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ORIGINAL ARTICLE

Energy productivity of uncommon herbs for solid fuel manufacturing

V.H. Kurhak[1*], M.A. Tkachenko[1], N.M. Asanishvili[1], V.V. Moisiienko[2], A.V. Holodna[1], A.M. Tkachenko[1], S.M. Slyusar[1], M.M. Ptashnik[1], L.P. Kolomiiets[1], Ya.S. Tsymbal[1], O.L. Oksymets[1], R.M. Kulyk[1], V.Z. Panchyshyn[2], S.V. Stotska[2], T.A. Sladkovska[2]

[1] National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Science of Ukraine", 2B Mashynobudivnykiv St, Chabany village, Kyiv Svyatoshinsky district, Kyiv region 08162, Ukraine

[2] Polissia National University, Ukraine, 7 Staryi Blvd, Zhytomyr 10008 Ukraine

**Corresponding author Email: kurgak_luki@ukr.net*

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The article presents the research results of the rare energy crop selection and optimization of their mowing timing to produce solid biofuels in the conditions of the Ukrainian Right-bank Forest-steppe zone. Among perennial energy crops on dark gray soils, the most productive was the *Miscánthus giganteus* J. M. *Greef*, *Silphium perfoliatum* L., *Polygonum weyrichii* Fr. Schm., *P. sachalinensis* L., *Sida hermophrodita* Rusby, and *Helianthus tuberosus* L. (1st year of use with parameters 11.1-15.8 t/ha dry mass, 194-281 GJ/ha of thermal energy and 6.0-8.6 t/ha of equivalent fuel). The highest linear growth had *Helianthus tuberosus* (1st year of use). The stem diameter of energy crops ranged from 2.8 mm to 16.8 mm. The stem's largest diameter had *Polygonum weyrichii*, *Sida hermophrodita,* and *Helianthus tuberosus* (1st year of use). The highest density and energy capacity of 1 m3 of dry unpressed chips had *Sida hermophrodita*, *Helianthus tuberosus*, *Miscánthus giganteus*, and *Polygonum divaricatum* L. with parameters respectively 125-138 kg and 2.00-2.56 GJ.

Keywords: perennial and annual energy crops, energy capacity, productivity, dry biomass, thermal energy, equivalent fuel.

Introduction

It is known that Ukraine is on the list of energy-dependent countries. Therefore, any reduction in the consumption of traditional non-renewable fossil fuels and replacement with renewable fuels is becoming too important for our country.

Ukraine has a significant potential for all types of renewable energy sources (hydropower, wind energy, solar energy, biomass energy, and others), but the most affordable and economically feasible in our conditions is realizing the biomass potential. Today its share in the country's energy supply is about 0.5% (0.7 million tons of equivalent fuel), while world consumption of biomass, as a fuel, is about 2 billion tons of equivalent fuel, almost 14% of total energy consumption. These data clearly show the degree of economic dependence on fossil fuels but simultaneously prove the feasibility and prospects for the development of renewable energy sources (Bezrukykh, 2006; Directive, 2009; Heletukha, 2010).

The share of energy obtained from biomass in renewable energy sources is about 80%. It will continue to be the primary and most promising source of alternative energy. This is due to obtaining fuel from biomass in any form (liquid, gas, solid fuel) and produces energy in any form (Bezrukykh, 2006; Tytko, 2010; Heletukha, 2010). Promising solid biofuels in the form of briquettes and pellets are "energy grass plants", giving considerable growth in a relatively short period.

Renewable energy production, including biomass, is developing dynamically in most European countries, where the share of biomass in total energy consumption reaches 20 % (Vodianykov, 2010; Order of the Cabinet of Ministers of Ukraine of September 3, 2014).

According to the calculations, Ukraine has significant potential for the production of energy plant bioresources. The theoretical potential of biomass is about 50 million tons of equivalent fuel, and economically feasible - 25-27 million tons, including non-traditional perennial energy grass crops (*Silphium perfoliatum* L., *Helianthus tuberosus* L., *Miscánthus giganteus* J. M. Greef) respectively - 0.60 and 0.35 million tons (Directive, 2006; Kurgak, 2013; Order of the Cabinet of Ministers of Ukraine of October 1, 2014).

Energy production based on new highly productive grass energy crops, which are not widespread in the agricultural sector of Ukraine, has obvious advantages. The output of thermal energy per hectare for growing energy crops is different (Kurhak, 2016;

Zhavoronkova, 2010). Among herbaceous energy crops, the highest energy output for solid fuels can be obtained from crops such as *Sorghum bicolor*, *Zea mays*, *Miscanthus,* and *Panicum virgatum* L. (Heletukha, 2010).

Due to the withdrawal from active cultivation of large areas of erosive lands, on some of them can be grown perennial grasses, which will not only protect the soil from erosion but also become a source of bio raw materials for the production of fuel briquettes, pellets in rural areas (Kurgak, 2013, 2016, 2020; Petrychenko, 2014).

However, experimental data on the comparative energy potential of uncommon energy grass crops until recently in the northern part of the Forest-Steppe of Ukraine are still insufficient, which became the subject of our research and coverage of their results in this article.

Materials and methods

Our research was conducted during 2011-2016 in the Forest-Steppe zone of Ukraine on dark gray podzolic coarse-grained light loam soil in NSC "Institute of Agriculture of National Academy of Agrarian Science, Ukraine (Chabany town). The humus content in the 0-20-cm layer of soil is 2.4%; pH - 5.2; hydrolytic acidity - 4.2 mg-eq/100 g of soil; alkaline hydrolyzed nitrogen - 13.1, mobile phosphorus - 17.1, and exchangeable potassium 12.9 mg per 100 g of soil. We investigated 12 plants, namely 11 perennial crops *Polygonum sachalinensis* L., *Miscánthus giganteus* J. M. Greef, *Sida hermophrodita* Rusby, *Silphium perfoliatum* L., *Polygonum Weyrichii* Fr. Schm., *Helianthus tuberosus* L., *Polygonum divaricatum* L., *Rumex confertus* Willd., *Solidago canadensis* L., *Hyssopus officinalis* L., *Agastachef oeniculum* Pursh Kuntze), and annual *Helianthus annuus* L.

Weather conditions on mineral soils in 2011-2016 were generally favorable for the studied energy crops' vegetation. More favorable weather conditions, including rainfall, were created in the spring and summer and less favorable in the autumn. Low precipitation at above-normal air temperatures in August and September did not negatively affect the further formation of energy crops. However, the frosts led to the cessation of crops' vegetation and contributed to an acceleration of dehydration and harvest maturity, which occurred at the end of October. In some years, the onset of frosts occurred in November, which extended the vegetation of energy crops and delayed biofuels' harvest.

Field studies were performed according to generally accepted methods (Methodical, 1983; Methods, 1994). Crop accounting was performed by the method of continuous biomass mowing at the accounting site and weighing biomass during harvest maturity for the harvesting of solid fuels in four iterations. Determination of dry matter content in biomass during crop accounting was performed by drying the raw material in an oven at a temperature of 105 °C.

A field experiment to study the comparative energy productivity of rare herbaceous plants to produce solid biofuels was conducted against the background of annual fertilization with $N_{60}P_{60}K_{60}$ in early spring.

The content of thermal (gross) energy (MJ) in 1 kg of dry matter of biomass was determined according to DSTU 8066: 2015 (2015) by the formula:

$$E = 0.240CP + 0.398CF + 0.201CFC + 0.175NFE,$$

where CP –crude protein content in dry matter of biomass,%;
CF – crude fat content in dry matter of biomass, %;
CFC – crude fiber content in dry matter of biomass, %;
NFE – nitrogen-free extractives content in dry matter of biomass, %;
0.240, 0.398, 0.201 and 0.175 - constant energy coefficients.

In the dry plant, mass determination of crude protein content, crude fat, crude fiber was performed by infrared spectroscopy and the content of nitrogen-free extractives - by calculation according to DSTU 4674: 2006 (2006).

Agrochemical parameters of the soil were determined at the beginning of the experiment in the soil layer 0-20 cm according to generally accepted methods, namely: humus – by Tyurin methodic according to DSTU 4289: 2004 (2004); nitrogen, hydrolyzed by alkali – by Cornfield methodic following DSTU 7863: 2015 (2015); mobile phosphorus and potassium – by Kirsanov and Machigin methodic according to DSTU 4115-2002 (2002); pH (saline) – by the potentiometric method following DSTU ISO10390: 2001 (2001).

Mathematical processing of the obtained experimental data was performed by analyzing the variance method (Dospekhov, 1979).

Results and discussion

Studies have shown (Table 1) that on average in 2011-2016, with the application of $N_{60}P_{60}K_{60}$, uncommon energy crops provided 5.3-15.8 t/ha of dry matter, 88-313 GJ/ha of thermal energy, and 2.8-8.6 t/ha of equivalent fuel.

The most productive plants were *Polygonum sachalinensis*, *Sida hermophrodita* and *Helianthus tuberosus* (14.6–16.2 t/ha of dry mass, 260–281 GJ/ha of thermal energy and 7.8-8.8 t/ha of equivalent fuel). The crops characterized by an average level of energy productivity were *Polygonums*, *Silphium perfoliatum*, *Helianthus tuberosus*, *Miscánthus giganteus*, *Solidago canadensis*, *Rumex confertus*, and *Helianthus annuus* (9.0–12.6 t/ha, 158–214 GJ/ha and 3.1-6.9 t/ha). We registered low output for *Agastachef oeniculum* and *Hyssopus officinalis* (5.3–5.6 t/ha and 94–98 GJ/ha and 2.8–3.6 t/ha).

Table 1. Comparative energy productivity of energy crops, the average for 2011-2016.

Crop	Dry mass, t/ha	Thermal energy, GJ/ha	Equivalent fuel, t/ha
Polygonum weyrichii	12.2	214	6.7
Polygonum divaricatum	10.0	176	5.8
Polygonum sachalinensis	14.6	260	7.8
Hyssopus officinalis	5.3	94	2.8
Sida hermophrodita	15.8	281	8.6
Silphiumper foliatum	11.6	206	6.4
Helianthus tuberosus	12.6	224	6.9
Helianthus tuberosus (first year)	16.2	281	8.8
Miscánthus giganteus	11.5	201	6.9
Agastachef oeniculum	5.6	98	3.1
Solidago Canadensis	9.0	158	3.1
Rumex confertus	9.2	166	4.0
Helianthus annuus	11.1	194	6.0
LSD_{05}, t/ha	0.5	-	-

On average, in 2011-2016, the most promising in terms of growing technology and sufficient productivity were *Sida hermophrodita*, *Helianthus tuberosus*, *Polygonum sachalinensis*, *Silphium perfoliatum*, *Polygonum weyrichii,* and *Miscánthus giganteus*, planted in previous years, as well as *Helianthus annuus.*

Biometric indicators of energy crops before biomass harvesting are given in table 2. The view of their grass before harvest is shown in Figure 1. The highest linear growth in this year's conditions had *Helianthus tuberosus* (1st year of use), the average height of which was 3.20 m. Second place in height was– *Polygonum sachalinensis*, *Sida hermophrodita* and *Silphium perfoliatum* (2.73-3.05 m), the third – *Polygonum weyrichii* and *P. divaricatum, Helianthus tuberosus* (plantings of past years), *Miscánthus giganteus* and *Helianthus annuus* (1.98-2.49 m) and on the last - *Hyssopus officinalis* and *Agastachef oeniculum* (0.59-1.09 m).

Table 2. Biometric parameters of uncommon perennial and annual energy crops, the average for 2015-2016.

Crop	Height, cm	Stem diameter, mm	Degree of lying, %	The density of grass, shoots/m^2	The share of leaves, %	Weight of 1 m^3 of dry cuttings from stalks, kg
Polygonum weyrichii	249	16.8	50-70	34	5	115
Polygonum divaricatum	236	15.4	20-30	33	22	126
Polygonum sachalinensis	305	15.6	-	38	21	103
Hyssopus officinalis	59	2.8	-	352	34	73
Sida hermophrodita	275	14.6	-	50	13	128
Silphium perfoliatum	273	11.7	-	54	27	92
Helianthus tuberosus	221	12.2	-	21	30	138
Helianthus tuberosus (first year)	320	14.0	-	14	25	106
Miscánthus giganteus	220	9.3	-	63	27	125
Agastachef oeniculum	109	4.1	-	78	20	72
Solidago canadensis	139	5.5	-	158	30	71
Rumex confertus Willd.	138	8.9	-	40	27	-
Helianthus annuus L.	198	11.6	-	38	32	40
LSD_{05}, t/ha	11	0.8	-	6	3	7

The stem diameter of energy crops ranged from 2.8 mm to 16.8 mm. The largest diameter had *Polygonums*, *Sida hermophrodita*, *Helianthus tuberosus* - 1st year of use (14.0–16.8 mm). They were followed by *Helianthus tuberosus*, *Silphium perfoliatum*, and *Helianthus annuus* with a 11.6–12.2 mm stem diameter. The smallest diameter of the stem had *Hyssopus officinalis* and *Agastachef oeniculum*. The density, expressed by the mass of 1 m^3 of unpressed dry cuttings from the stems of the studied herbaceous plants, ranged from 40 to 138 kg. The appearance of unpressed chips of different crops is shown in Figure 2.

The highest density had *Sida hermophrodita*, *Helianthus tuberosus*, *Miscánthus giganteus*, *Polygonum divaricatum* (125–138 kg), which indirectly indicates their highest calorific value, and the lowest had *Hyssopus officinalis Agastachef oeniculum* and especially *Helianthus annuus.*

The proportion of leaves on plant stems ranged from 5 to 34%. The highest level had *Solidago canadensis, Hyssopus officinalis*, *Helianthus tuberosus*, *Miscánthus giganteus* and *Helianthus annuus* (30–34 %) and lowest – *Polygonum*s *divaricatum* and *sachalinensis*, *Sida hermophrodita*, *Silphium perfoliatum*, *Agastachef oeniculum* (5–22 %).

The stem density of the studied energy crops ranged from 14 to 352 stems per 1 m^2. Low-growing plants (*Hyssopus officinalis*, *Agastachef oeniculum* and *Solidago canadensis*) had the highest density (78–352 stems), and the lowest amount (14–38 stems) had tall plants, especially plantations of *Helianthus tuberosus* (first year), which, in contrast to the old plantations, is characterized by increased branching at the bottom of the stems.

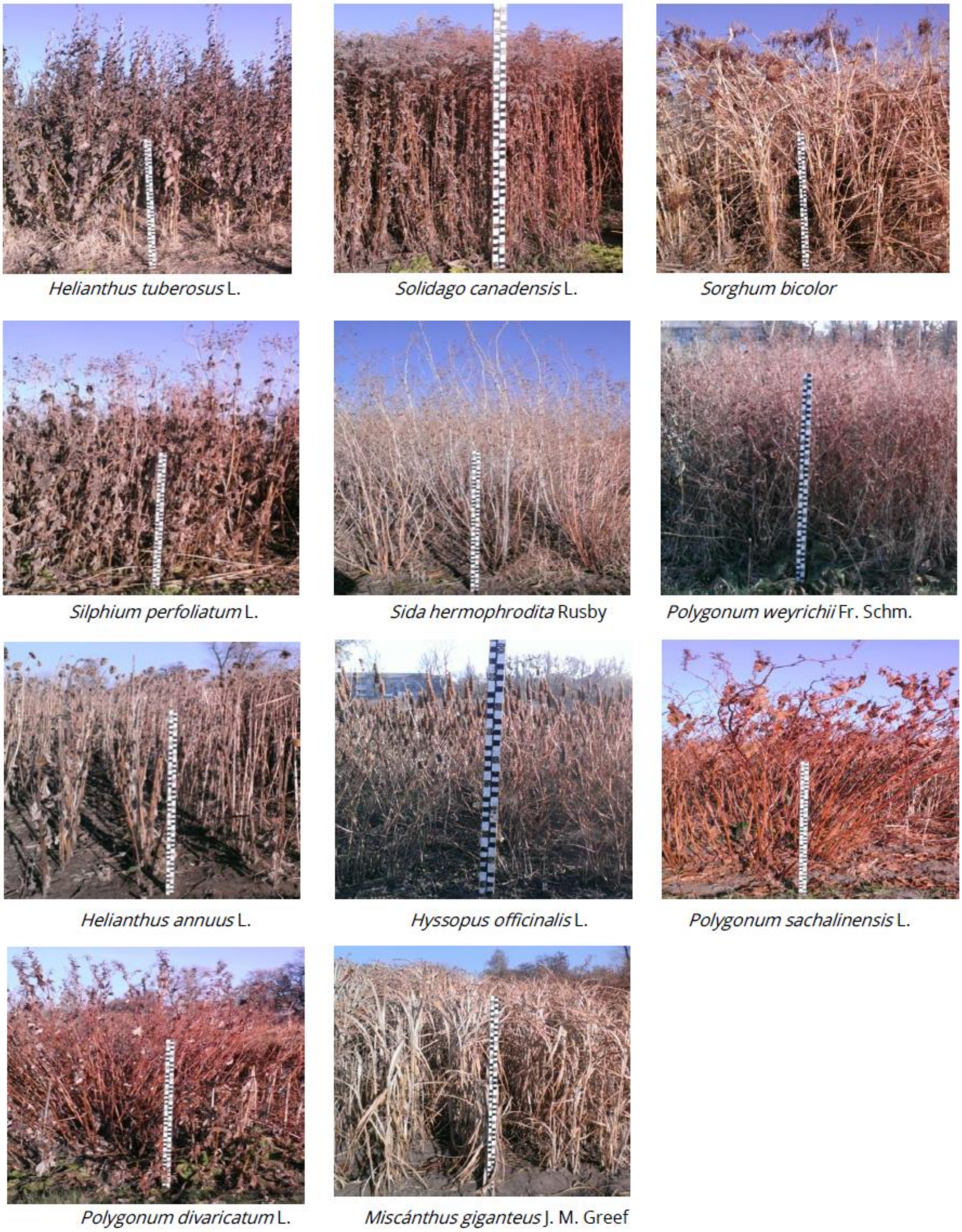

Fig. 1. Herbaceous energy crops during solid biofuel harvest

Suitability evaluation of the studied crops for mechanized harvesting for solid fuel production showed that most of them did not fall under the $N_{60}P_{60}K_{60}$ application, indicating their suitability for this process. Among the studied species, a particular fall of stems was recorded in *Polygonum weyrichii* with a 50–70% slope, indicating some difficulty with harvesting. The stems of *Polygonum divaricatum* and *P. sachalinensis* were inclined by 20-30%. Therefore, in terms of possible falling, the most suitable for mechanized harvesting were *Polygonum sachalinensis*, *Silphium perfoliatum*, *Sida hermophrodita*, *Helianthus tuberosus,* and *Miscánthus giganteus*.

Dry mass content analysis for the biomass of energy crops (Table 3) showed that for the period of accounting (the first and second decade of October) in 2015, it ranged from 46.6 to 57.4%. Thus, according to this indicator, the biomass requires drying to the standard dry matter content (11–13%) and additional costs after harvesting to manufacture solid biofuels.

Fig. 2. Chips of energy crops as a solid biofuel or as raw material for the pellets manufacturing

Table 3. Dry matter and thermal energy content in energy crops, the average for 2015-2016.

Crop	The dry matter content at different mowing times, %					The content of thermal energy in dry chips	
	09.09	28.09	23.10	1.11	10.11	MJ/kg	GJ/m^3
Polygonum weyrichii	47.3	49.7	55.0	81.1	86.5	17.7	1.77
Polygonum divaricatum	33.1	42.7	53.3	73.1	78.2	18.0	2.32
Polygonum sachalinensis	33.8	42.3	47.2	63.9	68.8	17.9	1.79
Hyssopus officinalis	32.1	42.3	49.7	65.3	72.0	18.2	1.13
Sida hermophrodita	46.7	51.7	58.4	77.4	84.1	17.7	2.34
Silphium perfoliatum	23.6	31.3	53.4	51.5	56.2	18.0	1.73
Helianthus tuberosus	36.7	46.5	48.3	55.9	60.0	17.8	2.56
Helianthus tuberosus (first year)	38.2	42.4	46.6	47.6	52.3	17.4	2.00
Miscánthus giganteus	41.4	44.5	56.9	62.8	70.3	17.4	2.37
Agastachef oeniculum	42.5	44.5	47.7	77.9	83.0	18.1	1.19
Solidago Canadensis	36.4	46.5	56.8	62.4	79.0	17.7	1.17
Rumex confertus	53.2	-	-	-	-	17.8	0.75
Helianthus annuus	43.2	45.2	57.4	60.7	77.3	17.9	0.74
LSD_{05}			3.5			0.6	0.08

The highest dry matter content in biomass had *Rumex confertus*, *Sida hermophrodita*, *Miscánthus giganteus*, *Solidago canadensis*, *Polygonum weyrichii, Polygonum divaricatum* and *Silphium perfoliatum* (53.3–57.4 %), and the lowest – *Helianthus tuberosus* and *Polygonum sachalinensis* (46–47 %).
The thermal energy content in the dry biomass of energy crops was in the range from 17.4 to 18.2 MJ/kg and depended little on the species. In contrast to the energy productivity per 1 kg of the dry mass of chips, the energy productivity of 1 m^3 of dry chips of the studied rare crops due to the different density of 1 m^3 differed significantly and ranged from 1.17 to 2.56 GJ/m^3, which indicates their highest calorific value.
Analysis of the dry matter content in November showed that in dry and relatively warm weather with night frosts, its amount increases in all types of energy crops by 10.3-38.8% and is in the range of 51.5 to 81.1%, which indicates lower drying costs compared to the previous sampling period. The highest dry matter content had *Polygonum weyrichii* and *Polygonum divaricatum*, *Sida hermophrodita* and *Agastachef oeniculum* (73.1–81.1 %), indicating the possibility of harvesting their biomass during this period for the production of solid biofuels without drying. The analysis conducted on November 7, 2014, four days after the preliminary sampling on the day of mowing, showed that in warm and dry sunny weather, the dry matter content increased by 5-17% and ranged from 52.3 to 86.5%. The pattern of the dry mass content coincides with the previous account.
The highest dry matter content had *Polygonum weyrichii* and *Polygonum divaricatum*, *Sida hermophrodita* and *Agastachef oeniculum*, *Helianthus annuus*, *Solidago canadensis* indicating the possibility of harvesting their biomass during this period for the production of solid biofuels without drying. The lowest dry matter content had *Silphium perfoliatum* and *Helianthus tuberosus* (56.2–60.0%), indicating the need to dry biomass in the technological production cycle of pellets or granules.
The thermal energy content in the dry biomass of uncommon energy crops was in the range from 17.4 to 18.2 MJ/kg and depended little on the crop. The slightly higher thermal energy content of 1 kg of dry biomass had *Hyssopus officinalis* and *Agastachef oeniculum* and lower – *Helianthus tuberosus* and *Miscánthus giganteus*. In contrast to the energy productivity per 1 kg of the dry mass of chips, the energy intensity of 1 m^3 of dry chips of the studied energy crops due to the different density of 1 m^3 differed significantly and ranged from 1.13 to 2.56 GJ/m3. The highest energy productivity of 1 m3 of dry chips had *Sida hermophrodita*, *Helianthus tuberosus*, *Miscánthus giganteus*, *Polygonum divaricatum* (2.00–2.56 GJ), which indicates their highest calorific value, and the lowest had – *Hyssopus officinalis*, *Agastachef oeniculum* and especially *Helianthus annuus* (0.75-1.19 GJ). *Polygonum weyrichii*, *Polygonum sachalinensis* and *Silphium perfoliatum* according to this indicator, had an average position.
Therefore, we have identified these energy crops as promising in terms of productivity. During harvesting in the ripening phase of seeds, they meet the technical requirements and are suitable for solid biofuels production.

Conclusions

Among perennial energy crops on dark gray soils, the most productive are *Miscánthus giganteus*, *Silphium perfoliatum*, *Polygonum weyrichii* and *sachalinensis*, *Sida hermophrodita*, and *Helianthus tuberosus* during the first 2-3 years of use with parameters of 11.1-15.8 t/ha of dry mass and 194-281 GJ/ha of thermal energy and 6.0-8.6 t of equivalent fuel. During the autumn harvest for the production of solid biofuels, the highest dry matter content in biomass had *Sida hermophrodita*, *Silphium perfoliatum*, *Solidago canadensis*, *Polygonum weyrichii,* and *divaricatum* with parameters of 53–58 %, and the lowest were *Helianthus tuberosus*, *Polygonum sachalinensis*, *Silphium perfoliatum* and *Helianthus tuberosus* with 46–47 %.
The highest linear growth had *Helianthus tuberosus* (first year) with an average height of 3.20 m, followed by *Sida hermophrodita*, *Polygonum sachalinensis*, *Silphium perfoliatum* (with the height of 2.73–3.05 m). Then were the *Polygonum weyrichii*, *Polygonum divaricatum,* and *Helianthus tuberosus* (after the third year), *Miscánthus giganteus* (1.98–2.49 m), and the last – *Hyssopus officinalis* and *Agastachef oeniculum* (0.59–1.09 m). The stem diameter of energy crops ranges from 2.8 mm to 16.8 mm. The largest

diameter had *Polygonums*, *Sida hermophrodita* and *Helianthus tuberosus* (first year). The smallest stem diameter had *Hyssopus officinalis* and *Agastachef oeniculum*.
The highest density and energy productivity of 1 m^3 of dry unpressed chips had *Sida hermophrodita*, *Helianthus tuberosus*, *Miscánthus giganteus*, *Polygonum divaricatum* with parameters of 125-138 kg and 2.00-2.56 GJ, respectively. The growth of perennial energy crops, such as *Polygonum sachalinensis*, *Silphium perfoliatum*, *Miscánthus giganteus*, *Polygonum weyrichii*, *Sida hermophrodita*, *Helianthus tuberosus*, *Polygonum divaricatum*, and *Rumex confertus* could produce 10-15 t/ha of dry matter and 200-278 GJ/ha of thermal energy in the Forest-Steppe of Ukraine.

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