensity, plant morphology, and environmental responses. These crops require distinct agronomic practices for cultivation and have diverse applications, primarily for bioenergy production (Vogel et al., 2018; Varvel et al., 2018; Ţîţei et al., 2015; Casler et al., 2018; Berezyuk et al., 2021).

The Russian invasion of Ukraine has significantly impacted soil quality, particularly through heavy metal and petroleum-based contaminations. Research indicates that military actions lead to the accumulation of toxic substances, including lead (Pb), cadmium (Cd), and polycyclic aromatic hydrocarbons (PAHs), which pose challenges for agricultural sustainability (Kovalchuk et al., 2023; Mikhalovska et al., 2023). However, certain energy crops, such as miscanthus and switchgrass, demonstrate phytoremediation potential, effectively absorbing and stabilizing contaminants in polluted soils (Kulyk et al., 2020; Shevchuk et al., 2022).

Given these challenges, further research is needed to evaluate the adaptability of energy crops under post-conflict conditions and their role in soil restoration.

Research objective

This study aims to perform a comprehensive agroecological assessment of perennial species from the Poaceae family and determine the optimal conditions for maximizing biomass productivity in energy crop cultivation within Ukraine's steppe and forest-steppe zones. Given the ongoing military actions in Ukraine, which have led to extensive soil contamination, the study also seeks to evaluate the resilience of energy crops in degraded and potentially hazardous environments.To achieve this objective, the study will: assess the adaptive capacity and phenological characteristics, including the duration of the growing season, of energy crops under diverse agroclimatic conditions in the steppe and forest-steppe zones; quantify the yield potential and biomass accumulation of monoculture energy crops as influenced by specific environmental and edaphic factors within the studied regions; investigate the potential of selected energy crops to tolerate and remediate soils affected by contamination from heavy metals, explosives, and other pollutants resulting from military actions, contributing to ecological restoration and sustainable land use in post-conflict Ukraine.

The long-term cultivation of energy crops has been shown to exert a positive ecological impact, contributing to an increase in soil organic matter content and improving the soil water balance. These processes are closely linked to carbon cycling and overall soil health (Tryboi et al., 2024; Roik & Hanzhenko, 2021; Roik et al., 2021). Furthermore, energy crops hold potential beyond biofuel production, as they serve as raw materials for value-added products derived from biofuel processing residues.

The utilization of biomass derived from energy crops follows a hierarchical structure based on the complexity of its conversion processes and final applications. At the most fundamental level, solid biofuels are produced, representing the most accessible and technologically straightforward form of biomass utilization. This process primarily involves direct combustion or mechanical processing into pellets and briquettes.

At a more advanced level, technological processes enable the conversion of biomass into liquid and gaseous biofuels, such as bioethanol, biodiesel, and biogas. These processes typically involve biochemical (fermentation) or thermochemical (pyrolysis, gasification) pathways, which require greater technological input and optimization. The third level of complexity includes the production of cellulose, chemical-thermomechanical pulp, and other lignocellulosic materials that serve as precursors for paper, packaging, and biodegradable polymers. These applications significantly enhance the value chain of bioresources by supporting sustainable industrial processes.

Beyond these applications, biomass-derived compounds are utilized in the pharmaceutical and medical sectors, where complex biorefinery techniques enable the extraction of bioactive compounds and biopolymers for therapeutic and biomedical applications. More advanced chemical processes involve the production of hydrogen as a clean energy carrier, which requires sophisticated catalytic and thermochemical conversion methods. At the highest level of technological complexity, biomass serves as a raw material for the military-industrial complex (MIC), where specialized processes are employed for the synthesis of nitrocellulose and other energy-dense compounds used in explosives and propellants. The integration of biomass into high-value industrial applications highlights its strategic importance beyond energy production.

MATERIALS AND METHODS

Biomass for biofuel production

The suitability of biomass from energy crops for biofuel conversion is determined by several key parameters, including energy content, bulk density, moisture content, and chemical composition. These factors influence both the efficiency of biofuel production and the economic feasibility of large-scale biomass utilization. High energy yield per unit area, ease of cultivation, and adaptability to marginal lands further define the agronomic and economic potential of specific energy crops (Tubeileh et al., 2014; Geletukha & Zheliezna, 2017).

Bioenergy in general is focused on the use of local plant energy resources and the capabilities of territorial communities, including the cultivation of energy crops. Therefore, a country that has a significant share of energy produced from biomass in its energy balance gains the most important benefit – energy independence from global trends in the rising cost of fossil fuels.

The most common energy crops in Ukraine today are as follows. These include representatives from the willow family, Salicaceae – species from the genus *Salix* (*Salix alba* L., *Salix viminalis* L.), from the grass family (Poaceae) – switchgrass (*Panicum virgatum* L.). A wide range of species from the genus *Miscanthus*: *Miscanthus x Giganteus* Greef & Deuter ex Hodkinson & Renvoize, *Miscanthus sinensis* Anderss, *Miscanthus sacchariflorus* (Maxim) Benth., and poplar species (*Populus*). All these crops are perennials, with their lifespan reaching 10–15 years. It should be noted that, in some cases and under certain agro-technical measures and conditions, this term can be extended up to 30 years.

Field experiments

Field experiments were conducted from 2018 to 2023, taking into account various soil and climatic conditions of the steppe and forest-steppe zones. The experiments conducted in the conditions of the northern steppe belong to the Dnipro district of the Dnipropetrovsk region, located on degraded soils (marginal lands).

The soil-forming rock is technosol. The soils of the experimental plots had the following characteristics that correspond to the definition of "marginal": humus content – low – at or below 2.8%, alkaline-hydrolyzed nitrogen – 105.5 mg/kg of soil, phosphorus – 114.6 mg/kg of soil, salt pH is 6.8. The climate of the steppe is moderately continental with insufficient (unstable) moisture, cold winters, and hot dry summers. The period was characterized by unstable weather conditions.

The experiments conducted in the conditions of the southern forest-steppe are territorially located in the Poltava region, situated on marginal soils. The soil-forming rock is field carbonate loess-like clay. Soil characteristics – meadow-chernozem washed medium-sweetened soils (depression). Agrochemical characteristics of the soils: humus content – low, at 2.7%, alkaline-hydrolyzed nitrogen – 120.1 mg/kg of soil, phosphorus – 86.5 mg/kg of soil, salt pH is 6.2.

The climate of the forest-steppe is moderately continental with average (in some years – insufficient) moisture, cold winters, and hot, and in some years, dry summers.

Experiments set up

The experiment was conducted using a two-factor scheme in the steppe and forest-steppe zones of Ukraine from 2019 to 2023. The area of the sowing plot was 50 m², the accounting plot area was 30 m², and the variants were arranged using a systematic method. The total experimental area was 0.36 ha. The experiment was repeated four times. The experiment was set up using a systematic repetition method: in each repetition, the variants were randomized on the plots. The experimental scheme is shown in Figure 1.

Agrotechnology in the experiments

The technology for growing energy crops in the experiments followed the generally accepted practices for the respective research zones, in accordance with scientific recommendations (Fedorchuk et al. 2017). The predecessor for all energy crops was the herbaceous vegetation growing on virgin lands.

The preparation of the experimental plots consisted of plowing the soil profile to a depth of 20–22 cm, followed by disking and summer-autumn cultivation as weeds appeared. Seed sowing was done both manually and with small-seed drills "Amazone" with a row spacing of 45 cm, followed by rolling the sowings.

The energy crop varieties selected for the experiments were: switchgrass variety 'Zoryane'; perennial sorghum variety 'Columbo'; creeping sorghum variety 'Bison'; Big Bluestem variety 'Americus'. The seed material of introduced energy crops was obtained through the implementation of the international scientific project "Pellets for Power", and the varieties of Ukrainian origin were provided by the originators. The seed material met the basic seed quality standards for these varieties.

Inter-row cultivation was carried out only in the first and second years of vegetation on monoculture sowings using a KRH-5.6 cultivator.

During the setup of the experiment, mineral fertilizers were not applied as base or supplementary fertilizers for the crops. The experiment was conducted using the method of systematic repetitions: in each repetition, the variants of the experiment were arranged on the plots either randomly or sequentially.

Methods

The selection and establishment of experimental plots were carried out according to the methodology of experimental research in agronomy (Rozhkov et al., 2016) using a two- or three-factor experimental design. Weather indicators, such as the average daily air temperature and monthly precipitation, were recorded each year to compare with the multi-year averages for each zone. Recordkeeping and observations of the plants were conducted according to the relevant methods:
- Plant resistance to environmental conditions and lodging was measured following the methodology (Volkodav, 2001);
- Phenological observations were recorded according to the classification:
  - 0 – emergence;
  - 1 – appearance of three true leaves;

Growing Conditions (Factor A)	Energy crops* (Factor B)
Steppe Forest-Steppe	Sw
	Sa
	Bb
	Ig

Figure 1. Experimental scheme: Sw – monoculture sowing of switchgrass, Sa – monoculture sowing of perennial sorghum, Bb – monoculture sowing of Big Bluestem, Ig – monoculture sowing of creeping sorghum

- 2 – tillering;
- 3 – booting;
- 4 – stem elongation;
- 5 – panicle appearance;
- 6 – flowering;
- 7 – waxy seed maturity;
- 8 – full seed maturity;
- 9 – physiological maturity;
- 10 – end of vegetation;

- No recording of pests and diseases was conducted in the experiments as their assessment was not part of this study. However, it should be noted that no disease symptoms or pest damage were observed during visual inspections of all experiments.
- Biomass yield was recorded separately for each repetition by mowing the biomass and weighing it. After drying, the dry matter content was determined (Kulyk & Elbersen, 2012).

Laboratory studies were carried out at the certified scientific laboratory of agroecological monitoring at the Poltava State Agrarian University.

Statistical calculations of the data were conducted according to the methodological guidelines (Ermantraut et al., 2007).

RESULTS OF THE RESEARCH

Adaptive properties and duration of the vegetation period of energy crops

The adaptive properties of the energy crops under study, as noted earlier, are high. In this regard, our research confirmed the conclusions of other authors regarding the overall resilience of energy crops to external environmental factors (Table 1). According to the results of long-term studies, it has been determined that the growing conditions of energy crops affect their drought tolerance.

In the steppe conditions (8.8–9.8 points), compared to the forest-steppe (8.2–9.4 points), an increased resistance to drought in energy crops was recorded. Among them, perennial sorghum and Indian grass had a drought resistance score above 9.0, while switchgrass and Big Bluestem had lower scores. This can be explained by the origin of the plants, their introduction characteristics, and the peculiarities of the structure and functioning of their underground (root systems) and aboveground vegetative mass (leaves and stems).

According to literature sources, it has been found that due to the accumulation of sugar-containing substances in the tillering nodes and the upper part of the root system, or rhizomes, at the time of the end of the growing season, energy crops are capable of withstanding adverse wintering conditions (Salvatore et al, 2008). It is precisely these features that explain the different reactions of the plants in terms of their frost resistance during the research period.

Thus, the greatest resistance (more than 8.0 points) to lodging was observed in Big Bluestem and Indian Grass plants in two growing locations. This indicator was lower for perennial sorghum and prutopodible millet in steppe conditions (6.4–7.0 points), and significantly lower in forest-steppe conditions (5.2–6.0 points).

Overall, over the years of research, all energy crops studied showed high adaptive potential to various growing conditions. Perennial sorghum showed a tendency to lodging, with an average resistance score of 5.2 points (forest-steppe conditions) or above average (steppe conditions).

According to the phenological observations, different periods for inter-phase transitions and

Table 1. Adaptive properties of energy crops according to growing conditions, 2019–2023 years

Growing conditions (Factor A)	Energy crops (Factor B)	Drought resistance, points	Frost resistance, points	Lodging resistance, points	Overall resistance, points
Steppe	*Sw*	8.9	9.5	7.0	8.5
	Sa	9.5	8.2	6.4	8.0
	Bb	8.8	8.5	8.8	8.7
	Ig	9.8	9.5	8.9	9.4
Forest-Steppe	*Sw*	8.4	9.2	5.5	7.7
	Sa	9.4	7.8	5.2	7.5
	Bb	8.2	7.8	8.5	8.2
	Ig	9.5	9.6	8.9	9.3

Note: *Sw* – monoculture planting of switchgrass, *Sa* – monoculture planting of perennial sorghum, *Bb* – monoculture planting of Big Bluestem, *Ig* – monoculture planting of sorghum-sudangrass.

the growing season of energy crops were determined (Table 2, Figure 3). The cultivation of energy crops in the Steppe, compared to the Forest-Steppe, significantly extended the duration of the interphase periods of the individual studied plants. This ultimately affected the length of the vegetative period of energy crops depending on their growing conditions (Figure 2).

During the research, the dates of plant growth and development stages were determined, and the variation in the duration of the growing season was established based on the conditions of energy crops cultivation in different climatic zones. Thus, the growing season of switchgrass in the Steppe conditions lasted about 190 days, while in the Forest-Steppe conditions it lasted 180 days.

Table 2. Phenological observations of the developmental and growth phases of energy crops, 2019–2023

Growing conditions	Energy crops*	Parameter**						
		V/V	K	V/T	VV	K	D/N	Z/V
Steppe	*Sw*	II decade of April	III decade of April	I decade of May	III decade of June	II decade of July	I decade of October	III decade of October
	Sa	II decade of April	III decade of April	I decade of May	III decade of June	II decade of July	I decade of October	III decade of October
	Bb	II decade of April	III decade of April	I decade of May	III decade of June	II decade of July	I decade of October	I decade of November
	Ig	II decade of April	III decade of April	I decade of May	III decade of June	II decade of July	I decade of October	I decade of November
Forest-Steppe	*Sw*	II decade of April	III decade of April	I decade of May	I decade of July	III decade of July	I decade of October	I decade of October
	Sa	II decade of April	III decade of April	I decade of May	I decade of July	III decade of July	I decade of October	I decade of October
	Bb	II decade of April	III decade of April	I decade of May	I decade of July	III decade of July	I decade of October	I decade of October
	Ig	II decade of April	III decade of April	I decade of May	I decade of July	III decade of July	I decade of October	I decade of October

Note: *: *Sw* – monoculture plantings of broomcorn millet, *Sa* – monoculture plantings of perennial sorghum, *Bb* – monoculture plantings of Big Bluestem, *Ig* – monoculture plantings of creeping sorghum. **: V/V – vegetative recovery; K – tillering; V/T – booting; VV – panicle emergence; K – flowering; D/N – seed maturation; Z/V – end of vegetation.

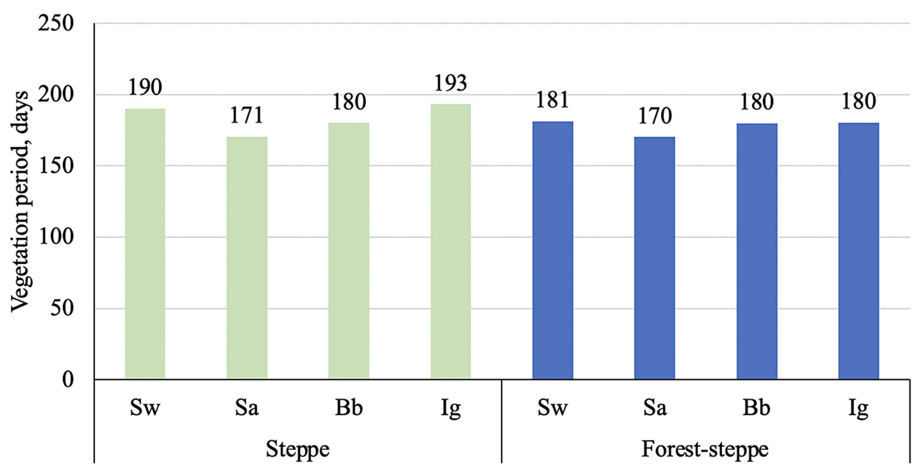

Figure 2. Duration of the growing season of energy plants, 2019-2023 Source: built by the authors Note: Sw – single-species sowing of broomcorn millet, Sa – single-species sowing of perennial sorghum, Bb – single-species sowing of Big Bluestem, Ig – single-species sowing of creeping sorghum

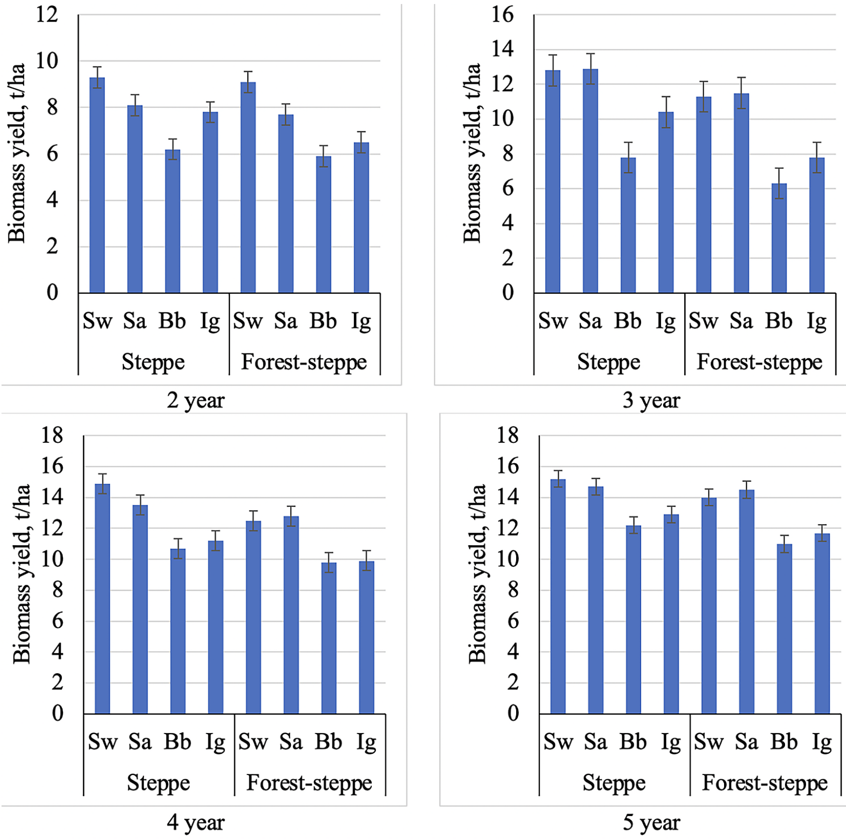

Figure 3. Biomass yield of energy crops in the second to fifth years of vegetation depending on growing conditions, 2019-2023 Note: Sw – Monotypic sowings of proso millet, Sa – Monotypic sowings of perennial sorghum, Bb – Monotypic sowings of Big Bluestem, Ig – Monotypic sowings of fall panicum. Source: built by the authors

The growing season of Indian grass was 190 days in the steppe and 180 days in the forest-steppe.

The growing seasons of Big Bluestem did not differ under different climatic conditions and lasted about 180 days both in the steppe and in the forest-steppe. Similarly, during the research period, the growing seasons of perennial sorghum did not differ and were around 170 days.

Level of yield of energy crops

During the years of the research, the highest yield of dry biomass was formed by perennial sorghum and drooping sorghum. The yield of Big Bluestem was significantly lower (Table 3).

In monotypic sowings, the biomass yield under the conditions of the forest-steppe for fall panicum was at the level of 8.9 t/ha in the second year, 10.1 t/ha in the third year, 14.9 t/ha in the fourth year, and 15.9 t/ha in the fifth year. The biomass yield of Big Bluestem varied between 4.4 and 9.3 t/ha. The biomass yield of perennial sorghum increased from 7.7 t/ha (2nd year) to 11.0 t/ha (3rd year), 13.5 t/ha (4th year), and 14.7 t/ha (5th year).

In monotypic sowings, the biomass yield under the conditions of the steppe for fall panicum was at the level of 7.8 t/ha in the second year, 10.4 t/ha in the third year, 11.2 t/ha in the fourth year, and 12.9 t/ha in the fifth year. The biomass yield of Big Bluestem varied between 5.9 and 11.0 t/ha. The biomass yield of perennial sorghum increased from 7.7 t/ha (2nd year) to 11.5 t/ha (3rd year), 12.9 t/ha (4th year), and 14.5 t/ha (5th year).

It should be noted that starting from the third year of cultivation, all crops, especially fall panicum and Big Bluestem, showed very slow growth in biomass production (Fig. 3).

On average, during the study years, energy crops provided different yields of dry biomass. This indicator was influenced by both the species characteristics of the plants and the soil-climatic conditions of cultivation. Overall, the biomass yield of energy crops was highest in the conditions of the steppe (7.8–11.2 t/ha), while it was significantly lower in the conditions of the

Table 3. Dry biomass yield of energy crops, 2019–2023

Growing conditions (Factor A)	Energy crops (Factor B)	Year of vegetation					Average over the years	Total over the years
		First	Second	Third	Fourth	Fifth		
Steppe	Sw	3.8	9.3	12.8	14.9	15.2	11.2	56.0
	Sa	4.4	8.1	12.9	13.5	14.7	10.7	53.6
	Bb	2.2	6.2	7.8	10.7	12.2	7.8	39.1
	Ig	3.8	7.8	10.4	11.2	12.9	9.2	46.1
Forest-Steppe	Sw	4.8	9.1	11.3	12.5	14.2	10.4	51.9
	Sa	5.6	7.7	11.0	12.9	14.5	10.3	51.7
	Bb	3.9	5.9	6.3	9.8	11.0	7.4	36.9
	Ig	4.0	6.5	7.8	9.9	11.7	8.0	39.9
LSD_{05}(Factor A)		0.62	0.80	1.52	1.17	0.95	1.58	-
LSD_{05}(Factor B)		0.97	1.71	2.80	2.19	1.82	1.93	-
LSD_{05}(Factors A and B)		0.51	0.56	0.74	0.55	0.57	0.75	-

Note: Sw – monotypic sowing of broomcorn millet, Sa – monotypic sowing of perennial sorghum, Bb – monotypic sowing of Big Bluestem, Ig – monotypic sowing of fall panicum.

forest-steppe, ranging from 7.4 to 10.4 t/ha (Figure 4). On average, during the study years, the highest biomass yield among energy crops was recorded in monoculture sowings of broomcorn millet (11.2 t/ha for the steppe and 10.4 t/ha for the forest-steppe) and perennial sorghum (10.7 t/ha for the steppe and 10.3 t/ha for the forest-steppe). The total biomass yield over all years of the study is characterized by the volume of biomass from energy crops in monoculture sowings, which varied significantly depending on the studied crop and growing conditions (Figure 5). The highest biomass volume during the study years was provided by broomcorn millet (56.0 t/ha for the steppe and 51.9 t/ha for the forest-steppe) and perennial sorghum (53.6 t/ha for the steppe and 51.7 t/ha for the forest-steppe). Other variants had significantly lower biomass volumes: Indian grass (46.1 t/ha for the steppe and 39.9 t/ha for the forest-steppe), and the lowest biomass volume was recorded in big bluestem (39.1 t/ha for the steppe and 36.9 t/ha for the forest-steppe). This indicates that the total biomass volume over the study period of energy crops largely depends on the soil-climatic conditions under which the plants' vegetation occurred, as confirmed by the analysis of variance table (Table 4). According to the obtained data, it was determined that growing conditions have a significant impact on the yield level of different energy crops, with notable differences observed between them.

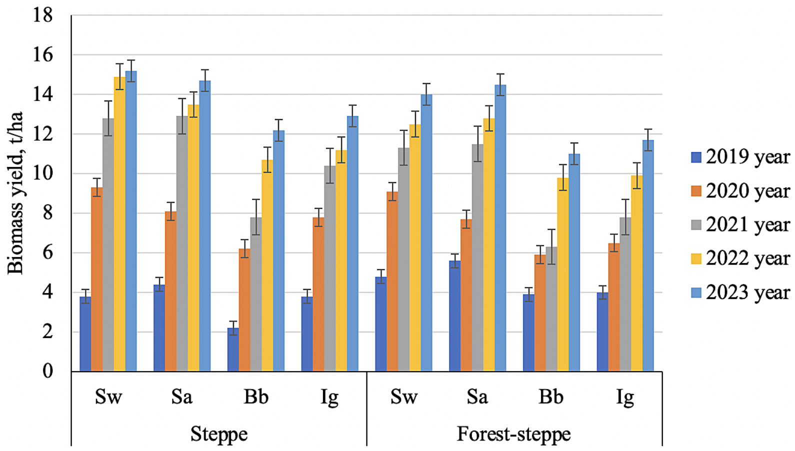

Figure 4. Biomass yield of energy crops depending on growing conditions, average for 2019–2023. Note: Sw – monoculture sowings of broomcorn millet, Sa – monoculture sowings of perennial sorghum, Bb – monoculture sowings of big bluestem, Ig – monoculture sowings of creeping sorghum. Source: built by the authors

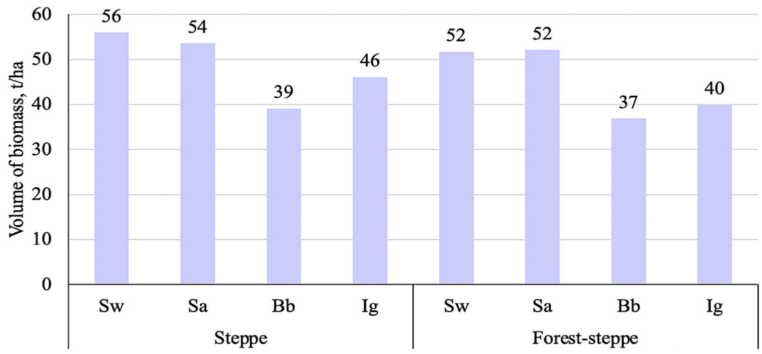

Figure 5. Biomass volume of energy crops depending on growing conditions, overall for 2019–2023: Sw – monoculture sowings of broomcorn millet, Sa – monoculture sowings of perennial sorghum, Bb – monoculture sowings of big bluestem, Ig – monoculture sowings of Indian grass

Table 4. Variance analysis of the experimental data

Parameter	SS	Degr. of – Freedom	MS	F	p
Intercept	12646.48	1	12646.48	1111.572	0.000000
Factor A (year)	395.02	2	197.51	17.360	0.000000
Factor B (crops)	10.41	5	2.08	0.183	0.968682
“FactorA” · “FactorB”	293.50	10	29.35	2.580	0.006336
Error	1843.09	162	11.38	-	-

CONCLUSIONS

During the study years, which were characterized by fluctuating climatic conditions, the following was established: the highest drought resistance was observed in creeping sorghum and perennial sorghum in both climatic zones. The highest frost resistance was shown by creeping sorghum and broomcorn millet; the highest resistance to lodging was observed in creeping sorghum. A higher percentage of lodging was recorded for broomcorn millet and perennial sorghum in the forest-steppe zone compared to the steppe.

It was determined that the vegetative period of energy crops is variable and depends on the timing of the interphase growth and development periods of the plants. This is related both to the biology of the plants and to the conditions of their vegetation. In the steppe, compared to the forest-steppe, the vegetative period was longer, ranging from 170.6 to 192.0 days (the longest was in creeping sorghum). In the forest-steppe, the vegetative period of energy crops ranged from 170.3 to 181.3 days, with the longest period observed in broomcorn millet. Soil-climatic conditions have a significant impact on the formation of biomass yield of energy crops from the Poaceae family. In the steppe, compared to the forest-steppe, higher biomass yields of energy crops were obtained (average over 4 years): from 7.8 to 11.2 t/ha, while in the forest-steppe, the yield was significantly lower, ranging from 7.4 to 10.4 t/ha.

It was determined that the highest biomass volume during the study years was provided by broomcorn millet (56.0 t/ha for the steppe and 51.9 t/ha for the forest-steppe) and perennial sorghum (53.6 t/ha for the steppe and 51.7 t/ha for the forest-steppe). Other variants had significantly lower biomass volumes: creeping sorghum (46.1 t/ha for the Steppe and 39.9 t/ha for the forest-steppe), with the lowest value recorded in big bluestem (39.1 t/ha for the steppe and 36.9 t/ha for the forest-steppe).

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