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INFLUENCE OF COMPOSTED SEWAGE SLUDGE ON THE WOOD YIELD OF WILLOW SHORT ROTATION COPPICE. AN ESTONIAN CASE STUDY

The study assessed the effect of composted municipal sewage sludge on the wood yield of an experimental willow short rotation coppice (SRC) during the second harvest cycle. The mean values of BOD_7, total N and total P met the legislative limits set to prevent groundwater pollution at the soil depth of 40 cm. We demonstrated that more productive plants of the first harvest cycle could lose that trait during the next. The second harvest cycle was more productive in terms of wood yield than the first for plants of both treatments. Sludge treated willows had significantly higher wood yield.

1. INTRODUCTION

The establishment of and research into short rotation coppice (SRC) of willows (*Salix* sp.) was initiated in the1960's following the forecast of a shortage in raw material for the Swedish pulp and paper industry [1, 2]. Later the general aim was to substitute fossil fuels with wood from SRC [3, 4]. Currently willow SRCs are used for commercial, environmental and scientific purposes in several European countries (e.g. Sweden, Finland, Denmark, Poland, UK and Estonia). The crop is mainly cultivated on farmland, planted in double row system and harvested every 2–4 years during a total estimated economic lifespan of 25 years (cf. [5, 6]).

The most evident positive ecological and environmental effects of the wood biomass from SRC are its neutral net contribution of CO_2 to the atmosphere compared with fossil fuels [3, 7] and high available energy output per unit of fossil fuel used for its production [4]. High demand of water, macro- and micronutrients supplemented by high biomass productivity creates an opportunity to use SRC as a vegetation filter to

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utilise municipal wastewater and sludge [3, 5, 8]. The most common willow species used in such SRC plantations are *Salix dasyclados*, *S. burjatica*, *S. schwerinii*, *S. viminalis* and their hybrids (e.g. [4]).

Willow plantations are known to be nutrient demanding and respond well to fertile sites [2, 9]. For high-producing SRC additional fertilisation is needed to compensate for the removal of the biomass at harvest in order to maintain the balance of nutrients in the soil [3, 10]. Besides contributing to eutrophication, the provision of commercial fertilisers to SRC also poses sustainability problems. Industrial fixation of nitrogen (N) for commercial fertiliser production is energy demanding and the world supply of phosphorus (P) is limited [11]. Furthermore, the use of commercial mineral fertilisers to provide an adequate nutrient supply for the SRC increases the cost of production [10]. Organic wastes or biosolids such as pre-treated municipal sewage sludge and farm animal manure have the potential to provide plant nutrients at low or negative cost for the producer [12]. In contrast to wastewater, the N-P-K balance in wastewater sludge is not optimum for willows [1, 8, 13] but could be easily and cheaply improved by mixing sludge with other residues such as wood ash [5]. Sewage sludge is less expensive and with optimised transportation costs its application is economically much more viable than using mineral fertilisers in SRC cultivation.

In Estonia, the application of unprocessed sewage sludge is restricted by legislation for use only in green areas, for re-cultivation of mining districts, disturbed sites and for covering landfills [14]. The sludge is typically composted to mineralise organic compounds it contains and to avoid the risk of spreading disease. Composted sewage sludge may also be used with several restrictions in agriculture except for the production of food and feed crops. To avoid the risk of environmental pollution, the content of heavy metals in the composted sewage sludge must be analysed before it is allowed for use. However, where there are no industrial inputs to the wastewater purification plant, the concentration of these hazardous compounds is typically negligible in the sludge [15].

In order to diminish the utilisation costs of sludge and to find alternatives to mineral fertilisers, the options for spreading composted sewage sludge on farmland or in plant nurseries are gaining more interest. Since the health risks of applying composted sewage sludge to land growing energy crops are rather low, it would be reasonable to use it as an additional nutrient source in SRC to facilitate the wood production.

The main aim of the study was to evaluate the impact of application of composted municipal sewage sludge on the SRC aboveground wood yield in various willow clones at one Estonian experimental plantation. It was hypothesised that the quantity of composted sewage sludge applied would not only increase wood yield but also not pollute groundwater. Previously gathered data were also used in order to identify any changes in the particular plants/plantation wood yield during different harvest cycles. The multi-annual database also facilitated an analysis of the influence of climatic factors on clone annual wood yield.

2. MATERIALS AND METHODS

Site description. The experimental willow SRC studied is located in South East Estonia, close to the village of Nõo (58°17'N, 26°33'E) on private land previously used for traditional agricultural production. The soil type is a Stagnic Luvisol consisting of two deposits, silty and sandy materials on loamy till, it is compacted and of reduced porosity possibly resulting in a lack of available water during summers with extensive periods of drought. The length of vegetative period (VP) is approximately six months usually extending from late April to late October. Climate data characterising the study area are presented in Table 1.

Table 1

Climate data of the region under study in 2001–2005

Year	Average temperature of VP [°C][a]	Total precipitation [mm][b]	Total precipitation of VP [mm]
2001	13.4	823.2	590.2
2002	12.0	533.4	253.2
2003	11.9	743.6	510.1
2004	12.3	732.7	528.3
2005	12.9	604.3	405.1

[a]The source of temperature data is The Institute of Environmental Physics of Tartu University.

[b]The source of precipitation data is The Estonian Meteorological and Hydrological Institute.

The plantation was established in May 1995 with cuttings of six *S. viminalis* clones (78101, 82007, 78112, 78021, 78183, 78195) and one *S. dasyclados* clone (91090) in separate plots with an area of approximately 1300 m^2 per each clone. The clone numbers refer to the Swedish clone numbering system and the last two digits will hereafter refer to the clones. The cuttings of ca. 20 cm long were planted manually in a double row design with the basal part downwards. The alternating inter-row distance was 0.75 and 1.25 m and spacing between cuttings within the rows was 0.5 m. The overall planting density was 20 000 plants per ha and the total area of the plantation was ca 0.91 ha. The plantation was not cut back at the end of the establishment year.

The plantation was harvested manually to the stump height of ca. 5–10 cm from the ground after the end of the vegetative period of 2000. In spring 2001, before plant re-sprouting composted municipal sewage sludge was spread to the soil surface using a manure spreader that applied the sludge to one half of each clone plot of the SRC.

The other half of the clone plots was left untreated and we considered this as a control area in our study. The spreading of composted sewage sludge in spring 2001 was the only application of nutrients in this experimental site during the study period.

Before application, the sewage sludge was mixed with sawdust and tree bark and composted in wastewater treatment plant for at least half a year. The content of heavy metals and nutrients was analysed in a certified laboratory before the usage in the SRC. The results of analyses confirmed that the heavy metals content of sludge was substantially lower than the limits set for wastewater sludge allowed for use in agriculture [14]. The sludge contained 35% dry matter of which 50% were organic compounds. The nutrient levels applied (calculated according to the sludge content of total N, total P and K) to the treated SRC area were ca 300 kg of N, 220 kg of P and 45 kg of K per ha.

Due to the intervention by a third party both fertilised and control plots of clone 83 were harvested in winter 2002. Therefore the wood production pattern of that clone cannot be compared to that of the rest of clones.

Experimental methods. Gravitational water collected from the uppermost level of soil in plots of clones 01 and 21 was isolated horizontally at 10 and 40 cm depth with lysimeters during spring 2001. The lysimeters were constructed from two shovel--shaped stainless steel plates with the total area of 0.6 m^2. The system worked like a small-scale drain enabling the collection of water moving through the soil towards the groundwater into plastic water bottles. In total, eight lysimeters were used – two in the treated area and two in the control one per depth per clone. Within 24 h of collection all water samples were transported to a certified laboratory where total N, total P and BOD_7 content were measured. Water samples were only collected during the first two years following sludge treatment from 2001 to 2002. Further water sampling was considered unnecessary since we assumed the leakage of nutrients would decrease over time. The actual availability of water samples varied according to the weather conditions such that during the vegetative period the volume of water reaching the lysimeter water collection vessels was sometimes insufficient to carry out all the necessary analyses. During the first two years of the second harvest cycle, we managed to analyse gravitational water on six occasions, five of those during the vegetative period. Four samples were collected in 2001 and two during the following year.

For plant growth, estimation 30 plants in both sludge treated and control plots were randomly selected from each clone. In 2000, prior to harvest, these plants were marked with paint at stool surface near the ground for further identification during the non-destructive sampling. The diameter of all living shoots of these plants was measured with an electronic digital calliper at the height of 55 cm above the soil surface (D_{55}). Sampling procedures were carried out during the plant dormancy periods of 2000–2003 and in 2005. For estimating the wood production of various clones, the allometric relationship between shoot diameter and dry weight was used. To calculate the dry weight (DW) of plants we applied the second order polynomial equation:

$$DW = aD_{55}^2 + bD_{55} + c$$

The parameters of this equation used for particular willow species and shoot age are shown in Table 2.

Table 2

Parameters of the second order polynomial equation applied for calculation of plant dry weight[a]

Species	Shoot age	a	b	c	R^2	n
Sv	1	0.873	–5.258	11.244	0.97	300
Sd	1	0.609	–3.111	6.063	0.98	150
Sv	2	1.027	–7.486	18.320	0.98	120
Sd	2	0.839	–7.136	24.381	0.97	60
Sv	3	1.346	–12.395	44.563	0.98	121
Sd	3	0.976	–7.165	14.856	0.99	60
Sv	5	4.821	–75.847	341.830	0.98	30
Sd	5	2.794	–10.939	–73.010	0.96	30

[a]Sv – *S. viminalis*, Sd – *S. dasyclados*; a, b, c – parameters of the second order polynomial equation; R^2 – adjusted determination coefficient; n – number of samples.

These parameters were obtained from previous destructive measurements of the shoots of respective species and age groups engaged in our studies during the period of ten years. The data included an analysis of the results from various plantations and in the case of *S. viminalis* from several clones. The parameters for *S. dasyclados* were obtained from the data of clone 90 only. The adjusted determination coefficient (R^2_{adj}) of the equation fitness ranged between 0.96 and 0.99. The second order polynomial equation was used based on the results of the previous study since this described the wood production of thicker shoots more accurately than other widely used options [16].

The wood yield data from the final year (2000) of the first six-year-long harvest cycle were used to evaluate the site factor impact before the sludge treatment experiment and to analyse plant wood yield dynamics in different harvest cycles. Due to the fixed locations of the plants studied in the SRC, it was possible to analyse the correlation between the wood yield of particular plants across two harvest cycles. For this comparison, only the control area data was used in order to rely on the assumption of more stable growing conditions for plants.

From 2002, the average annual wood yield per clone/plot was calculated by subtracting the average shoot dry weight of plants of particular clone/plot in previous year from that of the year when the plant sampling was being carried out. For 2001, the fieldwork data of clones 07 and 95 was lost due to technical reasons. An assumption was made that the annual wood yield in 2004 and 2005 was half of that calculated by subtracting the plant shoot weight in 2003 from that estimated in 2005 since in 2004 the fieldwork was not carried out.

For statistical analyses, the general linear models (GLM) procedure of the SA System v. 9.1 [17] program package was applied. For detection of statistically significant differences between the average dry weight of plants of different clones in treated and control area in 2005, Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ) was used. The significance level of all analyses was set to $p < 0.05$.

3. RESULTS

The average values of BOD_7, total N and total P analysed in gravitational water samples are given in Table 3. Control and Treated values refer to untreated and sludge treated plantation areas, respectively. The lysimeters lay beneath the willow clones 01 and 21. Missing values in 2001 were due to insufficient amount of sampling water.

Table 3

Average results of gravitational water analyses collected from the lysimeters in 2001 and 2002[a]

Year	Area	Depth [cm]	BOD_7 [mg/dm^3]	Total N [mg/dm^3]	Total P [mg/dm^3]
2001	Control	10	3.2	3.9	2.3
	Treated	10	4.5	4.8	1.3
	Control	40	3.1	1.7	0.4
	Treated	40			0.3
2002	Control	10	2.1	1.3	0.1
	Treated	10	1.5	2.8	2.1
	Control	40	1.6	2.7	0.4
	Treated	40	1.7	2.4	0.5

[a]For details, refer to the text.

The mean values of BOD_7 and total N did not exceed the limits (for both 15.0 mg/dm^3) set in respective Estonian regulations for pollution load of wastewater allowed to enter natural water bodies [18]. The mean values of total P were occasionally up to 1.5 times higher than the limit (1.5 mg/dm^3) at the soil depth of 10 cm. However, the average content of total P in gravitational water tended to decrease with increasing soil depth and met the respective limits at the depth of 40 cm in both years of gravitational water sampling.

The statistical analysis of plant wood yield prior to the first harvest in 2000 revealed that the site factor was not significant at both SRC and clonal level ($p > 0.05$ in both cases). Comparison of plantation areas having been or not treated with composted municipal sewage sludge at the beginning of the following harvest cycle did not show any significant initial differences and the average plant dry weight in both areas was around 2000 g (Fig. 1).

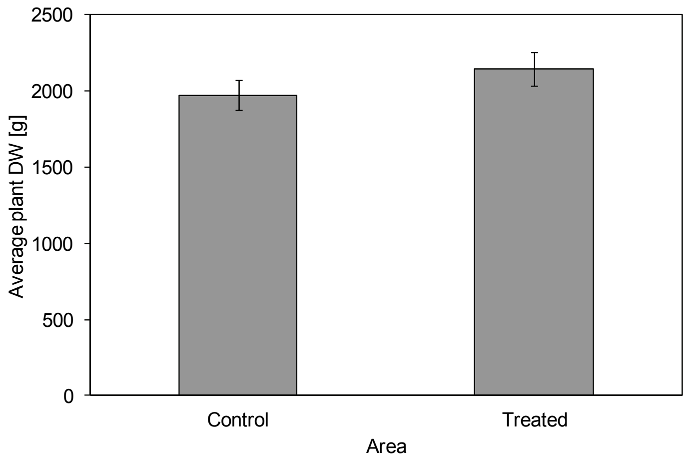

Fig. 1. The average plant dry weight (DW) of clones before the first harvest and sewage sludge treatment in 2000. Control and Treated refer to plantation areas that remained untreated or were treated with composted municipal sewage sludge at the beginning of the second harvest cycle, respectively. The vertical bars indicate standard error

Monitoring of the identified plants in the control area between the first and the second harvest cycle enabled evaluation of the plant wood yield correlations between the two harvests. During the second harvest cycle, these plants produced 19% more wood than during the first one. However, the correlation was quite weak ($R^2 = 0.29$) indicating that not all plants with higher wood yield at the end of the first harvest cycle were similarly productive during the second cycle (Fig. 2).

When the wood yields of control and sludge treated plants were compared in 2005, statistically significant differences were found. By the end of the second harvest cycle plants treated with composted municipal sewage sludge were substantially heavier than control plants ($p < 0.0001$). In 2005, average dry weight of control and sludge treated plants was 3000 g and 4700 g, respectively (Fig. 3). In 2005, the average dry weight of control and sludge treated plants were also both significantly higher than the respective value of plants at the end of the first harvest cycle.

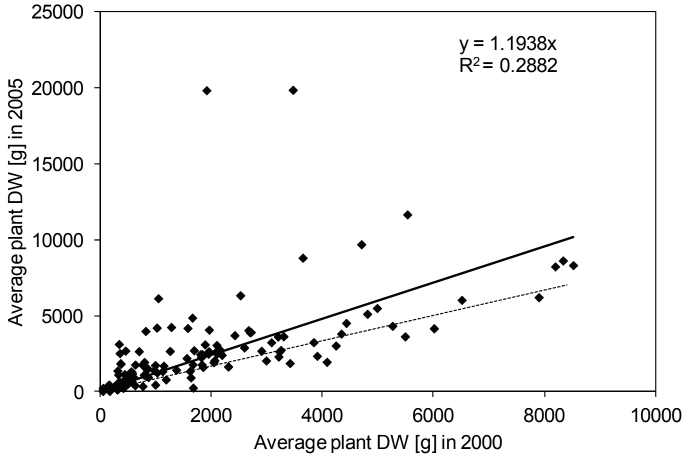

Fig. 2. The correlation between plant average dry weights (DW) in control area in 2000 and 2005 illustrated by the solid line. Dotted line illustrates the theoretical situation assuming the equal growth of plants during two harvest cycles. Dots refer to the average dry weight values of monitored distinct plants with fixed addresses

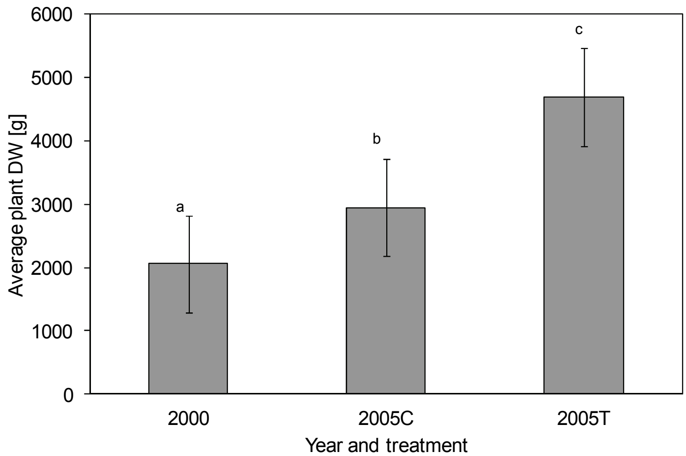

Fig. 3. The comparison of average plant dry weights (DW) at the end of the first and the second harvest cycle. Letters C and T refer to control and sludge treated areas, respectively. The vertical bars indicate standard error. Statistically significant differences are indicated by different letters on the top of the bars

Comparing the annual wood yield of willows in control and treated plots for the second harvest cycle confirmed that sludge treated plants were more productive during all years of the experiment. The pattern of relative wood yield changed in time with 2002 and 2005 being the most prolific years for sludge-treated plants. In Table 4, the relative difference in average wood yield of plants on treated plots compared with the respective yield of plants on control plots in 2001–2003 and in 2005. The yield for control plants is set to 100% for each year

Table 4

Average wood yield of plants

Year	Yield [%]
2001	137
2002	162
2003	142
2005	159

In terms of average annual wood yield it was revealed that plants were most productive during the final two years of the second harvest cycle. During that period the average annual wood yield of plants of almost all clones and both treatments was at least two times higher than for the first three years of the same harvest cycle (Fig. 4).

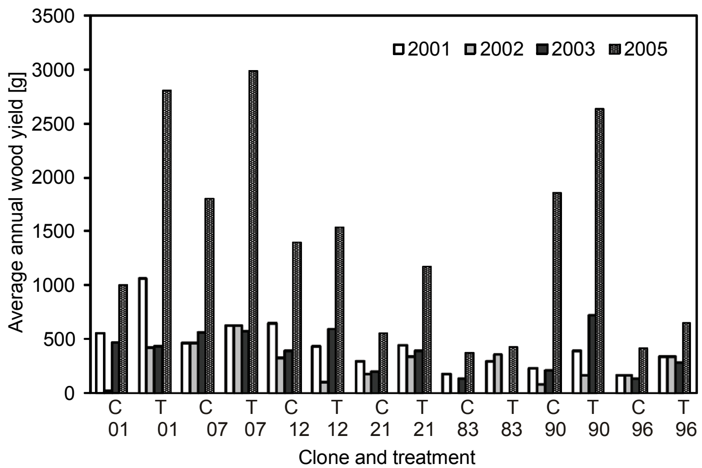

Fig. 4. The average annual wood yield of plants of studied clones in 2001–2003 and in 2005. Letters C and T refer to control and sludge treated areas, respectively. The average annual wood yield of clones 07 and 95 for 2001 is an arithmetical mean of the yield of those clones in 2002. Data of all clones for 2005 assumes that the wood yield in 2004 was half of the total estimated in 2005

The clone factor had a statistically significant impact ($p < 0.0001$) on plants average dry weight indicating that the shoot growth among clones varied to a great extent. At the end of the second harvest cycle, the most productive plants in the average were from *S. viminalis* clones 07, 01 and *S. dasyclados* clone 90 in sludge-treated plots. The greatest differences in average annual wood yield between treated and control plants were detected on clones 01, 07 and 21 in 2005. On the other hand, clone 12 showed no significant response to the sewage sludge treatment.

By the end of the second harvest cycle there were increasing differences in the wood yield of the more and less productive clones despite the treatment. However, none of the clones studied had statistically significantly lower or higher average plant dry weight than the following or previous clone in the yield ranking list because of the high variability of data at the plant level. The clone with the highest average plant dry weight in both areas was 07 (Table 5). Other more wood-productive clones in both areas were 01, 12 and 90 but their ranking depended on treatment. Regardless of the same rank order of clone 21 in both areas it was relatively more successful in terms of wood production in sludge treated conditions, whereas the yield of clone 95 was low under both conditions. In Table 5, the ranking of clones according to the average dry weight of plants at the end of second harvest cycle is shown. Control and Treated refer to untreated and sludge treated plantation areas, respectively. Values with the same letters are not significantly different (REGWQ-Test).

Table 5

The ranking of clones

Control			Treated		
Clone	Average dry weight [g]	REGWQ grouping	Clone	Average dry weight [g]	REGWQ grouping
07	5124	A	07	7805	A
90	4244	BA	01	7542	A
12	4164	BA	90	6568	BA
01	3054	BAC	12	4201	BAC
21	1792	BC	21	3530	BAC
95	1297	C	95	2255	BC
83	1046	C	83	1179	C

Assessing the influence of climatic factors revealed that the average air temperature during the vegetative period had a positive correlation with the wood yield of plants ($p < 0.05$). Analysis of the impact of precipitation showed that neither the total annual precipitation nor precipitation during the vegetative period had a statistically significant effect on plant wood yield.

4. DISCUSSION

Our results revealed that the level of nutrients applied (300 kg of N, 220 kg of P and 45 kg of K per ha) did not cause any substantial or persistent hazard to gravitational water. The content of total P in the gravitational water of the topsoil (10 cm) was above the legislative limits of 1.5 mg/dm^3 [18] on some occasions. The main reason for high values of total P in the topsoil gravitational water of the control area in 2001 was probably due to excessive application in the composted sewage sludge leading to horizontal drift of nutrients in precipitation water from fertilised plots to the untreated area. At the depth of 40 cm, the average values of the total P met the legislative limits in both years. The dilution effect was most probably caused by the concentration of fine root biomass and high microbial activity in the risosphere. It has been reported previously that 40–55% of fine root biomass of willows can be found in the uppermost 10 cm soil layer. The fine root biomass gradually decreases in lower soil layers so that at the depth of 30–40 cm only 10% or less of willow fine roots can be found [19]. Furthermore, Truu et al. [20] showed that in willow vegetation filters, the main purification processes resulting from high microbial activity took place in the upper 10 cm of similar soil type thus reducing significantly the concentration of pollutants in deeper soil. Therefore we can conclude that the SRC studied in our experiment utilised the applied composted sewage sludge effectively and the risk of groundwater pollution was negligible.

At the end of the first harvest cycle no substantial differences existed in average plant dry weight between the plantation parts that remained untreated or were fertilised with sewage sludge after the first harvest. Therefore we assumed that the natural edaphic and hydraulic conditions of different plantation parts were quite similar which was essential to enable monitoring of the influence of sewage sludge on plant wood yield without real replication plots.

It has been demonstrated that, in SRC the wood production pattern of particular plants can change during different harvest cycles [16, 21]. This was also confirmed by results of our study, since the correlation between the wood yield of monitored plants at the end of first and second harvest cycle was quite weak. The correlation remained quite weak (R^2 = 0.56, data not shown) even if the two outliers showing exceptionally high plant DW in 2005 were excluded from the dataset. Those two plants were situated close to the border of the plantation and could be affected by the edge effect.

The growth advantage of some larger plants during the first harvest cycle could suffer from harvesting or respond to changed conditions during the second harvest. Most probably not all plants tolerated the harvest similarly and were suppressed by others in competition for resources afterwards. Although it has been widely reported that some plant diseases can also cause large variation in wood yield of willows (e.g. [22]), most of monitored plants appeared healthy throughout the study and those with mechanical damage caused by ungulates were excluded from the correlation dataset. Even if we did not identify any significant pathogen attacks in the studied plants, the disease factor could be one of the reasons for the poor growth recorded from some plants during our experiment.

Regardless of the shorter second harvest cycle, the wood yield of plants increased from the first to the second harvest irrespective of the treatment. Higher yield of plants in the control area in 2005, when compared with the same value of the respective area at the end of the first harvest cycle was most likely the consequence of the establishment difficulties of the plantation. Despite repeated weed control during the year of establishment, willows suffered from competition with weeds during the first years after SRC establishment. The negative effect of weed proliferation on willow SRC wood yield and survival has been documented widely (cf. [13, 23, 24]). Additionally in the year before and during establishment there were long summer drought periods and the willow growth was rather slow [25]. The higher wood yield of control plants by the second harvest was probably largely due to the existence of a large and effective root system developed during the first 5-year long harvest cycle.

In our experiment, sludge treated plants were on average significantly heavier than control plants by the end of the second harvest cycle, confirming that the application of composted sewage sludge significantly increased the wood yield of treated plants. This finding is corroborated by the results of other authors demonstrating the positive effect of organic treatment and the high demand for nutrients in willow wood production. For example, Adegbidi et al. [12] demonstrated that willows in organically ameliorated plots produced significantly more wood than in the control area. Gruenewald et al. [26] had difficulties with survival of plants when studying willow growth characteristics in dry and nutrient-poor reclaimed mine site conditions. Such results can be anticipated due to the high nutrient demand of willows [2, 3] which stresses the necessity of additional fertilisation of SRC especially for high wood yield on poor soils. However, contrary results can be also found demonstrating no [27] response of willow SRC wood yield to sewage sludge application.

The relative advantage of sludge treated plants in terms of wood yield was quite variable during the period 2001–2005 (Table 4). Plants were relatively more productive in 2002 and 2005 when the estimated wood yield of sludge treated plants was nearly 60% higher than that of control plants. The yield increase was similar [28] or slightly higher [12] than reported by other authors for fertilised willow plantations. However, we should keep in mind that the relative advantage of fertilised plants depends on the annual growth success of control plants. Therefore, the higher relative yield of sludge treated plants in some years can actually reflect the poor shoot growth of control plants. It has been demonstrated that fertilisation significantly reduces the ratio of fine root biomass in the total biomass balance of willows [19]. Under less favourable conditions plants allocate more products of photosynthesis to below ground biomass [29]. Therefore sewage sludge application to SRC can be a reasonable method to enable higher wood yield of SRC in suboptimum growing conditions.

In general, during the final two years of the second harvest cycle, plants were clearly more productive than for the first three years of our study and for the majority of clones the annual wood yield was at least double during this period. The same pattern has also been described by other authors demonstrating that remarkable wood production increase in willow SRC commonly occurs during the later years of harvest cycle [24, 30]. Moreover, poor growing conditions of the first harvest cycle can have a cumulative repressive effect on the plant growth during the first years of second harvest cycle [23, 28].

In our experiment, the wood yield among different clones varied to a great extent despite of the generally positive effect of sludge application resulting in average annual wood yield of 10 t/ha and 15 t/ha (data not shown) for control and sludge treated plants, respectively. This is confirmed by earlier research, which also demonstrated high variability in the productivity of willow clones in fertilised SRCs. For example, Heinsoo et al. [9] showed that fertilisation increased the average wood dry matter production of one Estonian plantation more than two-fold during the first 4-year long harvest cycle but the production between clones was quite different. In addition to fertilisation other factors like tree species/clone individual characteristics, the suitability of planting material for the local climate [9], soil type and pH all tend to affect the actual productivity of plants [31].

The sludge treatment did not lead to significant shifts in clone yield rankings, with the less productive clones maintaining their relative positions irrespective of treatment. In the case of the four most productive clones, the yield ranking order varied between treatments. The plants of clone 01 seemed to benefit from the sludge treatment more than the rest as the average yield increase of these was approximately 2.5-fold. The highest average dry weight in both sludge treated and control plants was estimated in the case of clone 07. It differs from the results of Heinsoo and Koppel [16] who in their study of another Estonian SRC showed that the productivity of clone 07 was exceeded by clones 90 and 01 at the end of the second four year long harvest cycle. In their work, clone 90 was the most successful in terms of wood yield irrespective of treatment, similarly this clone was also among the most productive in our case. Contradictory results in terms of plant growth and production characteristics between different plantations of the same clones have been demonstrated earlier too [24, 28]. Such results imply that in the case of moderate and short cultivation situations and under different local conditions one should be rather careful before recommending particular clones for further or wider commercial exploitation.

According to previous data, it was reasonable to assume that water will be the main limiting factor for wood production when adequate nutrients are available to willow SRC provided either by a fertile soil or by additional fertilisation [32]. For example, in the UK it is suggested that plantations are established in areas where annual rainfall is at least 600 mm [33]. However, neither the total annual precipitation nor that of the vegetative period (varying from 253 mm to 590 mm between various years) had any significant effect on annual wood yield of plants in the current study. Most probably the water deficit in this particular plantation was not harsh enough to affect plants significantly in the long run. No influence of rainfall on the wood yield of willows was demonstrated earlier by Tahvanainen and Rytkönen [24] either. Contrary to the precipitation, the mean temperature of vegetative period had a significant effect on the annual wood yield in the current study. More prolific growth of willows in warmer years has also been confirmed by other authors [30]. Such findings could be associated with climate dependent phenological traits of willows such as bud-burst date, leaf unfolding speed or duration of leafy period that can affect the growth [34]. However, analysing the impact of these factors was beyond the scope of this study and should be considered in further research.

5. CONCLUSIONS

The applied load of composted municipal sewage sludge did not cause any substantial or persistent hazard to gravitational water. Monitoring of identified plants showed there was quite poor correlation in wood yield between different harvest cycles. During the second harvest cycle, the wood yield of willows was higher than that of the first one irrespective of treatment. Clones differed from each other both in terms of plant wood yield and by their response to sewage sludge treatment. Willows treated with sewage sludge produced significantly more wood than control plants. Therefore we can conclude that composted municipal sewage sludge can be used as a fertiliser to promote the growth of SCR willow stand.

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REFERENCES

[1] MIRCK J., ISEBRANDS J.G., VERWIJST T., LEDIN S., *Development of short-rotation willow coppice system for environmental purposes in Sweden*, Biomass Bioenergy, 2005, 28 (2), 219.
[2] MITCHELL C.P., STEVENS E.A., WATTERS M.P., *Short-rotation forestry – operations, productivity and costs based on experience gained in the UK*, For. Ecol. Manage., 1999, 121 (1–2), 123.
[3] PERTTU K.L., *Environmental justification for short-rotation forestry in Sweden*, Biomass Bioenergy, 1998, 15 (1), 1.
[4] VOLK T.A., ABRAHAMSON L.P., NOWAK C.A., SMART L.B., THARAKAN P.J., WHITE E.H., *The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremedation*, Biomass Bioenergy, 2006, 30 (8–9), 715.
[5] DIMITRIOU I., ERIKSSON J., ADLER A., ARONSSON P., VERWIJST T., *Fate of heavy metals after application of sewage sludge and wood-ash mixture to short-rotation willow coppice*, Environ. Poll., 2006, 142 (1),160.

[6] WILKINSON J.M., EVANS E.J., BILSBORROW P.E., WRIGHT C., HEWISON W.O., PILBEAM D.J., *Yield of willow cultivars at different planting densities in a commercial short rotation coppice in the north of England*, Biomass Bioenergy, 2007, 31 (7), 469.

[7] HELLER M.C., KEOLEIAN G.A., VOLK T.A., *Life cycle assessment of willow bioenergy cropping system*, Biomass Bioenergy, 2003, 25 (2), 147.

[8] PERTTU K.L., KOWALIK P.J., *Salix vegetation filters for purification of waters and soils*, Biomass Bioenergy, 1997, 2 (1), 9.

[9] HEINSOO K., SILD E., KOPPEL A., *Estimation of shoot biomass productivity in Estonian Salix plantations*, For. Ecol. Manage., 2002, 170 (1-3), 67.

[10] ADEGBIDI H.G., VOLK T.A., WHITE E.H., ABRAHAMSON L.P., BRIGGS R.D., BICKELHAUPT D.H., *Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State*, Biomass Bioenergy, 2001, 20 (6), 399.

[11] ROSENQVIST H., ARONSSON P., HASSELGREN K., PERTTU K., *Economics of using municipal wastewater irrigation of willow coppice crops*, Biomass Bioenergy, 1997, 12 (1), 1.

[12] ADEGBIDI H.G., BRIGGS R.D., VOLK T.A., WHITE E.H., ABRAHAMSON L.P., *Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics*, Biomass Bioenergy, 2003, 25 (4), 389.

[13] PERTTU K.L., *Environmental and hygienic aspects of willow coppice in Sweden*, Biomass Bioenergy, 1999, 16 (4), 291.

[14] *The requirements for sewage sludge usage in agriculture, green areas creation and recultivation* (in Estonian), RTL 2003, 5, 48, https://www.riigiteataja.ee/ert/act.jsp?id=761407

[15] DIMITRIOU I., *Safe reuse of municipal wastewater and sewage sludge for irrigation and fertilization*, [in:] K. Heinsoo, I. Dimitriou, S. Foellner, G. Buergow (Eds.), *Short rotation plantations: Guidelines for efficient biomass production with the safe application of wastewater and sewage sludge*, Ulster Farmers Union, 2008, 28–32.

[16] HEINSOO K., KOPPEL A., *Choice of willow (Salix spp.) clones for establishment under short rotation forest plantations in Estonia*, [in:] K.S. Verma, D.K. Khurana, L. Christersson (Eds.), *Short rotation forestry for industrial and rural development*, Indian Society of Tree Scientists, Nauni, 2005, 53.

[17] *SAS Customer support Center*, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513, USA, http://support.sas.com/

[18] *The procedure for sewage discharge into the water body or soil* (in Estonian), RT I 2001, 69, 424, https://www.riigiteataja.ee/ert/act.jsp?id=13136367

[19] HEINSOO K., MERILO E., PETROVITS M., KOPPEL A., *Fine root biomass and production in a Salix viminalis and Salix dasyclados plantation*, Estonian J. Ecol., 2009, 58 (1), 27.

[20] TRUU M., TRUU J., HEINSOO K., *Changes in soil microbial community under willow coppice: The effect of irrigation with secondary-treated municipal wastewater*, Ecol. Eng., 2009, 35 (6), 1011.

[21] LAUREYSENS I., PELLIS A., WILLEMS J., CEULEMANS R., *Growth and production of a short rotation coppice culture of poplar. III. Second rotation results*, Biomass Bioenergy, 2005, 29 (1), 10.

[22] MCCRACKEN A.R., DAWSON W.M., *Rust disease (Melampsora epitea) of willow (Salix spp.) grown as short rotation coppice (SRC) in inter- and intra-species mixtures*, Ann. Appl. Biol., 2003, 143 (3), 381.

[23] BERGKVIST P., LEDIN S., *Stem biomass yields at different planting designs and spacings in willow coppice systems*, Biomass Bioenergy, 1998, 14 (2), 149.

[24] TAHVANAINEN L., RYTKÖNEN V.-M., *Biomass production of Salix viminalis in southern Finland and the effect of soil properties and climate conditions on its production and survival*, Biomass Bioenergy, 1999, 16 (2), 103.

[25] KOPPEL A., PERTTU K., ROSS J., *Estonian energy forest plantations – General information*, [in:] K. Perttu, A. Koppel (Eds.), *Short rotation willow coppice for renewable energy and improved environment*, SLU, Uppsala, 1996, 15.
[26] GRUENEWALD H., BRANDT B.K.V., SCHNEIDER B.U., BENS O., KENDZIA G., HÜTTL R.F., *Agroforestry systems for the production of woody biomass for energy transformation purposes*, Ecological Engineering, 2007, 29 (4), 319.
[27] STYSZKO L., FIJAŁKOWSKA D., SZTYMA-HORWAT M., *Influence of fertilization with compost from municipal sludge on the content of dry matter and the yield of energy willow planted on light soil*, Environ. Prot. Eng., 2011, 37 (3), 37.
[28] HOFMANN-SCHIELLE C., JUG A., MAKESCHIN F., REHFUESS K.E., *Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. I. Site–growth relationships*, For. Ecol. Manage., 1999, 121 (1–2), 41.
[29] OSTONEN I., PÜTTSEPP Ü., BIEL C., ALBERTON O., BAKKER M.R., LÕHMUS K., MAJDI H., METCALFE D., OLSTHOORN A.F.M., PRONK A., VANGUELOVA E., WEIH M., BRUNNER I., *Specific root length as an indicator of environmental change*, Plant Biosystems, 2007, 141 (3), 426.
[30] KOPP R.F., ABRAHAMSON L.P., WHITE E.H., VOLK T.A., NOWAK C.A., FILLHART R.C., *Willow biomass production during ten successive annual harvests*, Biomass Bioenergy, 2001, 20 (1), 1.
[31] WILLEBRAND E., LEDIN S., VERWIJST T., *Willow coppice systems in short rotation forestry: Effects of plant spacing, rotation length and clonal composition on biomass production*, Biomass Bioenergy, 1993, 4 (5), 323–331.
[32] LINDROTH A., BÅTH A., *Assessment of regional willow coppice yield in Sweden on basis of water availability*, For. Ecol. Manage., 1999, 121 (1–2), 57–65.
[33] ROWE R.L., STREET N.R., TAYLOR G., *Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK*, Renewable Sustainable Energy Rev., 2009, 13 (1), 271.
[34] WEIH M., *Genetic and environmental variation in spring and autumn phenology of biomass willows (Salix spp.): effects on shoot growth and nitrogen economy*, Tree Physiol., 2009, 29 (12), 1479.