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Dredged sediment as a substrate for biomass production of willow trees established using the SALIMAT technique

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Abstract

The periodic dredging of inland waterways and the subsequent disposal of the dredged sediment result in the continuous establishment of contaminated sites. As this dredged sediment is rich in nutrients, occupies extended areas and is often unsuitable for agriculture and public works due to the presence of contaminants, planting energy crops is one option for the remediation of this waste material. To evaluate dredged sediment as a substrate for growing willows, a 20×150 m disposal depot was successfully planted using rolls of connected willow rods (SALIMAT). Rods of a *Salix fragilis* clone and a *Salix triandra* clone were equally mixed in each mat. This SALIMAT proved to be an economic and effective planting technique for large areas of wet substrate. Leaf nutrient contents were determined to identify potential limiting growth factors Biomass production and tree survival over 4 years of stand development were assessed for three different planting spacings (10, 20 and 40 cm). Results of the foliar analyses indicated that both species were supplied with sufficient N, P, K and Ca to ensure optimal growth. The introduction of SALIMAT resulted in the rapid development of a high-density fast growing stand characterised by shoot densities of up to 54 shoots/m^2. An average annual production of 13.4 ton DM/ha was measured. The mixture of the two clones did not result in a polyclonal stand as *Salix triandra* was suppressed by *Salix fragilis*. The development of a willow stand was unsuccessful on parts of the depot with a sand fraction of 60%.

Keywords: *Salix fragilis*; *Salix triandra*; Dredged sediment; SALIMAT; Biomass production; Foliar nutrient concentrations; Phytostabilisation

1. Introduction

Periodic dredging of inland waterways is vital to ensure future navigation but it is a continuous source of large volumes of dredged materials that have to be discarded. Due to poor water management during the recent decades, most fine-grained sediments of the Belgian inland waterways are polluted with contaminants. The dredged silt is enriched with an excess of nutrients, heavy metals, organic compounds, pesticides and pathogens and the disposal results in the

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establishment of contaminated but fertile sites with few beneficial uses. In Flanders, each year about 135–160 ha of land are needed to dispose of the 4,000,000 m^3 of sediment dredged from inland waterways. Part of this volume (1,500,000 m^3) consists of non-brackish sediment, which is hydraulically transported as a suspension to landfill depots and is dewatered by superficial drainage. Currently, the disposal on land is typically in the form of a complete containment or a landfill with few other functions. The shortage of available land for such disposals is becoming an increasingly important problem.

The extensive reclamation of derelict and contaminated sites by the introduction of a vegetation cover has received increased attention in recent years. The focus in dealing with the reclamation of contaminated land is gradually shifting away from the traditional 'removal and disposal' techniques to more integrated in situ approaches such as phytoremediation. The use of a vegetation cover may allow a complete long-term rehabilitation of extended contaminated sites to be achieved [1]. The introduction of a vegetation cover is cheap and effective in reducing both surface erosion, through the development of a root system and a litter layer, and percolation of contaminants to watercourses through transpiration and interception of rainfall. If energy crops, such as willow trees, are used for the revegetation of contaminated sites with few alternative uses, additional income can be generated through the production of biomass for energy [2].

In recent years, fast growing willow species have been planted and studied on derelict land, often contaminated with heavy metals, including agricultural land used for sewage sediment and wastewater disposal [3,4], sanitary landfills [5] and industrial wasteland [6]. Trees on these sites were shown to remain healthy and productive in the presence of extremely high levels of contamination that build up slowly over time [7]. Using trees to reclaim contaminated sites enhances their visual appearance by adding structural diversity and by screening visually obtrusive elements. Trees also reduce erosion, stabilise substrates and initiate processes of soil development and nutrient cycling [8]. Willows are recognised as effective vegetation filters [2] because they have a high biomass productivity, an effective nutrient uptake [9], a high evaporation [10] and a pronounced clone specific capacity for taking up heavy metals [11,12]. As land-disposed, dredged sediment is rich in nutrients, occupies extended areas and is often unsuitable for use in agriculture and public works due to the presence of contaminants, planting energy crops could be a viable method for remediation of this waste material.

Due to the wet conditions of hydraulically confined dredged sediment, the generally used planting methods with cuttings cannot be used to introduce willow stands [13]. Field trials showed that the introduction of loose plant material (cuttings, seeds) was generally not successful as the plant material floats away due to rainfall or superficial draining before rooting occurs. The vertical planting of cuttings into the sediment, using a small boat, showed acceptable results but this method is expensive and highly labour intensive. To overcome these problems, the Laboratory of Forestry of the Ghent University and the firm De Vos 'Salix' developed a technique for planting willow on wet, inaccessible substrates such as dredged sediment. This technique, called SALIMAT, is based on the vegetative reproduction of willow from horizontally inlayed willow rods. Willow rods of a length of 2 m are tied together with biodegradable string and subsequently rolled around a central disposable tube. Different planting densities can be achieved with this technique as the length of the string used to hold the rods together can be adjusted. The technique offers multiple advantages [13]: (i) SALIMAT can be mechanically manufactured off site, (ii) it is easy to store and transport and (iii) it is a practical, low-cost, mechanised planting method.

This paper reports on the experiences with the SALIMAT technique for the introduction of willow on wet substrates. It evaluates the use of dredged sediment as a substrate for the growth of fast growing willow species based on leaf nutrient contents. The biomass production and tree survival over 4 years of stand development are reported for three different planting densities.

2. Materials and methods

2.1. Site description

In March 1993, a $150 \times 20\ m^2$ depot at the experimental site in Menen (Belgium) was raised by 2 m with dredged sediment from the adjacent river

Leie. The dredged sediment was mixed with water and pumped hydraulically into the depot. Excess water was removed through an overflow collector at the end of the depot. One week later, the depot was planted with willow using the SALIMAT technique. The SALIMATS were unrolled horizontally by dragging the tube right across the width of the depot. Three different spacings between the rods were tested, 10, 20, and 40 cm, with four replications of each planting density over the length of the depot. Two indigenous species, *Salix triandra* L., Almond willow (clone 'Noir de Villaines') and *Salix fragilis* L., Crack willow (clone 'Belgisch rood'), were equally mixed in each mat. After the establishment of the stand, a 22-point grid was defined. No additional management inputs such as herbicides and fertilisers were used in the trial.

2.2. Sampling and measurements

After the first growing season, every grid point ($n = 22$) was sampled down to 25 cm to determine the substrate's main chemical and physical characteristics. Leaves were collected from the stand in the 2nd week of August of the first and second growing seasons for the determination of their nutrient contents. At each of the 22 grid points two to three trees were cut and all leaves were stripped. The leaves collected at each grid point were bulked and subsampled for analysis. After each growing season, from 1994 to 1997, at least 12 circular plots (four for each spacing) with a diameter of 1 m were randomly chosen and cut from the stand at ground level to determine the above ground biomass. Trees were subsequently cut in pieces and weighed on the site. Subsamples of the wood were taken to determine the moisture content. Samples were dried in a forced air oven for 3 days at 105°C. Shoot density was counted after the first and third growing season in randomly chosen 3.14 m^2 sample plots.

2.3. Analyses

The soil samples were analysed for soil pH (H_2O) and electrical conductivity (EC). Nitrogen was determined using the Kjehldahl method [14], the soil carbon content was analysed using the Walkley and Black methods [15]. Other nutrients (P, K, Mg, Ca) and metals (Cd, Pb, Zn, Cu and Ni) were extracted from 3 g subsamples with an *aqua regia* extraction of HCl and HNO_3 and were subsequently determined with an inductively coupled plasma (ICP) spectrophotometer. The particle size distribution of the dredged sediment was analysed using the pipette method based on Stokes sedimentation law [16].

The sampled leaves were ground with a mortar and pestle and dried at 70°C for 3 days before analyses. Leaves were digested by dry ashing for 2 h at 450°C, the ash then being taken up into HNO_3. Leaf nutrient concentrations of P, K, Mg and Ca in the digests were determined on ICP. Leaf nitrogen concentrations were determined using the Kjehldahl method [14].

3. Results

3.1. Substrate characteristics

The hydraulic filling of the depot resulted in the establishment of a swampy, impassable terrain, which was waterlogged at several places. Due to the different sedimentation characteristics of the sediment fractions two areas could be observed in the depot: close to the inlet of the depot a sand plate developed as the heavier sand fraction settled fast while the silt and clay fractions were transported further from the inlet as they remained in suspension. The length of this sand plate was about 10 m, the other 140 m was characterised by a slight texture gradient. Results of the physical and chemical analyses of the substrate samples are presented in Table 1. The minimum and maximum values give an indication of the texture-correlated nutrient and contaminant concentrations with minimal values describing the sand plate characteristics and maximal values representing the concentrations found in the most clayey parts of the depot.

3.2. Stand establishment

By dragging the tubes across the depot the SALIMAT planted itself by slightly sinking into the sediment under its own weight. Establishment of the SALIMAT was successful as the rods sprouted 1 week after planting. SALIMATS on the sand plate (20×10 m^2) close to the inlet of the depot did not produce shoots, as rods did not sink into the substrate. It is thus vital that the rods should be covered with a layer of sediment and water to prevent

Table 1
Chemical characteristics of substrate samples (0–25 cm) at 22 gridpoints ($n = 22$)

	Unit	Mean	Standard error	Min.	Max.
pH-H_2O		7.0	0.0	6.4	7.2
EC	μS/cm	1695.8	123.3	951.0	2980.0
Carbon	%	3.3	0.2	1.7	5.6
$CaCO_3$	%	7.3	0.1	6.3	9.3
Sand (> 50 μm)	%	27.9	2.6	10.2	64.2
Silt (2–50 μm)	%	46.0	1.9	22.8	60.3
Clay (< 2 μm)	%	22.7	0.9	17.3	32.3
N	g/kg	2.9	0.2	1.7	4.6
P	g/kg	8.9	0.4	5.3	14.0
K	g/kg	4.3	0.2	2.8	5.7
Ca	g/kg	28.8	0.4	25.4	33.7
Mg	g/kg	3.4	0.1	2.9	4.0
Zn	mg/kg	577.0	21.7	441.2	818.6
Pb	mg/kg	121.4	4.1	86.9	159.2
Cd	mg/kg	4.6	0.2	3.0	6.8
Cu	mg/kg	75.4	2.7	56.9	101.4
Ni	mg/kg	45.1	2.3	28.1	72.1
Cr	mg/kg	107.7	3.9	82.6	148.5

desiccation. Based on the results of the particle size analysis (Table 1) it can be concluded that the introduction of SALIMAT will not be successful on mineral substrates with a sand fraction around 60%. After 1 month, a dense cover of small willow shoots covered the rest of the depot.

3.3. Nutrient concentrations of the leaves

The results of the foliar analysis are used in this study to identify potential limiting growth factors of the sediment. Rytter and Ericsson [17] concluded that the most commonly used base for expressing the nutrient status of plants, i.e. nutrient amount per unit dry weight of leaves, gives an adequate description of the nutritional status of *Salix* trees on fertile soils. To evaluate the nutrient status of dredged sediment for the growth of willows the leaf nutrient contents on a leaf dry weight basis (Table 2) are compared with the threshold contents of nutrients in leaves for sufficient and optimal growth as postulated by Van den Burg [18] (Table 3). No visual indications of nutrient deficiency were observed in this trial.

The concentrations of N in the *Salix fragilis* and *Salix triandra* leaves sampled in the first growing season were 2.79% and 3.55%, respectively, indicating that both species were well supplied with nitrogen [18]. The amount of available N in the dredged sediment can be considered to be sufficient for *Salix fragilis* and optimal for *Salix triandra*. The N concentrations of both clones in the first and second growing season were comparable but this was not the case for the foliar P concentrations of both clones. Mean phosphorus concentrations in leaves of the 2-yr-old *Salix fragilis* and *Salix triandra* trees were 7.95 and 8.44 g P/kg, respectively, while the concentrations in the 1-yr-old stand were 2.57 and 2.99 g P/kg. In every growing season, the concentrations of phosphorus in the leaves of both clones surpassed the 2.1 g P/kg level for optimal P supply [18]. Rytter and Ericsson [17] reported the highest P content of 4–5 g P/kg in the second half of the season.

Mean foliar potassium concentrations in the first growing season of 21 and 19 g K/kg in the *Salix fragilis* and *Salix triandra* leaves, respectively, were also higher than the threshold values for optimal growth. Van den Burg [18] recommended 8 and 18 g K/kg as threshold values for sufficient and optimum growth. The fast growing willow stands on fertile arable soils in the study of Rytter and Ericsson [17] featured concentrations between 15 and 20 g K/kg in their aerial tissue.

Table 2
Mean values with standard errors for the foliar nutrient contents (g/kg) of *Salix fragilis*, 'Belgisch rood' and *Salix triandra*, 'Noir de Villaines' in the first two growing seasons ($n = 22$)

		S. fragilis 'Belgisch Rood'		*S. triandra* 'Noir de Villaines'	
		Mean (g/kg)	St. error	Mean (g/kg)	St. error
1993					
	N	27.91	0.82	35.52	0.42
	P	2.57	0.07	2.99	0.10
	K	21.45	0.78	19.45	0.64
	Ca	17.66	0.76	11.92	0.40
	Mg	1.68	0.04	1.55	0.03
1994					
	N	28.23	0.39	35.3	0.35
	P	7.95	0.25	8.44	0.22
	K	20.76	0.56	18.51	0.30
	Ca	14.71	0.44	9.82	0.16
	Mg	2.87	0.06	2.03	0.08

Table 3
Nutrient concentrations (g/kg) in *Salix* leaves for sufficient and optimal growth of willow [18]

	Sufficient (g/kg)	Optimal (g/kg)
N	22.0	30.0
P	1.8	2.1
K	8.0	18.0
Ca	3.5	4.5
Mg	1.6	3.0

The willows growing on the dredged sediment were provided with a high level of Ca. Mean Ca concentrations in the *Salix fragilis* and *Salix triandra* trees reached 17.7 and 11.9 g Ca/kg, respectively, in the first growing season and far exceeded the critical Ca concentration for optimal growth of 4.5 mg Ca/kg reported by van den Burg [18] although in the second growing season Ca levels were lower (Table 2). According to Rytter and Ericsson [17], vigorous *Salix viminalis* L. stands on fertile clayey soils were characterised by foliar Ca concentrations between 12 and 15 g/kg.

Foliar Mg concentrations were 2.87 and 2.03 g/kg for the *Salix fragilis* and *Salix triandra*, respectively, in their second growing season. Willows are well supplied with Mg if they contain between 2 and 2.5 g/kg of this element in their foliage [17,18]. Concentrations found in leaves sampled during the first growing season were below these threshold values, indicating an insufficient supply for this period, although no visual symptoms of Mg deficiency were observed.

3.4. Shoot density

High densities of shoots per hectare were observed after the first growing season (Table 4). A distance of 10 cm between the rods resulted in the highest total shoot density of 545,000 shoots/ha with 20 or 40 cm spacings leading to 330,00 and 230,000 shoots per hectare, respectively. After the first growing season 20% of all shoots had died in the 10 cm spacing while these percentages were 5% and 20% for the 20 and 40 cm treatments, respectively. However, with 440,000 living shoots/ha, the number of living shoots in the 10 cm treatment was still 40% and 136% higher than the number in the 20 and 40 cm treatments. *Salix fragilis* showed the better stand establishment on dredged sediment as was shown by the higher shoot densities in all treatments. In the mats with 10 cm of spacing, one third of the total living shoots are of the *Salix triandra* clone resulting in a *triandra/fragilis* ratio of 0.5. This difference declined with increasing rod spacing, with a ratio of 0.6 at the 20 cm spacing and 0.7 at 40 cm.

Two growing seasons later, the total number of trees (dead and living) was reduced by 53%, 25%

Table 4
Shoot densities of *Salix fragilis*, 'Belgisch Rood' and *Salix triandra*, 'Noir de Villaines' in their first and third growing season at three different rod distances (shoots/m^2)

Year	Rod distance	*S. triandra* (shoots/m^2)	*S. fragilis* (shoots/m^2)	Sum living (shoots/m^2)	Dead (shoots/m^2)	Living + dead (shoots/m^2)
1993	10	15.25[a]	28.50[a]	43.75[a]	10.75[a]	54.50[a]
	20	11.75[ab]	19.25[ab]	31[ab]	1.75[b]	32.75[ab]
	40	7.50[b]	11[b]	18.50[b]	4.75[ab]	23.25[b]
1995	10	4.25[a]	6.25[a]	10.50[a]	15[a]	25.50[a]
	20	6.50[a]	5.50[a]	12[a]	12.75[a]	24.75[a]
	40	3.75[a]	5.75[a]	9.50[a]	8.75[b]	18.25[b]

[a]Letters indicate homogenous subgroups with no significant differences between means according to Tuckey's post hoc test ($\alpha = 0.05$).

and 20% for the 10, 20 and 40 cm treatments, respectively. After 3 years the effect of the rod spacing on the density of living trees was negligible, as the number of living trees in all treatments had decreased to about 110,000 per ha with no significant differences between the treatments. The density of dead shoots however still reflected the spacing density. Shoot densities of *triandra* trees were just below those of *fragilis* in each treatment. In the 10 and 40 cm treatments the *triandra*/*fragilis* ratio was 0.66, whereas in the 20 cm treatment slightly more *triandra* than *fragilis* trees were found as indicated by a ratio of 1.16.

3.5. Biomass production

After the first growing season, 10.3 ton DM/ha of total standing biomass was measured over the whole of the depot (Fig. 1). With increased spacing between the rods from 10 to 40 cm the yield dropped from 11.97 to 8.23 ton DM/ha. Dead wood constituted about 14–15% of the total biomass in all treatments, indicating that the amount decreased proportionally with increased rod spacing. With the 10 cm spacing the amount of *Salix fragilis* biomass was more than double the biomass of *Salix triandra*. This difference was smaller at lower planting densities. Tree growth was the most vigorous in the second growing season with an increment of 17.5 ton DM/ha/yr. The amount of living and dead biomass increased by 17 and 0.5 ton DM/ha, respectively. The percentage of dead wood was lower than in the first growing season as only about 5–8% (for 40 and 10 cm spacings) of the above ground biomass was found to be dead. If the stand was harvested after 3 yr, the mean yield of the three treatments would reach 43.1 ton DM/ha of which 8.5% was dead. Only one quarter of the biomass consisted of *Salix triandra* indicating inferior growth compared to the *Salix fragilis* clone. This percentage decreased to 15% after the fourth growing season. Four years of stand development resulted in a standing above ground biomass of 55.7 ton DM/ha, representing a mean annual biomass production of 13.9 ton DM/ha/yr.

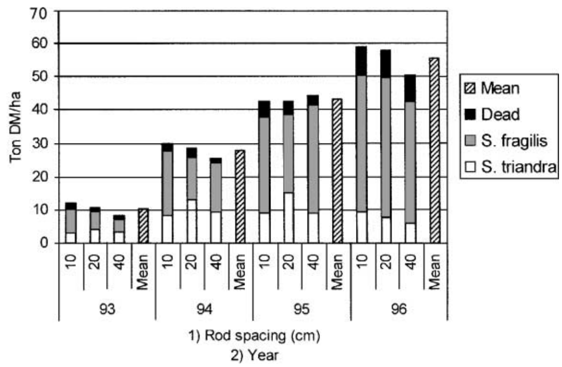

Fig. 1. Mean DM biomass determined after each growing season of a mixed stand of *Salix triandra*, 'Noir de Villaines' and *Salix fragilis*, 'Belgisch Rood' on dredged sediment (ton DM/ha).

4. Discussion

The SALIMAT planting technique proved to be successful for the rapid introduction of a dense willow stand on land disposed, dredged sediment. Within a few weeks after introduction, the dredged sediment depot was covered by a dense willow stand, with a number of positive consequences already described by several authors [2,8,11]. Owing to the production of a large amount of litter there is, with time, an increase in the humus content of the substrate that favours the biochemical stabilisation of the dredged sediment by increased nutrient cycling and the activation of a soil biotic community leading to the initiation of soil formation and the creation of a forest microclimate [19]. Through the development of a high-density, perennial root system and the accumulation of organic matter and litter on the soil surface, the dispersal of contaminants by wind or runoff is greatly reduced [20]. Nutrients and metals are stabilised against leaching as water infiltration is reduced by increased evapotranspiration and as rainwater is intercepted by the canopy [10,19]. In addition, the high evaporation rates increase the dewatering speed of the sediment. At the same time the site is landscaped and integrated into its environment. In this way, confined dredged sediment disposal sites that were previously derelict can be transformed to more aesthetically appealing elements in the landscape. Considering the above-mentioned beneficial influences of cultivating fast growing energy crops, the introduction of the SALIMATS can be regarded as a phytostabilisation step in the remediation of dredged sediment depots. In addition to the use of willows for phytostabilisation they can also be used for phytoextraction of heavy metals. Studies have shown that there is a relatively large uptake of cadmium into the shoots of *Salix* plants with reported Cd contents ranging from 0.4 to 3.9 mg/kg [11,21,22]. This implies a potential to clean dredged sediment of cadmium through the export of metals with the repeated harvest of biomass. However, only if the high yields of *Salix* are combined with greater rates of metal uptake than so far reported, would the use of willows for phytoremediation of metals from soils be effective [20]. Dickinson et al. [23] calculated that cadmium concentrations could only be reduced by 10 mg/kg in 16 years if plant yields of 10 ton DM/ha/yr and tissue concentrations of 250 mg/kg were achieved.

An important factor for the success of the SALIMAT technique is the moisture content of the substrate. The substrate should be wet or saturated with water to allow optimal rooting of the *Salix* rods. It is vital, therefore, that the SALIMAT sinks slightly into the substrate to avoid desiccation. The technique is not suited to gravel, sandy textured soils or consolidated sediment (crusts). This study showed that SALIMAT introduction is not successful on mineral substrates with a sand fraction of 60% or higher. Only a small area of the depot close to the inlet had such a high sand fraction, the rest of the depot being filled with medium textured, dredged sediment. The medium texture across the majority of the depot and the neutral pH of the dredged substrate can be considered optimal for willow growth and nutrient availability [9,24]. In addition, the high buffering capacity of the sediment due to the high amounts of $CaCO_3$ present will prevent acidification and reduce metal leaching. It is possible to apply the SALIMATS on dry surfaces if the precautions necessary to prevent dessication of the rods are followed. On dry surfaces, the SALIMATS can be unrolled with a tractor or by hand and should then be covered with a thin layer of soil. Another limitation is that the SALIMAT introduction is restricted to the period from November until the end of April. Activities should be planned to finish dredging and land filling during this period to optimise field conditions for SALIMAT application.

The results of the foliar macronutrient levels indicate that the *Salix* species were growing under favourable conditions for the production of biomass. To summarise the comparison of leaf nutrient concentrations with those of van den Burg [18], the amounts of available P, K, and Ca present in the dredged sediment were sufficient to ensure optimal growth of willow. In addition, the foliar N, P, K, Ca and Mg concentrations of both clones in this experiment were comparable with the nutrient concentrations of willows growing on fertile arable soils in Sweden as reported by Rytter and Ericsson [17]. The N concentration of the *Salix fragilis* trees was slightly below the 3% N threshold for optimal growth. The amount of available N in the dredged sediment can thus be considered sufficient for *Salix fragilis* and optimal for *Salix triandra*. In general, nitrogen is the element most limiting the production of biomass in short rotation forestry (SRF) when all other factors are favourable [9]. Rytter and Ericsson [17] determined foliar nutrient concentrations of 2-yr-old *Salix viminalis* stands on very fertile arable soils in Sweden during August and September, and recommend 30 g N/kg as optimal for growth in accordance with van den Burg [18]. Jug et al. [25] also concluded that concentrations above 3% are needed for optimum growth as they observed that willows supplied with N fertiliser only showed superior yields when foliar concentrations were between 3% and 4%. Concentrations above 4% indicated luxury uptake.

With an increment of 13.91 ton DM/ha/yr in the first 4 years after establishment, the willow stand on dredged sediment was highly productive. The high biomass production is additional evidence of the suitability of dredged sediment as a substrate for the growth of fast growing willow species. In SRF, yields normally vary from 10 to 15 ton DM/ha/yr depending on management and site characteristics, while exceptional productions up to 20 ton DM/ha/yr have been reported [24]. Biomass yields in this study were achieved with clones that had not been selected for high biomass production, probably underestimating the potential biomass production with selected *Salix viminalis* clones. After the first growing season there were differences in yields between the different spacings tested as the yield increased with increasing planting density. These differences became smaller in later growing seasons especially between the 10 and 20 cm treatments. The biomass production over 4 yr obtained with these two planting densities was about 58 ton DM/ha. Using 40 cm between the rods resulted in a lower yield of 50 ton DM/ha after 4 yr. In each of the four growing seasons the amount of dead wood decreased with decreasing planting density. Competition between trees is most intense when higher plant densities are used. Mortality in the first year after introduction was greatest as shoots were vulnerable to stress and competition. In the second growing season, mortality was reduced due to the selection that had occurred during the first growing season. Following the second growing season the percentage of dead biomass increased again, indicating mortality due to increased competition between trees combined with lower increments of living biomass. All treatments featured the same percentage of dead wood after four growing seasons (15%) indicating a proportional increase of dead and living biomass with increased plant density. Willebrand et al. [26] concluded for SRF that the dependence of yield on initial planting density disappears at higher densities and becomes weaker at low densities in later rotations. As very high densities of shoots are obtained using the SALIMAT technique it is likely that after several more growing seasons, yields would be similar for all three treatments. The differences between treatments would also disappear if the stand was coppiced after 4 yr. This is indicated by the similar densities of living trees after 3 yr for each of the three treatments. After coppicing, the stools of these trees will grow the shoots for the next rotation.

The mixture of *Salix triandra* and *Salix fragilis* in the SALIMATS did not result in a polyclonal stand as the *Salix triandra* was suppressed by the *Salix fragilis*. After 4 yr only 15% of the living biomass consisted of *Salix triandra*. *Salix fragilis* is known to be rather undemanding of soil type, and to grow well in locations with elevated moisture content or in dry valleys. It is one of the tallest tree-like willows as it can attain a height of 20 m. *Salix triandra* is a shrub or small tree up to 9 m high and is one of the easiest rooting willows [27]. Only on the borders and on the sandiest spots next to the inlet of the depot did *Salix triandra* trees survive. The fact that only *Salix triandra* was established on these sandy parts can be explained by its good rooting capabilities, even when the rods did not sink entirely into the dredged sediment. This highlights another advantage of the SALIMAT technique. Clones, which grow in different soil and moisture conditions, can be incorporated into one SALIMAT. In this way, surfaces with a great variability in soil and moisture conditions, which is often the case with larger disposal sites for dredged sediment, can be successfully planted over their entire area. If only one clone was used, spots with unfavourable growth conditions would remain as open gaps in the stand. This would result in an ineffective capping of the site and in a lower biomass production per hectare.

5. Conclusions

The SALIMAT planting technique proved to be successful for the rapid introduction of a dense willow stand on land disposed, dredged sediment and was highly efficient and cost effective compared to traditional planting techniques. The introduction of SALIMATS results in an effective ‘green capping’ of the polluted site through the development of a high-density, fast-growing stand with a long growing season. From the leaf analysis and yield results it can be concluded that this dredged sediment provided a suitable substrate for the growth of fast growing trees for biomass production. Although the production of biomass on dredged sediment shows promising results, some remarks can be made from a management point of view. In traditional SRF for example, cuttings are planted in rows to allow mechanical harvesting. Using the SALIMAT technique to introduce the trees results in a dense stand, which is difficult to access with machinery. Since SRF is based on several rotations, knowledge on the coppicing, tending and harvesting of these stands is needed. Additional research should thus focus on the management of these sites.

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