Successive impact of the nitrogen fertilization of basket willow (*Salix viminalis* L.) on the canopy architecture in 9th and 10th year of regrowth of shoots

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Abstract. The purpose of the present paper was an assessment of the successive impact of fertilization with nitrogen on the regrowth dynamics of the shoots of 10 genotypes (three clones and seven varieties) of basket willow (*Salix viminalis* L.) in the 9th and 10th year of cultivation. In 2008–2015, mineral nitrogen fertilization was applied in the whole experiment in four doses. The measurements of height and thickness of willow shoots, of the quantity of live and dead shoots in the snag and live and dead snags on the plot were performed in the experiment realized in 2016–2017. Biometric measurements showed that increased mineral nitrogen fertilization in the year of its application intensified shoots growth in height and thickness, yet in the successive impact, in the 9th and 10th year of willow vegetation weakening of shoot regrowth in height and thickness is observed, and the number of live shoots in the snag and live snags on the plot have reduced. In particular, negative successive impact of the nitrogen fertilization on the willow canopy architecture was demonstrated on the objects that were mowed twice in the first 4-year rotation and on the varieties that do not tolerate this treatment.

1 Introduction

In the production of willow biomass for energy purposes, maintaining snag planting per hectare in the whole 25-year cycle of its cultivation is important. The loss of live snags on the plantation reduces the production capacity of the willow, and a low yield of biomass limits the economic profitability of the willow crop [1]. It is accepted that the target planting of live willow snags per hectare on production plantations needs to be ca. 15 thousand pieces. For this reason, willow is planted in the initial planting, which should amount to 18 thousand cuttings per hectare [2–4]. In field experiments, the willow planting and its productivity is assessed in the first 3 to 4 years of cultivation. In the literature, there is no assessment of the successive impact with reference to the regrowth dynamics of willow shoots during the later years of cultivation with diversified nitrogen fertilization and in variants of its mowing.

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The purpose of the present paper was an assessment of the successive impact of fertilization with nitrogen on the regrowth dynamics of the shoots of 10 genotypes of basket willow (*Salix viminalis* L.) in the 9th and 10th year of cultivation on light soil in Middle Pomerania in Poland (16°24'N i 54°8'E).

2 Materials and methods

The measurements of height and thickness of willow shoots, of the quantity of live and dead shoots in the snag and of the quantity of live and dead snags on the plot were performed in the experiment realized in 2016–2017 in Kościernica (16°24′N and 54°8′E). In 2008–2015, mineral nitrogen fertilization was applied in the whole experiment, but in 2016 and 2017 this fertilization was not used. The first 4-year cycle of the regrowth of the shoots was in 2008–2011, the second – in 2012–2015. As part of the experiment in 2007, four doses of mineral nitrogen were randomized on large plots: 0 kg $N \cdot ha^{-1}$, 60 kg $N \cdot ha^{-1}$, 120 kg $N \cdot ha^{-1}$ i 180 kg $N \cdot ha^{-1}$, and within these doses on small plots: 10 genotypes of basket willow (*Salix viminalis* L.) – three clones: 1047, 1054, 1047D and seven varieties: Start, Sprint, Turbo, Ekotur, Olof, Jorr and Tordis. The soil used in the experiment was light, RIVa–IVb soil quality class, a good rye soil complex, appropriate podsolic – pseudopodsolic with a composition of light loamy sand up to the depth of 100 cm, and deeper: light loam. The humus content in the layer of 0–30 cm of soil was 1.41%. In 2007, on the plot sized 25.3 m^2, in two rows 56 willow cuttings were planted per row, that is 22,134 pcs.$\cdot ha^{-1}$. During the harvest, growing willow shoots on individual rows of the plot were mowed separately. In the first 4-year rotation, the first row was mowed twice (after 3 years and after annual regrowth), and the second row was mowed once (after 4 years of regrowth). In the second 4-year rotation, both rows were mowed after 4 years of regrowth. For the examined factors, a 4-way analysis of variance was conducted and the structure of variance components was determined. The significance of the effects was assessed with the F test. Data related to the representative weather profile for the Kościernica region were collected from the weather station of the Institute of Meteorology and Water Management in Koszalin [5]. In the year 2016, precipitation in Koszalin amounted to 810.1 mm and in the year 2017 it was 887.7 mm. Annual rainfall in Koszalin in the willow vegetation period (IV–X) was 575.6 mm in 2012 and 620.9 mm in 2017. The Sielianinow's hydrothermal coefficient for the growing season fluctuated from 1.90 in the year 2016 to 2.13 in the year 2017. Extremely dry conditions ($K< 0.7$) occurred in May 2017 and in September 2016, while very wet conditions ($K > 2.5$) occurred in both years in July and October.

3 Results and discussion

The research factors analysed in the experiment (willow genotypes, nitrogen doses in 2008–2015, shoot mowing variants in 2008–2011, measurement dates and years of shoot regrowth) had a significant impact on the canopy architecture (Table 1). A high effect of the interaction of willow genotypes was demonstrated with the nitrogen doses, with all the features of the canopy architecture and with the years of shoot regrowth, with the exclusion of the quantity of snags on the plot and the shoot mowing variants with the willow genotypes, and with the nitrogen doses with the quantity of snags on the plot, as well as with the years of shoot regrowth with the number of shoots in the snag.

Table 1. Successive impact of examined factors on the structure of variance components in analyses of features.

Variance component[1]	**Percentage structure of variance components in analyses**					
	Shoots		**Shoots in snag**		**Snags on the plot**	
	height	**thickness**	**live**	**dead**	**live**	**dead**
E	27.9***	20.0***	3.6***	5.9***	20.6***	20.6***
D	1.1***	0.4**	0.7***	2.0***	7.2***	7.2***
C	4.9***	3.9***	18.3***	9.4***	26.1***	26.1***
B	4.3***	2.5***	4.1***	23.7***	0.0	0.0
A	17.3***	30.4***	8.3***	2.1***	0.1***	0.1***
Σ A–E	55.5	57.2	35.0	43.1	54.0	54.0
ExD	**4.1*** **	**2.1*** **	**3.2*** **	**4.6*** **	**6.5*** **	**6.5*** **
ExC	0.5***	1.2***	1.8***	1.5***	**15.6*** **	**15.6*** **
DxC	0.4***	1.1***	0.9***	1.2***	**10.1*** **	**10.1*** **
ExB	2.3***	0.5	0.4**	1.9***	0.0	0.0
DxB	0.2***	0.0	0.0	0.7**	0.1***	0.1***
CxB	0.0	0.1	1.7***	3.7***	0.0	0.0
ExA	**17.3*** **	**17.0*** **	**6.1*** **	**3.8*** **	0.1***	0.1***
DxA	0.6***	0.1	2.3***	0.4*	0.1***	0.1***
CxA	2.4***	1.5***	**17.3*** **	**3.5*** **	0.0	0.0
BxA	0.2***	0.4*	2.8***	0.0	0.0	0.0
Σ other	16.5	18.8	28.5	35.6	13.5	13.5
Σ interactions	100.0	100.0	100.0	100.0	100.0	100.0

[1] The designation of variance components is given in Table 2.
Significance level: *α=0.05; **α=0.01;***α=0.001.

The average successive impact of the examined factors on the parameters of the willow canopy architecture is presented in Table 2. The fertilization of willow in 2008–2015 with the dose of 180 kg·ha^{-1} N weakened shoot regrowth in 2016–2017: as regards their height by 14.8% and as regards their thickness by 9.7%; it reduced the number of live shoots in the snag by 5.3%, it reduced the number of live snags on the plot by 47.6%, and it increased the number of dead snags on the plot by 51.9%. The willow genotypes and the shoot mowing variants in the first four-year rotation had a very strong successive influence on the canopy architecture parameters (Table 2). The extreme differences between the genotypes in height and thickness of the shoots were ca. 59%, in quantity of the shoots in the snag: live – 36% and dead – 76%, and quantity of the snags on the plot: live – 71% and dead – 88%. In the second willow mowing variant in the first four-year rotation (every 4 years), it caused the shoots to be longer (by 16%) and thicker (by 17.5%); there were more live shoots in the snag (by 34.8%). Furthermore, there were more live snags on the plot (by 34.7%) and fewer dead snags on the plot (by 141.8%).

The average successive impact of the interaction of the willow shoot mowing variant in the first 4-year rotation with nitrogen doses on the willow canopy architecture parameters is provided in Table 3. In the first mowing variant, the fertilization of willow in 2008–2015 with the 180 kg·ha^{-1} N dose~~,~~ weakened to a greater extent the shoot regrowth in 2016–2017 in their height and thickness, it resulted in a stronger reduction of the number of live shoots in the snag and of the number of live snags on the plot, and it increased the number of dead snags on the plot compared to the second mowing variant.

Table 2. Successive impact of examined factors on the parameters of willow biometric measurements in 2016–2017.

Examined factors		**Measurements of shoots**		**Shoots in snag**		**Snags on the plot**	
Factors	**Level**	**height [cm]**	**thickness [mm]**	**live [pcs.]**	**dead [pcs.]**	**live [pcs.]**	**dead [pcs.]**
Years of shoots regrowth [A]	2016	**171.0**	9.6	5.23	1.34	18.4	9.6
	2017	**237.9**	16.5	6.97	1.77	18.9	9.1
	NIR$_{0.05}$	2.3***	0.6***	0.17***	0.11***	0.1***	0.1***
Dates of measurements [B]	I	**177.9**	11.4	7.10	0.37	18.7	9.3
	II	211.7	13.7	5.72	2.13	18.6	9.4
	III	**223.6**	14.1	5.49	2.15	18.5	9.5
	NIR$_{0.05}$	2.8***	0.7***	0.21***	0.14***	0.2 n.s.	0.2 n.s.
Variant of shoots mowing[2] [C]	I	**186.7**	11.8	4.82	1.09	14.7	13.3
	II	**222.2**	14.3	7.39	2.01	22.5	5.5
	NIR$_{0.05}$	2.3***	0.6***	0.17***	0.11***	0.1***	0.1***
Nitrogen doses kg N·ha^{-1} [D]	0	**217.6**	13.6	6.14	1.31	21.7	6.3
	60	201.5	12.6	5.82	1.89	19.9	8.1
	120	209.0	13.6	6.62	1.72	18.0	10.0
	180	**189.6**	12.4	5.83	1.28	14.9	13.1
	NIR$_{0.05}$	3.3***	0.8***	0.24***	0.16***	0.2***	0.2***
Willow genotype [E]	1047	172.5	11.2	7.26	1.67	17.8	10.2
	1054	177.6	11.3	6.12	0.94	18.4	9.6
	1047D	180.8	11.4	6.86	1.95	19.3	8.7
	Start	**124.6**	8.1	4.65	0.54	7.4	20.6
	Sprint	142.9	9.5	5.29	1.17	15.2	12.8
	Turbo	179.6	11.2	6.55	1.91	20.5	7.5
	Ekotur	282.6	19.7	6.41	1.66	25.5	2.5
	Olof	252.8	16.5	5.22	1.75	18.4	9.6
	Jorr	223.5	12.8	6.01	2.25	20.0	8.0
	Tordis	**307.5**	19.1	6.67	1.68	23.7	4.3
	NIR$_{0.05}$	5.1***	1.3***	0.38***	0.25***	0.3***	0.3***
Average		204.3	13.1	6.10	1.55	18.6	9.4

[2] Mowing variant in the first 4-year rotation: I – mowing after 3-year and 1-year regrowth,
II – mowing after 4-year regrowth;
significance level: **n.s.** – no significance, ***α=0.001.

The average successive impact of the interaction of willow genotypes with the nitrogen doses on the willow canopy architecture parameters is presented in Tables 4 and 5. This data made it possible to arrange the willow genotypes in the order regarding their successive reaction to fertilization with nitrogen while accepting the assumption that large differences between the extreme values of the canopy architecture parameters qualify the genotype to a high sensitivity, while small differences qualify it to a small reaction.

Table 3. Impact of the interaction between variants of willow shoots mowing and nitrogen doses on parameters of willow canopy architecture.

Variant of shoots mowing[2]	Nitrogen doses $[\mathrm{kg\ N\cdot ha^{-1}}]$	Measurements of shoots		Shoots in snag		Snags on the plot	
		height [cm]	thickness [mm]	live [pcs.]	dead [pcs.]	live [pcs.]	dead [pcs.]
I	0	206.6	13.2	5.1	1.1	20.0	8,0
	60	183.9	11.3	4.8	1.4	17.0	11,0
	120	191.0	12.5	5.2	1.1	14.4	13,6
	180	165.2	10.3	4.2	0.8	7.6	20,4
II	0	228.6	14.0	7.2	1.5	23.5	4,5
	60	219.1	13.9	6.9	2.4	22.8	5,2
	120	226.9	14.7	8.1	2.3	21.7	6,3
	180	214.0	14.6	7.5	1.7	22.4	5,6
$\mathrm{NIR}_{0.05}$		4.6***	1.1***	0.3***	0.2***	0.3***	0.3***

[2] Mowing variant in the first 4-year rotation: I – mowing after 3-year and 1-year regrowth,
II – mowing after 4-year regrowth;
significance level: ***α=0.001.

Table 4. Impact of the interaction between willow genotypes and nitrogen doses in 2008–2015 on parameters of willow canopy architecture in 2016–2017.

Willow genotype	Nitrogen doses $[\mathrm{kg\ N\cdot ha^{-1}}]$	Measurements of shoots		Shoots in snag		Snags on the plot	
		height [cm]	thickness [mm]	live [pcs.]	dead [pcs.]	live [pcs.]	dead [pcs.]
1047	0	187.7	12.0	8.3	1.6	21.0	7.0
	60	173.5	10.6	6.7	2.2	20.5	7.5
	120	189.5	12.3	7.5	1.7	17.5	10.5
	180	139.3	9.9	6.6	1.1	12.5	15.5
1054	0	190.9	11.1	5.6	1.0	23.7	4.3
	60	204.4	13.3	6.3	0.7	19.7	8.3
	120	168.9	11.1	7.3	1.3	15.3	12.7
	180	146.2	9.8	5.2	0.8	15.1	12.9
1047D	0	188.4	11.2	6.5	1.7	24.0	4.0
	60	183.2	11.2	7.4	3.0	23.3	4.7
	120	173.1	12.3	7.4	2.0	16.7	11.3
	180	178.4	11.0	6.3	1.1	13.4	14.6
Start	0	163.1	10.3	6.1	0.5	11.5	16.5
	60	93.4	6.7	4.1	0.6	7.5	20.5
	120	74.3	5.2	3.6	0.7	3.6	24.4
	180	167.4	10.2	4.8	0.4	7.1	20.9
Sprint	0	165.7	10.4	5.5	1.5	22.2	5.8
	60	161.3	10.3	5.5	0.9	12.7	15.3
	120	135.0	9.3	5.7	1.6	12.4	15.6
	180	109.7	7.8	4.3	0.6	13.5	14.5
Turbo	0	176.0	10.6	6.0	1.9	24.7	3.3
	60	183.7	11.0	6.4	2.4	25.0	3,0
	120	192.4	12.3	7.8	1.9	21.0	7,0
	180	166.5	10.7	6.0	1.4	11.5	16,5

Table 4 (cont.). Impact of the interaction between willow genotypes and nitrogen doses in 2008–2015 on parameters of willow canopy architecture in 2016–2017.

Willow genotype	**Nitrogen doses [kg N·ha^{-1}]**	**Measurements of shoots**		**Shoots in snag**		**Snags on the plot**	
		height [cm]	**thickness [mm]**	**live [pcs.]**	**dead [pcs.]**	**live [pcs.]**	**dead [pcs.]**
Ekotur	0	304.4	20.4	7.0	1.6	26.7	1,3
	60	280.6	18.3	5.3	1.7	26.8	1,2
	120	293.8	20.6	7.5	1.3	24.9	3,1
	180	251.4	19.5	5.8	2.0	23.8	4,2
Olof	0	259.3	16.8	4.3	1.5	19.5	8,5
	60	239.1	16.5	5.4	2.3	16.9	11,1
	120	275.8	17.3	5.9	2.2	20.3	7,7
	180	237.1	15.4	5.2	1.0	17.3	10,7
Jorr	0	230.6	12.9	6.0	1.1	20.3	7,7
	60	221.0	13.3	5.7	3.3	21.8	6,2
	120	245.1	12.9	5.5	2.4	22.0	6,0
	180	197.2	11.9	6.8	2.2	15.7	12,3
Tordis	0	310.3	20.7	6.2	0.6	23.8	4,2
	60	275.0	15.0	5.4	1.8	25.3	2,7
	120	341.6	22.8	7.8	2.1	26.1	1,9
	180	302.3	17.8	7.3	2.2	19.5	8,5
NIR$_{0.05}$		10.3***	2.5***	0.8***	0.5***	0.6***	0.6***

significance level: ***α=0.001.

Table 5. Impact of the nitrogen doses applied in 2008–2015 on differences between the extreme values of parameters of willow canopy architecture in the years 2016–2017.

Willow genotype	**Measurements of shoots**		**Shoots in snag**		**Snags on the plot**	
	height [cm]	**thickness [mm]**	**live [pcs.]**	**dead [pcs.]**	**live [pcs.]**	**dead [pcs.]**
1047	50.2	**2.1**	1.7	1.1	8.5	8.5
1054	44.7	3.5	2.1	0.6	8.6	8.6
1047D	15.3	**1.3**	1.1	1.9	10.6	10.6
Start	93.1	5.1	2.5	**0.3**	7.9	7.9
Sprint	56.0	2.6	1.4	1.0	9.8	9.8
Turbo	25.9	**1.7**	1.8	1.0	13.5	13.5
Ekotur	53.0	**2.3**	2.2	0.7	3.0	3.0
Olof	22.2	**1.9**	1.6	1.2	3.4	3.4
Jorr	47.9	**1.4**	1.3	2.2	6.3	6.3
Tordis	66.6	5.7	2.4	1.6	6.6	6.6
NIR$_{0.05}$	10.3***	2.5***	0.8***	0.5***	0.6***	0.6***

significance level: ***α=0.001.

The arrangement of the varieties from the largest to the smallest successive reaction of fertilization with nitrogen performed in 2008–2015 with the canopy architecture parameters in 2016–2017 was as follows:
1 – height of the shoots: Start, Tordis, Sprint, Ekotur, 1047, Jorr, 1054, Turbo, Olof, 1047D,
2 – thickness of the shoots: Tordis, Start, 1054, Sprint, Ekotur, 1047, Olof, Turbo, Jorr, 1047D,
3 – live shoots in snags: Start, Tordis, Ekotur, 1054, Turbo, 1047, Olof, Sprint, Jorr, 1047D,
4 – dead shoots in snags: Jorr, 1047D, Tordis, Olof, 1047, Sprint, Turbo, Ekotur, 1054, Start,
5 – live and dead snags on the plot: Turbo, 1047D, Sprint, 1054, 1047, Start, Tordis, Jorr, Olof, Ekotur.

Figures 1 and 2 shows a successive impact of the interaction between selected examined factors and nitrogen doses on the selected parameters of willow biometric measurements.

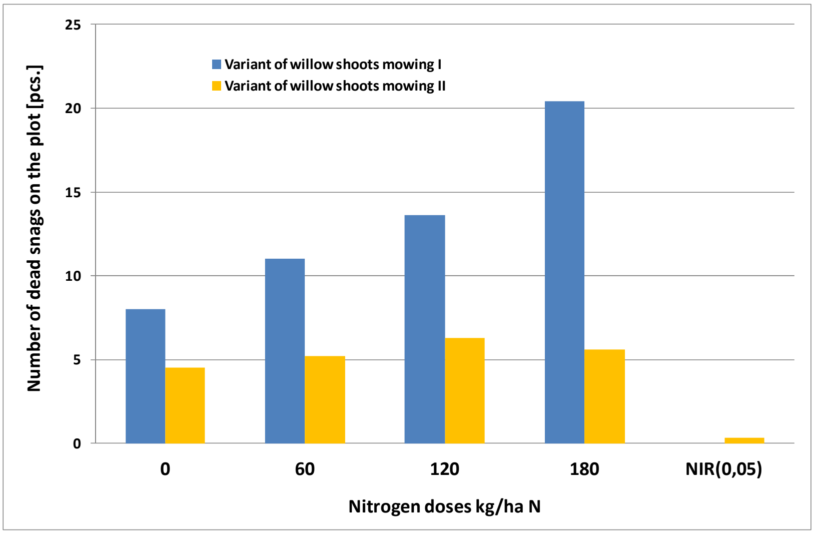

Fig. 1. Successive impact of the interaction between variants of willow shoots mowing and nitrogen doses on the number of dead snags on the plot.

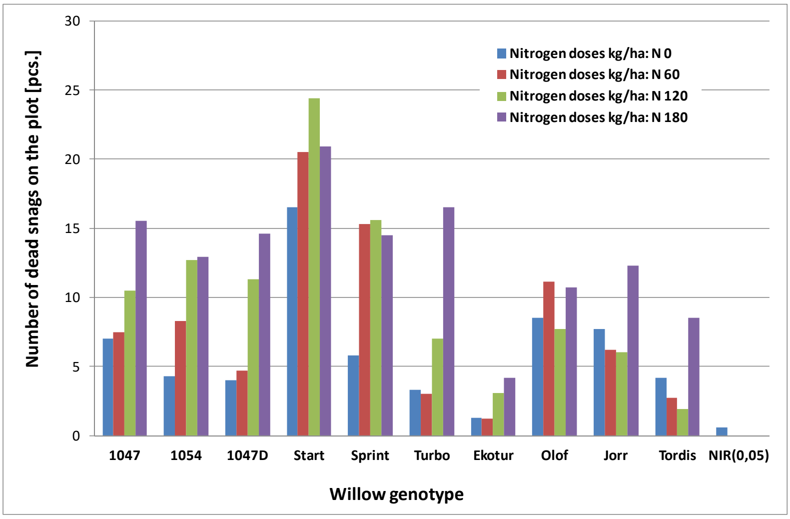

Fig. 2. Successive impact of the interaction between willow genotype and nitrogen doses on the number of dead snags on the plot.

The arrangement of the genotypes presented above in relation to the successive reaction of fertilization with nitrogen performed in 2008–2015 with the canopy architecture parameters in 2016–2017 provides an indication as to the diversification of the cultivation technology of the individual willow varieties and clones for energy purposes. The reaction of willow genotypes is not identical with the individual parameters of the canopy architecture,-such parameters of cultivation as: the number of live snags per hectare in 25-year production period, the height and thickness of re-growing shoots and the number of live shoots in the snag are decisive for the crop of willow biomass for energy purposes. In the investigations conducted by the authors, with the cultivation of willow on light soil, with harvest every 3 and 4 years, the biomass yield of the shoots increased as the nitrogen dose became higher [6]. In this experiment, three groups of genotypes were separated that differed regarding their reaction in the dry matter crop to fertilization with nitrogen: the first group reacted with a substantial increase of the yield to the dose of 60 kg N·ha^{-1} (1047, 1054, 1047D, Start, Turbo and Jorr); the second group: to the dose of 120 kg N·ha^{-1} (Ekotur), and the third group: to the dose of 180 kg N·ha^{-1} (Sprint, Olof and Tordis). In the second 4-year rotation, the annual increased fertilization with mineral nitrogen intensified the growth of willow shoots in their height and thickness, yet it reduced the number of live shoots in the snag and the number of live snags on the plot [7], and it enlarged the willow dry matter crop by 66.2% on average; however, this effect very strongly depended on the shoot mowing variant in the first four-year rotation and on the willow genotype [8]. In another experiment with willow in Middle Pomerania, intensive fertilization of willow with compost and mineral nitrogen in the first four-years starting from the establishment of the plantation caused, as a direct impact, an increase of the willow shoot growth in their height and thickness and dry matter crop by 40.3–55.6%, yet in the successive impact, without fertilization, from the seventh to ninth year of growth, it had a negative impact on the canopy architecture [9, 10].

The productivity of biomass is the basic criterion in the selection of willow genotypes in cultivation for energy purposes. Willow clones differ in the pace of obtaining their maximum production potential, and an increase of this pace also depends on the dose of fertilization with nitrogen. Water [11, 12] and nutrients, chiefly nitrogen [13], constitute the most important factors that limit the growth of willow shoots in regions with moderate climate. An optimal dose of nitrogen for the willow variety or clone has a favourable influence on biomass increment and on the technological values of the material. An excess of nitrogen may also cause the brittleness of shoots, while its deficiencies impede the productivity of photosynthesis [14]. According to Labrecque and Teodorescu [15], in order to obtain 20 t·ha^{-1} year^{-1} of dry mass through three rotations, willow that is cultivated in a short rotation system, should be annually fertilized with a dose of 150 kg N·ha^{-1}, 18 kg P·ha^{-1} and 60 kg K·ha^{-1}. In the technology of the cultivation of willow for energy purposes, streamlining of biomass production is assumed through the application of sustainable organic fertilization (sewage, sludge from municipal wastewater treatment plants, composts of different origin, liquid manure) and mineral (NPK), a limitation of planting density to ca. 15–22 thousand cuttings per hectare and harvest in a 3–4-year rotation [2, 3, 16]. In Sweden, ca. 50% of willow cultivations are fertilized with municipal sewage, and on the remaining cultivations, mineral fertilization with a dose of ca. 100 kg·ha^{-1} N is used, while in Canada, an equivalent of fertilization of 100–150 kg·ha^{-1} N is recommended taking into consideration organic fertilization [17]. Willow absorbs the largest quantities of nitrogen in the period from April to October, and does it most intensely from May to July [18]. The effectiveness of the use of nutritious elements is higher in longer production cycles than in one-year cycles [19]. There are reports stating that in the second cycle of cultivation, the biomass yield of shoots is higher than in the first cycle [15, 20].

In scientific and production studies, the issue of the selection of clones and varieties of willow in relation to the area of cultivation is omitted, along with their specific fertilizer and water requirements and long-term reaction to nitric fertilization. In the authors' investigations, it was demonstrated that in the two first rotations of harvest, an intensification of fertilization with nitrogen increases the growth of willow shoots and the biomass yield, yet in the later years of cultivation an increased dying out of snags and a weakening of shoot regrowth is observed, which is diversified with willow varieties and clones. This observation makes it possible to recommend in practice a greater planting density of cuttings with the use of an intensive nitrogen fertilization of those willow genotypes that react with strong dying out of snags.

4 Conclusions

1. The number of the years of shoot regrowth, the willow genotype, variants of shoots mowing in the first 4-year rotation of harvest, nitrogen doses in previous rotation and interaction of these factors had an impact on the willow canopy architecture in the 9th and 10th year of cultivation, described by the height and thickness of shoots, the quantity of live and dead shoots in the snag and the quantity of live and dead snags on the plot.
2. The fertilization of willow in the period from 1th to 8th year of cultivation with the high doses of mineral nitrogen weakened shoot regrowth as regards their height and thickness in the 9th and 10th year of cultivation. It also reduced the number of live shoots in the snag and the number of live snags on the plot and also increased the number of dead snags on the plot.
3. The negative impact of high doses of mineral nitrogen on the willow canopy architecture in the 9th and 10th year of cultivation was greater when using double mowing in the first 4-year rotation than when mowing once.
4. Willow varieties and willow clones differ in the successive impact on mineral nitrogen fertilization with the parameters of the willow canopy architecture, which gives an indication of the need to differentiate their cultivation technology.

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