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Long-Term Effect of Wood Ash and Wastewater Sludge Fertilization on Tree Growth in Short-Rotation Forest Plantations on Abandoned Agricultural Land: A Case Study

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Abstract: Short-rotation forest plantations on former agricultural land capture CO_2, provide bioeconomic materials, and mitigate climate change. This study aimed to enhance our understanding of the long-term effects of wood ash and wastewater sludge fertilization on various tree species (birch, hybrid aspen, grey alder, black alder, and hybrid alder) in short-rotation forestry plantations on abandoned agricultural land where tree growth measurements were taken over an 11-year period. After 11 years, the highest aboveground biomass (AGB) was observed for hybrid aspen clone No. 4 under wastewater sludge treatment (109.0 t ha^{-1}), birch under wood ash treatment (34.3 t ha^{-1}), black alder under wastewater sludge treatment (33.6 t ha^{-1}), grey alder under wastewater sludge treatment (40.9 t ha^{-1}), hybrid alder under control conditions (36.2 t ha^{-1}), and hybrid aspen clone No. 28 under wood ash treatment (37.2 t ha^{-1}). The average survival rate was 73% in control plots, 81% under wastewater sludge treatment, and 78% under wood ash treatment. Short-term positive impacts on tree growth were observed, effects that were not consistent over the long term. The impact of these treatments on tree growth varied between species, and the effects tended to diminish over time, which must be considered before fertilization.

Keywords: wastewater sludge; wood ash; tree plantation fertilization; fertilization effectiveness; short-rotation forestry (SRF)

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1. Introduction

Contemporary energy and environmental issues have led to a renewed focus on short-rotation forestry plantations for biomass production. Planting forests that grow quickly on former agricultural land is seen as a promising way to manage forests in Northern Europe and can help provide more raw material for bio-economies in the future while reducing climate change by capturing CO_2 from the air. Short-rotation forestry plantations are often established on low-fertility sites that are not used for food production, with all agricultural activities on these lands having ceased [1]. Afforestation of these lands may be a way to achieve climate change mitigation due to forests' ability to absorb and store carbon [2] Biomass-derived materials such as lignocelluloses can substitute for polymer materials from fossil resources (petroleum materials) [2]. Biopolymers, compared to fossil fuels, have slightly lower environmental impact [3] and could be used in biomedical applications [4]. Productive planted forests, particularly those in plantations, can match or even surpass the biomass productivity levels of agricultural energy crops [5].

In Latvia, current regulations allow for the registration of stands planted on agricultural land as plantation forests. This enables the application of various management measures and also leaves open the option to revert these areas back to agricultural production. The establishment of medium- or short-rotation plantation forests on unused agricultural lands remains one of the most cost-effective and efficient ways to manage a property [6].

Today, much low-yield farmland is planted with fast-growing trees such as hybrid aspen (*Populus tremuloides* Michx. x *Populus tremula* L.), poplar (*Populus* sp.), willow (*Salix* sp.), or birch (*Betula* sp.) [7,8]. Trees on this type of land produce high biomass yields but also deplete soil nutrients, so fertilization is required to maintain wood production [9]. The use of fertilizers in forestry is related to management intensification, which aims to increase the average amount of wood produced per land unit. Intensification shortens the crop cycle and increases the frequency of harvesting [10]; at the same time, the use of fertilizers like wood ash and wastewater sludge could lead to better waste management [11].

Biomass is an alternative to fossil fuels for the production of energy, and wood ash is a by-product of biomass combustion in boiler houses and power plants. Forest growth and CO_2 sequestration rates may be increased by forest fertilization [12]. Using wood ash as fertilizer can help manage forests' sustainably and may represent a green method for dealing with energy producers' waste issues. After biomass combustion, 0.7–3% of the weight of the biomass used is transformed to wood ash [13]. Wood ash disposal in landfills is costly; however, it contains many nutrients that are essential for the soil and can be used as an alternative to mineral fertilizer in tree plantations [14]. Wood ash fertilization helps replenish soil nutrients, adjust nutrient levels in tree stands, prevent soil from becoming too acidic, and enhance tree growth [15]. Wastewater sludge is a byproduct of wastewater treatment and can be used as biochar or a building material, incinerated, or buried in landfills [16–19]. However, it can also be used as fertilizer, as it contains a great deal of organic matter, nitrogen, phosphorus, and micronutrients; it has the potential to improve the quality of the soil by recycling the nutrients in the soil system, thus reducing or eliminating the need for inorganic fertilizer [20]. Wastewater sludge applied to former agricultural land may lead to better plant and tree growth without the use of synthetic fertilizers [21]. Previous results have shown that wood ash and wastewater sludge treatments have a positive effect on the growth (measured as height) of birch and grey alder in the first few years after planting [22]. Not only does fertilization potentially influence forest growth, but it can also have an impact on mortality rates: by increasing the availability of nutrients, fertilization can potentially decrease mortality rates by reducing nutrient competition [23].

The specific aim of this study was to contribute to the improvement of knowledge on the effect of wood ash and wastewater sludge fertilization on different tree species in short-rotation forest plantations on abandoned agricultural land over a long period. We hypothesized that the wood ash and wastewater sludge fertilization effect on tree growth in short-rotation forestry plantations is positive in the first years and will diminish after several years.

2. Materials and Methods

2.1. Study Site

The study site was set up on previously cultivated agricultural land underlain by mineral soils (*Luvic Stagnic Phaeozem*, *Hypoalbic and Mollic Stagnosol*, *Ruptic*, and *Calcaric*) [24] in the Skriveri district, located in the central region of Latvia (Figure 1). This took place during the spring of 2011, following the final plowing of the soil. The prevailing soil texture [25] primarily consisted of loam and sandy loam at the 0–20 cm depth range, transitioning to sandy loam at depths of 20–80 cm.

Meteorological data were taken from Skriveri meteorological station (5.5 km from the plantation), which is part of the Latvian Environment, Geology and Meteorology Center network. The average annual air temperature in the 2011–2021 period was 7.46 °C, with the highest average temperature recorded in 2020 at 8.66 °C and the lowest in 2012 at 6.06 °C. Maximum air temperature in the 2011–2021 period was 32.89 °C, and minimum air temperature was −29.62 °C. Average annual precipitation in this period was 772 mm, with the highest in 2012 at 935 mm and the lowest in 2019 at 558 mm [26].

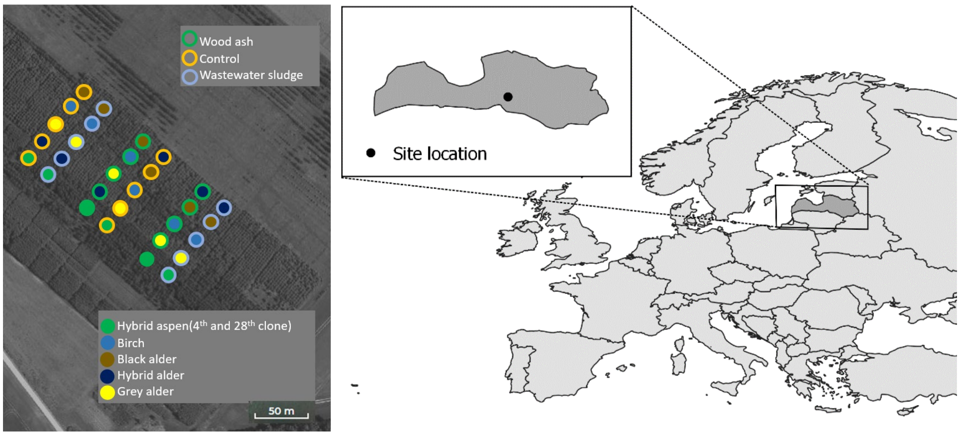

Figure 1. Planting site scheme and location of the study site.

2.2. Study Site Fertilization

Three different methods of soil fertilization were applied and compared (Table 1). Fertilization was performed mechanically using tractors and agricultural spreaders. The first method was no fertilization at all, for control purposes. The second method involved initial fertilization using wood ash, which contains a variety of minerals. The third method involved initial fertilization using wastewater sludge, which is rich in organic nitrogen, phosphorus, and carbon and contains a variety of other elements. The soil was fertilized only once in 2011, as homogenously as possible, with no further fertilization carried out. Two repetitions were performed for every tree species and each fertilizer, and every subplot covered an area of 0.044 ha (20 × 22 m).

Table 1. Fertilizers and nutrient inputs (kg ha^{-1}) through fertilization.

Fertilizer	Fertilization Dose	Origin	Major Nutrient Inputs through Fertilization		
			Ntot	**Ptot**	**Ktot**
Wood ash	6 t DM ha^{-1}	Boiler house, Sigulda	2.6	65	190
Wastewater sludge	10 t DM ha^{-1}	Wastewater treatment plant, Aizkraukle	259	163	22

2.3. Planting Material

For each fertilization type, five different tree species (Table 2) were planted in two repetitions. All tree species were mechanically planted by hand in 2011 using containerized seedlings. Two different clones (4 and 28) of hybrid aspen were planted to compare and evaluate their biomass production. In each subplot for birch, grey alder, black alder, and hybrid alder, eight tree lines were planted, with nine trees in each line. For each hybrid aspen clone, five lines with eleven trees per line were planted.

Table 2. Planting material and study design characterization.

Tree Species	Planting Material Supplier	Planting Scheme (m)	Planting Density (Trees ha^{-1})	Trees Planted in One Subplot (2011)
Hybrid aspen clone No. 28 (*Populus tremuloides* Michx. × *Populus tremula* L.)	JSC "Latvian State Forests" nursery in Kalsnava	2.0 × 2.0 m	2500	55
Hybrid aspen clone No. 4 (*Populus tremuloides* Michx. × *Populus tremula* L.)	JSC "Latvian State Forests" nursery in Kalsnava	2.0 × 2.0 m	2500	55
Silver birch (*Betula pendula* Roth)	JSC "Latvijas Finieris" nursery "Zabaki"	2.5 × 2.5 m	1600	72

Table 2. *Cont.*

Tree Species	Planting Material Supplier	Planting Scheme (m)	Planting Density (Trees ha^{-1})	Trees Planted in One Subplot (2011)
Grey alder (*Alnus incana* (L.))	JSC "Latvijas Finieris" nursery "Zabaki"	2.5 × 2.5 m	1600	72
Black alder (*Alnus glutinosa* (L.))	JSC "Latvijas Finieris" nursery "Zabaki"	2.5 × 2.5 m	1600	72
Hybrid alder (*Alnus hybrida* A. Br)	LSFRI "Silava" and forest research station nursery in Kalsnava	2.5 × 2.5 m	1600	72

2.4. Height, Diameter, and Aboveground Biomass Calculations

All sampling plots were measured at different times. For the first eight years (2011–2019), only tree height (H) was measured. In the first few years, a measuring tape was used, and a leveling staff was used in later years. In 2021, tree diameter at breast height (DBH) was measured with a tree caliper. For each tree trunk, measurements were performed in two directions (north–south and east–west), and the mean value was included in the calculations. All trees with DBH > 5.99 cm were measured and included in the calculations. Trees with DBH < 6.00 cm were considered shoots and excluded from further calculations. Tree height was calculated in 2021 using a DBH–height curve [27] fitted for each subplot, where the height of five sample trees was measured. Aboveground dry biomass (AGB) for every hybrid aspen, birch, grey alder, black alder, and hybrid alder trunk was calculated using allometric models that incorporated DBH and tree height [28,29].

2.5. Statistical Analyses

The R program [30] was used for all statistical analyses. The Shapiro–Wilk normality test was used to check the data for normal distribution and variance homogeneity. The Wilcoxon rank sum exact test was used for pairwise comparisons to assess differences in mean height, DBH, and AGB between different fertilization methods for each tree species, with a significance level of 0.05. In the text, significance levels are described as *** (<0.001)—highly significant, ** (0.001–0.01)—very significant, * (0.01–0.05)—significant, and NS—not significant. All results are shown as arithmetic means ± standard error of the mean (SEM).

3. Results

3.1. Fertilization Impact on Single Tree Height

In the birch sampling plots, there were no significant height differences between trees under the control treatment and those treated with wood ash and wastewater sludge ($p > 0.05$) directly after planting, at which time the mean tree height in the control plot was 0.5 m (Figure 2). However, in the first year, there were significant differences between trees in the control plot, with a mean height of 0.60 ± 0.02 m, and trees in the wastewater sludge plots, with a mean height of 0.66 ± 0.01 m ($p = 0.015$). In the second year, there was once again no significant difference between mean heights, with a mean height of 0.81 ± 0.02 m in the control plot. After the third year, trees under the wood ash and wastewater sludge treatments showed significant and very significant height increases, respectively, compared to trees under the control treatment (wood ash: $p = 0.016$; wastewater sludge: $p = 0.0092$), with mean heights of 1.24 ± 0.05 m under the control treatment, 1.39 ± 0.05 m under the wood ash treatment, and 1.44 ± 0.05 m under the wastewater sludge treatment. This pattern of significance continued in the fourth year, with wood ash still having a significant impact: the treatment produced a mean height of 2.29 ± 0.07 m ($p = 0.024$) compared to the control's mean height of 2.08 ± 0.08 m. By the eighth year, wood ash had a very significant impact on birch seedling growth, with a mean height of 7.31 ± 0.09 m ($p = 0.0021$) compared to the control's mean height of 6.85 ± 0.11 m. By the eleventh year, the significance levels decreased, and there were no significant differences observed between the control plot, with a mean height of 11.01 ± 0.07 m, and the fertilized plots.

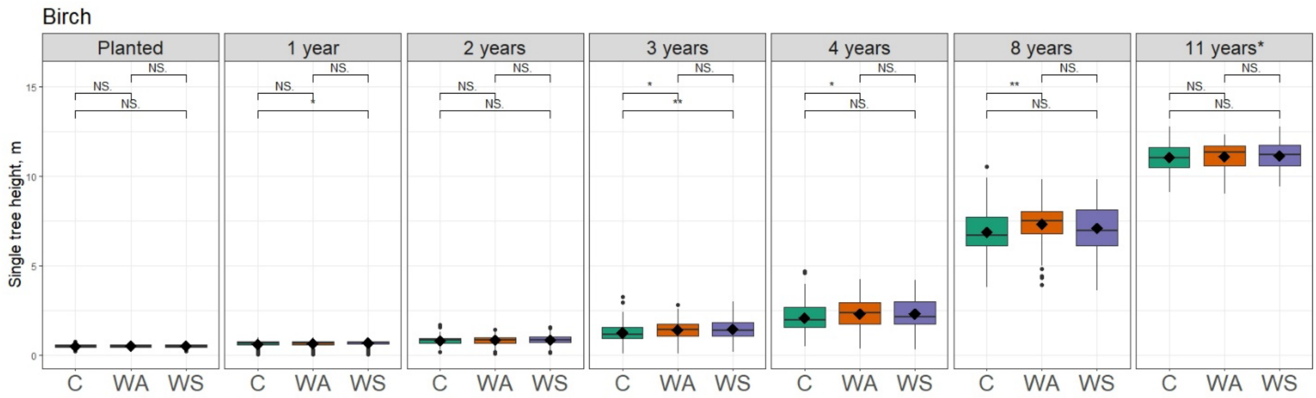

Figure 2. Single tree height in birch plantations with different fertilizers. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Significance levels of ** (0.001–0.01), * (0.01–0.05), and NS (not significant) show the results of the Wilcoxon test between fertilizers. ★ At the age of 11 years, tree height was not measured directly for every tree but calculated using the DBH–height function.

Directly after planting hybrid aspen clone No. 4, there was no significant height difference between the control group (with a mean height of 0.22 ± 0.006 m) and seedlings treated with wood ash, but there was a highly significant difference between the control and seedlings treated with sewage sludge, which had a mean height of 0.36 ± 0.02 m ($p = 7 \times 10^{-8}$) (Figure 3). After the first year, the mean height in the control plots was 0.66 ± 0.02 m, very significantly and significantly higher compared to the wood ash (0.53 ± 0.02 m, $p = 0.0003$) and wastewater sludge plots (0.58 ± 0.01 m, $p = 0.035$). By the second year, there were no statistically significant differences in height between the control group (1.45 ± 0.04 m) and the wood ash group, but there was a significant difference with the wastewater sludge group, which had a mean height of 1.55 ± 0.05 m ($p = 0.045$). This pattern of significance continued in the third, fourth, and fifth years, with significant height differences continuing only between the control group mean heights of 2.43 ± 0.09 m, 4.01 ± 0.14 m, and 5.85 ± 0.15 m and the wastewater sludge group mean heights of 2.68 ± 0.08 m, 4.56 ± 0.11 m, and 6.33 ± 0.14 m. In the eighth year, there was no difference, but in the eleventh year there was a significant difference between the control group, with a mean height of 14.39 ± 0.18 m, and the wastewater sludge group, with a mean height of 14.82 ± 0.19 m ($p = 0.047$).

Directly after planting hybrid aspen clone No. 28, highly significant height differences were found between the control plot's mean height of 0.21 ± 0.004 m and the wood ash plot's mean height of 0.18 ± 0.005 m ($p = 0.0067$) (Figure 3). After the first year, no differences were observed. After the second, third, fourth, and fifth years, differences were observed only between the control group (with mean heights of 0.95 ± 0.04 m, 1.59 ± 0.07 m, 2.60 ± 0.09 m, and 3.62 ± 0.14 m), and the wood ash plot (with mean heights of 1.08 ± 0.0 m, 1.76 ± 0.05 m, 3.10 ± 0.08 m, and 4.33 ± 0.11 m). After eight years, a significant difference was observed between the control plot height (7.79 ± 0.23 m) and the wastewater sludge plot height (7.12 ± 0.14 m) ($p = 0.022$). After eleven years, significant differences were not observed between the control and fertilized plots.

The hybrid alder height was first measured in the second year, at which time the mean height in the control plots (0.41 ± 0.02 m) was very significantly ($p = 0.0017$) higher than in the wood ash plots (0.32 ± 0.02 m) but was not significantly different from the mean height in the wastewater sludge plots (Figure 4). After the third, eighth, and eleventh years, the wood ash plots had mean heights of 0.97 ± 0.04 m ($p = 6.4 \times 10^{-5}$), 5.63 ± 0.07 m ($p = 1.8 \times 10^{-8}$), and 8.24 ± 0.04 ($p = 3.3 \times 10^{-7}$), respectively, showing highly significantly lower mean heights than the control plots (1.19 ± 0.03 m, 6.23 ± 0.07 m, and 8.57 ± 0.04 m, respectively).

Figure 3. Single tree height in hybrid aspen plantations (clones No. 4 and No. 28) with different fertilizers. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Significance levels *** (<0.001), ** (0.001–0.01), * (0.01–0.05), and NS (not significant) show the results of the Wilcoxon test between fertilizers. ★ At the age of 11 years, tree height was not measured directly for every tree but instead calculated using the DBH–height function.

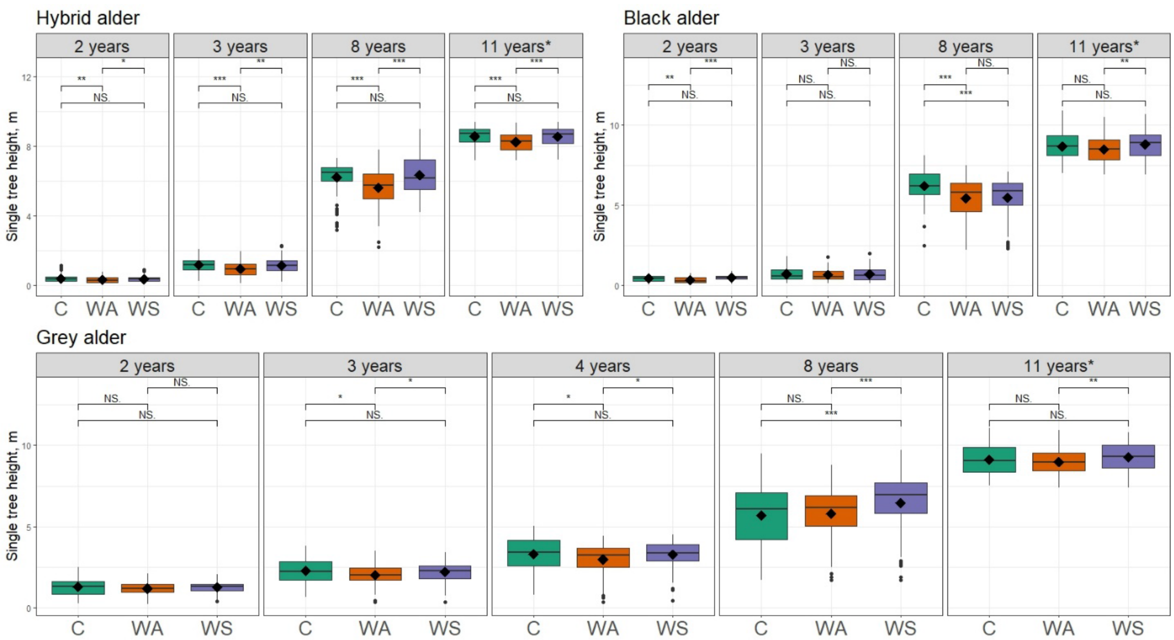

Figure 4. Single tree height in hybrid alder, black alder, and grey alder plantations with different fertilizers. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Significance levels *** (<0.001), ** (0.001–0.01), * (0.01–0.05), and NS (not significant) show the results of the Wilcoxon test between fertilizers. ★ At the age of 11 years, tree height was not measured directly for every tree but instead calculated using the DBH–height function.

The black alder height was first measured in the second year, at which time the mean height in the control plots (0.42 ± 0.02 m) was very significantly (p = 0.0026) higher than in the wood ash plots (0.33 ± 0.02 m) but was not significantly different from the mean height in the wastewater sludge plots (Figure 4). By the third year, both wood ash and wastewater sludge treatments did not show significant height differences compared to the control group, with a mean height of 0.71 ± 0.04 m. After the eighth year, there were highly significant height differences between the control group, with a mean height of 6.21 ± 0.06, and both the wood ash plots (5.43 ± 0.09 m) ($p = 2.2 \times 10^{-6}$) and the wastewater sludge plots (5.48 ± 0.09 m) ($p = 5.7 \times 10^{-5}$). Finally, in the eleventh year, there were no significant height differences between the control group and the seedlings treated with wood ash or wastewater sludge.

The grey alder height was first was measured in the second year, at which time no significant height differences were observed between the control group and the seedlings treated with wood ash or wastewater sludge (Figure 4). By the third and fourth years, the wood ash plots had mean heights of 2.02 ± 0.06 m ($p = 0.033$) and 2.97 ± 0.06 ($p = 0.05$), respectively, showing significantly lower average heights compared to the control plots (2.28 ± 0.08 m and 3.29 ± 0.05). By the eighth year, the significance levels changed. There was no significant height difference between the control group (with a mean height of 5.69 ± 0.13 m) and the wood ash plots but a highly significant difference with the wastewater sludge plots, which had a mean height of 6.46 ± 0.13 ($p = 1.3 \times 10^{-5}$). In the eleventh year, there were no significant height differences between the control group and the fertilized plots.

3.2. Single Tree DBH

When the plantation was 11 years old, the average DBH for birch under the control treatment was 10.03 ± 0.19 cm, while under the wood ash treatment it was 10.18 ± 0.17 cm, and under the wastewater sludge treatment it was 10.22 ± 0.16 cm, with no statistically significant differences between treatments (Figure 5). The black alder under the control treatment had an average DBH of 9.56 ± 0.15 cm, an average DBH of 9.08 ± 0.13 cm under the wood ash treatment, and an average DBH of 9.85 ± 0.16 cm under the wastewater sludge treatment, with no significant differences observed between treatments. The grey alder under the control treatment had an average DBH of 9.68 ± 0.16 cm, an average DBH of 9.3 ± 0.15 cm under the wood ash treatment, and an average DBH of 10.11 cm ± 0.18 under the wastewater sludge treatment, with no statistically significant differences between treatments. The hybrid alder had an average DBH of 10.23 ± 0.15 cm under the control treatment, an average DBH of 8.97 ± 0.13 cm under the wood ash treatment, and an average DBH of 10.06 ± 0.14 cm under the wastewater sludge treatment, with a highly significant difference observed between the control and wood ash treatments ($p = 2.3 \times 10^{-7}$), and no significant difference observed between the control and wastewater sludge treatments. The hybrid aspen clone No. 28 had an average DBH of 9.19 ± 0.17 cm under the control treatment, an average DBH of 9.3 ± 0.21 cm under the wood ash treatment, and an average DBH of 9.09 ± 0.21 cm under the wastewater sludge treatment, with no significant differences observed between treatments. The hybrid aspen clone No. 4 had an average DBH of 11.95 ± 0.26 cm under the control treatment, an average DBH of 12.35 ± 0.23 cm under the wood ash treatment, and an average DBH of 12.77 ± 0.29 cm under the wastewater sludge treatment, with a small difference observed between the control and wastewater sludge treatments ($p = 0.047$), and no significant difference between the control and wood ash treatments.

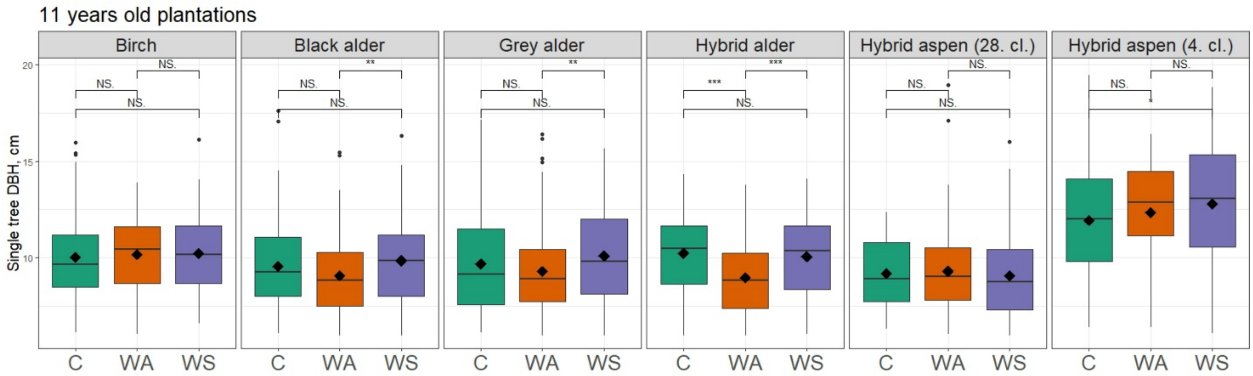

Figure 5. Single tree DBH in 11-year-old plantations of birch, hybrid aspen, hybrid alder, black alder, and grey alder with different fertilizers. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Significance levels *** (<0.001), ** (0.001–0.01) and NS (not significant) show the results of the Wilcoxon test between fertilizers. Trees with DBH < 6 cm were excluded from the dataset.

3.3. Single Tree and Planting Spot Biomass

The data indicate that the average single tree AGB varies between different tree species and treatments. At 11 years old, there was no significant difference between birch trees in the control and fertilized plots, where the mean tree biomass under the control treatment was 28.49 ± 1.37 kg, under the wood ash treatment it was 29.03 ± 1.10 kg, and under the wastewater sludge treatment it was 29.19 ± 1.16 kg (Figure 6). For the black alder, there was no significant difference between the control and fertilized plots, where the mean tree biomass under the control treatment was 18.89 ± 0.80 kg, under the wood ash treatment it was 16.42 ± 0.59 kg, and under the wastewater sludge treatment it was 20.11 ± 0.80 kg. For the grey alder, there was no significant difference between the control and fertilized plots, where the mean tree biomass under the control treatment was 20.06 ± 0.84 kg, under the wood ash treatment it was 17.82 ± 0.77 kg, and under the wastewater sludge treatment it was 22.09 ± 0.95 kg. For the hybrid alder, there was no significant difference between mean tree biomass under the control treatment (21.52 ± 0.72 kg) and the wastewater sludge treatment (20.54 ± 0.68 kg), but there was a highly significant difference between the control treatment and the wood ash treatment at 15.52 ± 0.58 kg ($p = 2.4 \times 10^{-6}$). For the hybrid aspen clone No. 28, there was no significant difference between the mean biomass of trees in the control and fertilized plots; mean tree biomass under the control treatment was 20.07 ± 0.98 kg, under the wood ash treatment it was 21.55 ± 1.64 kg, and under the wastewater sludge treatment it was 20.42 ± 1.36 kg. For the hybrid aspen clone No. 4, there was no significant difference between the mean tree biomass under the control treatment (41.43 ± 2.20 kg) and the wood ash treatment (44.42 ± 1.88 kg), but there was a significant difference between the mean biomass under the control treatment and the wastewater sludge treatment, at 50.50 ± 2.70 kg ($p = 0.047$).

Biomass from one planting spot may be higher compared to single tree biomass because black alder, grey alder, and hybrid alder usually grow several stems from one stool, while birch and hybrid aspen usually have one or sometimes two stems from one stool. When describing plantation biomass, total planting spot biomass may be more descriptive than single tree biomass. In this study, the birch and hybrid aspen clone No. 28 planting spot biomasses were identical to single tree biomass, because only one stem was growing in each planting spot (Figure 6). For the other tree species, total planting spot biomass was higher than single tree biomass, because more than one stem was growing from one planting spot. For the black alder, the average planting spot biomass under the control treatment was 27.54 ± 1.16 kg, under the wood ash treatment it was 27.53 ± 1.03 kg, and under the wastewater sludge treatment it was 27.63 ± 0.96 kg. For the grey alder, the average planting spot biomass under the control treatment was 26.59 ± 1.34 kg, under the wood ash treatment it was 22.59 ± 1.03 kg, and under the wastewater sludge treatment it was 27.27 ± 1.28 kg. For the hybrid alder, the mean planting spot biomass under the control treatment was 29.49 ± 0.84 kg, whereas under the wood ash treatment it was highly significantly lower at 19.72 ± 0.80 kg (p = 1.2 × 10^{-13}), and under the wastewater sludge treatment it was very significantly lower at 26.36 ± 0.86 kg (p = 0.0082). For the hybrid aspen clone No. 4, the average planting spot biomass under the control treatment was 42.37 ± 2.16 kg, under the wood ash treatment it was 47.17 ± 1.96 kg, and under the wastewater sludge treatment it was 53.31 ± 2.69 kg, which was very significantly (p = 0.0084) higher compared to the control treatment.

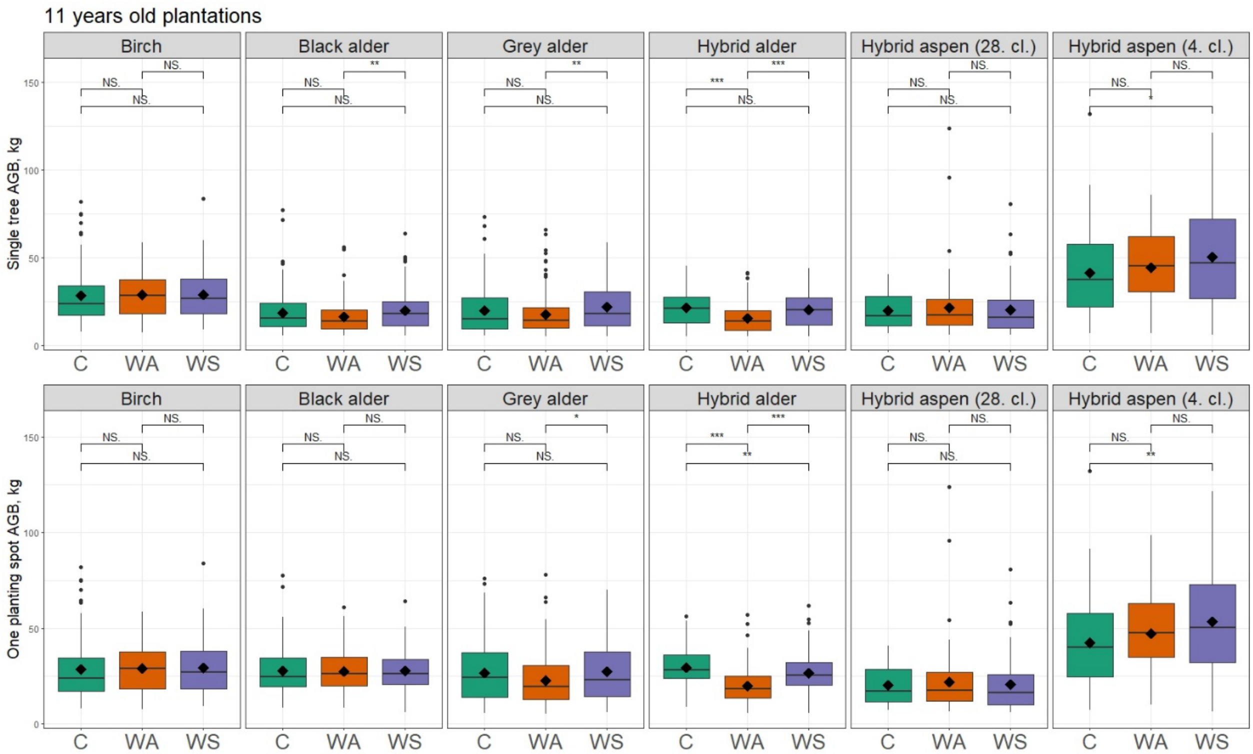

Figure 6. Single tree and single planting spot AGB in 11-year-old plantations of birch, hybrid aspen, hybrid alder, black alder, and grey alder with different fertilizers. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Significance levels *** (<0.001), ** (0.001–0.01), * (0.01–0.05), and NS (not significant) show the results of the Wilcoxon test between fertilizers. Trees with DBH < 6 cm were excluded from dataset.

3.4. Tree Survival Rate and Biomass from One Hectare

All trees were planted in 2011 and counted after 11 years. One tree seedling was planted in each planting spot. Trees were counted if their DBH was over 5.99 cm, otherwise they were counted as shoots and excluded from the dataset. The best survival rates were found for grey alders at 86–89% and hybrid alders at 80–89% (Figure 7). The lowest survival tree rate was found in hybrid aspen No. 28 clone sampling plots, where the rate was 42–68%. The average survival rate among all tree species in the control plots was 73% (42–87%), in the wastewater sludge plots it was 81% (68–90%), and in the wood ash plots it was 78% (60–89%). The lowest survival rate was found in hybrid aspen No. 28 clone control plots, at 42%, and the highest was found in hybrid alder wood ash plots, at 90%.

Tree AGB per hectare varied among the tree species and treatments (Figure 7). The highest AGB was observed for hybrid aspen clone No. 4 under the wastewater sludge treatment at 109.4 t ha^{-1}, and the lowest was observed for hybrid aspen clone No. 28 under the control treatment at 21.0 t ha^{-1}. The highest AGB for birch was observed under the wood ash treatment, at 34.3 t ha^{-1}; for black alder under the wastewater sludge treatment, at 33.6 t ha^{-1}; for grey alder under the wastewater sludge treatment, at 40.9 t ha^{-1}; for hybrid alder under the control treatment, at 36.2 t ha^{-1}; for hybrid aspen clone No. 28

under the wood ash treatment, at 30.6 t ha^{-1}; and for hybrid aspen clone No. 4 under the wastewater sludge treatment, at 109.0 t ha^{-1}.

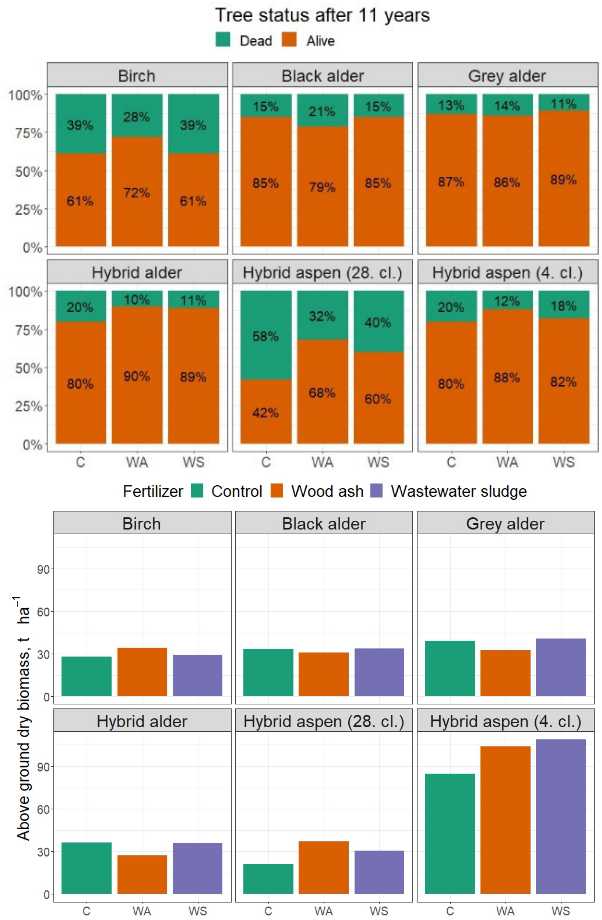

Figure 7. The survival rate and total aboveground biomass of different tree species per hectare in 11-year-old plantations. Fertilizers: C = control; WA = wood ash; WS = wastewater sludge. Trees with DBH < 6 cm were excluded from the dataset.

4. Discussion

This study focuses on short-rotation forest plantation growth parameter changes on abandoned agricultural land when wood ash and wastewater sludge are applied as fertilizers before planting. Using wood ash and wastewater sludge as fertilizers in tree plantations could solve two problems—the need to use waste materials efficiently and the need for higher tree biomass yields after fertilization. In forestry, in terms of profitability, it is recommended to perform fertilization a couple of years before final felling or when mean tree diameter is 16–20 cm [31], while in short-rotation willow plantations where biomass is harvested in short cycles (3–5 years), fertilization is recommended after every harvest [32]. It has previously been unclear how significant the fertilization effect is in tree plantations on abandoned agricultural land or how long it lasts if fertilization is performed before planting and trees are harvested after 10–15 years. This study shows how significantly and for how long fertilization with wood ash and wastewater sludge affects the mean tree height, DBH, survival rate, and biomass of different tree species in an 11-year period. Most fertilization experiments with wood ash and wastewater sludge have been undertaken in forests or on extracted peat soils; prior to the present study, little research had been performed on the fertilization of short-rotation plantations on abandoned agricultural land.

To compare wood ash and wastewater fertilization effects, during the first eight years tree height was measured, while in the eleventh year tree DBH was measured. For all tree species, the effect of fertilization changed year by year; in some tree species it was highly significant, but fertilization showed no consistent effects over a longer period for any species. When DBH was measured in the eleventh year, significant differences were found only in hybrid aspen (clone No. 4) and hybrid alder stands. Experiments in which wood ash fertilization was performed on cutaway peatlands showed positive results compared to controls in the first few years after planting [33]. In our experiment, wood ash dosage was 6 t DM ha^{-1} and thus lower compared to the dosage used in other studies in which the growth of young birch trees was found to be most favorable when the largest amounts (10–15 t ha^{-1}) of wood ash were applied [34]. On abandoned mineral soils in silver birch and grey alder stands (both 20,000 plants ha^{-1}), mineral fertilizers did not have a significant effect on biomass production and had no clear effect on tree survival after six years [35]. At our study site, the fertilization effect was significant for some tree species in the first few years but diminished after eleven years. The effect of fertilizing forest sites with nitrogen usually diminishes after five years, although in some cases it can last 12 years [36]. Experiments in forest sites with coniferous trees have found that the effect of fertilization with wood ash and potassium sulfate in Norway spruce stands lasted at least four years [37], while the effect of wood ash fertilization (at a rate of 5–10 t ha^{-1}) lasted 10 years in Scots pine and Norway spruce seedlings [38] and up to 15 years in Norway spruce stands with initial fertilization [39]. However, in a mature forest where Norway spruce was fertilized with wood ash (3 t ha^{-1}), standing volume and increment five years after fertilization was not significantly different from controls [40]. In naturally regenerated grey alder sites on peat and organic soils in Finland, fertilization with wood ash did not affect leafless aboveground biomass production [41], and a similar effect was found when wood ash was combined with nitrogen fertilizers [42]. A more recent study also found that fertilization with wood ash did not affect leafless aboveground biomass production in naturally regenerated grey alder sites on peat and organic soils [41]. In poplar stands on former agriculture lands where fertilizers were used, a growth response to fertilization was found one to three years after planting but was not found in later years [43]. It has been observed that wood ash application does not seem to have any immediate effect on the growth of plants in mineral soils [44], such as those at our site. However, some studies have shown a positive effect of fertilization in naturally regenerated grey alder sites on mineral soils: when fertilized with wood ash and nitrogen, trees were significantly taller compared to controls after six years, while on peat soils, fertilization did not affect mean tree height and diameter [41].

The total AGB for tree species in this study site was similar to or lower than that found in other studies. In cases where species like black alder, grey alder, and hybrid alder grow multiple stems emerging from a single planting spot, the total planting spot biomass was higher than the single tree biomass. This distinction can provide a more accurate representation of biomass in plantation scenarios. AGB per hectare varied among the tree species and treatments.

In Estonia, leafless AGB in seven-year-old hybrid aspen plantations averaged from 2.18 t ha^{-1} to 8.54 t ha^{-1} and averaged 8 t ha^{-1} in Southern Sweden when including branches in young stands [45,46]. In hybrid aspen plantations in Latvia with an initial density of 2500 trees ha^{-1}, the average stock at the age of 10 years was 160 m^3 ha^{-1}, and the average stock of the five most productive clones reached 230 m^3 ha^{-1} [47]. The highest AGB in this study (109.0 t h^{-1}) was recorded for hybrid aspen (clone No. 4) plots with wastewater sludge treatment, higher than that found by a study in Estonia in which 40.0 t ha^{-1} was reported in a 13-year-old hybrid aspen plantation with 4080 trees ha^{-1} (compared to 2500 trees ha^{-1} at our site) on abandoned agricultural land without fertilization [48]. However, in our control sites AGB was 21.0 t ha^{-1} (clone No. 28) and 84.7 (clone No. 4), which is closer to the results of the Estonian study, although the planting density was 1.6 times lower.

The optimal grey alder planting density for biomass production is 3000–6000 trees ha^{-1}, with an optimal rotation period of 15–20 years [49]; this is a higher density than our grey alder and hybrid alder sites, with 1600 trees ha^{-1} at planting. A previous study shows that AGB for a 13-year-old grey alder stand on abandoned agricultural land without fertilizer application was 63.4 t ha^{-1} (at a density of 6170 trees ha^{-1}) [48], which is higher than our grey alder control site with 39.0 t ha^{-1} and hybrid alder control site with 36.2 t ha^{-1}, although in our sites planting density was 3.8 times lower. Another previous study found that in a 12-year-old grey alder stand planted on abandoned agricultural land in Estonia with a density of 6750 trees ha^{-1}, AGB was 68.8 tons ha^{-1} [50]. Further, previous research shows that the mean annual increment of AGB of grey alder in naturally regenerated forest sites culminates at the age of 10–15 years, at 4.3–5.5 t ha^{-1} yr^{-1} [12], while in our control grey alder site the mean annual increment of aboveground woody biomass was 3.5 t ha^{-1} yr^{-1}, and in our control hybrid alder site it was 3.3 t ha^{-1} yr^{-1}; this is 30–67% lower and could be explained by the presence of fewer trees in plantations compared to naturally regenerated stands.

The mean annual increment in our black alder sites at 11 years with a planting density of 1600 trees ha^{-1} was 2.8–3.0 t ha^{-1}, compared to an AGB of 35.1 t ha^{-1} (mean annual increment 3.82 t ha^{-1}) in 10-year-old black alder stands on abandoned farmland with a density of 21600 trees ha^{-1} and 49.6 t ha^{-1} (mean annual increment 3.51 t ha^{-1}) in 13-year-old stands with 9860 trees ha^{-1} [51].

In our birch stands, AGB was 28.0 t ha^{-1} under the control treatment, 29.2 t ha^{-1} under the wastewater sludge treatment, and 34.3 t ha^{-1} under the wood ash treatment. In Latvia, previous research found that in 15-year-old birch stands on agricultural land, the mean annual AGB increment varied from 4.66 m^3 ha^{-1} per year on heavy clay soil to 29.82 m^3 ha^{-1} per year on pseudogley soil with a tree density of 2000–3300 tree per ha^{-1} [52]. In Estonia, the same age mean annual increment on abandoned agricultural land with a tree density of 1090–2430 trees per ha^{-1} was 6.9–9.3 m^3 ha^{-1} per year [53]. On peat land in Finland, biomass production in a 10-year-old stand was 40.0 t ha^{-1} (mean annual increment of 4.0 t ha^{-1}), and at 14 years old was 59.0 t ha^{-1} (mean annual increment of 4.2 t ha^{-1}); however, the planting density was 25,000 stems ha^{-1} [54,55], which is 15 times higher than our site. On abandoned farmland in Sweden with 22,300 trees ha^{-1}, total biomass in an 11-year-old stand was 57.7 t ha^{-1} (mean annual increment 5.3 t ha^{-1}) and in a 12-year-old stand with 45,000 trees ha^{-1} it was 101.3 t ha^{-1} (mean annual increment 8.44 t ha^{-1}) [56]. These results far exceed our results, which indicate a mean annual increment of 2.54–3.12 t ha^{-1}. However, our planting density was 13–28 times lower. In a 12-year-old birch stand with a planting density similar to ours (specifically, 1479–4444 trees per ha^{-1}), AGB was 17.5 to 60.3 t ha^{-1} (mean annual increment 1.41–5.0 t ha^{-1}) [57] and thus similar to our results. Study results underscore the complexity of biomass dynamics in short-rotation forest plantations on abandoned agricultural land and emphasize the necessity of tailoring management strategies to specific tree species and their responses to different treatments. The study limitations are that soil properties are not identical and homogeneous in all plantation subplots and could affect tree growth differently in every subplot. The general results could be different in other sites, locations, and soil types because this study was conducted on a specific plantation of abandoned agricultural land with specific soil characterization, which is hard to replicate in other sites.

5. Conclusions

This study investigated the use of wood ash (6 t DM ha^{-1}) and wastewater sludge (10 t DM ha^{-1}) as fertilizers in short-rotation forestry plantations on abandoned agricultural land in Latvia. While wood ash and wastewater sludge fertilization can have positive short-term impacts on tree growth, these effects are not consistent over the long term, and optimal practices may vary depending on factors such as dosage, soil type, and tree species. The findings reveal that the effects of wood ash and wastewater sludge fertilization on tree height varied over time, with some tree species showing significant responses; however, these effects were not consistent across all tree species and tended to diminish over time. The mean DBH after 11 years for birch, black alder, grey alder, hybrid aspen clone No. 28, and hybrid aspen clone No. 4 showed no statistically significant differences between the control, wood ash, and wastewater sludge treatments. However, for hybrid alder, a highly significant difference was observed between the control and wood ash treatments, and for hybrid aspen clone No. 4 a small difference was observed between the control and wastewater sludge treatments. This indicates that the impact of these treatments on tree growth can vary according to the specific tree species or clone.

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