Journal of Elementology ISSN 1644-2296

Niksa D., Stolarski M.J., Krzyżaniak M., Załuski D. 2022.
Organic carbon, total nitrogen and macronutrients in soil under short-rotation willow and poplar plantations.
J. Elem., 27(1): 181-199. DOI: 10.5601/jelem.2022.27.1.2236

RECEIVED: 10 January 2022
ACCEPTED: 19 February 2022

ORIGINAL PAPER

ORGANIC CARBON, TOTAL NITROGEN AND MACRONUTRIENTS IN SOIL UNDER SHORT-ROTATION WILLOW AND POPLAR PLANTATIONS*

Dariusz Niksa[1], Mariusz J. Stolarski[1], Michał Krzyżaniak[1], Dariusz Załuski[1]

[1] Department of Genetics, Plant Breeding and Bioresource Engineering University of Warmia and Mazury in Olsztyn, Poland

Abstract

Plant cultivation for energy purposes in a short rotation coppice system not only provides biomass for industry and power generation, but it is also beneficial for the environment. This study examined the effect of the species (cultivar/clone), harvest cycle and fertilization on selected soil parameters. A four-factorial strip-split-split-plot experiment was conducted in the north-east section of Poland. The treatment were two willow - Ekotur and Żubr (*Salix viminalis* L.) and one poplar cultivar (*P. nigra x P. maximowiczii* Henry) that were grown in one- and three-year harvest cycles. The species were fertilized with mineral and organic fertilizers (0, 85 and 170 kg ha^{-1} N). Soil samples were collected prior to the growing season (early spring) in 2016, 2017 and 2018. The experiment demonstrated that the annual cycle contained significantly more organic carbon (1.09%) than the triennial cycle. Moreover, organic carbon content was higher (p=0.0009) at sites where cultivars of *S. viminalis* L. were grown compared to those where the poplar clone was grown. Furthermore, total nitrogen content, phosphorus and potassium were higher at sites with the annual cycle. In contrast, these parameters were similar at most sites in the triennial cycle. These results indicate that fertilization did not affect soil organic carbon, pH, total nitrogen and macronutrients content in the triennial harvest cycle. The research needs to be continued during longer plantation use to confirm or refure these relationships.

Keywords: soil organic carbon, Short Rotation Woody Crops, pH, phosphorus, potassium, magnesium, *Salix*, *Populus*.

Dariusz Niksa, Ph.D., Department of Genetics, Plant Breeding and Bioresource Engineering, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, 10-719, Olsztyn, Poland, e-mail: dariusz.niksa@uwm.edu.pl, ORCID ID: 0000-0002-6361-9340.

* This study was financed by the National Science Centre, Poland, as part of the project “Changes and carbon content modelling in lignocellulosic plant biomass and soil based on qualitative and quantitative fertilization differentiation”, Grant no. 2016/23/N/NZ9/02738.

Introduction

Biomass of lignocellulosic plants, such as willow (*Salix* spp.) and poplar (*Populus* spp.) grown as short-rotation woody crops (SRWC), has been used for energy generation for over 40 years (Sirén et al. 1987). The main benefit of an SRWC plantation is that they can provide good quality biomass for up to 20 years. Although this period can be extended, plantation longevity is determined by genetic, environmental and agrotechnical factors. The yield obtained from plantations of high-yielding cultivars and clones of willow or poplar can be as high as 20 Mg (year ha)$^{-1}$ (Adegbidi et al. 2001, Stolarski et al. 2011), but it is much lower on commercial plantations (Stolarski et al. 2011, 2019, Mola-Yudego et al. 2015).

The lower yield on large-scale commercial plantations is the result of SRWC plantations being located on marginal soils to avoid competing with food production (Stolarski et al. 2011). Planting willow and poplar trees on marginal soils has several advantages, for instance they provide biomass which can be converted to renewable fuels and they cover soil which otherwise might have been left fallow (Blanco-Canqui et al. 2010).

Soil carbon sequestration is important not only for reducing CO_2 content in the atmosphere but also because it improves soil health and sustainability (Paustian 2014). Carbon in soil occurs in two forms: organic and inorganic (Batjes 2014). The former, which is the main component of humus/organic matter, is quite valuable in the temperate climate since it has a beneficial effect on several qualitative soil parameters, such as: structure, air conditions, ability to accumulate water and nutrients, fertility and as a habitat for soil organisms (Lal 2016). On the other hand, carbon in inorganic compounds, as a component of primary and secondary carbonates, is more important in dry and steppe climate (Lal 2015, 2016). Therefore, an increase in the soil organic carbon (SOC) level by SRWC cultivation is of key importance because marginal soils often have low soil organic carbon. It is notable that the content of organic carbon in arable land accounts for 50-75% of its original content before anthropotransformation, and the decrease is caused by mineralization, leaching and erosion (Lal 2016). It is clear that the main elements of the SRWC system, such as no ploughing for a number of years and a vast root system, help to limit these processes which have a negative impact on soil, thereby contributing to the restoration of their natural properties. Therefore, the cultivation conditions during an SRWC plantation lifespan are nearly identical as in long term afforestation of arable lands, where the beneficial effect on SOC sequestration in soil is well understood (LaganiÈRe et al. 2010, Bárcena et al. 2014).

It has been demonstrated that setting up a plantation on marginal lands increases soil organic C (Jug et al. 1999, Kahle et al. 2007, Pellegrino et al. 2011, Dimitriou et al. 2012). However, it brings about an opposite effect on grasslands and pastures, where the SOC content decreases significantly

(Dowell et al. 2009). SOC losses are attributed to preparing a seedbed by ploughing, which is why a decrease in the SOC levels should be expected in the initial years of a plantation (Hansen 1993, Jug et al. 1999). On the other hand, other studies have shown that SRWC may not change SOC (Grigal, Berguson 1998, Coleman et al. 2004, Pacaldo et al. 2013, Walter et al. 2015, Tariq et al. 2018). This shows that it is difficult to predict the effects of SRWC on C sequestration.

Apart from organic carbon, pH and macro- and micronutrients content in soil are important elements of soil chemistry because they define its fertility and, in consequence, they are key yield-affecting factors. Studies have shown that there is a positive correlation between the chemical parameters (N, P, K, Mg) and the carbon content in soil (Sartori et al. 2007). Like with SOC, planting and establishment of SRWC on arable soils may cause nutrient losses or soil nutrient decreases (Jug et al. 1999). Given the above, this study aimed to investigate whether willow and poplar plantations in a SRWC system contribute to soil organic carbon sequestration, soil pH, total soil N and macronutrients.

MATERIALS AND METHODS

Description of the experiment

The experiment was located at the Research Station in Łężany (Production and Experimental Farm Łężany Ltd. since 2018) and it is within the administrative borders of the village of Leginy (53°59′ N 21°09′ E), on land owned by the University of Warmia and Mazury (UWM) in Olsztyn, Poland. The Koppen Climate Classification subtype for this region is “Dfb” (Hemiboreal climate).

The experiment was set up in 2013, on acidic and slightly acidic soil of sandy and loamy formations (Table 1).

Triticale was sown as the preceding crop and herbicides were applied after harvest in the autumn of 2012 to eliminate perennial weeds. In the following spring, the standing biomass was chopped, ploughed to a depth of 30 cm, harrowed, and then willow and poplar cuttings were planted manually. Fertilizer was not applied after planting while some agrotechnological procedures (application of herbicides) were carried out three times to control weeds.

The plants of willow and poplar were harvested in 2013, 2014 and 2015. In 2016, a four-factorial strip-split-split-plot design was set up, where the splits were: two harvest cycles (annual and triennial), three plant genotypes willow Ekotur cultivar (*Salix viminalis* L.), willow Żubr cultivar (*Salix viminalis* L.) and poplar clone Max-5 (*Populus nigra* × *Populus maximowiczii* Henry), two types of fertilization (mineral and organic – agricultural biogas

Table 1

Soil parameters before establishment of the plantation in 2013

Parameter	Unit	Horizon (cm)			
		(0-26)	(26-46)	(46-75)	(75-150)
Soil texture		loamy sand	sandy loam	sandy clay loam, slightly gravelly	sandy loam, slightly gravelly
Clay ($\leq$0.002 mm)	(mg kg^{-1})	600	1100	1600	1400
Silt (0.002< d $\leq$0.05 mm)	(mg kg^{-1})	1600	230	1900	1700
Sand (0.05< d $\leq$2.0 mm)	(mg kg^{-1})	7800	6600	6500	6900
Specific density	(Mg m^{-3})	2.63	2.64	2.64	2.61
pH (KCl)	-	4.7	5.4	5.6	7.3
SOC	(g kg^{-1})	10.3	-	-	-
Total N	(mg kg^{-1})	11	-	-	-
P	(mg kg^{-1})	61	35	45	49
K	(mg kg^{-1})	145	62	47	32
Mg	(mg kg^{-1})	32	47	54	76
C:N ratio	-	9,4:1	-	-	-

plant digestate) and three nitrogen doses (0, 85, and 170 kg N ha^{-1}). Each treatment was replicated 3 times. The initial planting density was 20,000 plants ha^{-1}.

In the beginning of each growing season, liquid digestate (without dehydration) and mineral fertilizers (granulated) were applied in 2016 (a one- and three-year cycle), 2017 (one-year cycle) and 2018 (one-year cycle) at appropriate doses. For the one-year harvest cycle, fertilizers were applied annually and for the three-year harvest cycle fertilizers were applied once, in 2016.

Soil sampling procedure

Soil from the humic horizon (20 cm) was collected in the spring of 2016, 2017 and 2018. Composite soil samples (15 cores/plot) were collected with a 20 cm soil probe. A collective sample (ca. 2 kg) for each factor combination was obtained. Immediately after collection, samples were packed into plastic bags and transported to the laboratory.

To prepare the samples for chemical analysis, they were air-dried and passed through a 2 mm sieve.

The SOC content was determined with the spectrophotometric method on a Genesis 6 spectrophotometer. pH was determined as per PN ISO 10390:1997 (Polish Standard. Determination of pH.); potassium (K) – with the spectrophotometric method as per PN-R-04023:1996 (Egner-Riehm method) – Polish Standard. Determination of available potassium in mineral soils; phosphorus (P) as per PN-R-04022:1996/Az1:2002 (Egner-Riehm method) – Polish Standard. Determination of available phosphorus in mineral soils; magnesium (Mg) as per PN-R-04020:1994/Az1:2004 (Schachtschabel method) – Polish Standard. Determination of available magnesium in mineral soils and total nitrogen (Nt) with the Kjeldahl method as per PB 29 ed.4 27.11.2014.

Statistical analysis

A repeated-measures ANOVA in a four-factor 2 x 3 x 2 x 3 strip-split-split-plot model was applied. Two harvest cycles, three plant species, two types of fertilization and three nitrogen doses were permanent grouping factors and the three years of the experiment were regarded as the repeated measure factor. Multiple comparisons with Bonferroni correction with $p<0.05$ were applied to assess the mean significance difference. Bonferroni's least significant difference values (B-LSD) were shown in tables and graphs. All analyses were conducted with Statistica 13.3 software (Tibco Software Inc.).

Table 2 and Figures 1-12 show the mean for the most valuable of the results. For SOC, the mean values of the following are shown: harvest cycle (A), species (cultivar/clone) (B), fertilizer type (C), fertilizer dose (D) and the interactions between these factors. Furthermore, for the other soil parameters, the interactions between the experiment year (Y) and the harvest cycle, species (cultivar/clone), fertilizer type and dose are also shown.

RESULTS AND DISCUSSION

The SOC values were higher in the annual (10.9 g kg^{-1}) than triennial cycle (Table 2). Significantly higher soil SOC content was found under the Ekotur and Żubr willow cultivars (11.1 and 11.4 g kg^{-1}, respectively) compared to the sites under the poplar Max-5 clone (10.4 g kg^{-1}). This relationship was especially distinct in the annual harvest cycle. However, the fertilizer type did not significantly differentiate this parameter in a given harvest cycle (Figure 1). Significantly higher SOC levels in soil compared to the control plots (0 kg^{-1} ha^{-1} N) were found at sites where both willow cultivars and the poplar clone were grown in annual cycle and where fertilizers were applied (85 and 170 kg^{-1} year ha^{-1} N) (Table 2, Figure 2).

SOC and nutrients reach the soil together with the biomass that is left in the field after harvest, which comprises decaying leaves, weeds and shoots left behind in the field and stumps, fine and coarse roots. Moreover, soil can contain more SOC in nutrients due to field management, i.e. fertilization. The accumulation of organic carbon in the soil is a long-term process, which

Table 2

SOC content under cultivation of SRWC species in annual and triennial harvest cycle depending on fertilization objects and nitrogen dose (g kg^{-1})

Species (variety/clone) (B)	Type of fertilization (C)	Nitrogen dose (kg N ha^{-1}) (D)	Harvest cycle (A)		Mean
			annual	triennial	
Ekotur	organic	170	12.9	9.6	11.2
		85	12.5	9.2	10.8
		0	10.2	10.6	10.4
	mineral	170	13.0	12.2	12.6
		85	11.5	11.2	11.3
		0	10.2	10.6	10.4
	mean		11.7	10.6	11.1
Żubr	organic	170	13.1	11.3	12.2
		85	12.0	9.4	10.7
		0	10.7	10.7	10.7
	mineral	170	13.0	11.6	12.3
		85	12.7	10.5	11.6
		0	10.7	10.7	10.7
	mean		12.0	10.7	11.4
Max-5	organic	170	11.6	9.1	10.4
		85	11.0	9.8	10.4
		0	9.2	10.2	9.7
	mineral	170	10.5	12.2	11.4
		85	10.9	11.2	11.1
		0	9.2	10.2	9.7
	mean		10.4	10.5	10.4
Mean			10.9	10.1	10.5
A - (p=0.0014; B-LSD=0.22); **B** - (p=0.0009; B-LSD=0.58); **C** - (p=0.002; B-LSD=0.33); **A*B** - (p=0.0012; B-LSD=1.08); **A*C**- (p=0.0003; B-LSD=0.69); **B*C*D**- (p=0.0018; B-LSD=1.39); **A*B*C*D** - (p<0.0001; B-LSD=2.13)					

A-.... **A*B**-...– p-values and B-LSD values for each factor and interactions (p<0.05).

is why the experiment period analyzed in this study (3 years) is relatively short to observe and demonstrate this process. This was confirmed in a study conducted in Germany under similar climatic conditions, where no distinct changes in SOC content were observed in soil on willow and poplar SRC plantations (Tariq et al. 2018). In Germany, willow and poplar plantations increased SOC levels over 6 and 12 years (Kahle et al. 2007). No significant differences were found in that study between the SOC content in soil under willow and poplar plantation in the triennial harvest cycle, as in our experiment in the same cycle in the cultivation of the willow Żubr cultivar and the

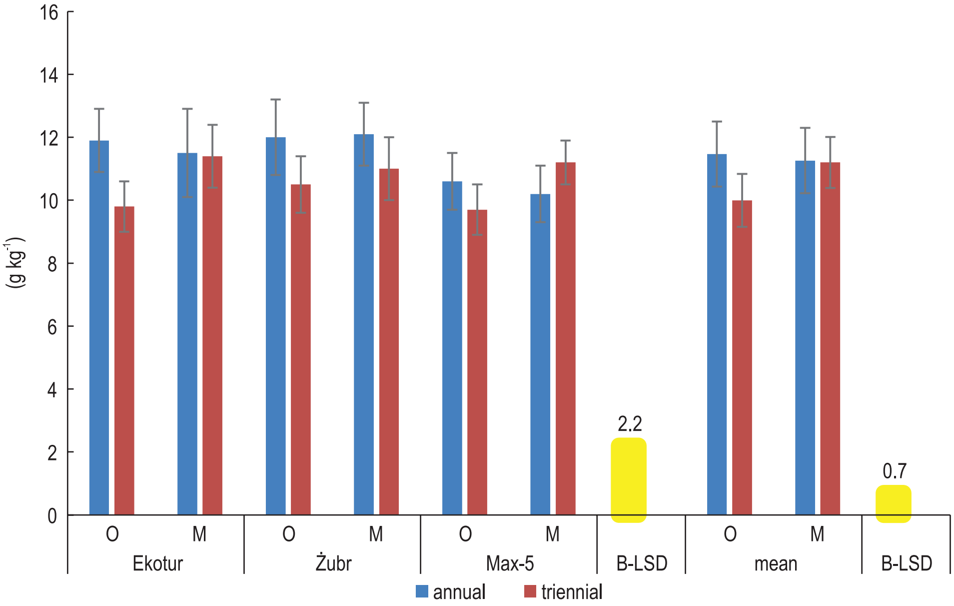

Fig. 1. SOC content under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects, and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

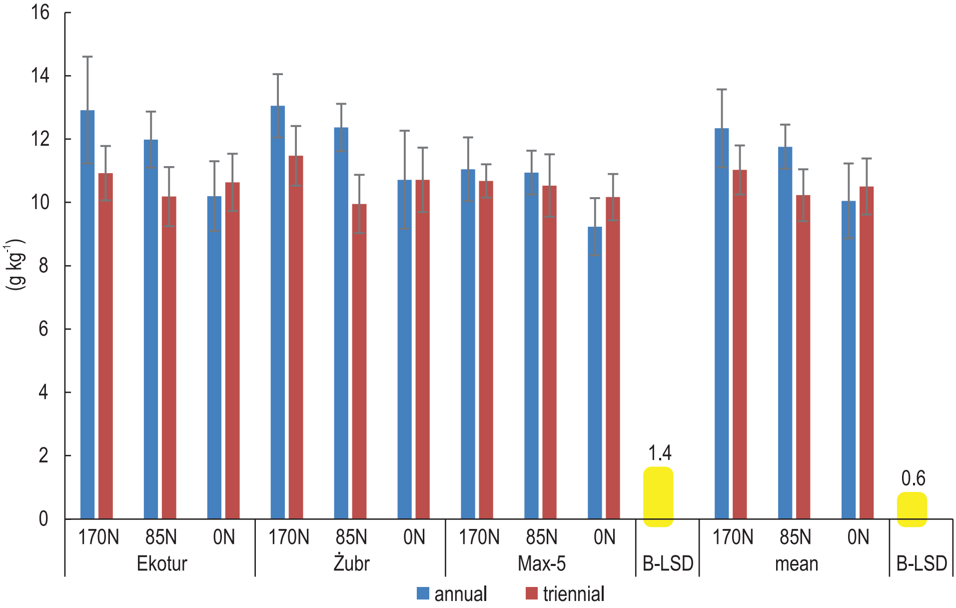

Fig. 2. SOC content under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation): 170N, 85N, 0N – nitrogen dose, B-LSD – Bonferroni test value

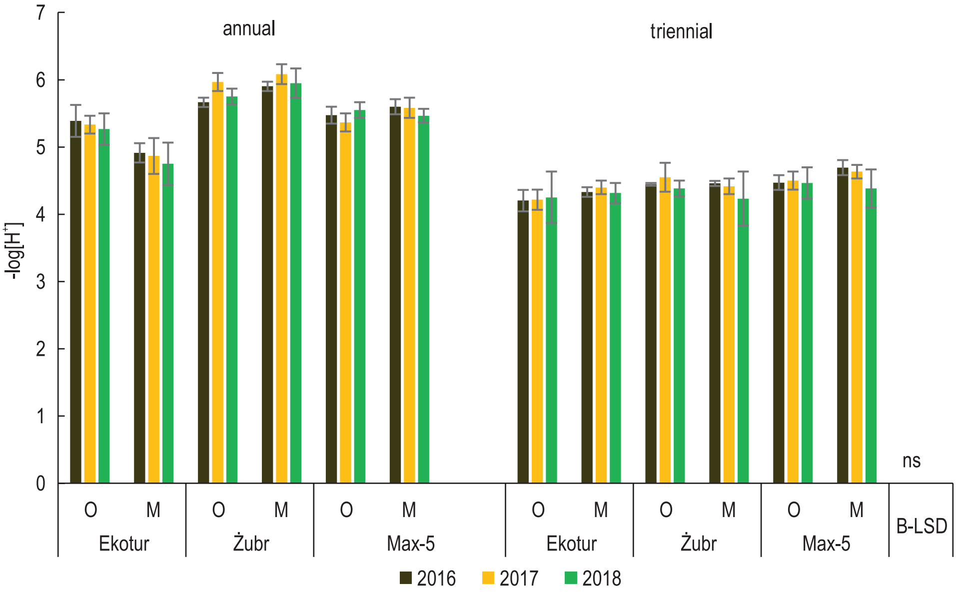

Fig. 3. pH in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects, and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

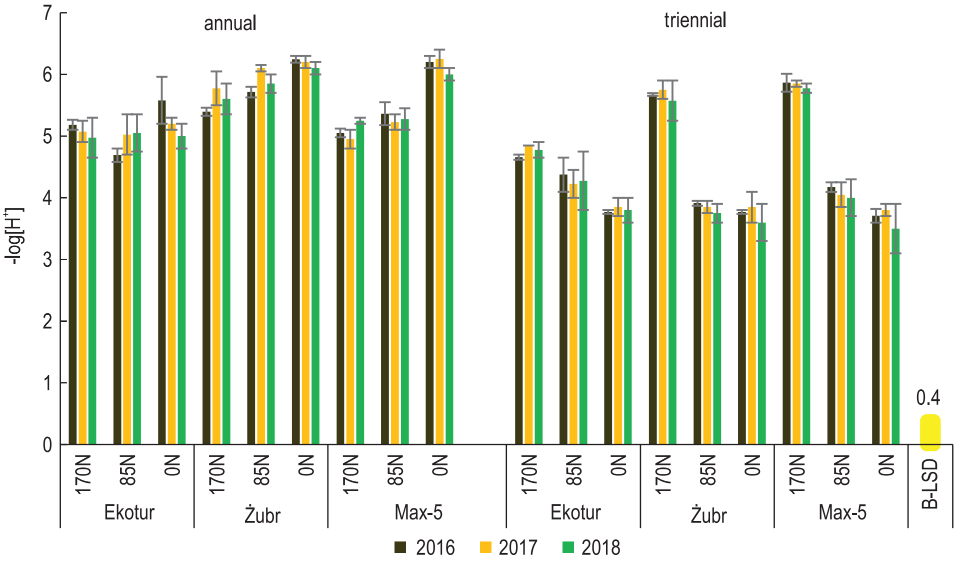

Fig. 4. pH in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation) 170N, 85N, 0N – nitrogen dose, B-LSD – Bonferroni test value

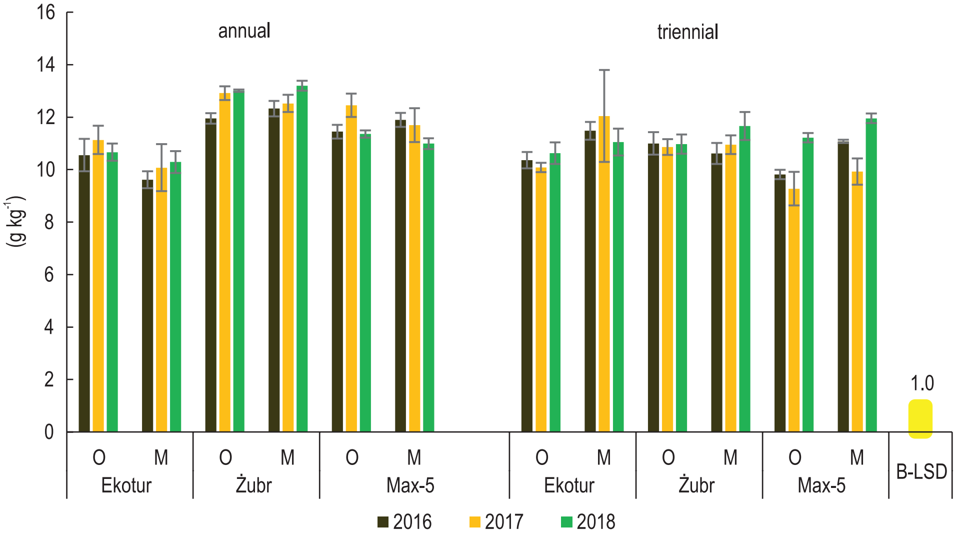

Fig. 5. Total nitrogen in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects, and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

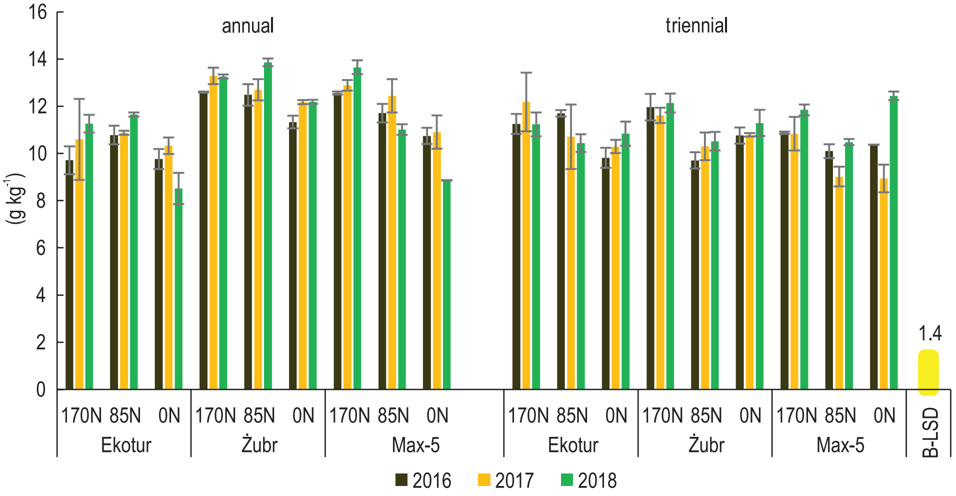

Fig. 6. Total nitrogen in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation): 170N, 85N, 0N – nitrogen dose, B-LSD – Bonferroni test value

poplar Max-5 clone. However, unlike in the current study, Kahle et al. (2007) did not verify any significant differences between the harvest cycles and found slightly (but not significantly) more carbon accumulated in the soil in the longer cycle (6 years) than in the shorter cycle (3 years). Likewise, a significantly higher SOC content in soil on a poplar plantation was

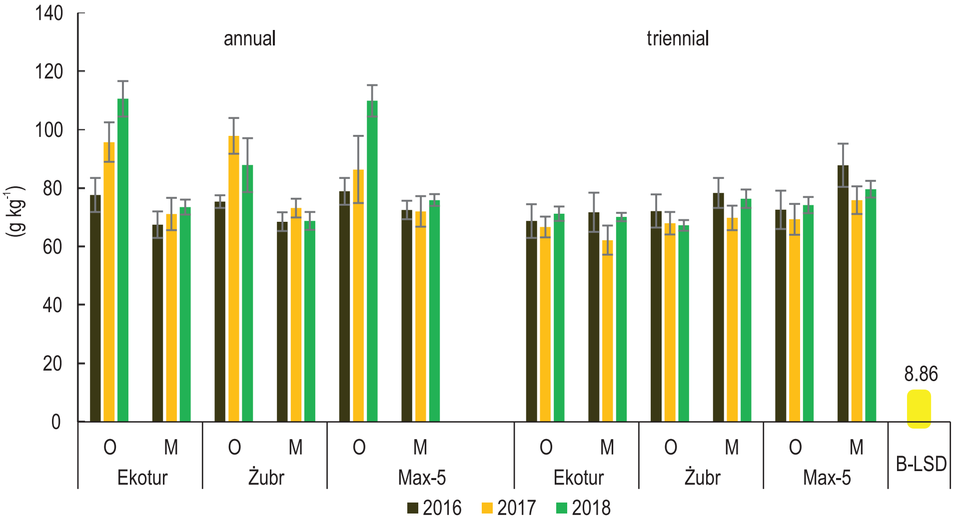

Fig. 7. Phosphorus in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

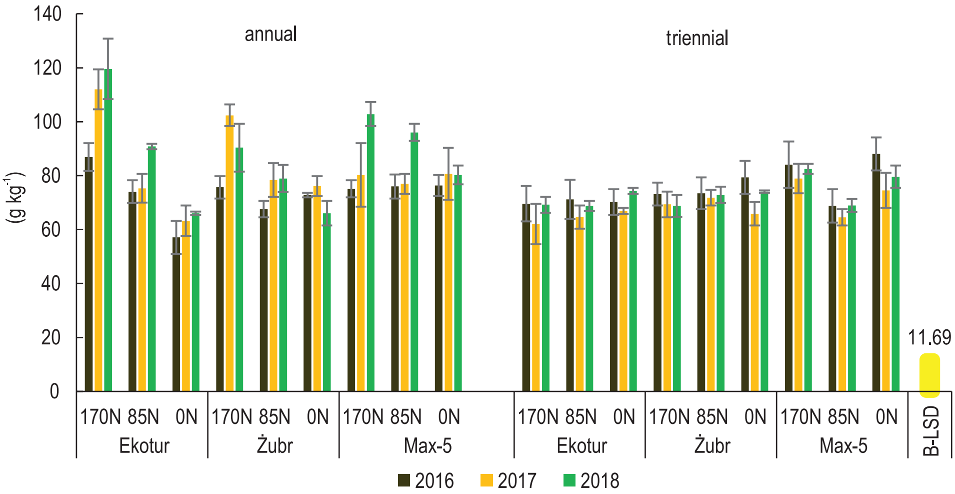

Fig. 8. Phosphorus in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation): 170N, 85N, 0N – nitrogen dose, B-LSD – Bonferroni test value

observed by Pellegrino et al. (2011) after 10 years of an experiment. Significantly higher SOC content was demonstrated in the current study in the annual cycle than in the triennial cycle. However, this may have been caused by the application of organic and mineral fertilizers at the beginning of each growing season in the annual cycle. Similarly, an SOC content increase

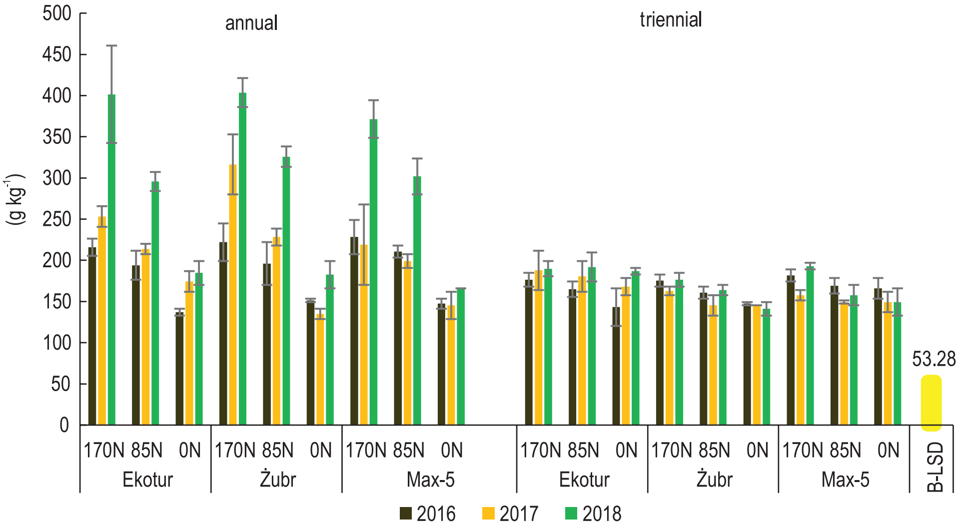

Fig. 9. Potassium in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

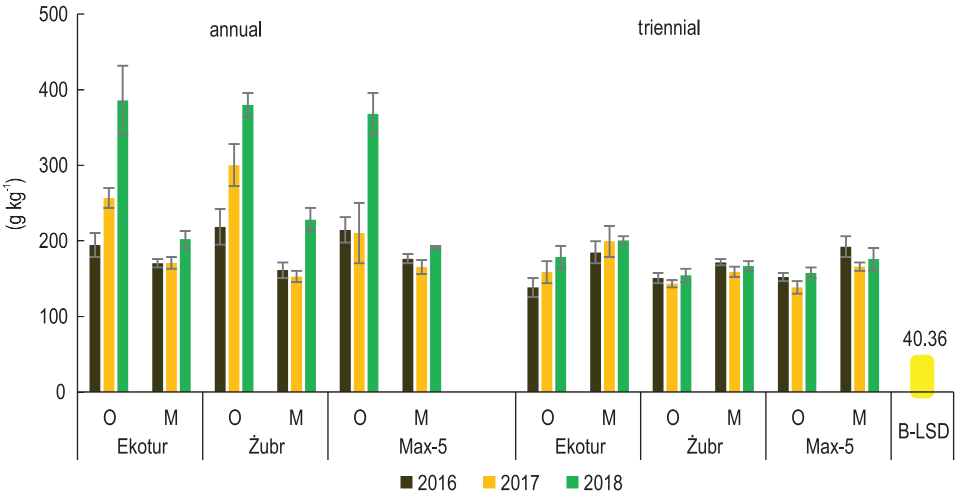

Fig. 10. Potassium in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation): 170N, 85N, 0N – nitrogen dose, B-LSD – Bonferroni test value

in the cultivation of fast-growing willow (*S. viminalis* L.) in the climate of Poland was observed when municipal sewage sludge was used (Styszko et al. 2017).

The fertilization type did not significantly differentiate pH in soil (Figure 3). The higher mean pH in the current experiment was measured at sites where

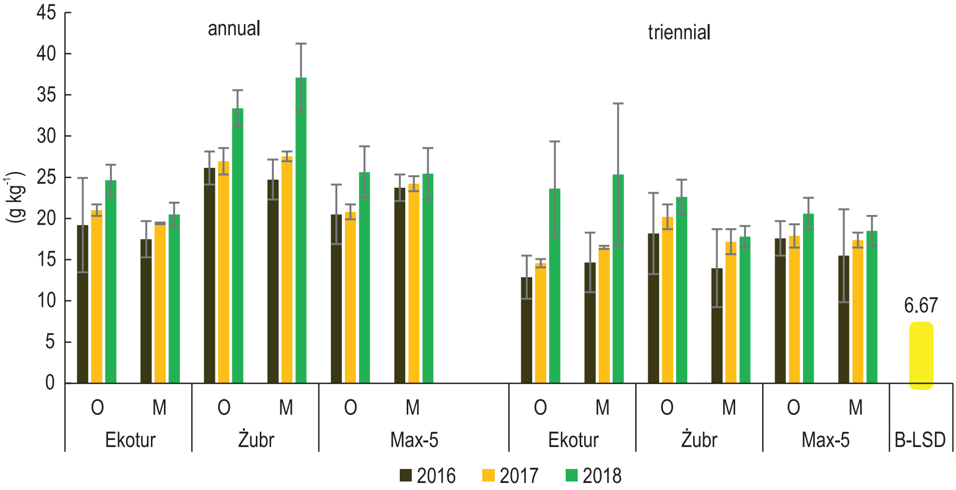

Fig. 11. Magnesium in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on fertilization objects and mean values for the experiment (bars represent standard deviation): O – organic fertilizer, M – mineral fertilizer, B-LSD – Bonferroni test value

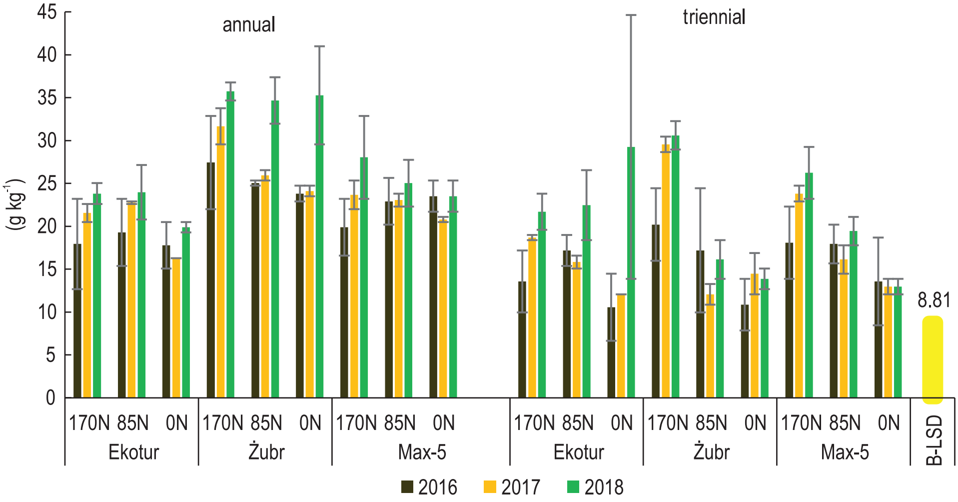

Fig. 12. Magnesium in soil under cultivation of SRWC species in annual and triennial harvest cycles depending on nitrogen doses, and mean values for the experiment (bars represent standard deviation): 170N, 85N, 0N –nitrogen dose, B-LSD – Bonferroni test value

the plants were grown in the annual cycle, regardless of the species. The lowest pH was recorded at sites with the willow Ekotur cultivar, both in the annual and triennial harvest cycle. For this variety, the soil pH was lower in the annual cycle sites (Figure 4). Differences in this parameter were especially found in the cultivation of the willow Żubr cultivar and the Max-5 poplar clone harvested in annual cycle, where the pH was higher in the unfertilized than fertilized treatments. The opposite relationship was observed with the highest N dose in the triennial cycle, where the soil pH was higher at sites with the highest N dose. The soil pH did not change significantly during the successive experiment years, regardless of the harvest cycle, species (cultivar/clone), fertilizer type or the nitrogen dose.

Overall in the experiment, pH lay within the range of 4.7-6.2 at the annual cycle sites and 3.6-5.9 at the triennial cycle sites. This shows that the plants were grown mainly at sites with strongly acidic and acidic soil.

Soil pH is important because it influences the availability of essential nutrients. SRWC plantations are set up mainly on marginal soils, where pH is often low. Soils with pH 5.0-7.5 will produce satisfactory growth, although willow and poplar are tolerant to pH outside this range (Caslin et al. 2010). Lower pH was measured at sites where the plants were grown in the triennial cycle. Similarly, lower pH was observed in a similar study conducted on acidic soil in Canada (Arevalo et al. 2009). Furthermore, a slight (-0.2) pH decrease after a decade was observed over a 10-year period in Poland (Lutter et al. 2016).

The highest soil N_t content was found at the sites where the Żubr cultivar was grown in the annual harvest cycle, regardless of the fertilization type (Figure 5). Although fertilizers were applied every year in the annual cycle (once in the triennial cycle), no significant differences were demonstrated in the N_t content in the annual and triennial harvest cycles for the willow Ekotur cultivar and the poplar Max-5 clone between the sites with organic fertilization. Considering the nitrogen dose, significantly higher N_t levels were observed in the annual cycle at sites where fertilizers were applied compared to the control sites (Figure 6). On the other hand, considering the successive experiment years, a tendency was demonstrated for the N_t level in the soil to increase with the plantation age, both in the annual and triennial harvest cycle, at most sites where fertilizers were applied. Moreover – unlike in the annual cycle for the willow Ekotur cultivar and the poplar Max-5 clone – the N_t content in soil increased at triennial cycle sites where fertilizer was not applied. Overall, the N_t content was between 9 and 14 mg kg^{-1} for the annual cycle sites and between 9 and 12 mg kg^{-1} for the triennial cycle sites.

The N_t content increased in soil under the willow and poplar SRWC. Similar relationships were observed in research conducted in Italy, where poplar was grown in annual, biennial and triennial harvest cycles (Pellegrino et al. 2011). However, fertilization was applied in the studies cited above only at the stage of plantation establishment, and a greater tendency for N_t to accumulate was demonstrated at sites where plants were harvested in the triennial cycle compared to the annual cycle. This corresponds to the current findings only to a certain extent, considering sites with no fertilization in the annual and triennial cycle – greater increases in the N_t content in the soil after a triennial cycle were recorded in a longer cycle. Unlike in the current study, Styszko et al.. (2017) did not demonstrate an increase in the N_t content in soil in willow cultivation at sites where mineral fertilization was applied.

The experimental plots were established on soils with similar and narrow C:N ratios (Table 3). Even though organic matter is supplied to the soil with post-harvest residues, organic fertilizers, etc. and the C:N ratio becomes wider and reaches approx. 20-40, this organic matter is rapidly mineralized to CO_2, while the majority of the mineralized N is incorporated into the microbial biomass (Quaye, Volk 2013). According to Blume et al. (2016), due to the decomposition of organic matter supplied to the soil, the C:N value in the soil decreases to 10. This value is comparable with that obtained in the authors' previous studies. The C:N ratio of 10:1 demonstrates that the soil nitrogen

Table 3

C:N ratio

Species (variety/clone) (B)	Type of fertilization (C)	Nitrogen dose (kg N ha^{-1}) (D)	Harvest cycle (A)		Mean
			annual	triennial	
Ekotur	organic	170	11.2	9.4	10.3
		85	11.1	8.7	9.9
		0	10.7	10.3	10.5
	mineral	170	11.5	9.4	10.4
		85	10.5	9.9	10.1
		0	10.7	10.3	10.5
	mean		10.9	9.7	10.3
Żubr	organic	170	9.9	9.5	9.7
		85	9.4	9.4	9.4
		0	9.0	9.8	9.4
	mineral	170	10.1	9.7	9.9
		85	9.6	10.1	9.8
		0	9.0	9.8	9.4
	mean		9.5	9.7	9.6
Max-5	organic	170	8.4	9.3	8.8
		85	9.7	9.8	9.8
		0	9.0	9.6	9.3
	mineral	170	8.5	9.7	9.1
		85	9.0	11.5	10.2
		0	9.0	9.6	9.3
	mean		8.9	10.0	9.4
Mean			9.3	9.3	9.3

undergoes rapid mineralization and release to be available for plant uptake (Brust 2019).

The P content in soil was shown to increase significantly after three years of the experiment both at sites where the willow Ekotur cultivar with the poplar Max-5 clone was grown in the annual harvest cycle and where organic fertilizers were used (Figure 7). However, no significant differences were shown in this cycle regarding the sites where mineral fertilization was applied, and in the triennial harvest cycle, regardless of the experiment factors. Furthermore, considering the nitrogen dose, significant differences in the P content in soil were demonstrated only in the annual cycle at the sites where nitrogen was applied at 170 and 85 kg ha^{-1} N (Figure 8). After three years of the experiment, the significantly highest content of phosphorus in soil was found at sites where the willow Ekotur cultivar (120 mg kg^{-1}) and the poplar Max-5 clone (103 mg kg^{-1}) were grown in the annual harvest cycle in plots where the highest nitrogen dose was applied. Overall, the P content was between 57 and 120 mg kg^{-1} for the annual cycle sites and between 62 and 88 mg kg^{-1} for the triennial cycle sites.

A significant increase in the P content in soil was demonstrated in other studies in which soil parameters were analyzed after three years of the experiment, where two willow clones were grown in the triennial harvest cycle on plots where organic fertilization as biosolid compost was used (Quaye, Volk 2013). This effect of fertilization was achieved only in the annual harvest cycle in the current study. Furthermore, Pellegrino et al. (2011) compared the P content in soil under poplar cultivation in the annual, biennial and triennial harvest cycles, and found the P content to be the highest at sites where the plants were grown in the triennial cycle. Considering the sites where willow was grown with no fertilization, similar relationships were observed in the current study because the soil at sites in the triennial harvest cycle contained more phosphorus than sites in the annual cycle.

Similar to P, the K content in soil was shown to increase significantly after three years of the experiment both at sites with the willow Ekotur and Żubr cultivars and with the poplar Max-5 clone grown in the annual harvest cycle and where organic fertilizers were used (Figure 9). However, unlike with phosphorus, a significant increase in the potassium content in soil was observed in the annual cycle at sites where the willow Żubr cultivar was grown and where mineral fertilizers were applied, and in the triennial cycle at sites where the Ekotur willow cultivar was grown and where organic fertilizers were used. Furthermore, considering the nitrogen dose, significant differences in the K content in soil were demonstrated only in the annual cycle at the sites were nitrogen was applied at 170 and 85 kg ha^{-1} N (Figure 10). After three years of the experiment, the significantly highest content of potassium in soil was determined at sites where plants were grown in the annual harvest cycle, where the highest nitrogen dose was applied (402, 404 and 371 mg kg^{-1}, for the willow Ekotur and Żubr cultivars, and the poplar Max-5 clone, respectively). Overall, the K content was between 135 and

404 mg kg^{-1} for the annual cycle sites and between 141 and 193 mg kg^{-1} for the triennial cycle sites.

Quaye and Volk (2013) also observed a significant increase in the potassium content in soil on plots where willow was grown and where organic fertilization was applied. Furthermore, it was determined in another study in which a poplar plantation was analyzed for 10 years that the K_2O content in soil remained on an unchanged level, as in the current study at sites in the triennial harvest cycle. Especially the absence of changes at sites where no fertilization was used shows a sufficient level of nutrient cycling during the initial years of the experiment. However, nutrient depletion may appear in a longer perspective (Kahle et al. 2007).

A significant increase in the magnesium content in the soil in the annual harvest cycle was observed after three years of the experiment at sites under the willow Żubr cultivar, and in the triennial cycle – at sites under the willow Ekotur cultivar, regard-less of the fertilization type (Figure 11). It is noteworthy that the content of Mg was found to increase at all the sites after three years of the experiment, but the differences were significant in only two cases. Furthermore, considering the nitrogen dose, significant differences in this parameter in soil were demonstrated only at sites where the Żubr cultivar was grown in the annual cycle (at the sites where nitrogen was applied at 170 and 85 kg ha^{-1} N) and in the triennial cycle (at the sites where nitrogen was applied at 170 kg ha^{-1} N) and at sites where the Ekotur cultivar was grown (the sites with no fertilization in the triennial cycle) – Figure 12. After three years of the experiment, the significantly highest content of magnesium in soil was determined at sites where plants were grown in the annual harvest rotation where the highest nitrogen dose was applied (24, 36 and 28 mg kg^{-1}, for the willow Ekotur and Żubr cultivars, and the poplar Max-5 clone, respectively). Overall, the Mg content was between 16 and 36 mg kg^{-1} for the annual cycle sites and between 13 and 31 mg kg^{-1} for the triennial cycle sites.

In the current study, organic fertilization significantly increased the magnesium content in soil only in the cultivation of the willow Ekotur cultivar in the triennial harvest cycle. A similar significant increase in the Mg content in the triennial harvest cycle in willow cultivation with organic fertilization was observed by Quaye, Volk (2013). Notably, the magnesium content in the soil in the annual harvest cycle did not increase significantly at sites where organic fertilization was used, even though it was applied every year.

CONCLUSIONS

The results of this experiment show that the possibility of identifying significant differences in the SOC content in the soil in plots where fast-growing willow and poplar species are grown is limited in the climatic conditions of Poland. Although there is evidence in the literature that growing SRWC for energy generation increases the SOC content in the humic horizon, this parameter was not shown to increase in this study. The application of organic fertilizers in the annual cycle and, in consequence, supplying additional organic matter to the soil every year, resulted in significantly higher SOC content in the soil in this cycle compared to the triennial cycle, in which fertilization was applied only once (at the beginning of the growing season in the cycle). Considering the other parameters, higher pH, N_t and macronutrients content were found at most of the other sites than at those with the triennial harvest cycles. Furthermore, considering the effect of the fertilization on other soil parameters, a significant in-crease in the N_t, P, K content was observed at sites where all the cultivars/clones were grown in the annual harvest cycle. In contrast, these parameters were similar in the triennial cycle at most sites throughout the experiment.

As pointed out above, further research is needed due to the relatively short period covered by this study. Despite this, the results provide valuable information on the effect of fertilization and its justifiability for improving soil parameters in the annual and triennial harvest cycle. A comparison of the sites with and without fertilization shows that fertilization did not affect the basic soil parameters, such as soil organic carbon, pH, total nitrogen and macronutrients content, in a longer, triennial harvest cycle. However, these parameters depend largely on the soil abundance before an SRWC plantation was set up. Therefore, the research needs to be continued during longer plantation use, which would help to verify or falsify these relationships.

ACKNOWLEDGEMENTS

We would like to thank the staff of the Department of Genetics, Plant Breeding and Bioresource Engineering for their technical support during the experiment.

REFERENCES

Adegbidi H.G., Volk T.A., White E.H., Abrahamson L.P., Briggs R.D., Bickelhaupt D.H. 2001. *Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State.* Biomass Bioenerg, 20: 399-411. DOI: 10.1016/S0961-9534(01)00009-5

Arevalo C.B.M., Bhatti J.S., Chang S.X., Sidders D. 2009. *Ecosystem carbon stocks and distribution under different land-uses in north central Alberta, Canada.* Forest Ecol Manag, 257: 1776-1785. DOI: 10.1016/j.foreco.2009.01.034

Batjes N.H. 2014. *Total carbon and nitrogen in the soils of the world.* Eur J Soil Sci, 65: 10-21. DOI: 10.1111/ejss.12114_2

Bárcena T.G., Kiær L.P., Vesterdal L., Stefánsdóttir H.M., Gundersen P., Sigurdsson B.D. 2014. *Soil carbon stock change following afforestation in Northern Europe: a meta-analysis.* Glob Change Biol, 20: 2393-2405. DOI: 10.1111/gcb.12576

Blanco-Canqui H. 2010. *Energy crops and their implications on soil and environment.* Agron J, 102: 403-419. DOI: 10.2134/agronj2009.0333

Blume H.-P, Brümmer G.W., Fleige H., Horn R., Kandeler E., Kögel-Knabner I., Kretzschmar R., Stahr K., Wilke B.-M. 2016. *Soil Science.* Scheffer/Schachtschabel, Springer Berlin – Heidelberg, ISBN 978-3-642-30941-0, ISBN 978-3-642-30942-7 (eBook), DOI 10.1007/978-3-642-30942-7

Brust G.E. 2019. *Effective farm management strategies for organic produce and plant food production*: *Safety and Practice for Organic Food.* 1st Edition, Biswas D. and Micallef S. (eds.). ISBN 9780128120606, ISBN 9780128120613 (eBook), https://doi.org/10.1016/B978-0-12-812060-6.00009-X

Caslin B., Finnan J., Johnston C., Mc Cracken A., Walsh L. (eds.) 2010. *Short Rotation Coppice; Willow Best Practice Guidelines.* https://www.afbini.gov.uk/sites/afbini.gov.uk/files/publications//Short%20rotation%20coppice%20willow%20best%20practice%20guidlines.pdf acessed 18 August 2021

Coleman M.D., Isebrands J.G., Tolsted D.N., Tolbert V.R. 2004. *Comparing soil carbon of short rotation poplar plantations with agricultural crops and woodlots in North Central United States.* Environ Manage, 33: 299-308. DOI: 10.1007/s00267-003-9139-9

Dimitriou I., Mola-Yudego B., Aronsson P., Eriksson J. 2012. *Changes in organic carbon and trace elements in the soil of willow short-rotation coppice plantations.* BioEnergy Res., 5: 563-572. DOI: 10.1007/s12155-012-9215-1

Dowell R.C., Gibbins D., Rhoads J.L., Pallardy S.G. 2009. *Biomass production physiology and soil carbon dynamics in short-rotation-grown Populus deltoides and P. deltoides × P. nigari hybrids.* Forest Ecol Manag, 257: 134-142. DOI: 10.1016/j.foreco.2008.08.023

Grigal D.F., Berguson W.E. 1998. *Soil carbon changes associated with short-rotation systems.* Biomass Bioenerg, 14: 371-377. DOI: 10.1016/S0961-9534(97)10073-3

Hansen E.A. 1993. *Soil carbon sequestration beneath hybrid poplar plantations in the North Central United States.* Biomass Bioenerg, 5: 431-436. DOI: 10.1016/0961-9534(93)90038-6

Jug A., Makeschin F., Rehfuess K.E., Hofmann-Schielle C. 1999. *Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany*. III. *Soil ecological effects.* Forest Ecol Manag, 121: 85-99. DOI: 10.1016/S0378-1127(98)00558-1

Kahle P., Hildebrand E., Baum C., Boelcke B. 2007. *Long-term effects of short rotation forestry with willows and poplar on soil properties.* Arch. Agron. Soil Sci., 53: 673-682. DOI: 10.1080//03650340701648484

Laganière J., Angers D.A., Paré, D. 2010. *Carbon accumulation in agricultural soils after afforestation: a meta-analysis.* Glob Change Biol, 16: 439-453. DOI: 10.1111/j.1365-2486.2009.01930.x

Lal R. 2016. *Report 4B – Soil carbon sequestration.* In: *Thematic Reports.* FAO, 2016, p 36.

Lal R., Negassa W., Lorenz K. 2015. *Carbon sequestration in soil.* Curr Opin Environ Sust, 15: 79-86. DOI: 10.1016/j.cosust.2015.09.002

Lutter R., Tullus A., Kanal A., Tullus T., Tullus H. 2016. *The impact of short-rotation hybrid aspen (Populus tremula L.×P. trem-uloides* Michx.*) plantations on nutritional status of former arable soils.* Forest Ecol Manag, 362: 184-193. DOI: 10.1016/j.foreco.2015.12.009

Mola-Yudego B., Díaz-Yáñez O., Dimitriou I. 2015. *How much yield should we expect from fast-growing plantations for energy? Divergences between experiments and commercial willow plantations.* BioEnergy Res., 8: 1769-1777. DOI: 10.1007/s12155-015-9630-1

Pacaldo R.S., Volk T.A., Briggs R.D. 2013. *No significant differences in soil organic carbon contents along a chronosequence of shrub willow biomass crop fields.* Biomass Bioenerg, 58: 136-142. DOI: 10.1016/j.biombioe.2013.10.018

Paustian K. 2014. *Soil: Carbon Sequestration in Agricultural Systems.* In: *Encyclopedia of Agriculture and Food Systems.* Van Alfen N.K., Ed., Academic Press, Oxford. DOI: 10.1016//B978-0-444-52512-3.00093-0

Pellegrino E., Di Bene C., Tozzini C., Bonari E. 2011. *Impact on soil quality of a 10-year-old short-rotation coppice poplar stand compared with intensive agricultural and uncultivated systems in a Mediterranean area*. Agr Ecosyst Environ, 140: 245-254. DOI: 10.1016/j.agee.2010.12.011

PB 29 ed.4 27.11.2014. *Determination of total nitrogen*. Research Procedure of the Chemical and Agricultural Research Laboratory in Olsztyn.

Polish Standard. 1997. *Determination of pH*. PN-ISO 10390:1997. Polish Committee for Standardization, Warsaw, Poland.

Polish Standard. 1996. *Determination of available potassium in mineral soils*. PN-R-04022:1996/Az1:2002. Polish Committee for Standardization, Warsaw, Poland.

Polish Standard. *Determination of Available Phosphorus in Mineral Soils*. PN-R-04023:1996. Polish Committee for Standardization, Warsaw, Poland, 1996.

Polish Standard. 1994. *Determination of available magnesium in mineral soils*. PN-R-04020:1994/Az1:2004. Polish Committee for Standardization, Warsaw, Poland.

Quaye A.K., Volk T.A. 2013. *Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems*. Biomass Bioenergy, 57: 113-125. DOI: 10.1016/j.biombioe.2013.08.002

Sartori, F., Lal R., Ebinger M.H., Eaton J.A. 2007. *Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA*. Agr Ecosyst Environ, 122: 325-339. DOI: 10.1016/j.agee.2007.01.026

Sirén G., Sennerby-Forsse, L. Ledin, S. 1987. *Energy plantations – short rotation forestry in Sweden*. In: *Biomass regenerable energy*. Hall, D.O., Overend, R.P., Eds. Wiley, Chichester, 35-45.

Stolarski M.J., Niksa D., Krzyżaniak M., Tworkowski J., Szczukowski S. 2019. *Willow productivity from small- and large-scale experimental plantations in Poland from 2000 to 2017*. Renew Sust Energ Rev, 101: 461-475. DOI: 10.1016/j.rser.2018.11.034

Stolarski M.J., Szczukowski S., Tworkowski J., Klasa A. 2011. *Willow biomass production under conditions of low-input agriculture on marginal soils*. Forest Ecol Manag, 262: 1558-1566.

Styszko L., Fijalkowska D., Dabrowski J. 2017. *The effect of fertilization with compost from municipal sewage sludge on the quality of light soil under cultivation of coppice willow during four-year cycle*. Rocz Ochr Środ, 19: 618-632.

Tariq A., Gunina A., Lamersdorf N. 2018. *Initial changes in soil properties and carbon sequestration potential under monocultures and short-rotation alley coppices with poplar and willow after three years of plantation*. Sci Total Environ, 634: 963-973. DOI: 10.1016/j.scitotenv.2018.03.391

Walter K., Don A., Flessa, H. 2015. *No general soil carbon sequestration under Central European short rotation coppices*. GCB Bioenergy, 7: 727-740. DOI: 10.1111/gcbb.12177