J. Elem. s. 1021–1036 DOI: 10.5601/jelem.2014.19.3.725

EFFECT OF SEWAGE SLUDGE APPLICATION ON THE GROWTH, YIELD AND CHEMICAL COMPOSITION OF PRAIRIE CORDGRASS (*SPARTINA PECTINATA* LINK.)

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Abstract

Prairie cordgrass is a perennial C4 grass characterized by high adaptability to different habitats. The highest yields are obtained on sites with sufficient water supply, on soils of coarse or medium texture and with a wide range of the C:N ratio. Sewage sludge may be the source of nutrients for the crops grown for renewable energy purposes.

The objective of the research was to evaluate the effect of sewage sludge fertilization on the growth and yield of prairie cordgrass and the content of crude ash, macronutrients and heavy metals in the plant biomass in the first three years of cultivation.

The experiments were conducted at the Pawłowice Agricultural Experimental Station near Wroclaw, in 2008-2010. Their aim was to investigate the impact of differentiated sewage sludge applications and harvest periods on the growth, yield formation and chemical composition of prairie cordgrass. Two-factor experiments in a split-plot design were conducted. The first factor was a dose of sewage sludge: 0, 1.4, 2.8 and 4.2 t ha^{-1} DM, corresponding to the nitrogen fertilization of 0, 50, 100, 150 kg ha^{-1}, and the second factor was the harvest time: autumn and winter.

The sewage sludge dose of 2.8 t ha^{-1} DM, compared to the control, significantly increased the plant height by 4%, one shoot mass by 11%, the number of shoots per 1 m^2 by 14% and the dry mass yield by 22%, but it showed no influence on the yield structure formation and the content of macronutrients and heavy metals. The postponement of the harvesting time from autumn to winter resulted in drier plants, lower dry mass yield and less crude ash, K, Mg and S.

Key words: prairie cordgrass, sewage sludge, harvest period, crude ash, macronutrients, heavy metals.

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WPŁYW NAWOŻENIA OSADEM ŚCIEKOWYM NA ROZWÓJ, PLONOWANIE I SKŁAD CHEMICZNY SPARTINY PRERIOWEJ (*SPARTINA PECTINATA* LINK.)

Abstrakt

Spartina preriowa jest wieloletnią trawą o cyklu fotosyntezy C-4, charakteryzującą się dużą zdolnością adaptacyjną do różnych siedlisk. Najlepiej plonuje na stanowiskach o dostatecznej ilości wody, na glebie o gruboziarnistej lub średniej teksturze i szerokim stosunku C do N. Źródłem składników pokarmowych dla roślin uprawianych na cele energetyczne mogą być osady ściekowe.

Celem badań było określenie wpływu nawożenia osadem ściekowym na rozwóji plonowanie spartiny preriowej oraz kształtowanie zawartości popiołu surowego, makroskładników i metali ciężkich w biomasie w pierwszych trzech latach uprawy.

W latach 2008-2010 w Rolniczym Zakładzie Doświadczalnym Pawłowice k. Wrocławia badano wpływ zróżnicowanego nawożenia osadami ściekowymi i terminu zbioru na rozwój, kształtowanie plonu i skład chemiczny spartiny preriowej. Dwuczynnikowe doświadczenie założono w układzie „split-plot". Pierwszym czynnikiem była dawka osadu ściekowego: 0, 1,4, 2,8 i 4,2 t ha^{-1} s.m., co odpowiadało nawożeniu azotem: 0, 50, 100, 150 kg ha^{-1}, a drugim – terminy zbioru: jesienny i zimowy.

Osad ściekowy w dawce 2,8 t ha^{-1} s.m., w porównaniu z kontrolą, zwiększał istotnie wysokość roślin o 4%, masę 1 pędu o 11%, liczbę pędów na 1 m^2 o 14% oraz plon suchej masy o 22%, natomiast nie miał wpływu na kształtowanie struktury plonu oraz zawartość makroskładników i metali ciężkich. Przesunięcie terminu zbioru z jesiennego na zimowy skutkowało mniejszym uwilgotnieniem roślin, wpłynęło na zmniejszenie plonu suchej masy oraz zawartości popiołu surowego, K, Mg i S.

Słowa kluczowe: spartina preriowa, osad ściekowy, termin zbioru, popiół surowy, makroskładniki, metale ciężkie.

INTRODUCTION

Spartina pectinata (prairie cordgrass) is a perennial C4 grass. It forms loose clumps of 0.90 to 2.40 m tall plants with densely attached leaves up to 0.80-0.90 m long and 3 to 13 mm wide. The grass develops a strong and deep root system of 1.5 to 3 m long, which allows the plant to endure short-term droughts. In mid-summer, the plants grow 0.30 m long panicle-type inflorescences. Generative shoots are hollow (Majtkowski 2006). The number of culms per 1 m^2 ranges from 100 to 300 (Fraser, Kindscher 2005), exceeding 1000 culms under favourable conditions (Boe et al. 2009, Potter et al. 1995).

Prairie cordgrass shows high adaptability, growing well in different habitats, which supports its widespread occurrence, from Newfoundland to Canada. Although it flourishes in *hygrophilous plant communities* and on dry prairies (Majtkowski 2006), the highest yield is obtained on sites with adequate quantities of water, on coarse or medium texture soils with a wide range of C:N ratio. The grass is well adapted to soils with variable, seasonably excessively high water tables (Bonilla-Wardford, Zedler 2002, Mobberley 1956, Who et al. 2012). An optimum soil pH is 6.0 to 8.5, but *Spartina* *pectinata* also tolerates strong acidification. Its performance is poor on arid lands and heavy soils, but it tolerates grass burning (Johnson, Knapp 1993). It performs well under adverse conditions that occur in the vicinity of nitrogen production plants and coal mining dumps (Majtkowski 1997). Weiss et al. (2006) showed a high content of heavy metals, particularly Pb, in aerial parts of prairie cordgrass, which indicates its suitability for degraded land reclamation. The thermal needs of prairie cordgrass are not high. During winter dormancy, it withstands temperatures down to -39°C, and during the growing season it requires at least 110 days with temperatures above 0°C. Thus, it grows well throughout Poland and has gained great popularity in the Nordic countries. Despite its hardiness, prairie grass does not tolerate shady sites. The minimum depth of the root system is about 0.5 m. Its fertilization requirements are moderate.

In Poland, *Spartina pectinata* produces seeds, but because their germination capacity declines rapidly, vegetative propagation through division of the rhizomes in the spring is recommended (Majtkowski 2006). Prior to establishing a plantation, special attention should be paid to the careful weeding of a field, preferably several times. Usually, the weed control is necessary not only in the first, but also in the second year of cultivation. With the vigorous root system, prairie cordgrass does not require deep aeration of the soil. Organic fertilization is unnecessary. In Poland, prairie cordgrass is planted at 1.8-3.0 m inter-row and 0.5-0.75 m intra-row spacing (Majtkowski 2006). However, a higher density of planting, i.e. 0.9 x 0.35 m, is possible (Boe, Lee 2007).

Sewage sludge is a source of organic matter, which in the process of mineralization releases mainly N and P, and therefore may be recognized as an organic fertilizer with a strong, favourable impact on the balance of organic matter in the soil (Dusza et al. 2009, Żukowska et al. 2002). Types of sewage sludge differ in terms of fertilization values since their effect may be similar to that of mineral fertilizers, and sometimes close to manure (Gambuś, Wieczorek 2003). The presence of heavy metals in sewage sludge poses a risk of soil contamination with these elements and their uptake by plants (Szatanik-Kloc 2004). This is why sewage sludge may be a source of nutrients for crops not intended for human or animal consumption (Mercik et al. 2003). Sienkiewicz and Czarnecka (2012) demonstrated that an application of 280 Mg ha^{-1} of sewage sludge to alkaline soil elevated the content of available forms of Cu, Zn and Mn. However, it did not pose a threat to the environment. Instead, it improved the nutrition of plants with these elements. Fertilization with high doses of sewage sludge has a long-lasting effect on the microbial activity of the soil accumulation layer (Joniec, Furczak 2008). In the fourth year after the application of sewage sludge, evident stimulation of protease activity and nitrification process as well as slight inhibition of ammonification were observed (Joniec, Furczak 2008).

In the second year of cultivation, *Spartina pectinata* favourably responds to fertilization with mineral fertilizers in doses of 60-110 kg ha^{-1} N. The amounts of P and K should be determined based on soil fertility (Majtkowski 2006). The N: P: K ratio is recommended to be 1:0.4:0.5. Some studies have indicated that fertilization may be discontinued for a few years after establishing a plantation (Potter et al. 1995).

Kalembasa and Malinowska (2010) found that fertilization of sugar miscanthus with 30 t ha^{-1} of sewage sludge, regardless of the age of a plantation, significantly increased the content of heavy metals in the plant biomass compared to the control, and their uptake can be arranged in the following series with decreasing values: Zn> Cd> Ni>Cu>Pb>Cr>Co. The ash and sulphur content in the biomass of prairie cordgrass is influenced by nitrogen fertilization and the number of cuts (Kowalczyk-Juśko 2010). Plants harvested once in winter contain less ash and sulphur compared to those harvested twice. The ash of prairie cordgrass contains a prevalent quantity silica and smaller amounts of Ca, K, S, P and Mg oxides (Kowalczyk-Juśko 2009).

The objective of our study was to assess the effect of fertilization with sewage sludge on the growth and yield of prairie cordgrass and amounts of crude ash, macronutrients and heavy metals in the plant biomass in the first three years of cultivation.

MATERIAL AND METHODS

The field experiment was set up in a two-factor split-plot design. The first factor was a dose of sewage sludge: 0, 1.4, 2.8 and 4.2 t ha^{-1} DM, which corresponded to nitrogen fertilization doses of: 0, 50, 100, 150 kg ha^{-1}. The second factor was the harvest period: autumn and winter. The area of the plots was 3.5 m^2.

The experiment was established in alluvial soil, very light, on loose sand and sandy gravel, classified to the soil category V in the Polish soil valuation system. The content of available macroelements in the soil (mg kg^{-1}) was as follows: P (86-111) – high to very high; K (65-81) – low; Mg (27-45) – very low to low. The soil pH in 1 M KCl in the first and second year of the experiment was acidic (4.9-5.4) and slightly acidic (5.7-5.9) in the third year.

The experiment was set up on 11 June 2008 and prairie cordgrass was planted in the following spacing: 0.35x0.35 m (82 thousand seedlings ha^{-1}). *Spartina pectinata* was planted on the site where white mustard had been previously grown for seeds. During the growing season, the height of the stand was measured at two-week intervals. Prior to the harvest, the number of fully developed shoots (culms) per 1 m^2 was counted. Major morphological features were recorded on 10 shoots, i.e.: diameter at 0.10 m above the ground, the height of the plants before harvest and the number of leaves on the culm. In addition, the content of water in the leaves, in the culm and in the whole plant was measured by oven-drying method. Moreover, the yield structure of the aboveground parts of the plant and the yield of fresh and dry mass were determined.

The chemical analysis, performed in the laboratories of the Crop Production Department and Plant Nutrition Department at the Wrocław University of Environmental and Life Sciences, focused on:

- dry mass (oven-drying) – drying shredded plants for 4 hrs at the temp. of 105°C;
- crude ash – burning the plant material in an electric furnace at the temp. of 600°C;
- general nitrogen – the Kjeldahl's method;
- P an Mg – calorimetric method;
- K and Ca – flame photometry;
- S – the Barclay's method;
- Mn, Fe, Cu, Cd, Pb, Ni and Zn – flame atomic absorption spectroscopy (Varian 220 FS AA Spectrometer).

The chemical analysis of the sewage sludge was typical for that from municipal sewage treatment plants (Table 1). The sewage sludge was applied on 05.06.2008, 31.03.2009 and 25.03.2010. Apart from the doses of nitrogen introduced to the soil, according to the methodology, the sewage sludge contributed macro- and microelements as well as toxic elements to plants, whose weight was proportional to the dose of sewage sludge (Table 2). The data were statistically analyzed and their significance assessed at α=0.05. The AWA programme was used for data computation (Bartkowiak 1978).

Table 1

Chemical composition of sewage sludge from the Wrocław Sewage Treatment Plant, Janówek

Specification	Dry mass	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn	Ni	Pb	Cd
Unit	(g kg^{-1} DM)						(mg kg^{-1} DM)						
Content	200	35.7	12.9	1.8	19.5	7.0	412	2385	464	1260	47.6	36.4	2.46

Table 2

Macro- and microelements and heavy metals in a sewage sludge dose

DM sewage sludge dose (t ha^{-1})	(kg ha^{-1})									(g ha^{-1})		
	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn	Ni	Pb	Cd
1.4	50	18.1	2.5	27.1	9.8	0.57	3.33	0.64	1.76	66.6	51.0	3.4
2.8	100	36.2	5.0	54.3	19.6	1.15	6.66	1.29	3.53	133.3	102.0	6.8
4.2	150	54.3	7.5	81.5	29.3	1.72	10.00	1.93	5.29	199.9	153.0	10.4

RESULTS AND DISCUSSION

Despite the precipitation deficit during the planting (Table 3), no loss of plants occurred in the first year of cultivation, and some plants started blooming on July 30. The plant growth was inhibited on 15.11.2008. In the second and third year of the study, *Spartina pectinata* began to grow on 2.04.2009, and 6.04.2010, respectively. The precipitation during the growing season was higher than the long-term average. The onset of flowering was on 23 July 2009 and 25 July 2010, and the growth inhibition took place at the end of November.

Table 3

Weather conditions in 2008-2010
Data collected at the Wrocław-Swojec weather station

Month	Temperature (°C)				Precipitation (mm)			
	2008	2009	2010	average 1976-2005	2008	2009	2010	average 1976-2005
I	2.9	-2.3	-5.9	-1.0	56.7	34.6	40.6	31.9
II	3.9	0.2	-1.1	0.1	20.4	46.8	11.0	26.7
III	4.6	4.6	4.2	3.7	33.0	48.3	44.9	31.7
IV	8.9	12.0	9.3	8.3	87.1	30.9	45.4	30.5
V	14.3	14.2	12.7	14.1	37.3	67.6	140.7	51.3
VI	18.8	15.8	17.9	16.9	36.5	141.7	32.9	59.5
VII	19.8	19.5	21.4	18.7	65.6	134.2	78.6	78.9
VIII	18.8	19.3	18.9	17.9	94.0	53.5	61.5	61.7
IX	13.2	15.4	12.5	13.3	27.9	12.0	134.1	45.3
X	9.6	7.9	7.0	9.2	41.1	76.0	5.7	32.3
XI	6.1	6.8	6.5	3.7	29.6	32.5	66.4	36.6
XII	2.1	-0.4	5.3	0.2	20.5	51.9	63.2	37.4
Average temperature or total precipitation	10.3	9.42	8.2	8.8	549.7	730.0	772.6	527.4

In the first year of the study, prairie cordgrass did not lodge. The measurements of the standing crop's height showed that plants from the sites fertilized with sewage sludge at 4.2 t ha^{-1} DM were the highest (Figure 1).

Regardless of the dose of sewage sludge, *Spartina pectinata* was lodged in the second and third year of cultivation. In the second year, the beginning of lodging took place in mid-August, and at the end of July in the third year (Figures 2, 3).

The experimental factors did not affect the diameter of culms or the

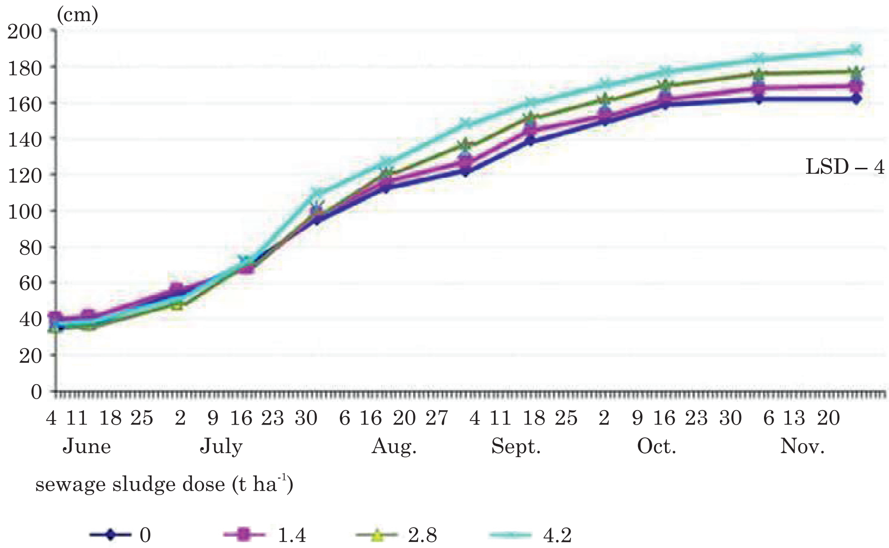

Fig. 1. Prairie cordgrass growth dynamics – 2008

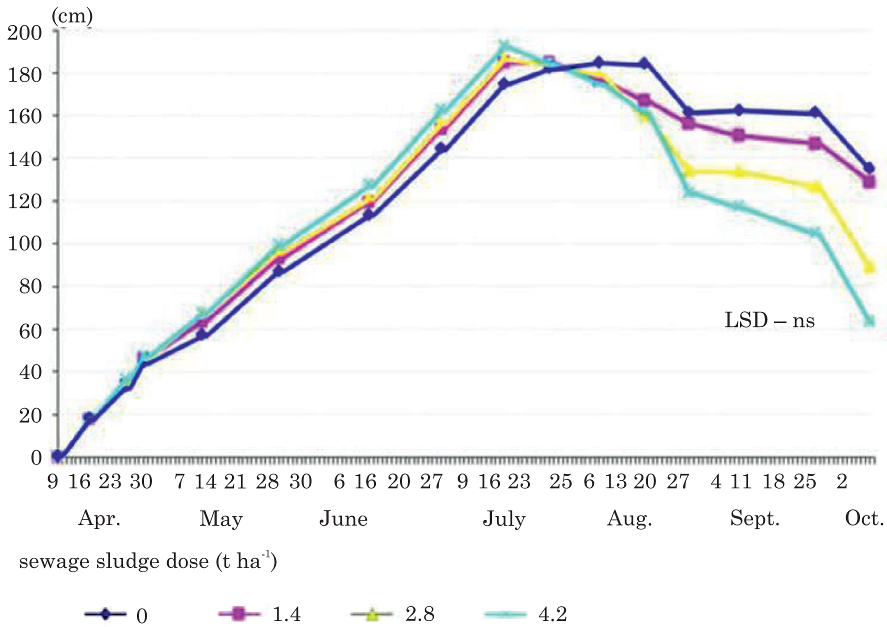

Fig. 2. Prairie cordgrass growth dynamics – 2009
ns – non-significant difference

number of leaves on one shoot (Table 4). As compared to the control, the dose of 4.2 t ha^{-1} DM of sewage sludge increased the height of shoots by 6%. The winter harvest, as compared to the autumn one, reduced the plant height by

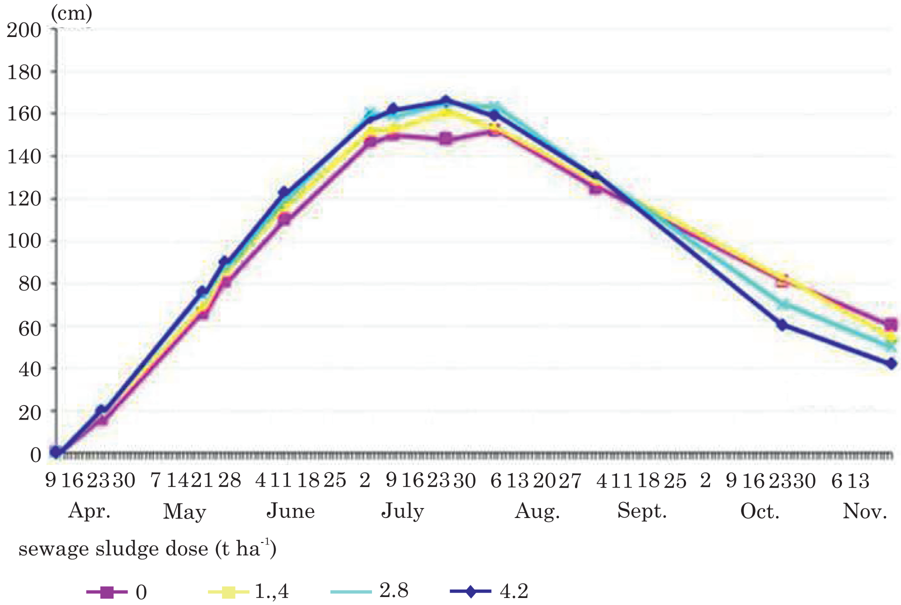

Fig. 3. Prairie cordgrass growth dynamics - 2010

ns - non-significant difference

Table 4

Morphological traits of prairie cordgrass shoots (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Diameter (mm)	Height before harvesting (cm)	No. of leaves per shoot
0			5.3	182	6.9
1.4			5.1	183	7.0
2.8			5.5	189	7.2
4.2			5.4	194	7.1
LSD (α=0.05)			ns	6	ns
	autumn		5.4	193	7.1
	winter		5.2	181	7.0
LSD (α=0.05)			ns	4	ns
		2008	5.5	169	6.7
		2009	5.2	182	7.3
		2010	5.2	209	7.3
LSD (α=0.05)			0.2	5	0.2

6% due to breaking of the plant tops. The weather conditions in the years of the experiment combined with the plantation age had a significant impact on morphological traits. The plants of 3-year old, compared to one-year old, were higher by 24%, produced more leaves, and the diameter of the culm was smaller because of light competing. This favored earlier plant lodging. The findings of KOWALCZYK-JUŚKO and KOŚCIK (2004) indicate that the height of prairie cordgrass in the fifth year of vegetation depended largely on the soil compactness. Plants on loamy and sandy soils were shorter than those on clay soils, where the height reached 1.69 m. On the other hand, MAJTKOWSKI (1998) found that *Spartina pectinata* reached the height of 2.30 m in the fourth year of growth. BOE et al. (2009) showed that the number of leaves on a shoot was from 4.4 to 4.8, and it was higher than that in plants reproduced generatively.

The experimental factors affected the culm's dry weight and its water content. The dose of 2.8 t ha^{-1} DM sewage sludge, compared to the control, increased the weight of culms by 8%, and that of a culm with leaves by 12% (Table 5). The winter harvest, compared to the autumn one, significantly reduced the weight of the culm leaves, the weight of culms and the weight of the entire aboveground part. The water content in the leaves, culms and culms with leaves increased as a result of the sewage sludge fertilization. The highest amount of water was observed in leafless culms, then in leafy culms and the lowest one was in leaves, which were losing water most quickly. A delay in harvesting resulted in lower moistening of leaves, culms and

Table 5

Prairie cordgrass dry mass structure and shoot moist content (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	1 shoot dry mass (g)			Percentage in shoot mass (%)		Water content (g kg^{-1})		
			leaves	culms	total	leaves	culms	leave-se	culms	above gro-und mass
0			5.4	4.9	10.3	52.1	47.9	296	508	406
1.4			5.8	4.8	10.6	55.2	44.8	314	506	420
2.8			6.2	5.3	11.5	52.8	47.2	334	543	444
4.2			6.4	5.2	11.6	54.7	45.3	344	555	459
LSD (α=0.05)			ns	0.4	0.9	ns	ns	ns	24	26
	autumn		6.6	5.5	12.1	54.1	45.9	373	544	466
	winter		5.3	4.6	9.9	53.3	46.7	271	513	400
LSD (α=0.05)			0.6	0.3	0.7	ns	ns	ns	12	1.1
		2008	5.1	4.0	9.1	56.0	44.0	429	610	530
		2009	6.3	6.1	12.4	50.9	49.1	234	481	360
		2010	6.3	5.1	11.4	54.3	45.7	302	494	406
LSD (α=0.05)			0.6	0.4	0.8	2.9	2.9	2.9	21	22

culms with leaves. The two-year old plants, compared to one-year old, had a higher culm weight and a lower water content.

The number of shoots per 1 m^2 increased in the subsequent years of the study and under the influence of sewage sludge fertilization (Table 6). In the third year of the experiment, as compared to the first year, the number of culms per 1 m^2 was over six-fold higher. The compactness of prairie cordgrass in the first years of cultivation depended primarily on the number of seedlings per 1 m^2, which are most often planted at 1.80-3.00 m inter-row and 0.50-0.75 m intra-row spacing. With the spacing as above, the plant population per one hectare ranges from 4444 to 11111. However, a higher density planting is possible, up to 0.25x0.25 m spacing between crops (Potter et al. 1995), 0.90x0.35 m (Boe, Lee 2007) or 1.00x0.50 m (Kowalczyk-Juśko 2013). In our study, the plant stance was 0.35x0.35 m, which corresponded to 82 thousand plants per 1 ha. A large number of plants meant strong compactness of the stand in the second year of the experiment and a total lack of weeds, which in the absence of registered chemical plant protection products becomes an important issue on the plantations with a small number of plants. Potter et al. (1995) demonstrated that in the natural conditions of East England, the number of shoots of prairie cordgrass per 1 m^2 steadily increased for four consecutive years, but in the 5^{th} and 6^{th} year it significantly dropped.

The yield of fresh and dry mass of prairie cordgrass was closely related to the number of shoots per 1 m^2 and affected by the factors examined and plantation age (Table 6). As compared to the control, the dose of 2.8 t ha^{-1} of sewage sludge increased one shoot weight by 11%, the number of shoots per 1 m^2 by 14% and the dry mass yield by 22%. The dry mass yield of the

Table 6

Number of shoots per 1 m^2 and biomass yield (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Number of shoots per 1 m^2 before harvesting (pcs)	Yield (t ha^{-1})	
				fresh mass	dry mass
0			119	13.1	7.74
1.4			133	14.4	8.58
2.8			136	17.1	9.48
4.2			138	17.9	9.83
LSD (α=0.05)			13	1.7	0.85
	autumn		132	19.1	9.89
	winter		131	12.2	7.93
LSD (α=0.05)			ns	1.4	0.66
		2008	40	5.6	3.60
		2009	96	13.0	8.00
		2010	259	28.3	15.13
LSD (α=0.05)			11	1.50	0.74

winter harvest, compared to that in autumn, was lower by 21% as a result of leaf breaking and leaf and culm rotting. Kowalczyk-Juśko and Kościk (2004) showed that the yield of prairie cordgrass in the fifth year of cultivation depended on the soil type and ranged from 10 to 16 t ha^{-1}. In other studies, Kowalczyk-Juśko (2013) found that the dry mass yield of one-year old prairie cordgrass did not exceed 1 t ha^{-1}, and that in the third year was 11 t ha^{-1}, with 180 shoots per 1 m^2. Based on the research conducted in South Dakota, Boe et al. (2009) found that the biomass yield of prairie cordgrass depended on the type of propagation. The yield of plants grown from seeds was 11.7 t ha^{-1}, and the yield of vegetatively propagated plants reached 14.6 t ha^{-1}. It should be stressed that the rhizome mass and that of underground shoots to a depth of 0.25 m in generatively reproduced plants was 20.6 t ha^{-1} and that in vegetatively propagated plants was 21.8 t ha^{-1}. Under the conditions of East England, Potter et al. (1995) found a wide variability in the prairie cordgrass yields between years of the study and a low correlation between the number of shoots and dry mass yield.

The doses of sewage sludge had no significant effect on the crude ash content and macronutrients in biomass of prairie cordgrass (Table 7). Kowalczyk-Juśko (2010) showed that the crude ash content in biomass of prairie cordgrass was on average 48 g kg^{-1} and that of sluphur was 1.1 g kg^{-1}. In our study, the content of these components was 37.7 and 1.84 g kg^{-1}, respectively.

Table 7

Crude ash and macronutrients (g kg^{-1}) in prairie cordgrass dry mass (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Crude ash	N	P	K	Ca	Mg	S
0			38.0	2.73	0.45	3.70	2.78	0.22	1.68
1.4			36.2	2.83	0.43	3.75	2.67	0.22	1.70
2.8			36.9	2.73	0.42	3.65	2.63	0.25	1.82
4.2			39.9	2.93	0.48	3.82	3.05	0.33	2.17
LSD (α=0.05)			ns	ns	ns	ns	ns	ns	ns
	autumn		40.4	2.85	0.43	5.02	2.74	0.31	2.14
	winter		35.1	2.77	0.46	2.44	2.83	0.20	1.54
LSD (α=0.05)			2.9	ns	ns	0.13	ns	0.07	0.27
		2008	43.0	3.09	0.39	3.80	2.94	0.24	2,26
		2009	35.6	2.68	0.44	3.81	2.68	0.19	1.56
		2010	34.7	2.66	0.51	3.58	2.74	0.34	1.70
LSD (α=0.05)			3.5	ns	ns	0.17	ns	0.09	0.33

The winter harvest of prairie cordgrass, due to breaking, caused a decrease of the crude ash content by 13%, K by 51%, Mg by 35% and S by 28%. Similar results were obtained by Kotecki et al. (2010) for *Miscanthus giganteus*, where the winter harvest decreased the dry mass yield by 9.5%, water content by 16.8 % and crude ash by 26%.

In the first year of study, *Spartina pectinata* contained more crude ash, K and S in the biomass than in the third year.

The accumulation of crude ash and macronutrients in prairie cordgrass biomass is a function of the yield and content of individual components. Therefore, in the absence of differences in the crude ash content and macronutrients, the uptake per area unit is proportional to the dry mass yield. As compared to the control, sewage sludge fertilization at 4.2 t ha^{-1} DM raised the accumulation of crude ash and uptake of all the macronutrients (Table 8).

The biomass of prairie cordgrass harvested in winter, as compared to the autumn harvest, accumulated less macroelements: N – by 25%, P – by 13%, K – by 58%, Ca – by 12% Mg by 50%, S – by 33%. The crude ash accumulation was lower by 38%. The highest uptake of macronutrients and ash accumulation were recorded in the third year of the study.

Five heavy metals (Mn, Fe, Cu, Ni and Zn) are microelements necessary for the growth and development of plants, and two (Cd and Pb) are toxic elements. The doses of sewage sludge had no significant effect on the heavy

Table 8

Crude ash and macronutrients (kg ha^{-1}) in harvested prairie cordgrass (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Crude ash	N	P	K	Ca	Mg	S
0			279	19.9	3.8	28.7	20.5	1.9	12.3
1.4			303	24.6	4.1	32.9	23.2	2.1	13.6
2.8			329	25.5	3.9	34.7	24.1	2.3	15.3
4.2			383	27.5	4.9	38.6	30.1	3.9	21.9
LSD (α=0.05)			30	2.4	0.4	4.0	2.2	0.4	1.5
	autumn		375	27.8	4.5	47.6	25.9	3.4	18.9
	winter		272	20.9	3.9	19.9	22.9	1.7	12.7
LSD (α=0.05)			24	1.9	0.4	3.2	1.8	0.3	1.2
		2008	157	11.1	1.4	14.5	10.6	0.9	8.5
		2009	288	21.5	3.5	30.9	21.5	1.6	12.8
		2010	526	40.6	7.7	55.8	41.3	5.3	26.1
LSD (α=0.05)			46	3.6	0.6	5.8	3.4	0.5	2.3

Table 9

Heavy metals (mg kg^{-1}) in prairie cordgrass dry mass (means by factors and years)

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Mn	Fe	Cu	Cd	Pb	Ni	Zn
0			233	45.7	2.39	0.26	3.84	1.41	32.9
1.4			240	37.9	2.31	0.31	4.21	1.40	33.2
2.8			234	37.8	2.32	0.34	3.29	1.54	34.0
4.2			234	51.3	2.48	0.26	3.76	1.55	34.5
LSD (α=0.05)			ns	ns	ns	ns	ns	ns	ns
	autumn		242	28.6	2.06	0.27	2.80	1.28	34.0
	winter		228	57.8	2.69	0.32	4.75	1.67	33.3
LSD (α=0.05)			ns	12.6	0.15	ns	0.54	0.14	ns
		2008	268	48.9	3.22	0.45	2.51	1.78	47.5
		2009	201	35.6	1.91	0.22	2.58	1.17	24.8
		2010	236	45.0	1.99	0.21	6.24	1.47	28.7
LSD (α=0.05)			43	ns	0.19	0.10	0.66	0.17	5.75

metal content in the dry mass of prairie cordgrass (Table 9). Similar results were obtained by Ociepa (2013). The postponement of harvest from autumn to winter resulted in an increase in the content of Fe, Cu, Pb, and Ni in biomass. Prairie cordgrass contained more Mn, Fe, Cu, Cd, Ni and Zn in the first year of cultivation than in the third year.

Kuziemska et al. (2011) showed that orchard grass grown on soils contaminated with Ni, limed and fertilized with sewage sludge, contained more Fe, Cu and Ni in the first year than in the third year. Fertilization of sugar miscanthus resulted in more heavy metals in the third year biomass than in the fourth year (Kalembasa, Malinowska 2010).

The uptake of heavy metals by *Spartina pectinata* was in the following series of decreasing values: Mn> Fe> Zn> Pb> Cu> Ni> Cd (Table 10). In the case of Mn, Fe, Pb, Ni and Zn, a correlation was observed between the doses of sewage sludge and the harvest periods. As compared to the control, on the plots fertilized with sewage sludge at 4.2 t ha^{-1} DM, an increase was recorded in the uptake of Mn by 27%, Fe (45%), Cu (30%), Pb (26%), Ni (37%) and Zn (23%). The plants harvested in winter, compared to those collected in autumn, accumulated less Mn, Cu, Cd, Ni and Zn. In the third year of cultivation, the uptake of heavy metals by prairie cordgrass was the highest.

Table 10

Heavy metals (g ha^{-1}) in harvested prairie cordgrass

DM sewage sludge dose (t ha^{-1})	Harvest time	Years	Mn	Fe	Cu	Cd	Pb	Ni	Zn
0	autumn		2093	271	17.0	1.8	22.9	10.2	269
	winter		1605	456	16.8	1.5	47.9	11.4	210
1.4	autumn		2326	192	17.6	2.4	35.7	13.1	306
	winter		1591	404	17.5	2.0	51.7	11.4	207
2.8	autumn		2546	203	19.1	2.7	20.0	12.2	318
	winter		1654	389	19.0	2.4	51.7	13.0	253
4.2	autumn		3094	594	23.7	2.6	31.3	16.9	364
	winter		1618	460	20.1	1.9	57.9	12.7	226
LSD (α=0.05)			349	47	ns	ns	5.8	1.9	38
Means by factors and years									
0			1849	363	16.9	1.7	35.4	10.8	240
1.4			1958	298	17.5	2.2	43.7	12.2	257
2.8			2100	296	19.1	2.6	35.9	12.6	286
4.2			2356	527	21.9	2.2	44.6	14.8	295
LSD (α=0.05)			207	31	1.4	0.2	3.2	1.2	24
	autumn		2515	315	19.4	2.4	27.5	13.1	314
	winter		1617	427	18.4	2.0	52.3	12.1	224
LSD (α=0.05)			175	25	ns	0.2	2.9	ns	21
		2008	948	165	11.3	1.6	9.2	6.2	170
		2009	1647	279	15.4	1.8	20.7	9.4	203
		2010	3603	668	29.9	3.1	89.9	22.2	434
LSD (α=0.05)			345	59	2.5	0.3	5.4	2.0	39

CONCLUSIONS

1. Fertilization with sewage sludge at a dose of 2.8 t ha^{-1} DM, compared to the control, significantly increased the plant height, weight of one shoot, number of shoots per 1 m^2 and dry mass yield, but had no significant effect on the yield structure and content of macroelements and heavy metals.

2. Winter harvest resulted in collecting drier plants, with less crude ash and inhibited uptake of all macroelements as well as Mn, Fe, Cd and Zn, which is favourable in the use of biomass for renewable energy.

3. Compared to the first year of cultivation, the third-year plants formed more shoots per 1 m^2, were higher and more leafy, the uptake of macroelements and heavy metals was higher, and the dry matter yield was over four-fold higher.

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