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Statistical Analysis of the Productivity of Phytocoenoses of Energy Cultures due to Implementation of Wastewater Sediment on Aluvisols of Ukraine

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ABSTRACT

The cultivation of energy crops is an important component of renewable bioenergy, which pursues the goal of reducing greenhouse gas emissions and determines the effective management of fertility and land use of marginal lands and disturbed areas of various nature. As a result of the conducted research, convincing relationships were established between the application of sewage sludge with a compensatory dose of mineral fertilizers and the productivity of grassy energy crops. The greatest increase in green mass is provided by the application of SS (SS – 40 t/ha + N10P14K58) for all studied crops. Applying sewage sludge with the addition of mineral fertilizers is an effective way to increase the productivity of green mass by 57–64% for such energy crops as Jerusalem artichoke, *Silphium perfoliatum* L, *Miscanthus giganteus*, and switchgrass (*Panicum virgatum* L).

Keywords: fertilizer, macronutrients, harvest, statistical analysis

INTRODUCTION

One of the key problems at the current stage of human development is ensuring further progress with low-cost energy resources, in particular renewable ones. The cultivation of bioenergy crops is considered as a means of providing stable sources of renewable energy with a zero balance of greenhouse gas emissions. However, their performance has not yet been fully realized and studied in different soil and climate zones (Campbell, 2013, Moon-Sub Lee et al., 2021, Heletukha 2020). It is known that the cultivation of energy crops is an important component of renewable bioenergy, which pursues the goal of reducing greenhouse gas emissions and determines the effective management of fertility and land use of marginal lands and disturbed areas of various nature (Lopushniak and Hrytsuliak, 2021).In European countries, biomass is considered as an important source of renewable energy and the vast majority of researchers predict that it will play a significant role in achieving carbon neutrality, mainly thanks to the cultivation of high-yielding energy crops (Wu and Muller, 2023; Lopushniak and Hrytsuliak, 2021; Kulyk, 2020). A promising direction for the cultivation of perennial woody and herbaceous energy crops is the formation of energy plantations on marginal degraded lands, which ensures minimal compromises with food production and the environment (Ni, 2020; Sandstad Næss, 2022). Bioenergy from marginal lands plays another important role of energy accumulation and periodic accumulation of energy resources under the conditions of seasonal fluctuations of solar and wind energy production (Campbell, 2013; He and Jaiswal, 2022), to which little attention is paid.

In Ukraine in the pre-war period, renewable energy sources provided only 4% of total energy consumption (Kulyk, 2020; Kaletnyk, 2021). However, many researchers note the significant potential for the use of biomass in Ukraine and predict a significant increase in the share of bioenergy in the country's energy balance in the medium term (Heletukha, 2020). In our opinion, this trend may intensify in connection with the destruction of the energy infrastructure associated with military actions on the territory of Ukraine, which occur mainly in the regions of intensive coal mining.

Therefore, it is important to determine the bioproductivity potential of agrophytocenoses of energy crops in different soil conditions of Ukraine under dynamic changes of climatic factors. In the foothills of the Carpathians of Ukraine, the conditions for growing phytoenergy crops are characterized by the hilliness of the terrain, the heterogeneity of the soil cover, a large number of relatively small areas suitable for growing cultivated plants with difficult access for heavy agricultural machinery, as well as stony soils depleted of organic matter. which are not suitable for cultivation. Together with a sufficient amount of precipitation and the availability of sufficient labor resources, this contributes to the development of phytoenergy in the region and the spread of bioenergy crop plantations.

The purpose of our research is a comparative assessment of the biomass productivity of various phytoenergy crops grown under the same conditions of mineral nutrition, namely, with the introduction of municipal sewage sludge (SS). Because it is known that the application of fertilizers based on SS, especially on nutrient-depleted soils, contributes to a significant increase in the productivity of agrophytocenoses, in particular, bioenergy crops (Lopushniak, 2021a; Kalenska, 2019).

MATERIALS AND METHODS

Field experiments were conducted in the Ivano-Frankivsk region of Ukraine on the territory of the village Tsenzhiv of the Yamnytsk United Territorial Community as part of a stationary experiment with various energy crops: Miscanthus (*Miscanthus giganteus*), switchgrass (*Panicum virgatum* L), Jerusalem artichoke and *Silphium perfoliatum* L, under which certain doses of sewage sludge were applied according to the options experiment (fresh and composted) and mineral fertilizers at the rate of $N_{90}P_{90}K_{90}$ (in options 3–8) (Lopushnyak, 2021a; Lopushnyak, 2021b). The scheme of field experiments included the following options: 1. Without fertilizers - control; 2. $N_{60}P_{60}K_{60}$; 3. $N_{90}P_{90}K_{90}$; 4. SS – 20 t/ha and $N_{50}P_{52}K_{74}$; 5. SS – 30 t/ha and $N_{30}P_{33}K_{66}$; 6. SS – 40 t/ha and $N_{10}P_{14}K_{58}$; 7. Compost (SS + straw (3:1)) – 20 t/ha and $N_{50}P_{16}$ K_{67}; 8. Compost (SS + straw (3:1)) – 30 t/ha and $N_{30}K_{55}$ (Lopushnyak, 2021a; Lopushnyak, 2021b).

Options 3–8 are balanced for entry the main nutrients – nitrogen content, of phosphorus and potassium was 90 kg/ha. Previous studies with the introduction of sewage sludge and composts based on them under the energy willow showed that the norms of SS application are 20–40 t/hais the most economically beneficial and ecologically safe, because it provides a 20–40% yield increase.

To carry out the experiments, samples of municipal sewage sludge were taken from sludge maps of the Ivano-Frankivsk aeration station of the state concern "Ekotechprom". As a result of the conducted research, the content of the main nutrients (nitrogen, phosphorus and potassium) for plants was established: humidity 77.0%, Nitrogen – 0.66% on dry matter, P_2O_5 – 2.60% on dry matter, K_2O – 2.18% on dry matter, pH – 8.1 As already mentioned, compost was laid, which was later used in field experiments. The compost was a homogeneous dark bulk mass with a moisture content of no more than 75% and a close to neutral (pH 7) reaction of the environment. In anaerobic conditions, raw materials undergo changes and transformations, on the basis of which the chemical composition of fertilizers changes. Composts have a chemical composition: organic matter – 78%, alkaline hydrolyzed nitrogen – 453.23 mg/kg, $N\text{-}NO_3$ – 752.1 mg/kg, mobile phosphorus – 401.3 mg/kg, exchangeable potassium – 224.3 mg/kg.

Table 1 shows the fertilizer application scheme according to the experiment options for each individual bioenergy crop. The data presented in the Table 1, reflect the amount of application of a certain macronutrient with a certain type of fertilizer (sewage sludge, compost based on sewage sludge and cereal straw, as well as mineral fertilizers as the main fertilizer (options 2 and 3) and an additional compensatory dose of mineral fertilizer calculated on the specified amount (90 kg/ha) of each nutrient (macronutrient). Thus, in columns N, P_2O_5, K_2O – the amount of each type of macronutrient applied with mineral fertilizers is displayed; in columns Nss, P_2O_5ss, K_2Oss – the

Table 1. Compositional and corresponding chemical composition of fertilizers

Marking variant of the experiment	Fertilizer option	N	P_2O_5	K_2O	Nss	P_2O_5ss	K_2Oss
M1	Control	0	0	0	0	0	0
M2	$N_{60}P_{60}K_{60}$	60	60	60	0	0	0
M3	$N_{90}P_{90}K_{90}$	90	90	90	0	0	0
M4	SS – 20 t/ha + $N_{50}P_{52}K_{74}$	50	52	74	40	28	16
M5	SS – 30 t/ha + $N_{30}P_{33}K_{66}$	30	33	66	60	47	24
M6	SS – 40 t/ha + $N_{10}P_{14}K_{58}$	10	14	58	80	66	32
M7	Compost – 20 t/ha + $N_{50}P_{16}K_{67}$	50	16	67	30	64	23
M8	Compost – 30 t/ha + $N_{30}K_{55}$	30	0	55	60	90	35

amount of macronutrient applied with organic fertilizers fertilizers (sewage sludge + straw). Manure, respectively, refers to the application of fertilizers. The total amount of fertilizers applied in each variant of the experiment, except for variant 2, was 270 kg/ha of the active substance. As already noted, variants 3–8 are balanced by application the main elements of mineral nutrition – NPK (Lopushnyak, 2021a; Lopushnyak, 2021b).

The area of the experimental plot is 35 m^2 for each plant, the placement of the plots in three repetitions is systematic. The scheme of planting energy crops, namely Miscanthus (*Miscanthus giganteus*), Jerusalem artichoke (*Helianthus tuberosus* L) and *Silphium perfoliatum* L., was 5.0×7.0 dm. Scheme of sowing switchgrass (*Panicum virgatum* L), with a row spacing of 7.0 dm, and the distance between plants in a row was 1.0 – 1.5 dm. All planting work was done manually.

Plant shoots appeared within three weeks. During the first month of the growing season of energy crops, many types of weeds emerged, so several (3–4 times) inter-row weeding was carried out in order to protect against weeds and loosen the top layer of the soil in the initial period. After the plants reach a height of 5–7 dm. soil cultivation was not carried out, as the plants successfully competed with weeds and suppressed their further development. In dry periods, weeding was not carried out, thereby preventing excessive drying of the soil. Harvesting was carried out in the winter period, which allows obtaining biomass with a higher percentage of dry matter, compared to spring-summer harvesting. The biomass samples taken during harvesting were weighed and dried to a stable weight and the productivity level per unit area was calculated. In the presented study, all productivity indicators are given in tons of dry matter per hectare of area (Syasyev, 2004, Jaya, 2014, Urbaniak, 2017). A known advantage of grass energy crops over woody energy crops is that they can be harvested every year. In the first year after planting, the phytomass of herbaceous energy crops was not collected due to its small amount (up to 5 t/ha of dry matter).

Statistical processing of the research results was carried out using the methods of mathematical statistics using the STATISTICA 6.0 and EXEL programs, as well as using the CorelDRAW graphic editor (Syasyev, 2004, Lopushnyak, 2021a, Lopushnyak, 2021b).

RESEARCH RESULTS

Comparative studies of biomass productivity of grassy energy crops under similar conditions of cultivation and application of identical rates of fertilizers established that different crops respond differently to the application of SS and depending on the application rate and form of application (fresh SS and composted with straw in a ratio of 3:1) provide different levels of plant biomass yield and productivity of culture phytocenoses (Table 2). In particular, the productivity of *Silphium perfoliatum* L increased from 14.7 t/ha in the control to 21.1–25.2 t/ha in the variants with the application of fresh SS and with the corresponding compensatory dose of mineral fertilizers (options 4 and 6), which was 6.4–10.5 t/ha of dry nuts higher than the control option without additives (option 1). At the same time, the use of composts with SS and straw had a certain advantage in the level of productivity of the studied crop, compared to the similar rate of application of fresh SS, and the yield was 21.5–24.0 t/ha with the smallest significant difference in indicators of 0.4 t/ha. A similar tendency to increase in

Table 2. Productivity of energy crops 2017–2022 t/ha of dry matter

№	Silphium perfoliatum	Jerusalem artichoke	Miscanthus giganteus	Panicum virgatum
Control	14.7	14.4	19.1	11.3
$N_{60}P_{60}K_{60}$	16.2	15.6	23.6	12.8
$N_{90}P_{90}K_{90}$	18.9	17.7	25.8	13.6
SS – 20 t/ha + $N_{50}P_{52}K_{74}$	21.1	20.6	26.4	15.2
SS – 30 t/ha + $N_{30}P_{33}K_{66}$	23.3	22.9	27.8	16.7
SS – 40 t/ha + $N_{10}P_{14}K_{58}$	25.2	24.5	29.8	18.9
Compost – 20 t/ha + $N_{50}P_{16}K_{67}$	21.5	21.5	27.3	16.0
Compost – 30 t/ha + $N_{30}K_{55}$	24.0	23.6	28.5	17.5
LSD_{05}	0.4	0.7	0.5	0.7

productivity due to application of fertilizer based on SS was also observed in indicators of productivity of Jerusalem artichoke. Productivity in the control reached 14.4 t/ha, and in the options with fresh SS and mineral fertilizers it increased by 6.2–10.1 t/ha and amounted to 20.6–24.5 t/ha (options 4–6). The introduction of compost contributed to an increase in Jerusalem artichoke productivity by 5.9 t/ha compared to the introduction of only mineral fertilizers (option 3) and was 23.6 t/ha.

Forms of application of SS (fresh and composted with straw in a ratio of 3:1) for the cultivation of miscanthus contributed to an increase in biomass productivity by 7.3–10.7 t/ha compared to the control (option 1). The application of composts at the rate of 20–30 t/ha and the corresponding doses of mineral fertilizers contributed to an increase in productivity compared to the application of mineral fertilizers (option 3) by 1.5–2.7 t/ha. The culture of switchgrass (*Panicum virgatum* L) was characterized by the following indicators of productivity in the control of 11.3 t/ha and 15.2–18.9 t/ha with the introduction of SS at the rate of 20–40 t/ha. The introduction of mineral fertilizers at the rate of 60–90 t/ha contributed to an increase in productivity by 1.5–2.3 t/ha, which in percentage was 11.8–27.6%.

It is appropriate to note that it was the introduction of fresh SS at the rate of 40 t/ha and $N_{10}P_{14}K_{58}$ (option 6) that contributed to increasing the productivity of miscanthus to 29.8 t/ha of dry matter, while the other studied energy crops at the same rate of fertilization provided a slightly lower level of productivity compared to this indicator – by 17.8% Jerusalem artichoke,

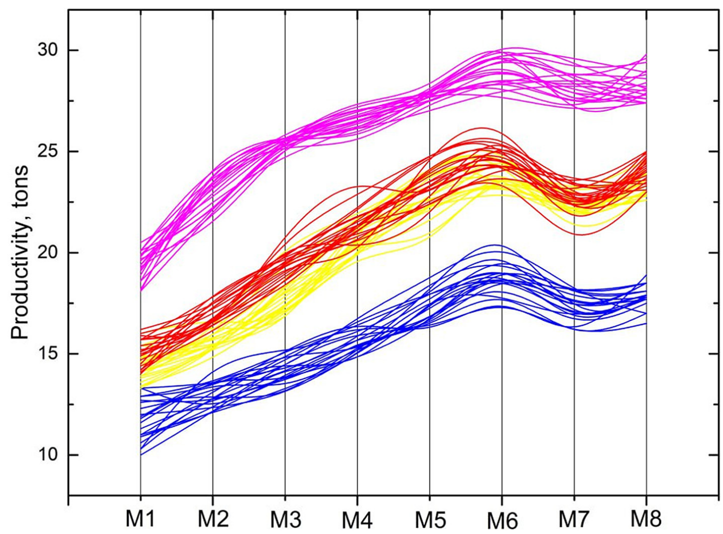

Figure 1. Distribution of the density of crop productivity probabilities (sylphia, Jerusalem artichoke, *Miscanthus giganteus*, switchgrass (*Panicum virgatum* L). depending on the rate of application of SS (M1-M8 – variants of the experiment)

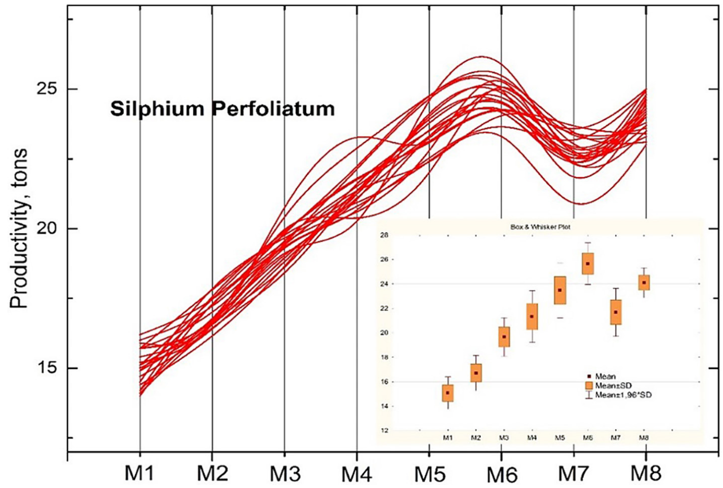

Figure 2. Probability density distribution of *Silphium perfoliatum* L productivity depending on the application rate of organic fertilizers (M1 – M8 – variants of the experiment) and a graphical representation of the average value (Mean) of Silphium productivity, the standard error of the study (Mean SD) and the 95 percent confidence level interval (Mean 1.96 SD)

by 15.4% *Silphium perfoliatum* and by 25.6% *Panicum virgatum*. Figure 1 shows the experimental distribution of the probability density of productivity indicators for 8 different options for applying fertilizers. Manure 1 (M1) shows a control group of plots that did not have artificially applied fertilizers. Other fertilizers corresponded to a certain amount of applied macronutrients (Table 1). Each experimental plot with different doses of fertilizers was divided into 21 parts. Thus, the experiment included 672 measurements (4 cultures, 168 plots for each of the experimental cultures). In Figure 2 shows the experimental density distribution of *Silphium perfoliatum* L productivity depending on applied fertilizers. The figure also shows a box-whisker plot for this distribution. As can be seen from Figure 2, for this crop, the optimal application of fertilizers is option 6. This combination of fertilizers not only ensures the maximum level of productivity for *Silphium perfoliatum* L, but also, given its low cost (mainly the cost of transportation and storage and application) and simplicity in application, this fertilizer can be widely applied during the cultivation of this crop. Of course, there remain questions related to the

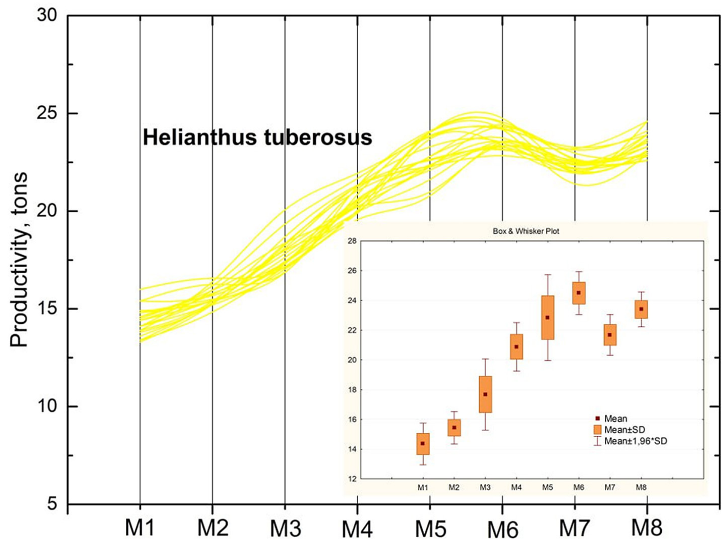

Figure 3. Probability density distribution of Jerusalem artichoke productivity depending on the rate of application of SS. (M1–M8 – variants of the experiment) and a graphic representation of the average value (Mean) of productivity

transition of heavy metals and other chemicals from sewage sludge to the raw mass of plants and the ecological risks associated with this process, but such research is beyond the scope of this article and was analyzed in our previous publications (Lopushniak and Hrytsuliak 2022, Fijałkowski, 2021, Kaletnik, 2021).

In Figure 3 shows the probability density distribution of Jerusalem artichoke productivity. It can be seen from the graph that the same conclusions as those made for *Silphium perfoliatum* L can be made for Jerusalem artichoke, for which the introduction of sewage sludge (M6) in the amount of 40 t/ha is optimal. In Figure 4 shows a distribution of the probability density of Miscanthus productivity similar to the previous one. The figure follows the same logic that is characteristic of Jerusalem artichoke and Sylphia, that is, option (M6) may be the optimal choice for the conditions. But unlike other cultures, option 8 (M8) can also be an acceptable option. The density distribution of switchgrass productivity probabilities (*Panicum virgatum* L.), shown in Figure 5 for switchgrass, as well as for all other energy crops, option (M6) is the optimal choice of the rate of application of SS.

Table 6 shows the correlations between certain types of mineral fertilizers (N, P_2O_5, K_2O) and the productivity of growing switchgrass (*Panicum virgatum* L) on a certain experimental plot (1–21).

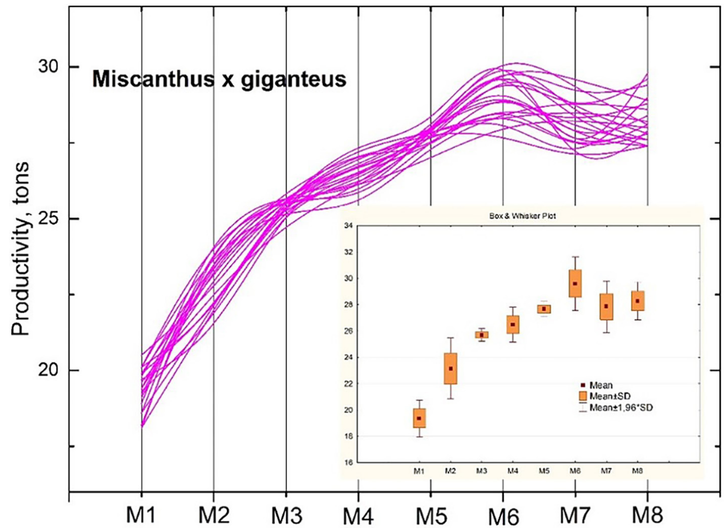

Figure 4. Probability density distribution of the productivity of *Miscanthus giganteus* depending on the rate of introduction of SS (M1–M8 – variants of the experiment) and a graphic representation of the average value (Mean) of the productivity of the culture, the standard error of the study (Mean SD) and the 95 percent confidence interval (Mean 1.96 SD)

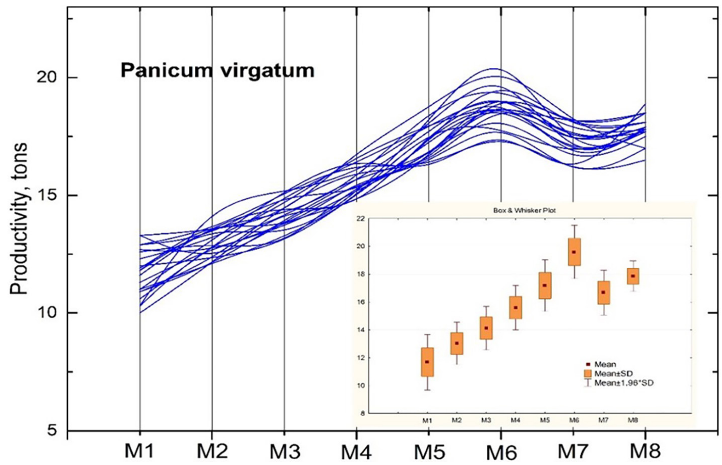

Figure 5. Probability density distribution of the productivity of *Panicum virgatum* L depending on the rate of introduction of SS (M1 – M8 – experimental options) and a graphical representation of the average value (Mean) of the productivity of the culture, the standard error of the study (Mean SD) and the 95 percent confidence interval (Mean 1.96 SD)

It can be seen from the table that the increase in the productivity indicator is most closely correlated with the introduction of SS. On the other hand, for mineral fertilizers M2–M3, this tendency is much less pronounced, or absent at all. Based on the value of the correlation coefficient, the following conclusions can be drawn: *r* if *r* acquires a value close to - 1, then there is a relationship between

Table 3. Correlations between types of mineral fertilizers (N, P_2O_5, etc.) and productivity of switchgrass (*Panicum virgatum* L). on the relevant research sites (1–21)

Variable	Color map of correlations r>= -0,40 -0,20 0 0,20 0,40 0,60 0,80 1					
	N	P2Î5	K2Î	Nss	P2Î5 ss	K2Î ss
SV1	-0,220258	-0,328165	0,390489	0,949193	0,889995	0,946737
SV2	-0,208881	-0,321777	0,398902	0,945090	0,890034	0,945800
SV3	-0,040548	-0,075581	0,549097	0,865931	0,728165	0,807896
SV4	-0,378935	-0,388745	0,234724	0,944510	0,802804	0,884185
SV5	-0,216724	-0,361042	0,374781	0,927461	0,907759	0,952039
SV6	-0,152286	-0,289145	0,412831	0,874392	0,862173	0,894271
SV7	-0,240201	-0,415597	0,316532	0,885233	0,915707	0,936911
SV8	-0,087541	-0,232811	0,497097	0,889974	0,865870	0,909291
SV9	-0,082078	-0,237103	0,489925	0,869104	0,857052	0,896497
SV10	-0,039830	-0,165495	0,556186	0,883764	0,829309	0,885766
SV11	-0,216425	-0,331161	0,389499	0,925979	0,875468	0,928648
SV12	-0,170719	-0,336082	0,420185	0,915964	0,911322	0,952348
SV13	-0,101216	-0,149770	0,499659	0,892995	0,759632	0,845703
SV14	0,013362	-0,118534	0,537215	0,828275	0,796454	0,841709
SV15	-0,431962	-0,482494	0,186967	0,984637	0,876351	0,953734
SV16	-0,433334	-0,494364	0,154690	0,947163	0,866040	0,927768
SV17	-0,369061	-0,469632	0,242929	0,969373	0,913970	0,969764
SV18	-0,104162	-0,212268	0,480253	0,889149	0,834012	0,884379
SV19	-0,367733	-0,492813	0,198599	0,919694	0,911178	0,942948
SV20	-0,259465	-0,378076	0,307682	0,883644	0,861962	0,896707
SV21	-0,352933	-0,375960	0,276819	0,936112	0,790667	0,881092

Table 4. Correlations between the application rates of SS (M1–M8 – experiment options) and the productivity of growing Miscanthus in the corresponding experimental plot (1–21)

Variable	Color map of correlations r>= -0,40 -0,20 0 0,20 0,40 0,60 0,80 1					
	N	P2Î5	K2Î	Nss	P2Î5 ss	K2Î ss
MS1	0,116934	-0,019208	0,674026	0,814858	0,773045	0,821034
MS2	0,097739	-0,043015	0,660084	0,828674	0,789044	0,838223
MS3	0,154892	0,035493	0,712817	0,788927	0,724106	0,781752
MS4	0,121084	-0,017265	0,683383	0,805125	0,759260	0,811875
MS5	0,211044	0,077506	0,748929	0,767103	0,715580	0,769244
MS6	0,203575	-0,024146	0,701754	0,728086	0,789871	0,799612
MS7	0,275089	0,069920	0,757536	0,686478	0,724052	0,741262
MS8	0,120689	-0,131829	0,611651	0,739381	0,840745	0,833024
MS9	0,220601	0,013288	0,711873	0,721204	0,767244	0,779046
MS10	0,131468	-0,042066	0,651694	0,746037	0,758501	0,781883
MS11	0,154652	-0,058836	0,654859	0,731148	0,787955	0,795441
MS12	-0,014417	-0,138479	0,572954	0,854736	0,801701	0,855568
MS13	0,005580	-0,113822	0,583007	0,836273	0,779079	0,834316
MS14	0,012144	-0,143206	0,570534	0,818440	0,801359	0,843002
MS15	0,008892	-0,185076	0,558150	0,831570	0,860411	0,883520
MS16	-0,013849	-0,206885	0,531614	0,839200	0,871272	0,892247
MS17	-0,044408	-0,151944	0,527082	0,878603	0,816298	0,872041
MS18	0,064695	-0,077339	0,618048	0,839170	0,800413	0,852567
MS19	0,223950	0,083184	0,752318	0,750443	0,704712	0,758115
MS20	0,031515	-0,008278	0,623582	0,855619	0,707730	0,796603
MS21	0,105497	-0,005645	0,664880	0,814465	0,744273	0,804114

the factors; tight feedback; if r = 0, then there is no connection; if r is close to +1, then there is a tight straight line between the factors; if r = 1 or = -1, then there is a functional relationship between the factors communication (22). The same applies to Jerusalem artichoke, data on

Table 5. Correlations between the application rates of SS (M1–M8 – experiment options) and the productivity of Jerusalem artichoke cultivation on the corresponding experimental plot (1–2)

Color map of correlations
r>= -0,40 -0,20 0 0,20 0,40 0,60 0,80 1

Variable	N	P2Î5	K2Î	Nss	P2Î5 ss	K2Î ss
TP1	-0,207298	-0,334730	0,400032	0,946710	0,902217	0,957176
TP2	-0,181605	-0,321292	0,398141	0,908213	0,885251	0,929459
TP3	-0,283320	-0,446075	0,287643	0,914194	0,926855	0,957639
TP4	-0,218605	-0,364035	0,379537	0,944108	0,919689	0,968571
TP5	-0,241923	-0,397895	0,352270	0,943968	0,937163	0,977328
TP6	-0,259624	-0,418150	0,326398	0,931286	0,931573	0,968483
TP7	-0,299409	-0,403138	0,312003	0,946410	0,886386	0,945323
TP8	-0,133879	-0,243154	0,461902	0,893375	0,831863	0,889415
TP9	-0,118056	-0,217924	0,491201	0,923623	0,837989	0,910532
TP10	-0,061002	-0,228631	0,511790	0,876965	0,866199	0,911573
TP11	-0,143650	-0,252550	0,463390	0,918467	0,849815	0,913156
TP12	-0,045168	-0,187300	0,535414	0,869318	0,829984	0,884861
TP13	-0,199853	-0,325952	0,404364	0,929931	0,876534	0,939579
TP14	-0,207651	-0,358383	0,391032	0,926978	0,905199	0,954398
TP15	-0,271220	-0,467287	0,294418	0,916570	0,956204	0,982512
TP16	-0,075369	-0,217397	0,507968	0,884229	0,849782	0,900905
TP17	0,010045	-0,126371	0,580895	0,855414	0,813404	0,865517
TP18	-0,390411	-0,442340	0,227715	0,987211	0,872089	0,955111
TP19	-0,414841	-0,416353	0,218138	0,988146	0,820114	0,921377
TP20	-0,246809	-0,315645	0,375171	0,952562	0,849161	0,923681
TP21	-0,116525	-0,248017	0,452656	0,882211	0,848953	0,895968

Table 6. Correlations between the rates of application of SS (M1–M8 – experimental options) and the productivity of growing *Silphium perfoliatum* L on the corresponding experimental site (1–21)

Color map of correlations
r>= -0,40 -0,20 0 0,20 0,40 0,60 0,80 1

Variable	N	P2Î5	K2Î	Nss	P2Î5 ss	K2Î ss
SF1	-0,161714	-0,269984	0,446600	0,939099	0,872267	0,934098
SF2	-0,109573	-0,215220	0,490253	0,917789	0,847219	0,909446
SF3	-0,174717	-0,285494	0,439076	0,947480	0,880956	0,944088
SF4	-0,175501	-0,267935	0,436129	0,950718	0,866801	0,935309
SF5	-0,169814	-0,275715	0,434386	0,944230	0,873316	0,938622
SF6	-0,182139	-0,305878	0,390372	0,910824	0,877487	0,922352
SF7	-0,177833	-0,272007	0,433154	0,940987	0,860279	0,926994
SF8	-0,186082	-0,280639	0,421304	0,936968	0,860952	0,924184
SF9	-0,226823	-0,236344	0,394142	0,956936	0,788356	0,887177
SF10	-0,257427	-0,313426	0,329190	0,927411	0,831030	0,895405
SF11	-0,132457	-0,333642	0,417154	0,883532	0,931610	0,947750
SF12	-0,080404	-0,259840	0,490778	0,893120	0,903780	0,936894
SF13	-0,058497	-0,093463	0,532199	0,893992	0,752289	0,836649
SF14	0,019352	-0,169334	0,578537	0,835903	0,851681	0,882354
SF15	0,026526	-0,127524	0,603543	0,857133	0,830909	0,877363
SF16	-0,070814	-0,178071	0,529901	0,898972	0,829760	0,889559
SF17	-0,089437	-0,163364	0,527040	0,903409	0,791133	0,870381
SF18	-0,113671	-0,148590	0,498322	0,899771	0,749476	0,842420
SF19	-0,088816	-0,113769	0,481204	0,847296	0,696294	0,787835
SF20	-0,108534	-0,206172	0,441475	0,841387	0,788911	0,834687
SF21	-0,241635	-0,284808	0,352480	0,913664	0,800687	0,871183

the correlation of its productivity with the application of fertilizers are shown in the Table 5. From it, it can be seen that the rates of introduction of SS are almost linearly correlated with the productivity in the increase of green mass. Tables 3–6 show the correlations between certain types of mineral fertilizers (N, P_2O_5, K_2O) and the productivity of growing the studied crops on the selected experimental plots (1–21).

It can be seen from the tables that the increase in the productivity indicator is most closely correlated with the introduction of SS. On the other hand, for mineral fertilizers M2–M3, this tendency is much less pronounced, or absent at all. Also, it can be seen from the correlation matrices that the application rates of SS are almost linearly correlated with the productivity of energy crops in the increase of green mass.

Taking this into account, it can be stated that the introduction of sewage sludge with a small addition of mineral fertilizers is an extremely effective way of increasing the productivity of green mass growth for all studied energy crops, namely Jerusalem artichoke, *Silphium perfoliatum* L, switchgrass (*Panicum virgatum* L) and Miscanthus (*Miscanthus giganteus*).

CONCLUSIONS

As a result of the conducted research, convincing relationships were established between the application of sewage sludge with a compensatory dose of mineral fertilizers and the productivity of grassy energy crops (Figs. 1–5). The greatest increase in green mass is provided by the application of SS (SS – 40 t/ha + $N_{10}P_{14}K_{58}$) for all studied crops. Thus, the introduction of sewage sludge with the addition of mineral fertilizers is an effective way to increase the productivity of green mass by 57–64% for such energy crops as *Jerusalem artichoke*, *Silphium perfoliatum* L, Miscanthus (*Miscanthus giganteus*), and switchgrass (*Panicum virgatum* L). Such a dose of fertilizer application is a relatively inexpensive way of increasing the productivity of agrophytocenoses (the main component of the cost is transportation to the place of planting plants and application to the soil), and also solves the problem of the accumulation of sewage sludge on sludge maps and municipal waste storage landfills.

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