Impact of P fertilisation on the growth performance of black locust (*Robinia pseudoacacia* L.) in a lignite post-mining area in Germany

M. Kanzler, C. Böhm, D. Freese

Abstract. Due to its ability to grow on marginal sites black locust (*Robinia pseudoacacia* L.) has been widely planted as a short rotation coppice (SRC) system that produce a renewable biomass feedstock in several post-mining areas of East Germany. However, as most of these sites are still in an initial stage of reclamation with low humus and nutrient contents, phosphorous can play a significant role as a plant limiting factor, because legumes require more P than other plants for their development. In April 2011, two experiments were conducted to evaluate the influence of higher rates and different applications of phosphorus fertiliser on the nutrition, survival, and biomass production of two different-aged black locust SRC plantations on the post lignite-mining site "Welzow-Süd", situated in NE Germany. Treatments were applied as triple superphosphate (30, 60 and 120 kg P ha^{-1}) and PK fertiliser (60 kg P ha^{-1}) through broadcasting or banding on recently harvested or planted trees, respectively. Soil, leaf and woody biomass data were analysed utilising the Mann-Whitney U test and the Spearman correlation coefficient (rS). Following two growing seasons, it was observed that the total dry weight yields of the black locust seedlings were increased strongly by up to 8 times when compared to the control group, particularly when TSP was applied through banding. P fertilisation, however, did not affect the biomass yield of six-year-old black locust trees, but P concentration in leaves among treatments of both sites was still significantly increased and sufficient from a quantity upwards of 60 kg P ha^{-1}. Taken together, a comparably moderate amount of P fertiliser (60 kg ha^{-1}) had a strong impact on P uptake and growth performance in the examined black locust seedlings, which reveals a high potential to improve the current fertilisation practices for SRC black locust plantations grown on our research site.
Keywords biomass yield, black locust, P fertilisation, post-mining area, reclamation, *Robinia pseudoacacia* L.

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Introduction

Black locust (*Robinia pseudoacacia* L.) is a nitrogen-fixing legume, native to southeastern North America and common in the early successional stages (Boring & Swank 1984). It can greatly improve soil properties in terms of enhanced nitrogen content and availability (Keskin & Makineci 2009, Rice et al. 2004), higher organic soil matter, organic carbon sequestration, soil structure and quality (Yüksek 2012). In addition, black locust is able to grow both at a fast rate and in a strong manner even under infertile soil conditions that are too poor for other annual or woody crops (Bongarten et al. 1992, Grünewald et al. 2009). As black locust is particularly known for its tolerance to drought stress, its low demand for nitrogen, and due to its ability to provide an additional income to those farmers whose properties are inappropriate for conventional agriculture, it is often planted on marginal sites such as post-mining landscapes (Grünewald et al. 2009). In the Lusatian mining area (Eastern Germany) continuously ongoing opencast mining activities still create a high potential for young reclamation areas in terms of agricultural reutilisation with low water retention capacity, low humus and nutrient contents, where conventional land use systems often fail (Böhm et al. 2011). In contrast, comparatively economical annual yields between up to 10 t dry mass ha^{-1} can be expected for such areas if the black locust is managed as a short rotation coppice (SRC); though this does depend on site conditions, rotation interval, plant age, coppice maturity and planting layout (Grünewald et al. 2009). Against this background, woody biomass production from fast growing trees in SRC for heat and energy supply is considered to be an alternative land use option for these marginal sites (Bungart & Hüttl 2001). Currently, more than 45 ha SRC planted with mainly black locust trees have already been established in the post-mining area of the lignite opencast mining site "Welzow-Süd", situated in NE Germany. However, despite their low requirements for nutrition and site conditions, insufficient phosphorus may reduce their N$_2$-fixation capacity, which could then result in a reduction of the plant's biomass production (Römer & Lehne 2004). Generally, legumes require more P than other plants for their root development, as well as the energy-driven processes that enhance their symbiotic N-fixation (Gillespie & Pope 1990b, Marschner & Marschner 2012), as such P is known as a limiting factor for plant growth (Misra et al. 1998). In this connection, phosphorus plays a significant role due to the fact that in soils it rapidly forms insoluble complexes with cations and is incorporated into the organic matter by microbes (Vance 2001), or is only available outside the rhizosphere (Schachtman et al. 1998). Hence, only the phosphate dissolved in the soil solution is actually available for plants. In unfertilised soils, this concentration ranges from 0.001 to 0.1 mg P l^{-1}, whereas optimal agricultural plant nutrition requires a phosphate concentration of at least 0.2 mg P l^{-1} (Pagel et al. 1982) or between 0.3 and 0.8 mg P l^{-1}, which additionally has to be constantly replenished by the mobilisation of P from the labile pool (Scheffer and Schachtschabel 1998, Mengel and Kirkby 2001). To further ensure an equal concentration of 0.2 mg P l^{-1} in soil solution, plant-available P contents (P$_{DL}$) of approximately 110 mg P kg^{-1} in soil is required for carboniferous mine soils due to higher P sorption and affinity (Freese 1988). Although required plant-available P contents are expected to be much lower for non-carboniferous substrates, several studies within the Lower Lusatian mining district have indicated insufficient quantities below 15 mg P kg^{-1} in non-carboniferous mine soils within the initial stages of reclamation (Vetterlein et al. 1999a, 1999b). This suggests that an adequate P supply has to be guaranteed by an appropriate use of fertiliser to increase the crop yield and stress-toleration of legume plants, an increase needed in order to ensure a woody biomass renewable energy supply and therefore successful agricultural

reutilisation of these reclaimed mining areas. Because no common P fertilisation recommendations to improve growing conditions for black locust previously existed for these sites, it was necessary to close this knowledge gap. The aim of this study was therefore to investigate the field impacts of P fertilisation rates and forms of application on the tree growth, biomass production, and nutrition of black locust trees in different-aged SRCs growing in a post-mining area. As a result, two experimental sites were established on two mine spoils in divergent stages of reclamation.

Material and methods

Site description

The two sites established for the purposes of this study are located in the post-mining area of the lignite opencast mining "Welzow-Süd" (51 35′ 58″ N, 14 16′ 44″ O) in the state of Brandenburg, Germany (Figure 1).

Figure 1 Location map showing the study area in East Germany

Welzow-Süd belongs to a region of Germany which is influenced by a continental climate. With a mean annual temperature of 9.3 °C and an average annual precipitation sum of 560 mm covering the period of 1951-2003 (meteorological station Cottbus), this post mining site is one of the driest areas in Germany. Two main types of substrates can be identified here: lignite- and pyrite-containing substrates stemming from Tertiary sediments, and lignite- and pyrite-free substrates from Quaternary sediments (Schaaf 2001). Common characteristics are a mainly sandy texture, a low-content of recent organic matter, and a low-nutrient status (Grünewald et al. 2009, Wilden et al. 1999). In both study sites, the dominant soil texture at the topsoil level is loamy sand and mainly consists of pyrite-free substrates from Quaternary sediments. Generally, soil formation is in an initial stage and the soil structures are still instable. The whole research area is not groundwater influenced and was partially reforested with mainly black locust trees at a density of approximately 9,200 trees each hectare (Böhm 2012).

Experimental design and sampling methods

The research was carried out in the autumn of 2011 in two black locust SRCs which were chosen for a randomised fertilisation experiment. The first experiment took place in a six-year-old coppice (site A) which had been recently harvested and was already in the second rotation, while the second trial was carried out in a recently established plantation (site B). The randomised block design consisted of 25 blocks with different fertilisation levels and treatments, all with five replications each. Plot size was around 160 m², but only the inner area of approximately 64 m² was sampled and used as a treatment zone to avoid boundary or carry-over effects. Depending on plant density, approximately 60 trees covered the treatment area. Triple superphosphate (TSP, 46% P_2O_5) was used as a basic source of phosphorus, but

additional variations with a PK-fertiliser (15% P_2O_5, 30% K_2O) were also realised and applied manually by hand. P-treatment levels in the first experiment were 0, 30, 60 and 120 kg ha^{-1} of elemental P broadcasted as TSP and 60 kg ha^{-1} added as PK-fertiliser (Figure 2). The treatments at the second site did not differ in the amount of phosphorus which was given (60 kg ha^{-1} each), but did in relation to the form of application and P source, in which PK and TSP were either broadcasted or banded. Both sites were treated in April 2011, as fertiliser was applied to the recently harvested (site A) and planted (site B) trees, respectively. In order to adjust the nutrition with potassium, and to accelerate phosphorus uptake by the plant (Römer & Lehne 2004), all plots were additionally treated with potassium oxide (K_2O) to a level of 180 kg elemental K ha^{-1} each. In order to take into account the ability of legumes to fix atmospheric nitrogen, as well as to save resources and prevent possible N leaching into deeper spoil layers on non-carboniferous sandy mine spoils (Vetterlein et al. 1999a), any donation of mineral nitrogen fertiliser was avoided.

Soil and Leaf Sampling. Soil samples for the analyses of chemical properties were taken on 20th April 2011, immediately before fertilisation, and also four months after. Considering the fact that topsoil is the most fertile and important layer for plant growth (Antonijevic et al. 2012), sampling was performed up to a depth of 30 cm. For each of the 50 plots, composite samples of 8 cores were taken. Samples were instantly stored in a freezer pack and directly transported to the laboratory. Leaf samples were taken in August as a composite sample of five leaflets from the lower and middle crown (three from the sunny and two from shadowed canopy) of five randomly chosen, average individuals from each plot in each site. Sampled trees were marked for further research.

Tree Growth Measurements and Survival Rate. The tree height and shoot basal diameter (SBD) at 10 cm from the ground soil of the surviving trees were measured annually in winter 2011/12 and 2012/13, respectively. Within the treatment area of each plot, 24 leaf-
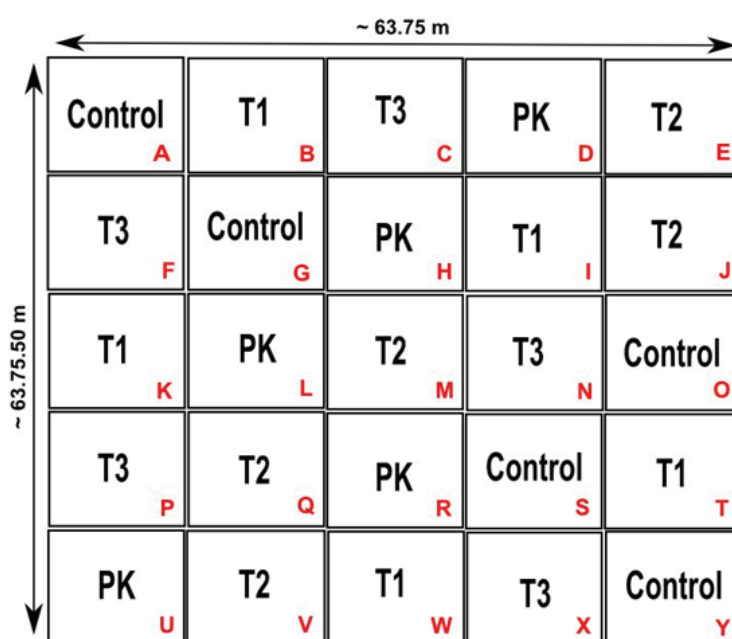

Figure 2 Randomized block design on site A with 5 treatments levels and a control group. Treatments are 30 (T1), 60 (T2) and 120 (T3) kg P ha^{-1} as triple superphosphate and 60 kg P ha^{-1} PK fertiliser (PK)

less trees (every third tree in each row with a treatment zone containing six rows) were measured, whereas all individuals within the treatment zone were considered in order to aid in determining the survival rate. The woody above-ground dry biomass for each plot was predicted with an allometric equation according to Böhm et al. (2011) and later projected for each treatment in hectares. The mortality rate was not included for yield prediction due to its suspected independence from P fertilisation.

Chemical analysis

The soil contents of nitrate nitrogen and ammonium nitrogen (NO_3-N, NH_4-N) were extracted and analysed according to DIN ISO 14256. Following this, the soil samples were then air-dried, homogenised and sieved ≤ 2 mm. Soil pH was measured in 0.01 mol L^{-1} $CaCl_2$ solution (soil solution ratio = 1:2.5). Plant-available phosphorus (P_{DL}) and potassium (K_{DL}) were determined according the VD-LUFA DL-method (Hoffman 1991). Foliage was oven-dried at 60 °C until the weight was constant before it was later grinded using a vibratory disc mill. The total contents of carbon (TC) and nitrogen (TN) for all plant and soil samples were measured with an ELEMENTAR VARIO III element analyzer. Soil organic content was estimated by the loss-on-ignition (LOI) method after igniting the soil samples at 450 °C in a muffle furnace for five hours (Barrington et al. 1994). After, carbon was measured again (TIC) and the TOC was calculated by the difference of TC and TIC. Phosphorus, potassium, magnesium and calcium in digested plant materials were diagnosed according to Schramel et al. (1993) using inductively coupled plasma spectrometry (ICP-AES - Unicam iCAP6000 Duo).

Statistical analysis

Statistical analysis was performed using IBM SPSS 21 (August 29th, 2012) software. All variables were tested for normal distribution using the Shapiro-Wilk-Test (W-test). Considering the fact that several individual variants (treatments) were not normally distributed, we used the non-parametric Kruskal-Wallis test (H-test) to identify any influence of the treatments on other tested parameters. Subsequently, the Mann Whitney test (U-Test) was applied to detect the pairwise differences. In order to evaluate the variations between soil nutrients among treatments before and after fertilisation, we utilised the Wilcoxon sign rank test. Furthermore, the Spearman correlation coefficient (rS) was computed to express relationships between different soil, leaf and biomass properties. The minimal significance level (α) for rejection of the null hypothesis was 0.05.

Results

Chemical soil properties

The first soil analysis of April 2011 revealed comparable alkalescent soil pH values among treatments for site A (Table 1) and small variations in acidic values between 5.8 and 6.5 for the B site. As expected, soil contents of plant-available nutrients before the fertilisation of both sites were generally very low. However, it should be noted that the nutrient status for banded treatments should be taken with caution as the fertiliser was concentrated in slim lines along the tree rows, due to sampling points being distributed randomly in the whole treatment area.

Soil analysis after fertilisation (August 2011) showed that the concentrations of mineralised N among all treatments of both sites declined, while available soil P increased significantly for all plots on both sites which were treated with at least 60 kg P ha^{-1} broadcasted TSP. Extractable K in soil significantly increased ($p < 0.05$) only in banded PK fertilised groups (RS). The total content of nitrogen (TN) was similar

among treatments and sites, except for Control at site A. Overall, low total carbon (TC) pools between 0.45 and 0.67% were detected, whereas contents for site A were up to 49% higher than those of site B. This contrasted sharply with the total organic carbon contents (TOC), as the values for site B were almost twice the value of those detected on site A. C/N ratios between 23 and 27 occurred at site A, whereas slightly wider ratios with values around 30 were determined for site B.

Plant nutrition

While foliar N and K contents among TSP 30 kg P ha^{-1} (T1), TSP 120 kg P ha^{-1} (T3) and PK 60 kg broadcasted P ha^{-1} (PK) at site A were comparable, TSP 60 kg P ha^{-1} (T2) tree leaves contained approximately 37% more N than those of Control (Figure 3). Conversely, Control trees accumulated 27% more K than those of T2. However, the largest amounts of Ca and Mg were accumulated in the foliage of trees on T3. The lowest Mg and Ca contents were determined for T2, but the adjacent values for the

repetitions diverged widely. Yet, even taking this into account, no significant differences in the contents of the aforementioned elements among treatments were detected.

As had been expected, the foliar P content on site A steadily increased with higher fertiliser rates ($r = 0.629$, $p < 0.01$) and reached its zenith at T3. Thus, though foliage P of Control was significantly lower than all other treatments, no significant increase upwards of a quantity of 60 kg P ha^{-1} occurred. N detected in
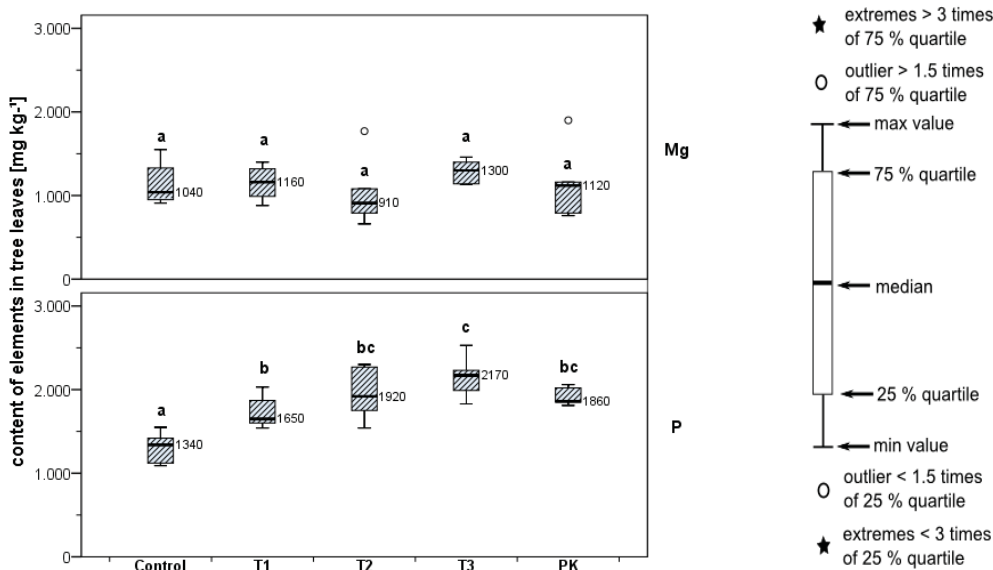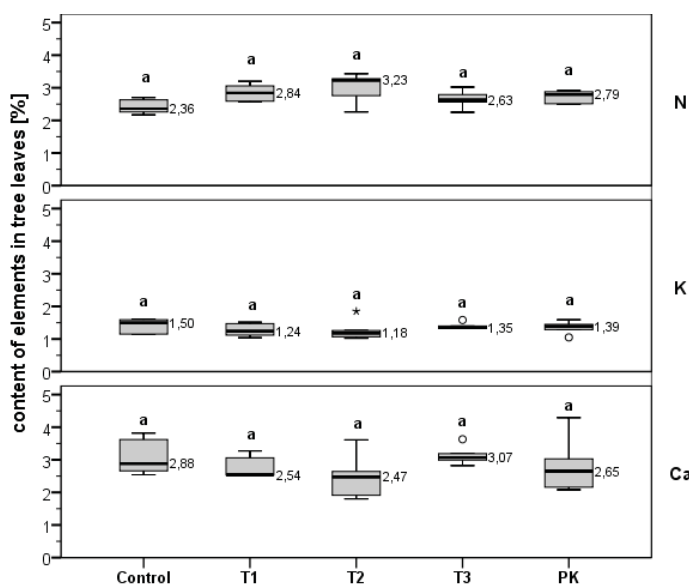

Figure 3 Contents of nutrient elements in tree leaves among treatments on site A. Different letters indicate a significant difference ($p < 0.05$) among different treatments

Table 1 Soil chemical characteristics (0-30 cm depth) among different treatments upon both study sites before and after fertilisation

site	treatment	April 2011				August 2011							
		pH	N_{min}	P_{DL}	K_{DL}	pH	TN	TC	TOC	C/N	N_{min}	PDL	KDL
			mg kg^{-1} soil				%			ratio	mg kg^{-1} soil		
A	C	7.8^a	3.7^a	17.0^a	31.0^a	7.8^a	0.02^a	0.60^a	0.29^a	25a	1.3^a	19.0^a	32.0^a
	T1	7.9^a	4.3^a	14.0^a	29.0^a	7.8^a	0.01^a	0.67^a	0.27^a	23a	1.6^a	17.0^a	34.0^a
	T2	7.8^a	4.3^a	16.0^a	31.0^a	7.7^a	0.01^a	0.51^a	0.24^a	27a	1.8^a	26.0^a	35.0^a
	T3	7.8^a	4.1^a	15.0^a	37.0^a	7.8^a	0.01^a	0.59^a	0.26^a	25a	2.0^a	23.0^a	32.0^a
	PK	7.9^a	3.7^a	13.8^a	35.0^a	7.8^a	0.01^a	0.63^a	0.25^a	23a	2.1^a	17.0^a	41.0^a
B	C	6.3^a	2.0^a	4.4^a	26.0^a	6.6^a	0.01^a	0.50^a	0.41^a	32a	1.1^a	3.3^a	21.0^a
	TB	5.8^a	1.9^a	2.9^a	25.0^a	5.4^a	0.01^a	0.54^a	0.45^a	28a	1.3^a	21.0^b	19.0^a
	TS	6.0^a	1.6^a	4.9^a	19.0^a	6.6^a	0.01^a	0.45^a	0.39^a	26a	1.1^a	20.0^{ab}	20.0^{ac}
	RB	6.4^a	1.7^a	3.8^a	17.0^a	7.3^a	0.01^a	0.50^a	0.36^a	31a	1.2^a	20.0^b	45.0^b
	RS	6.5^a	1.7^a	3.9^a	19.0^a	6.0^a	0.01^a	0.50^a	0.36^a	36a	1.0^a	6.7^{ab}	46.0^{bc}

Note. Values are given as median of a subset of plots (n = 5). Treatments on A site are: 30 (T1), 60 (T2) and 120 kg P ha^{-1} (T3) applied as triple superphosphate and 60 kg P ha-1 applied as PK fertiliser (PK). On site B plots were treated with 60 kg P ha^{-1} as triple superphosphate through broadcasting (TB), banding (TS) and as PK fertiliser broadcasted (RB) and banded (RS). Different letters indicate a significant difference ($p < 0.05$) among values within a column of each site separately. Bold printed values indicate a significant change between sampling dates of a single parameter among treatments at the $p < 0.05$ level.

tree leaves of the B site in most cases was up to 57% higher than those at the A site (Figure 4) and correlates closely with the P foliage content ($r = 0.745$, $p < 0.01$). PK 60 kg broadcasted P ha^{-1} (RB) and RS accumulated the highest amount of N and were significantly different from those of Control and TSP 60 kg broadcasted P ha^{-1} (TB) ($p < 0.05$), while remaining treatments had almost comparable N contents. Contrary to the results of site A, treatments significantly increased the foliage N content in tree leaves of black locust seedlings ($r = 0.700$, $p < 0.01$). In addition, foliage of RB and RS contained the highest amounts of K but were low in Mg, whereas a negative relationship between K and Mg among all treatments could be observed ($r = -0.770$, $p < 0.01$). On the other hand, foliage Ca and Mg were positively related to each other ($r = 0.802$, $p < 0.01$ site A, $r = 0.506$, $p < 0.01$ site B) on both sites.

Foliar P among treatments of the B site was correlated to the amount of added phosphorus and the form of application, respectively ($r = 0.581$, $p < 0.01$). Overall, P contents were comparable to those of site A and, except for the TB, significantly higher than the control group

($p < 0.05$). This was particularly pronounced between Control and banded treatments ($p < 0.01$).

Biomass yield and survival rate

The biomass yields among different treatments on site A for both measuring periods are given in Figure 5. In both years, trees in Control plots achieved the highest biomass yield, while T3 provided only average results.

In early spring 2012, the first signs of a devastating fungal disease appeared over the entire study site A. As a result, woody biomass declined for several treatments, as did T2 where dry woody biomass was approximately 26% lower than in the previous year. PK and T3 had barely noticeable biomass increases of not more than 2%, while those trees of T1 marked a surplus of at least 8%. With a surplus of 13%, Control did substantially better, yet no statistical yield differences among treatments were evident. In contrast, Figure 6 reveals significantly higher dry woody biomass for all treatments of site B when compared to Control (banded treatments $p < 0.01$, broadcasted

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treatments $p < 0.05$) at the end of 2011.

In addition, the maximum biomass yield was more than 8 times higher than Control when TSP was applied by banding. Likewise, it was significantly higher ($p < 0.01$) than TB and RB ($p < 0.05$). Thankfully TS, RS and RB produced favourable results, as TB was below expectations. In the following growing season (2012), TS trees sextupled their crop yield and remained the most profitable among all tested treatments on site B. Additionally, the average biomass yield of RS, which was merely ordinary at the end of the growing season of 2011, now increased more than eightfold and thus achieved the second-best result. Taken together, biomass yields of all banded treatments were substantially higher than at broadcasted groups after two years and thereby drew near to the performance of those black locust trees at site A which were five years older. Furthermore, the biomass yield in 2012 and 2013 for black locust trees on site B correlate closely with the P leaf concentration ($r = 0.656$, $p < 0.01$ in 2012, $r = 0.661$, $p < 0.01$ in 2013), the N leaf concentration ($r = 0.537$, $p < 0.01$ in 2012, $r = 0.513$, $p < 0.01$ in 2013) and the P application rate ($r = 0.541$, $p < 0.01$ in 2012, $r = 0.557$, $p < 0.01$ in 2013). By contrast, for site A only leaf N was significantly correlated with the biomass yield in 2013 ($r = -0,526$, $p < 0.01$).

On average, every fifth tree on site A and less than each tenth tree on site B, died within the first growing season (2011). In the following year it was already each forth tree that died
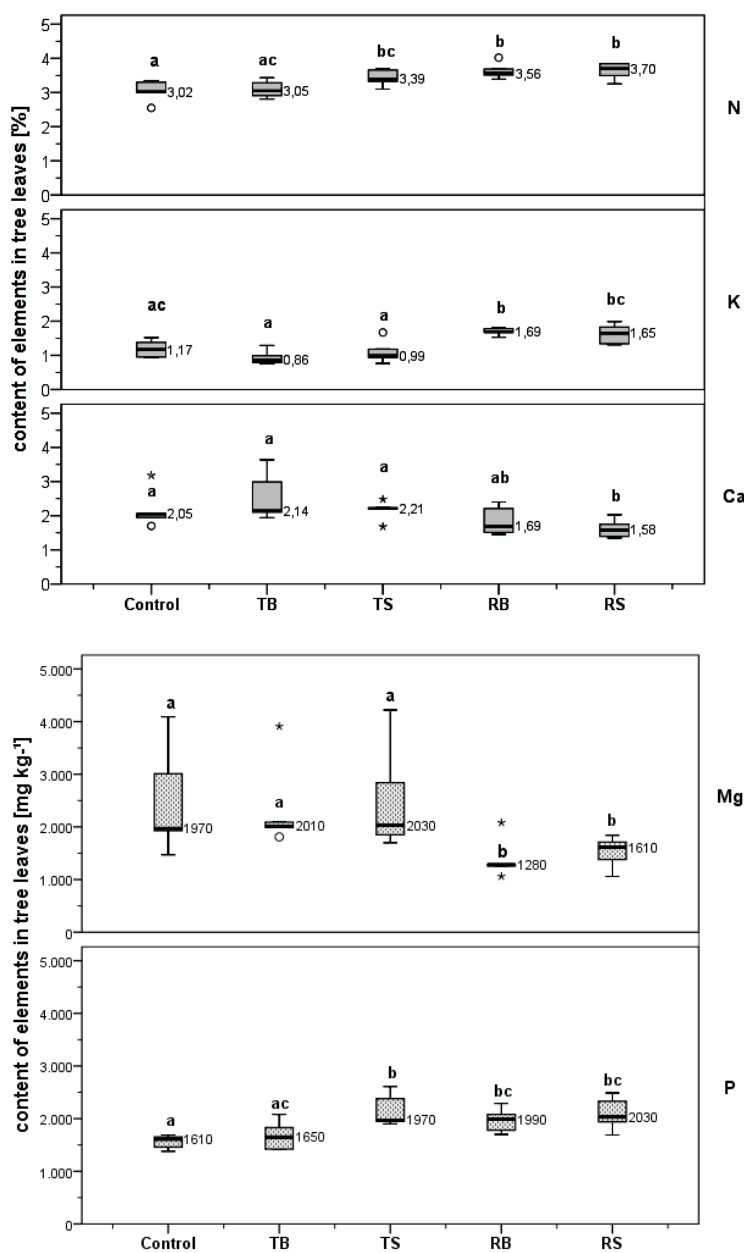

Figure 4 Contents of nutrient elements in tree leaves among treatments for site B. Different letters indicate a significant difference ($p < 0.05$) among different treatments

on site A, whereby T1 lost the highest (28%) and Control the lowest number (20%) of trees. Meanwhile, losses on our second experimental trail were hardly noticeable (lower than 4%). Yet, it should be noted that differences in loss rates among treatments on both sites were not statistically significant.
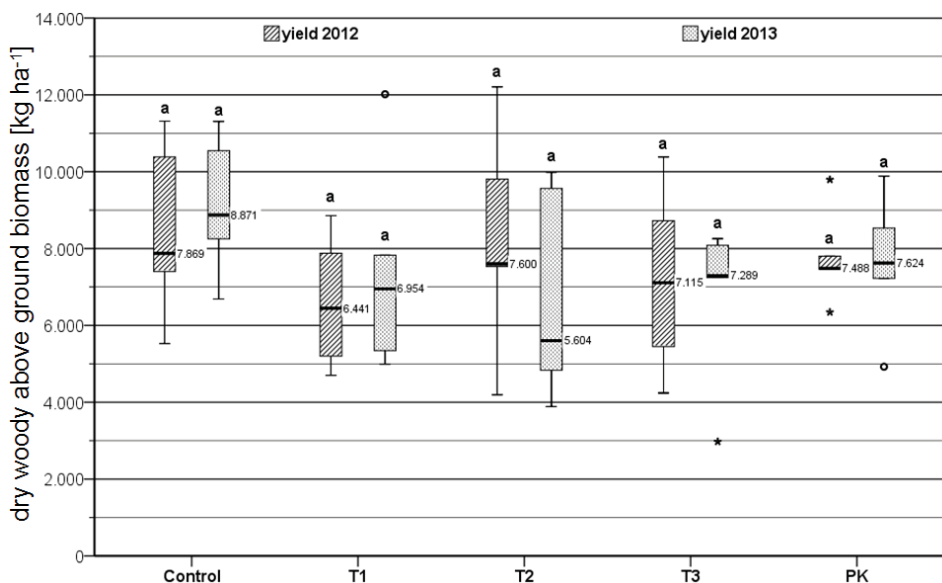
Figure 5 Total dry biomass for each treatment on site A for growing season 2011 and 2012. Values are median weights of a subset of plots (n = 5). Different letters indicate significant differences (*p* < 0.05) between treatments within a year
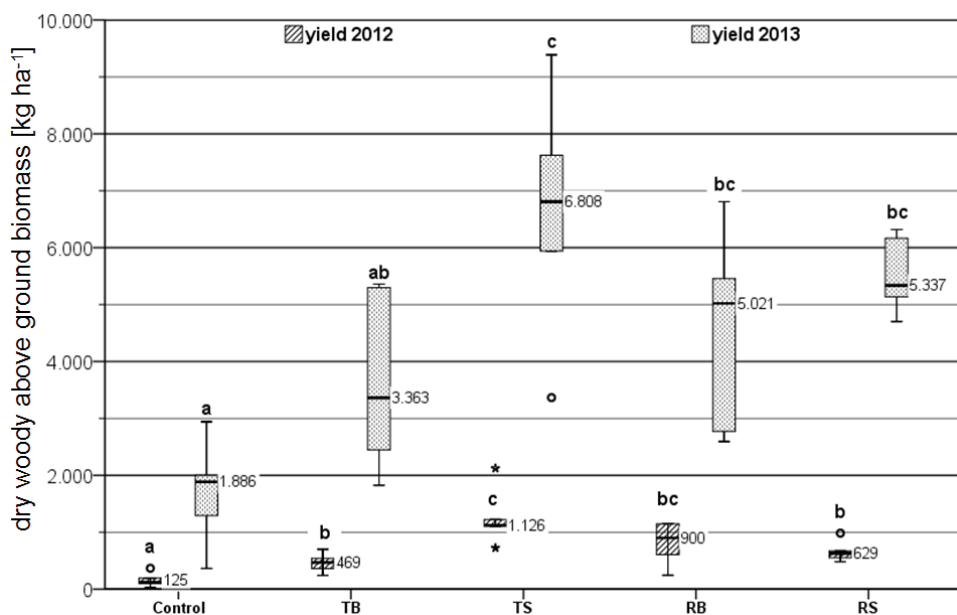

Figure 6 Total dry biomass for each treatment on site B for growing season 2011 and 2012. Values are median weights of a subset of plots (n = 5). Different letters indicate significant differences (*p* < 0.05) between treatments within a year

Discussion

P fertilisation and crop yield response

Soil analysis from April 2011 indicated very low amounts of plant-available nutrients and organic matter content in the topsoil of both study sites. This has, however, been reported as usual for mine spoils in the Lusatian lignite region (Heinsdorf 1992, Katzur & Hanschke

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1990, Vetterlein et al. 1999a, 1999b). As such, most of these areas are less suitable for agricultural crop production or require high fertilisation rates during the first years of reclamation (Katzur & Hanschke 1990). In fact, our findings confirm that even under these infertile soil conditions, black locust trees grown in Control group plots were able to achieve at least 4.4 t ha^{-1} a^{-1} (site A) and 0.9 t ha^{-1} a^{-1} (site B) of dry woody biomass within a period of two growing seasons. Although higher P fertilisation rates could not clearly improve biomass production at site A, banded TSP treatments at site B led to an average increase of approximately 8 times more woody dry biomass when compared to their control counterparts within the first growth period. After two growing periods, it was ascertained that yields of banded trees were superior to broadcasted trees. Therefore we can assume that, in addition to the type of fertiliser, the form of application can additionally improve the fertiliser use efficiency, which is also suggested by Brown & van den Driessche (2005) and Vetterlein et al. (1999a). In analogy to the results of Ntayombya & Gordon (1995), black locust seedlings performed well under PK fertilised conditions, even without any mineral nitrogen donations and under initial soil conditions. The lack of yield response to P fertilisation on site A, however, might have been caused by several reasons. First of all, the devastating fungal disease, primarily *Fusarium* spp. and *Phomopsis oncostoma* (Thüm.) Höhn. (Landgraf & Hydeck 2014), which initially appeared in Spring 2012, obscured any growth effects by destroying above-ground biomass, an occurrence particularly noticeable on those plots which had been fertilised. Secondly, the highest above-ground biomass yield and tree survival rate was determined in the control group, probably favoured by comparatively good preconditions in terms of soil TN and plant-available P and K.

P fertilisation and plant nutrition

Finally, and probably a key reason for a lack of response to P fertilisation, is that phosphorus was not a primary growth limiting element. Nevertheless, the amount of P fertiliser or form of application significantly increased the P content in foliage on both sites. Overall, foliage P concentration increased by up to 69% (site A) and 25% (site B) within the first vegetation period after fertilisation. Similar results were also obtained with different pine species, black locust and other legumes (Abarchi et al. 2009, Crous et al. 2008, Flinn et al. 1982, Reinsvold and Pope 1987). Leaf analysis additionally indicated an increase of N by up to 37% (site A) and almost 23% (site B) when compared to their control counterparts. Although there was no significant correlation between P application and N foliar content for site A, this correlation was present for site B. These results are in conformity with the findings of Pope and Andersen (1982), who explained the enhanced foliar N content through the stimulating effect on the nitrogen-fixing bacteria in P fertiliser application. Alternatively, the atmospheric deposition is also conceivable as an additional nitrogen source, especially for younger, frugal plants. In addition, black locust itself acts as a nitrogen source through leaf and root litter mineralisation and nitrification and can therefore generate up to 75 kg N ha^{-1} (Boring & Swank 1984). In addition, Heinsdorf (1987) indicated that the N uptake of black locust plants can be stimulated through a combination of P and K fertilisation, as an admixture of N results in a considerably reduced growth and therefore must be avoided at any rate. In fact, black locust seedlings require minimal amounts of nitrogen, at least initially, to support nodulation and thereby N2 fixation (Reinsvold & Pope 1987). Conversely, lower mineral N pool in soil, and higher N demands of plants with an already established root system, could be responsible for the negligible N accumulation in the foliage of fertilised trees at our first study

Table 2 The chemical composition of the plant foliage from black locust trees at both study sites in comparison to other published results

	Site A				Site B						Heinsdorf (1987)	Böhm (2012)	Mendel (2008)	Rhamo-nov (2009)	Epstein & Bloom (2005)	Jensen et al (2010) control site	Jensen et al (2010) mine site
	Control T1	T2	T3	PK	Control TB	TS	RB	RS	PK								
Macronutrients																	
NT (%)	3.06	2.84	3.23	2.63	2.79	3.02	3.05	3.39	3.56	3.7	3.23-4.13	4.7	3.58	2.65	N/A	N/A	N/A
CT (%)	45.61	45.33	45.61	44.15	44.59	44.71	44.64	45.5	44.79	45.55	N/A	48.1	44.6	53	N/A	N/A	N/A
P (mg kg^{-1})	1,600	1,650	1,920	2,170	1,860	1,610	1,650	1,970	1,990	2030	1,800-2,100	3,5	2,170	948	2,000	4,350	3,410
Mg (mg kg^{-1})	1,080	1,160	910	1,300	1,120	1,970	2,010	2,030	1,280	1610	1,800-1,900	1,3	1,380	1,618	2,000	3,290	3,880
Ca (mg kg^{-1})	25,150	25,420	24,680	30,670	26,490	20,500	21,440	22,100	16,940	15770	10,600-11,800	6,8	12,440	19,116	5,000	12,000	17,800
K (mg kg^{-1})	10,730	12,420	11,830	13,520	13,850	11,740	8,610	9,940	16,940	16480	12,000-13,500	19,7	17,350	6,554	10,000	25,800	24,500
Micronutrients																	
Fe (mg kg^{-1})	90	80	70	100	90	140	140	130	130	150	N/A	81.9	N/A	258	100	98.6	116
Mn (mg kg^{-1})	20	20	20	30	30	60	50	40		50	N/A	28.3	N/A	110	50	41.5	58.2
Ratio C:N	19.1	15.8	14.1	17.2	15.8	14.3	14.9	13.2	12.7	12.4	N/A	10.4	12.5	20	N/A	N/A	N/A

site. On the other hand, the decline in nutrient contents of legumes with age is caused by advancing cell-wall formations, a decreasing leaf/steam ratio, increasing proportions of senescent plant parts, and translocation of N and P from the leaves and stems to inflorescences (Abarchi et al. 2009). Nonetheless, soil available N pool should not be overestimated since, with increasing tree size and N demand, the soil source becomes secondary to enhanced supply through nitrogen fixation (Bongarten et al. 1992). Furthermore, the nitrogen fixation rate is often suppressed by increased N availability through fertilisation while also being frequently stimulated by increased P availability (Reed et al. 2007). A direct comparison of our leaf nutrient results to other studies with black locust (Table 2) clearly shows that, even without additional mineral applications and despite low soil available N supply, N foliage contents indicate a sufficient nutrient status. A similar situation occurred for leaf P content, at least for most of the fertilised treatments. In their control counterparts, however, the P levels were lower than in the majority of comparative studies. Nevertheless, those concentrations were still sufficient, since leaf contents of healthy woody plants are between 0.1 to 0.7% of dry weight (Aiello & Graves 1996, Smith 1978) and substantially lower values for a restriction in P nutrient supply on mine spoils were reported by Heinsdorf (1992). Despite this fact, P fertilisation still seems to be appropriate in order to exclude phosphorus as a yield restricting factor.

P-fertilisation and nutrient availability

In contrast to sufficient P and N foliage contents, the interaction of low Mg and high Ca or K contents among all treatments on both sites has to be regarded critically. In most plants, leaf magnesium content generally ranges around 0.10 – 0.50% of dry matter, but Mg deficits have been reported as common if loamy soils were strongly calcareous while containing low amounts of Mg or after liming of acidic soils (Bergmann 1993). Furthermore, Mg soil mobility, and thus the uptake by plants, may be diminished if high concentrations of H^+, K^+, Ca^{2+}, NH_4^+ and Mn^{2+} are available (Mengel and Kirkby 2001). Generally, an excess of macronutrients in soil can create deficiencies of other elements from iron antagonism or cation compensation (Jensen et al. 2010). Furthermore, our data suggests that this became particularly conspicuous if black locust seedlings were treated with PK fertiliser. Due to the fact that all treatments received the same amount of potassium, it can be concluded that potassium in this form is highly accessible for black locust trees. Alongside the ability to reduce pH, potassium can lead to P availability through cation exchange of Ca and therefore a phosphate desorption caused by electric negative repulsion (Lammers 1997). Nichols & Beardsell (1981) and Vanray & Vandiest (1979) reported an interaction between P and Ca uptake of some species, which in turn could not be confirmed by our results. However, leaf Ca concentrations over 2% are much too high and therefore not desirable (Heinsdorf 1987). In contrast to the macronutrient situation, Mn and Fe leaf contents among most of the treatments of site A were much lower than the published adequate respectively comparative values. Especially high rates of Fe play a key role in the N_2 fixing availability of plants (Schubert 2006). Jensen et al. (2010) consider a deficiency of Mn and Fe as a possible reason for a high mortality rate among different tree species on a reclaimed mine spoil. Although we have no exact results concerning the soil micronutrient levels of our study sites, it has been reported that even if the micronutrient level in soil is adequate, high soil pH and carbonate is usually the cause of micronutrient deficiencies in many of the calcareous soils especially in arid regions. In such cases the solubility and availability of micronutrients to plants decrease due to the change of their ionic form to an insoluble hydroxide or oxide of the elements (Brady and

Weil 2008). Finally, high carbonate content in soils can also lead to a high P immobilisation capacity through the precipitation of Ca phosphates (Freese et al. 1989, Pope & Andersen 1982, Vetterlein et al. 1999a), even at lower pH values (Vetterlein et al. 1999b). This might be one of the reasons for the comparatively small increases of extractable soil P after application. Broadcasting, however, led to an enrichment of phosphorus not only in the top 2-3 cm (Heinsdorf 1976), but in the whole topsoil (0-30 cm) that was sampled. Yet, even taking this into account, it is also conceivable that the labile P stocks had been underestimated by the DL-method, as the quality of the potentially available phosphorus is examined but the decisive factors for P uptake like intensity, rate and buffering of phosphates remain unconsidered. This is usually the cause of weak correlation coefficients of extractable P in soils and plant yields. However, this effect is quite common for the classic extraction methods like DL, CAL, Olsen P and the waterbased P extraction (Scheffer & Schachtschabel 1998). However, the DL-method is commonly utilised in the Lusatian lignite mining district (Vetterlein et al. 1999b) and is equivalent to the often used Bray Method for P determination on open-cast mine spoils (Vetterlein et al. 1999a). Despite such findings, Jungk et al. (1993) reported that a TSP fertilisation with more than 218 kg P ha^{-1} was necessary to significantly increase soil available P in order to achieve full yield in a crop rotation with sugar beet, winter weed, or winter barley, even on fertile, arable soil. Such high dosages of P fertiliser have been reported as necessary for soils with a high phosphate adsorption capacity (Jamer et al. 1998). Furthermore, negligible increases in soil available P, especially on site A, could also be ascribed to the enhanced uptake of older black locust trees, and a translocation of a considerable proportion to the plant roots. Misra et al. (1998), for example, reported that assimilates are used preferentially by the shoots of *Eucalyptus nitens* (Deane & Maiden) if conditions limit

photosynthesis, and preferentially by roots if conditions limit nutrient or water uptake. Nevertheless, it remains to be clarified wheather black locust trees distributes nutrients in a similar way. Intensive root development in turn can provide an enhanced P uptake by plants through a reduction of the diffusion paths in soil (Horst & Waschkies 1987), as well as through rhizosphere acidification mechanism (Fohse et al. 1991, Gillespie & Pope 1990 a,b, Horst & Waschkies 1987). Finally, a positive effect of fertilisation may have been incurred below-ground and therefore unrecognised by our research.

Conclusions

In the context of the present study, it was demonstrated that a comparatively moderate amount of phosphorus (60 kg ha^{-1}) had a strong impact on P uptake and the growth performance of examined black locust seedlings, especially when TSP was applied through banding. Moreover, the nutrition of the studied black locust trees after P fertilisation turned out to be sufficient, despite low soil nutrient contents and the lack of mineral nitrogen fertilisation, suggesting this tree species is suitable for further cultivation on the post-mining landscapes considered in our study. Taken together, these findings may help to improve the current fertilisation practices for recently planted or scheduled SRC black locust plantations even on reclaimed areas with comparable site conditions to increase their woody biomass production or create healthier plants to accelerate a successful reclamation process. Neithertheless, further results from a wider range of years would be required to determine the optimal fertilising intervals, rates and mixtures in order to avoid nutrient deficiency in older black locust trees, while taking P sorption capacity of mine spoils and ion antagonisms into account. For future research we propose the measurement of below-ground biomass in addition to only above-

ground biomass to fully understand nutrition interactions between above- and below-ground components of black locust trees.

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