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Original Research

The Effect of Chemical Soil Properties on Weed Infestation Structure in Willow (*Salix* L.) Short-Rotation Coppice

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Abstract

Differences in soil and habitat conditions, depending on the type of soil on which shrubby species of willow *Salix* L. are being grown for energy purposes, are reflected in weed infestation species diversity and the distinctiveness of these crops, and require an individual program of control and reduction of the abundance of competitive herbaceous vegetation. Our study aimed at determining soil parameters that have the greatest effect on weed infestation structure in a plantation of basket willow (*Salix* L.) coppice. The following chemical soil properties were taken into account as environmental variables: soil pH, soil moisture content, and humus, total nitrogen, potassium, and phosphorus content. Field research was carried out at five plantations of fast-growing basket willow (*Salix viminalis* L.) hybrids of the genotypes jorr, sprint, and turbo situated on disposal sites of sandy silts and sewage sludge-fertilized silts as well as fallow post-farmland and grassland. Obtained research results indicate soil reaction and soil moisture as factors that have the biggest effect on diversity of competitive herbaceous vegetation accompanying energy willow coppices.

Keywords: willow short-rotation coppice, weed communities, CCA ordination, soil properties

Introduction

Energy crop coppices, except when they provide biomass being utilized as a source of renewable energy, are used in biological reclamation of industrial lands, to increase local biological diversity in areas under agricultural use, or to form habitats for different animal groups [1-6]. They are also used to form protection zones against particulate and gaseous pollutants and wind protection belts, as well as to reinforce the banks of water bodies and courses [7]. In Polish conditions, native species of the genus *Salix* and *Populus* have the largest potential but only selected genotypes (clones) distinguishable by their productivity, depending on habitat conditions, soil character, frequency of cutting, and other agrotechnical measures used for energy crop coppices. The use of adaptive capabilities, high productivity, and phytoremediation potential of fast-growing willow (*Salix* L.) varieties makes it possible to set up a plantation on degraded and polluted soils where the outstanding ability of willow shrubs to remove heavy metals from soil is being displayed [8-13]. Energy crop plantations also are being set up on permeable soils or soil-less soils such as dredged material, which are enriched with processed municipal sewage sludge. This is supported by economic considerations, since the application of fertilization like this in energy crop plantations also means utilization of wastes such as sewage sludge. A condition for application of fertilization like this is a well developed root system of energy crops

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under cultivation that will catch nitrogen and phosphorus compounds and make their penetration and ground water contamination impossible [14-16].

The outlook for development of energy crops in Poland is favored by the unused potential of Polish agriculture, programs financed by the European Union, and large area of lands under agricultural use. At present, willow coppice plantations prevail, but it is being cultivated as nursery material and not to obtain biomass. They occupy an area of approximately 6,000 ha and are mainly situated in eastern and northern Poland [13, 17]. Due to the lack of local infrastructure responsible for receiving and burning biomass in the nearby SRC plantations, a few local producenrs are being forced to deliver produced biomass to bigger, distant conventional power stations. This causes an increase of production costs and decrease in profitability. However, in West European countries local governments create conditions to increase the area needed for energetic crops, provide receipt of produced biomass, and promote the development of small incineration plants. The increase of profitability of energetic crops in these countries is followed by the use of wastewater and sewage sludge in biomass production [18, 19].

The size of energy crop plantations and their multi-year cultivation cycle requires taking the costs of weed infestation control into account in economic calculations. In the first two years of managing a plantation, weeds generate a competition for willow being planted and therefore their chemical and mechanical control is used conventionally. In successive years the intense growth of willow seedlings results in the shading of soil, reduction of the number of common annual and photophilous arable weeds, and their replacement by perennial and sciaphilous species [5, 20]. Differences in soil and habitat conditions, depending on the type of soil on which shrubby species of willow are being grown for energy purposes, are reflected in the weed infestation species diversity and distinctness of these crops, and require an individual program of control and reduction of the abundance of competitive herbaceous vegetation [21-23]. It is necessary to identify both aggressive and dominant weed species and factors affecting the structure of weed infestation in energy crop plantations within the perspective of their future development.

Our study aimed at determining the soil parameters that have the largest effect on weed infestation structure in a plantation of basket willow (*Salix* L.) coppice. The following chemical soil properties were taken into account as environmental variables: soil pH, soil moisture content, and humus, total nitrogen, potassium and phosphorus content.

Materials

Field research was carried out in 2009-10 at five plantations of fast-growing basket willow (*Salix viminalis* L.) hybrids of the genotypes jorr, sprint, and turbo. For examination, 5-6-year-old experimental SRC plantations, 2.8-3.5 ha in area, were selected within the vicinity of the Odra River fairway within the area of Szczecin on disposal sites of sandy silts and sewage sludge-fertilized silts (at a dose of 20 t DM·ha^{-1}), as well as fallow post-farmland and grassland located in the flood-plain of the Odra River Braid (Roztoka Odrzańska). The crop stand amounted to approximately 25,000 willow seedlings per hectare, whereas the height of willow shoots during the study year was approximately 5-6 m. Immediately after the planting of willow seedlings (*Salix* sp.), a standard single spraying was applied in all examined plantations with herbicide preparation Azotop 50WP at a dose of 3 kg·ha^{-1} to remove competitive herbaceous vegetation. In the first year of willow coppice growing, additional mechanical weed control was performed.

Methods Soil Analysis

In each of 5 plantations, six test plots (50 m^2 each) were delimited in 2009. Aggregate soil samples were collected in the following year from each test plot, and soil analyses were made, allowing for determination of soil pH in KCl by potentiometric method, organic carbon using the Tiurin method, total nitrogen according to the modified Kjeldahl method, and total phosphorus by colorimetric method, whereas for potassium contents we used flame photometry. The scale of soil moisture content is given according to Bednarek et al. [24]. The herbaceous vegetation accompanying willow coppice in each test plot is described by means of phytosociological relevés made according to the Braun-Blanquet method. For the synthetic evaluation of distinguished weed species, degrees of phytosociological stability (S) and coverage indices (D) were used [25].

Statistical Calculations

Based on the phytosociological documentation of examined test plots, a variation pattern for the analyzed data was determined (occurrence of weeds in willow SRC), which is fully explained by the environmental variables considered (soil conditions).

For this purpose, the technique of direct ordination canonical correspondence analysis (CCA) was applied, while calculations were made using multivariate statistical package (MVSP) computer software, after the previous transformation of phytosociological relevés into an ordinal scale according to van der Maarel [26-28].

Latin nomenclature of plant species was given after Mirek et al. [29], while that of vegetation syntaxa after Matuszkiewicz [30].

Results

The analysis of syntaxonomic phytosociological relevés made on 30 test plots chosen in 5 SCR plantations allowed distinction of 8 plant associations infesting willow coppice in 2009 and coming from 5 vegetation classes: *Stellarietea mediae* R.Tx., Ohm. Et Prsg, 1950; *Epilobietea angustifolii* R.Tx. et Prsg 1950; *Artemisietea vulgaris* Lohm., Prsg. et R.Tx. in R.Tx. 1950; *Agropyretea intermedio-repentis* (Oberd. et al. 1967) Müller et Görs 1969; *Molinio-*

Table 1. The soil parameters of analyzed willow short-rotation coppices.

Soil parameters	Sandy silts	Sewage sludge fertilized silts	Fallow post-farmland	Over-dried degraded grassland	Wet degraded grassland
pH (KCl)	7.3	8.0	6.6	5.7	5.6
g $C_{org.}$·kg^{-1}	0.43	112	28	62	71
g N_{total}·kg^{-1} d.m.	0.19	38.0	5.4	17.8	16.1
g P·kg^{-1} d.m.	0.42	16.3	6.94	5.11	4.82
g K·kg^{-1} d.m.	0.17	0.73	1.96	1.31	0.86
Soil moisture	1	2	3	3	4

Table 2. Descriptive statistics for environmental variables.

Variable	Weighted mean	Weighted SD	Inflation factor
pH (KCl)	6.35	1.25	8.09
g $C_{org.}$·kg^{-1}	100.02	110.75	49.19
g N_{total}·kg^{-1} d.m.	20.96	23.45	16.91
g P·kg^{-1} d.m.	9.13	10.12	43.95
g K·kg^{-1} d.m.	0.947	0.502	3.083
Soil moisture	2.68	0.99	5.98

Arrhenatheretea R.Tx. 1937 [30, 23]; and their monitoring in the next study year.

Statistical Description of CCA Results

The application of canonical correspondence analysis (CCA) as a technique of direct ordination allowed arrangement of the samples (phytosociological relevés) documenting weed infestation of examined willow coppices by select environmental variables (pH, $C_{org.}$, N_{total}, P, K, and soil moisture) presented in Table 1. Weighted averages, standard deviations, and inflation factors for the analyzed environmental variables based on the results of chemical analyses of soils from all examined SRC plantations are presented in Table 2. The value of inflation factor for each analyzed variable is > 1.0; thus, it is possible to reject the assumptions about strong correlation of a given variable with other environmental variables.

Large eigenvalues of two first ordination axes D (> 0.7) demonstrate the unimodal structure of data, achieving the Gaussian curve spectrum (Table 3). The first axis explains over 21%, while the second one 16%, of direct variation in the occurrence of species in the analyzed samples (phytosociological relevés), induced by environmental variables. Large values of coefficients of the correlation between sample indices and environmental variables are evidence of a strong association between the species being found within the samples and the concentration of analyzed macro-elements and soil pH and moisture content.

Coefficients of the correlation of environmental variables with sample indices, being calculated as weighted averages of species indices, are shown in Table 4. The largest correlation along the 1st ordination axis between environmental variables and sample location occurs for soil moisture (negative correlation) – variable H, which explains 83% of vegetation variation, and soil pH (positive correlation) – variable pH, which differentiates vegetation in 70%, along the 2nd ordination axis a negative correlation for variables $C_{org.}$, N_{total}, and P (each of them explains approximately 60% of vegetation variation, whereas along the 3rd ordination axis a positive correlation for potassium content (variable K differentiates vegetation in approximately 31%).

The occurrence of samples across the ordination space is presented in Fig. 1. In this figure, the vectors of variables H and pH are the longest, being also strongly correlated with the first ordination axis, the evidence of which is a small gradient between these vectors and the axis. The values of variable pH in the diagram increase from the left side of the ordination space to the right, while those of variable H take the opposite direction. Potassium content has also an equally relatively strong effect on the values of the first ordination axis, where the vector of variable K is negatively correlated with this axis. The directions of variables H

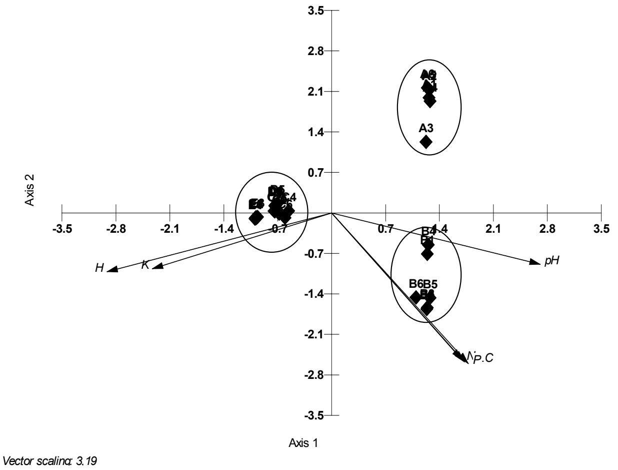

Fig. 1. The effect of environmental variables on distribution of the samples documenting willow SRC weed infestation under different soil and habitat conditions across the ordination scale.

Table 3. Canonical eigenvalues, percentages, and cumulative percentages of explained variance and coefficient of correlation between species and environmental variables.

Ordination indices	Canonical ordination axes			
	axis 1	axis 2	axis 3	axis 4
Eigenvalues	**0.945**	**0.715**	0.506	0.230
Percentage	21.89	16.56	11.71	5.32
Cumulative percentage	21.89	38.45	50.16	55.48
Coefficient of correlation	0.989	0.968	0.967	0.858

Table 4. Coefficients of the correlation of environmental variables with sample indices.

Environmental variables	Canonical ordination axes			
	axis 1	axis 2	axis 3	axis 4
pH (KCl)	**0.845**	-0.270	0.261	-0.102
g $C_{org.}\cdot kg^{-1}$	0.538	**-0.786**	-0.131	0.111
g $N_{total}\cdot kg^{-1}$ d.m.	0.529	**-0.777**	-0.176	0.081
g $P\cdot kg^{-1}$ d.m.	0.554	**-0.796**	0.026	-0.006
g $K\cdot kg^{-1}$ d.m.	-0.727	-0.295	**0.569**	0.057
Soil moisture	**-0.911**	-0.311	-0.195	-0.032

and K vectors are opposite to that of variable pH vector. The second ordination axis is optimized by the vectors of variables N_{total}, P, and $C_{org.}$, although they are strongly correlated with each other, the evidence of which is very small angles gradients between their vectors (Fig. 1).

In the right part of the diagram, above the 1st ordination axis, the samples (phytosociological relevés) documenting weed infestation of willow SCR plantation on sandy silt are clustered (Fig. 1). Their location across the ordination space indicates the low content of the analyzed macro-elements (N_{total} and P) and $C_{org.}$ in soil. Phytocenoses of annual ruderal weeds *Corispermo-Brometum tectorum* Krusem., Siss. et Westh. 1946 (samples A3 and A6) were observed there, in which the species such as *Bromus tectorum*, *Conyza canadensis*, *Agrostis capillaris*, *Rumex acetosella*, and *Lepidium ruderalne* scored the highest degree of phytosociological stability (S), i.e. degree V, and a coverage index (D) from 1,000 to 2,800. The second plant association observed (samples A1, A4, A2, and A5) was the plant community *Calamagrostietum epigeji* Juraszek 1928 that prefers poor sandy and humus-less soil, in which *Calamagrostis epigejos* scored degree V of phytosociological stability (S) and a high index of coverage (D), amounting to 6,350 (Table 5).

Below the 1st ordination axis, in the right part of diagram, a clear cluster is formed by the samples (phytosociological relevés) documenting weed infestation structure of willow SRC plantation on sandy silt enriched with sewage sludge. Their location within the ordination space is evidence of high nutrient content in this soil, mainly N_{total} and P, as well as $C_{org.}$. Nitrophilous, pioneer, and xerothermic phytocenoses of the plant associations *Salsoletum ruthenicae* Philippi 1971 (samples B2, B3, B5, and B6) and *Chenopodio rubri-Atriplicetum patulae* Gutte 1966 (samples B1 and B4) were identified there. In these samples, the highest degree of phytosociological stability (S), i.e. degree V, and a coverage index (D) amounting to 2,208 were scored by two species: *Lactuca serriola* and *Conyza canadensis* (Table 5).

On both sides of the 1st ordination axis, in the left part of the diagram, a large cluster is formed by the samples (phytosociological relevés) describing the weed infestation of willow SRC plantation on post-farmland, degraded over-dried and wet grassland. The responsibility for identification of the samples coming from post-farmland and degrade grassland is in the vectors of soil moisture and soil potassium content variables. The energy willow plantation set up on fallow post-farmland was infested by fallow plant association *Convolvulo arvensis-Agropyretum repentis* Görs 1966, in which degree V of phytosociological stability (S) and a coverage index (D) amounting to 2,208 was scored by *Elymus repens* (samples C1-C6). The willow SCR plantation on degraded and over-dried grassland was infested by nitrophilous plant association *Urtico-Aegopodietum podagrariae* Tx.1963 n.n (samples D1-D6), in which *Glechoma hederacea* and *Urtica dioica* scored degree V of phytosociological stability (S) and a coverage index (D) amounting respectively to 2,208 and 4,250. On the other hand, the willow SCR plantation set up on wet grassland was infested by the plant communities *Epilobio-Juncetum effusi*

Table 5. Floristic and phytosociological weed strucutre of research plots.

Geographical coordinates of research plots	Soil substratum	Plant associations [23]	Weed plant species	Constancy classes	Cover coefficient
				(S)	(D)
A1-A6 N 53.426233 E 14.593406	sandy silts	*Corispermo-Brometum tectorum* Krusem., Siss. et Westh 1946 *Calamagrostietum epigeji* Juraszek 1928	*Calamagrostis epigejos*	V	6350
			Bromus tectorum	V	2800
			Conyza canadensis	V	2416
			Agrostis capillaris	V	1780
			Rumex acetosella	V	1250
			Lepidium ruderale	V	1000
			Arenaria serpyllifolia	III	1333
			Festuca ovina	III	916
			Cerastium semidecandrum	II	200
			Linaria vulgaris	II	200
B1-B6 N 53.425441 E 14.590616	sewage sludge-fertilized silts	*Chenopodio rubri-Atriplicetum patulae* Gutte 1966 *Salsoletum ruthenicae* Philippi 1971,1946	*Lactuca serriola*	V	2208
			Conyza canadensis	V	2208
			Chenopodium album	IV	1437
			Bromus mollis	IV	1125
			Chenopodium strictum	IV	812
			Atriplex patula	IV	500
			Sonchus asper	IV	500
			Polygonum persicaria	III	1333
			Solanum nigrum	III	916
C1-C6 N 53.587359 E 14.820900	fallow post-farmland	*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943	*Elymus repens*	V	2208
			Urtica dioica	IV	812
			Artemisia vulgaris	IV	500
			Cirsium arvense	III	916
			Dactylis glomerata	III	500
			Carduus crispus	II	200
D1-D6 N 53.675155 E 14.644664	over-dried degraded grassland	*Urtico-Aegopodietum podagrariae* (R.Tx.1963 n.n.) em	*Urtica dioica*	V	4250
			Glechoma hederacea	V	2208
			Aegopodium podagraria	IV	2250
			Ranunculus repens	III	1333
			Stachys sylvatica	II	1125
			Dactylis glomerata	II	200
E1-E6 N 53.672816 E 14.639282	wet degraded grassland	*Calystegio-Epilobietum hirsuti* Hilbig, Heinrich et Niemann 1972 *Epilobio-Juncetum* effusi Oberd.1957	*Urtica dioica*	V	9166
			Juncus effusus	V	6250
			Scrophularia umbrosa	V	3291
			Agrostis canina	V	2300
			Agrostis stolonifera	V	1900
			Scutellaria galericulata	V	1125
			Holcus lanatus	IV	1437
			Lycopus europaeus	IV	1125
			Carex hirta	III	1333

Oberd.1957 (samples E1, E5, and E6) and *Calystegio-Epilobietum hirsuti* Hilbig, Heinrich et Niemann 1972 (samples E2, E3, and E4), in which the highest degree of phytosociological stability (S), i.e. degree V, was scored by the following species: *Urtica dioica*, *Juncus effusus*, *Scrophularia umbrosa*, *Agrostis canina*, *Agrostis stolonifera*, and *Scutellaria galericulata*. Among them, Urtica dioica was characterized by the highest coverage index (D), amounting to 9,166.

Discussion

Competitive herbaceous vegetation emerging in the first years after establishing a plantation usually reflect the previous character of land use in the area on which this plantation was set up [5, 31]. It is important to identify earlier the groups of dominating and troublesome weeds and prepare the methods of their abundance control in such a way that crop productivity is not lowered but on the other hand that soil environment and ground waters are not degraded [22]. The most important factors stimulating the growth and productivity of energy varieties of willow *Salix* sp. are high levels of ground waters, soil reaction from acidic to neutral (pH 5.5-7.0), and high soil moisture, which is closely related to habitat requirements of this species. For plantations of willow used for energy purposes, rich alluvial soils as well as those under agricultural use of higher soil quality class (IIIa and IIIb, IVa and IVb), where a high level of ground waters makes the growing of root plants and cereals difficult, are intended. Also, grassland on organic soils, being frequently abandoned and degraded as a result of improper management, is intended for energy willow plantations. High soil moisture and adequate quantity of easily assimilable nitrogen compounds coming from organic matter mineralization, with concurrent potassium deficiencies, are conducive for development of competitive herbaceous vegetation. It is of lasting nature and requires removal before establishing a plantation to make the rooting of energy willow plantings possible [21, 32]. This is confirmed by the present findings, which indicate soil moisture as a factor that has the biggest effect on diversity of competitive herbaceous vegetation in relation to willow plantings (approximately 83% of the total variation of examined vegetation). Therefore, proper identification of weed infestation structure in willow plantations in habitats with high moisture levels enables their effective control.

Sandy soils being characterized by high levels of ground waters and additionally fertilized with sewage sludge are also intended for plantations of properly selected willow genotypes. Sandy silt coming from Odra River fairway dredging, as a soil-less soil, is characterized by neutral reaction. Application of processed municipal sewage sludge with alkaline reaction (>7.0 pH) facilitates the introduction of expansive photophilous and nitrophilous species diaspores that luxuriantly infest energy crop plantations and create competitiveness for planted energy crop species. These species compete in the first two years for access to light and new space for settlement, and only later for availability of nutrients related to soil moisture [5, 7, 20, 33]. This also is confirmed by the present findings which indicate to soil reaction as one of the two most important factors that affect diversity of herbaceous vegetation accompanying energy willow coppices (approximately 70% of the total variation of examined vegetation).

Based on obtained research results, positive soil conditions favorable to energetic willow crops were found on investigated areas of the Odra basin on fallow post-farmland and degraded grassland – areas excluded from cultivation due to a dramatic decrease in agricultural profitability. Additional factors favorable to energetic willow crops on inundation areas in the Odra valley are high soil humidity and high groundwater level.

A unique element of the Odra valley landscape are dumps of sandy silt coming from Odra River fairway dredging, considered to be degraded land requiring biological reclamation. As the obtained research results show, energetic willow crops can be used to reclaim anthropogenically changed grounds, i.e. sandy silt used with sewage sediments.

Conclusions

1. Large values of the first two ordination axes (> 0.7) show a unimodal structure of data, achieving the Gaussian curve spectrum.
2. Substantial values of the coefficients of correlation between sample indices and environmental variables are evidence of a strong association between the weed species found within the samples and the content of K, P, $C_{org.}$, and N_{total}, and soil pH and moisture content.
3. The largest correlations between environmental variables and sample locations across the ordination space occur for soil moisture variables (negative correlation), which explains 83% of the variation of observed vegetation, and for soil pH variable (positive correlation), which differentiates the analyzed vegetation in 70%.
4. Fallow post-farmland and grassland located in the flood-plain of the Odra River Braid and sandy silt of anthropogenic origin enriched with sewage sediment, create potential areas for energetic willow crops in the West Pomeranian Voivodeship.

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