forests

MDPI

Article

Verifying the Utility of Black Locust (*Robinia pseudoacacia* L.) in the Reclamation of a Lignite Combustion Waste Disposal Site in Central European Conditions

Bartłomiej Woś *, Marek Pająk, Wojciech Krzaklewski and Marcin Pietrzykowski

Department of Ecology and Silviculture, Faculty of Forestry, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Krakow, Poland; marek.pajak@urk.edu.pl (M.P.); wojciech.krzaklewski@urk.edu.pl (W.K.); m.pietrzykowski@urk.edu.pl (M.P.)

* Correspondence: b.wos@ur.krakow.pl

Received: 4 July 2020; Accepted: 8 August 2020; Published: 12 August 2020

Abstract: N-fixing tree species, such as black locust, have achieved very promising results in the reclamation of technosols, especially those at combustion waste disposal sites, which have extremely poor nutrients and adverse physicochemical parameters. This paper presents an assessment of the survival rates, growth parameters, and quality and vitality of and nutrient supply (NPK) to black locust (*Robinia pseudoacacia* L.) specimens that were experimentally planted on a lignite combustion waste disposal site. The black locust seedlings were introduced directly into the combustion waste using two variants of NPK (7% N, 5.5% P_2O_5, and 9% K_2O) fertilisation, at doses of 250 and 500 kg ha^{-1}, and in control plots with no mineral fertilisation. No significant impacts of the applied mineral fertilisation were found on the soil properties, growth parameters, or nutrient supplies to the trees. Black locust introduced to the landfill after three years of revegetation was characterised by a very high survival rate of 95%–100%, as well as good growth parameters (height and diameter at the root collar). Nutrient supply was determined on the basis of the chemical composition of the leaves, which indicated an adequate supply of nitrogen, similar to levels found under natural conditions. In the case of K and P, the supply levels were lower than optimal when compared with data from the literature. However, at this initial stage of tree development on the combustion waste disposal site, nutrient supply is similar on all variants and is not a critical factor for successful black locust introduction. We suggest using growth parameters, survival, and vitality of trees as decisive factors for the reclamation of combustion waste landfill sites strategy. All these factors confirmed the usefulness of black locust to the reclamation of combustion waste disposal sites.

Keywords: reclamation; nutrient; technosols; fly ash; N-fixing species

1. Introduction

Combustion waste landfills generated by the burning of fossil fuels, such as lignite and hard coal, still pose a grave environmental threat [1]. They occupy large areas of the landscape, adversely affecting the adjacent areas [2]. This impact manifests itself, among other changes, in the quality of ground and surface waters due to strong alkaline waters infiltrating from landfills and air pollution via dust [3,4]. For these reasons, proper reclamation and the biological stabilization of combustion waste disposal sites are necessary. Revegetation of combustion wastes is complicated by their unfavourable chemical and physical properties [5]. Typical examples of combustion waste include the artificial ashes and slags that tend to become compacted, are susceptible to cementation, and possess unfavourable air–water properties, strong alkaline reactions, and nutrient deficiencies (in particular, nitrogen and phosphorus). They also often contain high concentrations of trace elements [6–8].

A special role in the biological stabilisation of combustion waste landfills is played by plants capable of symbiosis with bacteria-fixing atmospheric nitrogen [9,10]. The contributions of N-fixing tree species include favourable physicochemical transformations of artificial technogenic substrates, accumulation of organic matter, and colonisation by microorganisms and soil mesofauna [11,12]. After the first generation of N-fixing and pioneering species, more demanding species can then be introduced by afforestation on prepared technosols [7,10]. Alders (*Alnus* sp.) and black locust (*Robinia pseudoacacia* L.) are among the most commonly used N-fixing species in central Europe [7,11]. In particular, black alder is characterised by high survival rates and good growth parameters, such as diameter at breast height and mean height, measured 10 years after their planting in combustion waste [10]. However, because of their humidity and trophic requirements, alder does not grow for long in post-industrial sites, usually dying after 20–30 years [11]. For this reason, there is a need to test different N-fixing species for the reclamation of waste disposal sites.

Black locust, which is not a species native to Europe, has a long tradition of use in reclamation due to its ecological properties, including low habitat requirements and easy adaptation to transformed habitats, low sensitivity to industrial pollution, and, especially, its affinity for symbiosis with actinobacteria (genus *Rhizobium*) [13,14]. Symbiotic N-fixation may not only increase soil N content, but may also contribute to the increase of soil organic matter [15]. Thus, due to features such as rapid growth with high biomass production, high calorific value of biomass, and the ability to grow offspring, black locust is also used to establish plantations in short rotation coppice (SRC) systems on reclaimed post-mining sites [16,17]. There is still controversy, especially concerning managed forests, around the use of black locust due to its invasive origins [18]. Nevertheless, in extremely adverse post-industrial sites where few species can grow, testing with introduced species is justified. In addition, as a result of climate change and increasingly common extreme weather phenomena, such as droughts, there is a need to test not only native tree and shrub species. Often, native species cannot withstand long-term drought. One example of large-scale forest dieback and a change in natural distribution is the decay of Scots pine (*Pinus sylvestris* L.) stands in Europe. Up until now, Scots pine was considered an undemanding species, with a broad spectrum of ecological requirements [19,20].

The aim of the study was to assess survival, growth parameters, vitality, quality, and nutrient supply among black locust (*Robinia pseudoacacia* L.) introduced to lignite combustion waste disposal sites. We tested two NPK fertilisation combinations due to limited field possibilities at occupied industrial sites (landfills). We were concerned with the practical verification of the results at a realistic scale, rather than conducting a common garden experiment with extensive combinations and randomisation. The optimisation of fertilisation doses can be developed in the next stage of the experiment, after nutrient deficiency and growth parameters have been assessed from a long-term perspective.

2. Materials and Methods

2.1. Study Site

The Lubień disposal site of the Bełchatów Power Station is located in central Poland (51.2752 N; 19.2624 E). The climate at the site is temperate, with a mean annual precipitation ranging from 576 mm year^{-1} and an average annual temperature of approximately 8.8 °C (data for 1990–2012 from meteorological stations, source: tutiempo.net). The Lubień disposal site has been in operation since 1980 and currently occupies approximately 440 ha. Combustion waste containing nearly 85% bottom and fly ash and 15% slag is deposited there by hydrotransport. Freshly deposited combustion waste at the Lubień disposal site is characterised by sandy texture, high pH (over 8 in KCl), and the dominance of calcium ions in the sorption complex [7,10].

2.2. Description of the Experiment

The experiment was established in the spring of 2016 on the shelf of a landfill formed in 2004. In 2005, the study site was subjected to hydro-seeding with sewage sludge (4 Mg dry mass ha^{-1}), mixed with seeds (200 kg ha^{-1}) of cock's-foot grass (*Dactylis glomerata* L.) and Italian ryegrass (*Lolium multiflorum* Lam.), and was then left to natural succession. At the time of establishing the experiment in 2016, succession vegetation cover was approximately 90%, in which the dominant species were *Calamagrostis epigejos* (L.) Roth in the herb layer and *Barbula convoluta* (L.) Hedw in the moss layer. The experimental area was prepared by deep ploughing and harrowing of the surface. The experimental area was then divided into 16 plots of 7 × 6 m, separated by a buffer strip 1 m wide. Certified seedlings of shipmast locust HU/ROPS-22-511057 imported from Hungary were introduced to the experimental plots. We then planted 10 two-year-old seedlings in each plot, for a total of 160 seedlings. The height of the seedlings ranged from 30 to 40 cm and the diameter at root collar was from 0.5 to 0.7 cm. After one year following the introduction of the trees, NPK mineral fertilisation was applied in the form of a compound fertiliser containing soft rock phosphate (7% N, 5.5% P_2O_5, 9% K_2O, 0.1% B, 0.18% Fe, 0.1% Mn) on plots in six replications at the following doses: 250 and 500 kg ha^{-1}. We designated four plots without fertilisation as a control.

2.3. Soil Sampling and Analyses

In the spring of 2016, to determine the output characteristics of the combustion waste, soil samples were collected from the 0 to 20 cm horizon at 16 regularly distributed locations on the plot intended for the experiment. These were ultimately combined into four mixed samples. Soil samples were collected again in the spring of 2019, from 0 to 20 cm horizons at five points within each study plot; four were located in the corners and one was located in the centre of the plot. The samples were bulked to produce a mixed sample (1.0 kg mass of fresh materials) representative of the sampling plot. Furthermore, 24 mixed samples were used to determine basic soil properties.

The soil samples were dried and sieved through a 2.0 mm sieve and measured for pH in H_2O and 1 M KCl (1:2.5 soil:solution ratio) and electrical conductivity (EC) (1:5 soil:solution ratio at 21 °C). Total nitrogen (Nt) and sulphur (St) contents were determined with the LECO TruMac® CNS analyser. Prior to carbon analysis, the soil samples were treated with 10% HCl to remove carbonates. Available phosphorus (P_2O_5) and potassium (K_2O) were assayed in calcium lactate extract ($(CH_3CHOHCOO)_2Ca$) acidified with HCl to pH 3.6 (Egner–Riehm method). Phosphorus was determined using a CARY 300 Conc UV-Visible spectrophotometer, whereas potassium was determined by the ICP-OES iCAP™ 6000 Series spectrometer.

2.4. Tree Foliage Sampling and Chemical Analyses

Mature leaves were collected in the summer of 2019 from five trees regularly distributed along the diagonal of each plot from the crown tops of the SW exposition. The collected leaves from each plot were mixed to produce a composite sample representative of the plot [10].

The contents of N and S in the leaves were measured with the LECO TruMac® CNS analyser. Total K and P in the leaves were determined by atomic absorption spectroscopy ICP-OES (iCAP™ 6000 Series) after digestion in a mixture of HNO_3 (density = 1.40 g cm^{-3}) and 60% $HClO_4$ acid in a 4:1 ratio.

2.5. Assessment of Tree Growth Parameters

Tree measurements were conducted in the spring of 2019 after three years of growth. In each study plot, the survival of trees was assessed as a percentage of live trees in comparison to the total number of trees introduced. Diameters at root collar were measured (D_0) with an accuracy of 0.1 cm, and the heights (H) of all trees were measured with an accuracy of 0.01 m. The quality and vitality of trees were also assessed using the classifications used on reclaimed post-mining sites [21].

The following classification was used for quality assessment:

(I) Good quality trees: slight curvatures allowed, straight trunk, pronounced top.
(II) Medium quality trees: slight curvature, not always a pronounced top.
(III) Poor quality trees: crooked trunk, bushy, two-branch, no apex.

For the assessment of vitality, trees were classified into the following classes:

(I) Vital trees: pronounced top, pronounced green foliage colour, dense foliage.
(II) Average vital trees: less pronounced tops, no significant thinning of the foliage.
(III) Weakened trees: dying trees with stunted growth, thinned crown, discoloured foliage.

2.6. Statistical Analyses

Data sets were statistically analysed using the Statistica 13.1 programme. Significant differences between mean values of basic soil characteristics, survival, and growth characteristics of *Robinia pseudoacacia* from differing variants were tested via the Tukey's HSD (honestly significant difference) test (at $p = 0.05$). Distribution conformity of the investigated features was compared to normal distribution using the Shapiro–Wilk test. The average values of analysis characteristics for substrate were compared using ANOVA preceded by Leven's variance homogeneity test.

3. Results

3.1. Basic Soil Parameters

Before the black locusts were planted, the combustion waste technosols were characterised by their alkalinity (pH in H_2O = 7.9 and in KCl = 7.6) and EC amounting to 98.70 µS cm^{-1}. The Nt, St, K_2O and P_2O_5 contents of the technosols prior to the experiment were similar to those of the technosols planted with black locust (Table 1).

Table 1. Basic combustion waste technosol parameters.

Variable	pH in H_2O	pH in KCl	EC	Nt	St	K_2O	P_2O_5
			(µS cm^{-1})	(g kg^{-1})			
Start up characteristics	7.9 ± 0.0 $^{a\,1}$	7.6 ± 0.1 ^{a}	98.70 ± 4.33 ^{a}	0.22 ± 0.03 ^{a}	0.14 ± 0.02 ^{a}	0.13 ± 0.02 ^{a}	0.02 ± 0.01 ^{a}
Control	7.8 ± 0.0 ^{a}	7.2 ± 0.1 ^{a}	78.25 ± 8.53 ^{a}	0.25 ± 0.07 ^{a}	0.11 ± 0.01 ^{a}	0.08 ± 0.01 ^{a}	0.05 ± 0.01 ^{a}
250 kg/ha	7.8 ± 0.1 ^{a}	7.3 ± 0.1 ^{a}	85.67 ± 9.06 ^{a}	0.34 ± 0.09 ^{a}	0.10 ± 0.01 ^{a}	0.09 ± 0.01 ^{a}	0.04 ± 0.00 ^{a}
500 kg/ha	7.8 ± 0.1 ^{a}	7.3 ± 0.1 ^{a}	88.33 ± 5.75 ^{a}	0.32 ± 0.06 ^{a}	0.07 ± 0.01 ^{a}	0.09 ± 0.01 ^{a}	0.05 ± 0.01 ^{a}

[1]—mean ± SE; within columns, means followed by the same letter (a) do not differ statistically.

There were no significant differences in the average values of technosol properties between control plots and variants with mineral fertilisation. The 0 to 20 cm layers of technosols were characterised by alkaline reaction and low EC, from 78.25 to 88.33 µS cm^{-1}. Total nitrogen (Nt) content ranged from 0.25 g kg^{-1} on control plots to 0.34 g kg^{-1} with mineral fertilisation. Total sulphur (St) content in studied technosols ranged from 0.07 to 0.11 g kg^{-1}, while available potassium (K_2O) content ranged from 0.08 g kg^{-1} in control plots to 0.09 g kg^{-1} in plots with fertilisation. Lastly, the available phosphorus (P_2O_5) content ranged from 0.04 to 0.05 g kg^{-1} (Table 1).

3.2. Growth Parameters, Quality, and Vitality of Trees

Black locust introduced to the combustion waste landfill was characterised by very high survival, ranging from 95% to 100%. There were no significant differences in the average values of D_0 and H between the variants with fertilisation and unfertilised control plots (Table 2).

The quality assessment of black locust on the combustion waste landfill was average, as most of the tested trees were characterised by II (57–81%) and III quality classes (19–38%). Most of the trees analysed evinced I (63–79%) and II vitality classes (21–35%). Thus, we concluded that the vitality of black locust at the combustion waste landfill was good (Table 2).

Table 2. Survival, diameter at root collar, height, quality, and vitality of black locust in three years of growth on the combustion waste disposal site.

Variant	Survival	D_0	H	Quality Class			Vitality Class		
				I	II	III	I	II	III
	(%)	(cm)		(%)			(%)		
Control	100 ± 0 ᵃ	2.8 ± 0.0 ᵃ	209.0 ± 14.7 ᵃ	0 ± 0	81 ± 10 ᵃ	19 ± 10 ᵃ	79 ± 2 ᵃ	21 ± 2 ᵃ	0 ± 0
250 kg/ha	95 ± 3 ᵃ	2.6 ± 0.2 ᵃ	200.8 ± 13.8 ᵃ	3 ± 2 ᵃ	57 ± 8 ᵃ	40 ± 6 ᵃ	63 ± 14 ᵃ	35 ± 13 ᵃ	2 ± 2 ᵃ
500 kg/ha	100 ± 0 ᵃ	2.6 ± 0.2 ᵃ	203.5 ± 21.4 ᵃ	3 ± 2 ᵃ	59 ± 11 ᵃ	38 ± 12 ᵃ	66 ± 12 ᵃ	29 ± 11 ᵃ	5 ± 5 ᵃ

Within columns, means followed by the same letter (a) do not differ statistically.

3.3. Tree Foliage Nutrient Supply

The content of individual macroelements in the leaves of black locust in the studied variants was similar: for N, from 28.85 to 30.20 g kg^{-1}; for S, from 1.78 to 1.94 g kg^{-1}; for P, from 1.28 to 1.31 g kg^{-1}; and for K, from 4.96 to 5.02 g kg^{-1} (Table 3).

Table 3. N, S, K, and P contents in black locust leaves on research plots.

Variant	N	S	P	K
	(g kg^{-1})			
Control	30.30 ± 0.72 ᵃ	1.89 ± 0.10 ᵃ	1.28 ± 0.07 ᵃ	5.02 ± 0.60 ᵃ
250 kg ha^{-1}	29.56 ± 0.32 ᵃ	1.94 ± 0.21 ᵃ	1.31 ± 0.04 ᵃ	4.96 ± 0.28 ᵃ
500 kg ha^{-1}	28.85 ± 1.04 ᵃ	1.78 ± 0.09 ᵃ	1.30 ± 0.09 ᵃ	4.96 ± 0.34 ᵃ

Within columns, means followed by the same letter (a) do not differ statistically.

4. Discussion

Black locust was characterised by high survival (95%–100%) three years after its introduction to the combustion waste disposal site. Similarly, high survival (97%–100%) of black locust was found after three years of growth at the abandoned coal waste bank in western Pennsylvania, USA [22]. Black locust was also characterised by high survival (84%–91%) two to four years after the establishment of the plantation on post-mining sites of lignite opencast mining in Germany [23]. Lower survival (58%) of black locust was found on reclaimed surface mines in Appalachia [24].

The height of the black locust introduced into the combustion waste landfill was lower compared to the data obtained at the abandoned coal waste bank (from 225 to 328 cm after three years of growth) [22], as well as the three-year energy plantations (median 320 cm) established in the reclamation area of an opencast lignite mining area in the Lower Lusatia region (Germany) [23]. Lower values of heights obtained at the combustion waste landfill compared to values obtained at plantations should not, however, significantly affect the assessment of the suitability of black locust for biological stabilisation of disposal sites. The height and other growth parameters of black locust differ from habitat conditions and cultivar varieties [25]. The usefulness of black locust for combustion waste disposal sites may be indicated by its vitality: most of the black locust was classified within the best (I) class of vitality. The average quality found is a secondary feature. In sites that pose particular challenges to reclamation, the goal is not to produce good quality wood material, but rather rapid biological surface stabilisation [7].

Mineral fertilisation did not cause a positive growth response among black locust. Black locust usually reacts positively to mineral fertilisation, as has been documented, for example, in energy plantations [25]. However, no effect of mineral fertilisation on basal diameter, height, nor stem mass of black locust was recorded two years after introduction to the reclaimed lignite opencast mine in Appalachia. At this site, black locust was introduced in control plots, as well as plots with granular fertilisation in a dose of 36 kg N ha^{-1}, 30 kg P ha^{-1}, and 16 kg K ha^{-1}, irrigation, and a combination of irrigation and fertilisation [24]. The lack of any effect of mineral fertilisation on the growth parameters, as shown by our study, may be due to 90% of the area being covered by vegetation before the experiment was established. Over the course of 10 years, succession vegetation may have altered the condition of the soil, leading to the soil nutrients being higher than the thresholds required by the trees.

The influence of fertilisation on soil properties depends mainly on weather conditions and existing soil properties, especially texture, pH, and cation exchange capacity (CEC). After fertilisation, nutrients go into solution, and can either be taken up by the plants or leached into deeper soil horizons [26]. The sandy combustion waste technosols of the Lubień disposal site [7,10,11] are particularly conducive to nutrient leaching [27]. This may be the reason why there was no effect on the nutrient content in these soils, three years after fertilisation. In addition, in the case of P, there may have been a high alkaline reaction that formed barely soluble compounds [26].

Potassium content in black locust leaves in the combustion waste landfill was lower, while nitrogen and phosphorus content were similar to the values obtained at the abandoned coal waste bank in the USA (for N from 36.6 to 37.6 g kg^{-1}, K from 9.6 to 13.6 g kg^{-1}, and for P from 1.4 to 1.7 g kg^{-1}) [22]. Nitrogen content values in leaves similar to those obtained in the combustion waste landfill were obtained at the reclaimed lignite opencast mine in Appalachia [24]. Compared to the values obtained on the combustion waste landfill, much higher concentrations of P (3.8 g kg^{-1}), K (25.6 g kg^{-1}), and S (2.8 g kg^{-1}) were found in the leaves of black locust growing on the reclaimed Green Valley coal mine, Indiana, USA [26]. Twenty-five-year-old black locust growing at sites under the influence of industrial emissions, as well as in unpolluted areas in eastern Bulgaria, were characterised by a lower N content (21.7 and 21.0 g kg^{-1}, respectively, for polluted and unpolluted sites) and higher P (2.13 and 2.53 g kg^{-1}) and K (19.75 and 42.47 g kg^{-1}) contents, compared to our data [28]. Furthermore, P, K, and S contents were also lower compared to the adequate content of P (2 g kg^{-1}), K (10 g kg^{-1}), and S (1 g kg^{-1}) for green plants reported in the existing literature [29]. Nutrient content in locust leaves did not vary significantly depending on the dose of mineral fertilisation. The nitrogen content is not surprising because black locust is an N-fixing species entering symbiosis with diverse *Rhizobium* communities [30,31], and the lack of influence of mineral fertilisation on the N content was already reported [24]. Nevertheless, for other elements, there may be additional factors that hinder the uptake of elements. In the case of phosphorus, this may be a high alkaline reaction that forms barely soluble compounds [32].

5. Conclusions

Although we found no significant impact of the applied mineral fertilisation on the soil properties and growth parameters of, or the nutrient supply to, the trees, the results indicated and confirmed that, in general, black locust is a valuable species for use in the biological stabilisation of combustion waste disposal sites. After three years, the black locusts introduced to the disposal site were characterised by high survival and growth parameters, and vitality. The characteristic of high N content in black locust leaves was confirmed. The nutrient supply indicated adequate N supply, similar to the thresholds found under natural conditions. However, in the case of K and P, the supply was lower than the values reported in the literature. We concluded that at this initial stage of tree development on ameliorated combustion waste, nutrient supply is similar on all variants and is not a critical factor for successful black locust introduction. In this case, we suggest using growth parameters, survival, and vitality of trees as decisive factors for the reclamation of combustion waste landfill sites strategy. All these factors confirmed the usefulness of black locust to the reclamation of combustion waste disposal sites.

Author Contributions: Conceptualization, B.W., W.K., and M.P. (Marcin Pietrzykowski); methodology, B.W. and M.P. (Marek Pająk).; validation, B.W. and M.P. (Marek Pająk) investigation, B.W.; data curation, B.W.; writing—original draft preparation, B.W. and M.P. (Marek Pająk).; writing—review and editing, W.K. and M.P. (Marcin Pietrzykowski).; supervision, M.P. (Marcin Pietrzykowski). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Article was financed by a subvention from the Ministry of Science and Higher Education of the Republic of Poland for the University of Agriculture in Krakow for 2020.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pandey, V.C.; Bajpai, O.; Singh, N. Plant regeneration potential in fly ash ecosystem. *Urban For. Urban Green.* **2016**, *15*, 40–44. [CrossRef]
2. Weber, J.; Kocowicz, A.; Debicka, M.; Jamroz, E. Changes in soil morphology of Podzols affected by alkaline fly ash blown out from the dumping site of an electric power plant. *J. Soils Sediments* **2016**, *17*, 1852–1861. [CrossRef]
3. Dellantonio, A.; Fitz, W.J.; Čustović, H.; Repmann, F.; Schneider, B.U.; Grünewald, H.; Gruber, V.; Zgorelec, Z.; Zerem, N.; Carter, C.; et al. Environmental risks of farmed and barren alkaline coal ash landfills in Tuzla, Bosnia and Herzegovina. *Environ. Pollut.* **2008**, *153*, 677–686. [CrossRef]
4. Haynes, R.J. Reclamation and revegetation of fly ash disposal sites—Challenges and research needs. *J. Environ. Manag.* **2009**, *90*, 43–53. [CrossRef]
5. Ram, L.C.; Jha, S.K.; Tripathi, R.C.; Masto, R.E.; Selvi, V.A. Remediation of fly ash landfills through plantation. *Remediat. J.* **2008**, *18*, 71–90. [CrossRef]
6. Juwarkar, A.A.; Jambhulkar, H.P. Restoration of fly ash dump through biological interventions. *Environ. Monit. Assess.* **2007**, *139*, 355–365. [CrossRef] [PubMed]
7. Krzaklewski, W.; Pietrzykowski, M.; Woś, B. Survival and growth of alders (*Alnus glutinosa* (L.) Gaertn. and *Alnus incana* (L.) Moench) on fly ash technosols at different substrate improvement. *Ecol. Eng.* **2012**, *49*, 35–40. [CrossRef]
8. Uzarowicz, Ł.; Zagorski, Z.; Mendak, E.; Bartmiński, P.; Szara, E.; Kondras, M.; Oktaba, L.; Turek, A.; Rogoziński, R. Technogenic soils (Technosols) developed from fly ash and bottom ash from thermal power stations combusting bituminous coal and lignite. Part I. Properties, classification, and indicators of early pedogenesis. *Catena* **2017**, *157*, 75–89. [CrossRef]
9. Rai, U.N.; Pandey, K.; Sinha, S.; Singh, A.; Saxena, R.; Gupta, D. Revegetating fly ash landfills with *Prosopis juliflora* L.: Impact of different amendments and *Rhizobium inoculation*. *Environ. Int.* **2004**, *30*, 293–300. [CrossRef]
10. Pietrzykowski, M.; Woś, B.; Pająk, M.; Wanic, T.; Krzaklewski, W.; Chodak, M. Reclamation of a lignite combustion waste disposal site with alders (*Alnus* sp.): Assessment of tree growth and nutrient status within 10 years of the experiment. *Environ. Sci. Pollut. Res.* **2018**, *25*, 17091–17099. [CrossRef]
11. Pietrzykowski, M.; Woś, B.; Pająk, M.; Wanic, T.; Krzaklewski, W.; Chodak, M. The impact of alders (*Alnus* spp.) on the physico-chemical properties of technosols on a lignite combustion waste disposal site. *Ecol. Eng.* **2018**, *120*, 180–186. [CrossRef]
12. Józefowska, A.; Woś, B.; Pietrzykowski, M.; Schlaghamerský, J. Colonisation by enchytraeids as a suitable indicator of successful biological reclamation of post-mining technosols using alders. *Appl. Soil Ecol.* **2020**, *145*, 103300. [CrossRef]
13. Ashby, W.C.; Vogel, W.G.; Rogers, N.F. *Black Locust in the Reclamation Equation*; U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Broomall, PA, USA, 1985.
14. Vlachodimos, K.; Papatheodorou, E.M.; Diamantopoulos, J.; Monokrousos, N. Assessment of *Robinia pseudoacacia* cultivations as a restoration strategy for reclaimed mine spoil heaps. *Environ. Monit. Assess.* **2013**, *185*, 6921–6932. [CrossRef] [PubMed]
15. Johnson, D.W.; Curtis, P.S. Effects of forest management on soil C and N storage: Meta analysis. *For. Ecol. Manag.* **2001**, *140*, 227–238. [CrossRef]
16. Grünewald, H.; Böhm, C.; Quinkenstein, A.; Grundmann, P.; Eberts, J.; Von Wühlisch, G. *Robinia pseudoacacia* L.: A Lesser Known Tree Species for Biomass Production. *BioEnergy Res.* **2009**, *2*, 123–133. [CrossRef]
17. Kanzler, M.; Böhm, C.; Freese, D. Impact of P fertilisation on the growth performance of black locust (*Robinia pseudoacacia* L.) in a lignite post-mining area in Germany. *Ann. For. Res.* **2015**, *58*, 1. [CrossRef]
18. Vítková, M.; Müllerová, J.; Sádlo, J.; Pergl, J.; Pyšek, P. Black locust (*Robinia pseudoacacia*) beloved and despised: A story of an invasive tree in Central Europe. *For. Ecol. Manag.* **2017**, *384*, 287–302. [CrossRef]

19. Bigler, C.; Bräker, O.U.; Bugmann, H.; Dobbertin, M.; Rigling, A. Drought as an Inciting Mortality Factor in Scots Pine Stands of the Valais, Switzerland. *Ecosyst.* **2006**, *9*, 330–343. [CrossRef]
20. Galiano, L.; Martínez-Vilalta, J.; Lloret, F. Drought-Induced Multifactor Decline of Scots Pine in the Pyrenees and Potential Vegetation Change by the Expansion of Co-occurring Oak Species. *Ecosyst.* **2010**, *13*, 978–991. [CrossRef]
21. Pająk, M.; Krzaklewski, W.; Gawełek, P. Assessment of forest reclamation of a hard coal waste heap as exemplified by the "Brzeszcze" hard coal mine in Brzeszcze. *Zeszyty Naukowe. Inżynieria Środowiska/Uniw. Zielonogórski* **2013**, *149*, 68–78.
22. Sopper, W.E. Final Report for Project PSU-01. In *Revegetation of Abandoned Coal Refuse Banks*; Penn State University: State College, PA, USA, 1992.
23. Böhm, C.; Quinkenstein, A.; Freese, D. Yield prediction of young black locust (*Robinia pseudoacacia* L.) plantations for woody biomass production using allometric relations. *Ann. For. Res.* **2011**, *54*, 215–227.
24. Brinks, J.S.; Lhotka, J.M.; Barton, C.; Warner, R.C.; Agouridis, C. Effects of fertilization and irrigation on American sycamore and black locust planted on a reclaimed surface mine in Appalachia. *For. Ecol. Manag.* **2011**, *261*, 640–648. [CrossRef]
25. Straker, K.C.; Quinn, L.D.; Voigt, T.B.; Lee, D.K.; Kling, G.J. Black Locust as a Bioenergy Feedstock: A Review. *BioEnergy Res.* **2015**, *8*, 1117–1135. [CrossRef]
26. Marschner, H. *Mineral Nutrition of Higher Plants*, 3rd ed.; Elsevier Ltd./Academic Press: London, UK, 2012.
27. Lehmann, J.; Schroth, G. Nutrient leaching. In *Trees, Crops and Soil Fertility—Concepts and Research Methods*; Schroth, G., Sinclair, L., Eds.; CABI Publishing: Wallingford, UK, 2003.
28. Tzvetkova, N.; Petkova, K. Bioaccumulation of heavy metals by the leaves of *Robinia pseudoacacia* as a bioindicator tree in industrial zones. *J. Environ. Boil.* **2015**, *36*, 59–63.
29. Epstein, E.; Bloom, A.J. *Mineral Nutrition of Plants: Principles and Perspectives*, 2nd ed.; Sinauer: Sunderland, MA, USA, 2005.
30. Ferrari, A.E.; Wall, L.G. Nodulation and growth of black locust (*Robinia pseudoacacia*) on a desurfaced soil inoculated with a local *Rhizobium* isolate. *Boil. Fertil. Soils* **2006**, *43*, 471–477. [CrossRef]
31. Nicolescu, V.-N.; Hernea, C.; Bakti, B.; Keserű, Z.; Antal, B.; Rédei, K. Black locust (*Robinia pseudoacacia* L.) as a multi-purpose tree species in Hungary and Romania: A review. *J. For. Res.* **2018**, *29*, 1449–1463. [CrossRef]
32. Jensen, R.R.; Brake, S.S.; Wolf, S.F.; Bekker, M.F.; Hardin, P.J.; Jackson, M.W. Chemical element concentrations in black locust (*Robinia pseudoacacia* L.) and green ash (*Fraxinus pennsylvanica* Marsh.) leaves at the reclaimed Green Valley coal Mine, Indiana, USA. *Environ. Earth Sci.* **2009**, *60*, 1391–1405. [CrossRef]