EFFECTS OF SOIL PROPERTIES ON THE PERFORMANCE OF BLACK LOCUST (*ROBINIA PSEUDOACACIA*) IN A RECLAMATION AREA

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Abstract. In this research, we investigated nine black locust (*Robinia pseudoacacia* L.) plantations in a reclamation area of an opencast coal mine in Shuozhou, Shanxi, China. One hundred individuals of black locust in each of plantations were randomly selected, and variables related to growth and nutritional status were recorded. In addition, soil physiochemical and biological properties were analyzed. Results showed that there were significant differences (P<0.05) in the growth variables and leaf nutrient concentrations of black locust and soil properties among the nine plantations. According to the principal component analysis (PCA), Field moisture capacity, soil water content, number of fungi, urease activity and bulk density were the main soil influencing factors. During the multidimensional scaling (MDS) analysis, soil water content, bulk density, soil fungi and catalase affected the highest values of diameter at breast height (DBH) and top height (H) of black locust, and soil alkaline phosphatase affected crown diameter (CD). There was no significant relationship between death rate (DR) and soil properties. Among the factors, soil water content, soil bulk density and soil fungi had important effects on performance of black locust. Therefore, attention must be paid to the soil water content of black locust plantations in the reclamation area and ensure that each individual plant can absorb necessary water. At the same time, suitable soil bulk density and fungal inoculation may promote black locust's growth. The results will contribute to the cultivation and management of black locust.
Keywords: *ecological rehabilitation, plantation, growth variables, soil characteristics, black locust*

Introduction

Black locust (*Robinia pseudoacacia* L.) is a medium-sized deciduous tree native to subtropical and temperate regions of North America. In the early 17th century, it was introduced to Europe, and at the end of the 19th century, it was introduced to Qingdao, China by Germans (Xun et al., 2014). The applications and studies of black locust vary in different countries. American scientists have carried out several studies on expansion characteristics of black locust and the relationship between biomass and climate, soil conditions, and other external variables (Converse et al., 1995). In Greece and other Mediterranean countries, black locust is used as local auxiliary feed for livestock. Accordingly, cultivation and breeding are the main research topics. In Hungary, black locust is used for its excellent timber quality, and research has mainly focused on genetic

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improvement, plantation management, and resource development (Redei et al., 2001). In western and southern Europe, black locust is an important tree species for afforestation; therefore, research has focused mainly on breeding and cultivation modalities. In Bulgaria, black locust is used as the main tree species for revegetation to combat the serious pollution caused by the coal industry (Filcheva et al., 2000). In some other European countries and in South Korea, black locust is considered to be an invasive alien species, and research has mainly focused on the impact of black locust on native species and other ecological effects (Chang-Seok et al., 2003). As black locust has a wide ecological amplitude, fast growth, sand fixation capacity, soil conservation capacity, and notable ability to fix nitrogen, it has been widely planted as a revegetation and afforestation pioneer species in China (Zhao et al., 2018).

We studied black locust plantations in a reclamation area of an opencast coal mine in Shuozhou, Shanxi, China more than 20 years. With the extension of reclamation time, the incidences of shoot blight and tree death in black locust have gradually increased, however, the reasons for these increases are still not well understood. There is a close relationship between plants and soil. On the one hand, plants improve soil structure and fertility. On the other hand, soil provides nutrients and moisture for plants growth, so the growth, productivity, and reproductive capacity of plants are largely determined by soil properties (van der Putten et al., 2013). Although many studies have documented that black locust greatly improves the maturation of reclaimed soil, information about the impact of maturing soil on the performance of this species is lacking. Therefore, the objective of this study was to determine the main soil factors affecting the performance of black locust, providing a scientific basis for vegetation restoration.

Materials and Methods

Study area

The study area is situated in the reclamation area of Antaibao opencast coal mine (39°23′–39°37′N, 112°10′–113°30′E), which is located in Shuozhou, Shanxi, China. This district is located in the northern temperate and belongs to semi-arid continental monsoon climate, including windy weather during the winter and spring. The annual rainfall is 428–449 mm, which mainly falls between June and September; however, the annual evaporation is 1786–2598 mm, which is approximately five times greater than the amount of rainfall. The annual average temperature is 4.8–7.8°C, with extreme maximum and minimum temperatures of 37.9°C and –32.4°C, respectively, and the daily temperature difference is 18–25°C. The frost-free period is between 115 and 130 days. There are northwest winds, with a maximum wind speed of 20 m s^{-1} and annual average wind of 3.4 m s^{-1} (Guo et al., 2020). In addition, this district is also on the Loess Plateau and belongs to a typical ecologically fragile area. The vegetation is scattered with low coverage, and the zonal vegetation is steppe ecosystems. The soil type falls between Castanozems and Castano-cinnamon soils. Soil erosion and wind erosion are severe, and gullies have a roughly north-south dendritic distribution, with average cutting depths of 30–50 m, with mostly "V"-shaped channels, forming a typical Loess Plateau landscape. Mining-stripped soil was stacked as dump in the reclamation area, forming a stepped terrain with a platform-slope alternated distribution. The relative height of dump is 100-150 m, with a step height of 20–40 m and a slope angle of more than 30° (Cao et al., 2015). This structure increases the proneness for geological environmental disasters, such as collapse, landslides, and debris flows.

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Experimental design

Nine plots of black locust plantations with different altitude, age, and stand density were selected in present study (*Table 1*, *Fig. 1*). In each plot, 100 individuals of black locust were randomly selected and several variables related to black locust growth were investigated in August during 2015-2017. Leaves of black locust and soil samples were collected simultaneously. Three parallel studies were performed for the measurements of soil properties and leaf nutrition properties. One-way ANOVA analyzed the significant differences in soil and black locust properties; principal component analysis (PCA) analyzed the main soil properties; multidimensional scaling (MDS) explored the similarities among soil and black locust properties.

Table 1. *Basic characteristics of the sample plots. Initial planting conditions: black locust was 1-year-old and 30 cm high*

Plot	Vegetation Types	Age (a)	Altitude (m)	Stand Density (per 100 m^2)	Soil Texture	Terrain	Area (ha)	Geographical Location
1	black locust	22	1360	30	sandy loam	platform	0.3	39º27.651′N 112º20.041′E
2	black locust	22	1360	27	sandy loam	platform	0.3	39º27.710′N 112º20.011′E
3	black locust	22	1360	28	sandy loam	platform	0.3	39º27.667′N 112º20.032′E
4	black locust	20	1420	19	sandy loam	platform	0.3	39º27.670′N 112º19.859′E
5	black locust	20	1420	21	sandy loam	platform	0.3	39º27.615′N 112º19.867′E
6	black locust	20	1420	20	sandy loam	platform	0.3	39º27.654′N 112º19.877′E
7	black locust	18	1500	22	sandy loam	platform	0.3	39º27.634′N 112º19.675′E
8	black locust	18	1500	25	sandy loam	platform	0.3	39º27.606′N 112º19.663′E
9	black locust	18	1500	23	sandy loam	platform	0.3	39º27.577′N 112º19.646′E

Physiochemical and biological characterization of the soil

Ten randomly soil subsamples along “S” shape that were collected using an auger at 0–20 cm depths in each plot, mixing them as a soil sample. The samples were put in cloth bags and sent to laboratory for analysis. After removing the roots and plant residues, half of the soil samples were dried in natural air and sieved through a 40-mesh sieve for measuring the chemical properties and the other half of the soil samples were refrigerated at 4°C for measuring the biological properties. Soil physical properties were measured using soil samples collected with cutting rings into the aluminum boxes.

All physiochemical properties were measured using regular methods: soil water content by oven drying method, field moisture content and bulk density by cutting ring method (Rayment and Higgingson, 1992), Soil organic carbon by potassium dichromate oxidation and ferrous sulfate titration, total nitrogen content by the Kjeldahl method (Parkinson and Allen, 1975), available nitrogen by steam distillation (Liu et al., 2019),

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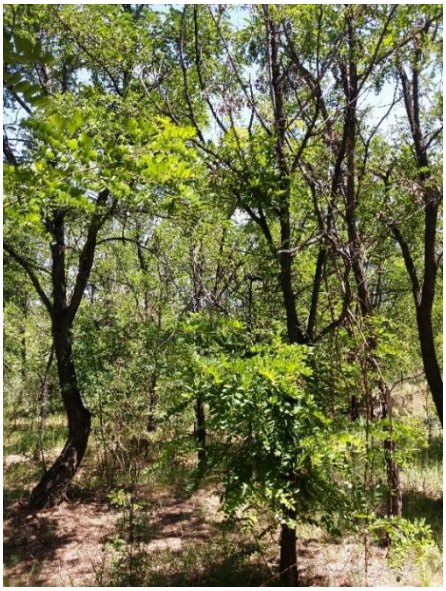
available phosphorus by spectrophotometry (Evolution 260 Bio; Thermo Scientific, USA), total phosphorus by colorimetry (Hu et al., 2019), soil pH by portable pH meter (Sartorius PB-21, Germany).



(a)

(b)

(c)

Figure 1. *(a) Robinia pseudoacacia plantation in plot 1-3. (b) Robinia pseudoacacia plantation in plot 4-6. (c) Robinia pseudoacacia plantation in plot 7-9*

For biological properties, four soil enzymes were measured by spectrophotometry, sucrase activity at 508 nm (Schinner and von Mersi, 1990), urease activity at 660 nm (Kandeler and Gerber, 1988), Polyphenol oxidaseactivity at 420 nm (Guan, 1986), alkaline phosphatase activity at 412 nm. Catalase activity was determined by potassium permanganate titration method. Spread plate counting method (Mallavarapu et al., 1998) was used for soil microbiological analysis. The following media were used for the culturing of soil microorganisms: bacteria: beef extract-peptone agar medium; fungi: Martin agar medium; actinomycetes: Gause's agar medium; nitrogen-fixing bacteria: Ashbey's nitrogen-free agar medium; denitrifying bacteria: denitrifying bacteria culture medium. The number of colony forming units was determined per 1 g of soil dry matter.

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Growth variables and leaf nutritional status

One-hundred black locust trees were chosen randomly in every sample plot of 0.3 ha. For each tree, diameter at breast height (DBH, diameter at 1.3 m), top height (H), crown diameter (CD) and death rate (DR) were recorded. In each plot, healthy leaves were taken randomly from 20 black locust trees in plastic bags for nutritional analysis. The leaves were dried at 80°C for 48 h and milled to a powder. The concentration of leaf C was determined by potassium dichromate oxidation and ferrous sulfate titration, leaf N by sulfuric acid digestion and hydrochloric acid titration (Parkinson and Allen, 1975), leaf P and K by sulfuric acid and peroxide digestion, leaf P by spectrophotometry and leaf K by atomic absorption (PinAAcle 800; PerkinElmer, USA), leaf Ca, Mg, Fe, Mn, Cu, and Zn by dry combustion method (Melgar et al., 2006).

Statistical analysis

Normality of the data was tested by the Kolmogorov-Smirnov and the Brown-Forsythe test for homogeneity of variance. Significant differences in soil and black locust properties among plots were analyzed by one-way ANOVA (F-test). The significance of results at the $P<0.05$ level was tested using Duncan's test. All results were given as mean ± standard deviation (n=3). In addition, correlations were computed using the Pearson correlation coefficient. The similarities among physicochemical and biological properties of the soil, leaf nutrient concentrations, and growth variables were explored by MDS (Proxscal). These statistical analyses were performed using the SPSS 17.0 statistical package (SPSS Inc., Chicago, IL, USA). Soil physicochemical and biological properties were subjected to PCA using Canoco 4.5 to identify the main soil properties of plots.

Results

Physiochemical and biological properties of the soil

Soil physiochemical and biological properties were significantly ($P<0.05$) different among nine plots (*Table 2*). The range of physiochemical properties was wider than those of the biological properties. Available nitrogen ranged from 21.27 in plot 6 to 68.91 mg kg^{-1} in plot 8. The values of soil organic carbon in different plots varied greatly and ranged from 19.22 to 50.27 g kg^{-1}. Soil water content and bulk density were higher in plot 1 to plot 6 and lower in plot 7 to plot 9, while field moisture capacity was on the contrary, the percentage of which did not exceed 21%. Soil organic carbon, pH, and soil total phosphorus were highest in plot 1 to plot 3 and lowest in plot 7 to plot 9. Available phosphorus and available nitrogen were higher in plot 7 to plot 9, but the lower values of available phosphorus were in plot 1 to plot 3 and available nitrogen was lower in plot 4 to plot 6. Overall, soil enzyme activity and the number of microorganisms were higher in plot 7 to plot 9 and lower in plot 4 to plot 6. However, the number of fungi and catalase and alkaline phosphatase activity were higher in plot 4 to 6, while the number of nitrogen-fixing bacteria and alkaline phosphatase activity were lower in plot 1 to 3.

PCA was applied to the soil physiochemical and biological properties to analyze similarities among the plots and to identify the main properties in each plot (*Fig. 2*). Most of the soil properties were clearly associated with the first axis that explained 68% of the total variation.

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Table 2. *Physicochemical and biological properties of the soil in the different plots. Data are shown as the mean ± SE, n = 3. a, b, c, and d indicate that there is a significant difference between the nine plots (P<0.05). Abbreviations: SWC soil water content, FMC field moisture capacity, BD bulk density, SOC soil organic carbon, TP total phosphorus, AP available phosphorus, TN total nitrogen, AN available nitrogen, POP polyphenol oxidase, ALP alkaline phosphatase, ACT actinomycetes, NFB nitrogen-fixing bacteria, DEB denitrifying bacteria*

Soil property	Plot								
	1	2	3	4	5	6	7	8	9
SWC (%)	9.25±0.18b	8.97±0.46b	9.00±0.48b	8.77±0.19b	8.79±0.20b	9.00±0.08b	5.26±0.03a	5.33±0.05a	5.32±0.06a
FMC (%)	5.76±0.21a	5.87±0.13a	5.63±0.12a	5.86±0.22a	5.20±0.54a	5.25±0.58a	20.42±0.80b	20.73±0.57b	19.81±0.37b
BD ($g\ cm^{-3}$)	1.53±0.03b	1.53±0.03b	1.55±0.01b	1.48±0.03b	1.56±0.08b	1.57±0.06b	1.20±0.07a	1.25±0.04a	1.17±0.05a
pH	8.48±0.01c	8.49±0.01c	8.47±0.00c	8.38±0.01b	8.37±0.01b	8.36±0.01b	8.21±0.01a	8.22±0.00a	8.22±0.01a
SOC ($g\ kg^{-1}$)	49.61±0.58c	49.83±0.38c	50.27±0.22c	28.56±1.15b	27.46±0.45b	28.78±0.99b	19.22±0.49a	19.64±0.20a	19.08±0.39a
TP ($g\ kg^{-1}$)	0.54±0.01c	0.54±0.01c	0.55±0.00c	0.44±0.00b	0.45±0.01b	0.43±0.00b	0.40±0.01a	0.41±0.00a	0.42±0.01a
AP ($mg\ kg^{-1}$)	3.72±0.03a	3.67±0.03a	3.69±0.05a	5.12±0.05b	5.07±0.02b	5.13±0.05b	6.36±0.08c	6.24±0.17c	6.17±0.12c
TN ($g\ kg^{-1}$)	0.73±0.02c	0.75±0.01c	0.73±0.01c	0.38±0.00a	0.35±0.01a	0.37±0.03a	0.52±0.01b	0.50±0.01b	0.51±0.02b
AN ($mg\ kg^{-1}$)	35.54±1.48b	36.08±1.08b	34.38±0.66b	21.80±0.51a	21.86±0.47a	21.27±0.19a	66.80±1.44c	68.91±0.76c	67.33±1.83c
Sucrase ($mg\ g^{-1}\ h^{-1}$)	0.16±0.00b	0.15±0.00b	0.16±0.01b	0.12±0.00a	0.12±0.01a	0.11±0.00a	0.28±0.00c	0.29±0.01c	0.28±0.01c
Urease ($mg\ g^{-1}\ h^{-1}$)	0.08±0.00b	0.09±0.01b	0.08±0.01b	0.07±0.01a	0.07±0.00a	0.07±0.00a	0.15±0.00c	0.15±0.00c	0.15±0.01c
Catalase ($mg\ g^{-1}h^{-1}$)	3.83±0.06b	3.80±0.04b	3.88±0.03b	4.11±0.02b	4.10±0.02b	4.12±0.01b	2.66±0.54a	2.97±0.31a	2.34±0.31a
POP ($mg\ g^{-1}h^{-1}$)	0.003±0.01b	0.003±0.00b	0.002±0.01b	0.001±0.02a	0.001±0.01a	0.001±0.00a	0.003±0.01c	0.003±0.00c	0.003±0.02c
ALP ($mg\ g^{-1}h^{-1}$)	0.03±0.02a	0.03±0.00a	0.04±0.01a	0.06±0.01bc	0.06±0.00c	0.06±0.02c	0.05±0.02b	0.05±0.00b	0.05±0.01b

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Bacteria (10^6cfu g^{-1})	6.05±0.10bc	5.92±0.04b	6.03±0.12bc	4.01±0.06a	3.98±0.08a	3.91±0.03a	6.22±0.03c	6.19±0.01c	6.21±0.03c
Fungi (10^3cfu g^{-1})	13.41±0.19b	13.78±0.18b	13.59±0.32b	13.89±0.05b	13.90±0.04b	13.85±0.02b	7.49±0.19a	7.92±0.24a	7.74±0.37a
ACT (10^4cfu g^{-1})	18.19±0.14b	18.44±0.11bc	18.28±0.21bc	9.95±0.12a	9.91±0.09a	10.05±0.05a	19.51±0.81cd	19.71±0.66d	18.78±0.33bcd
NFB (10^4cfu g^{-1})	13.63±0.55a	14.05±0.25a	13.42±0.39a	18.86±0.56bc	18.23±0.21b	18.81±0.32bc	19.32±0.21bc	19.84±0.55c	19.94±0.47c
DEB (10^4cfu g^{-1})	5.74±0.04abc	5.80±0.02c	5.75±0.05bc	5.66±0.02a	5.69±0.01ab	5.68±0.03ab	6.18±0.01d	6.21±0.02d	6.20±0.02d

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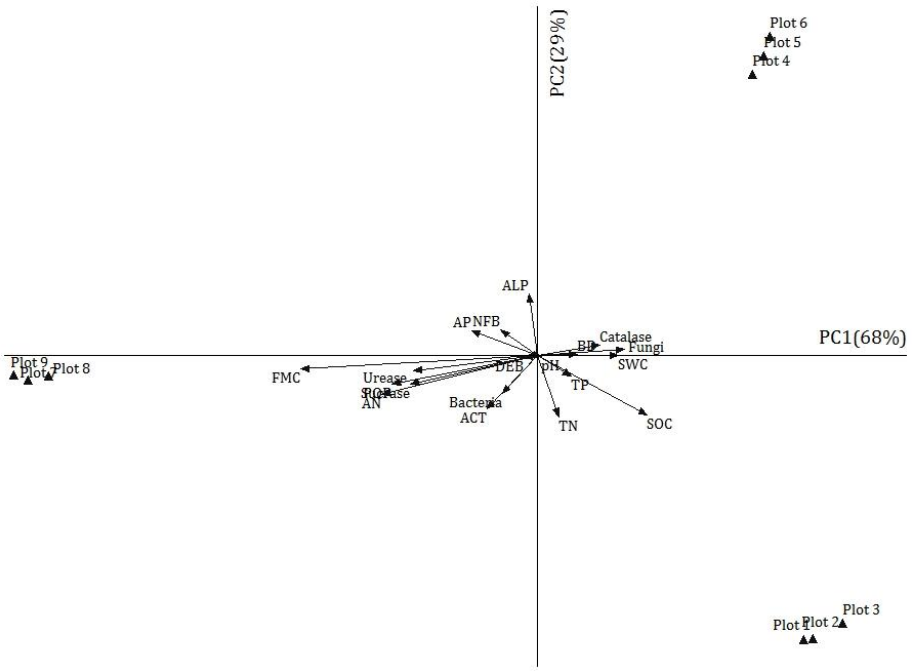

Figure 2. *PCA of the physicochemical and biological properties of the soil in the three plots. Abbreviations: SWC soil water content, FMC field moisture capacity, BD bulk density, SOC soil organic carbon, TP total phosphorus, AP available phosphorus, TN total nitrogen, AN available nitrogen, POP polyphenol oxidase, ALP alkaline phosphatase, ACT actinomycetes, NFB nitrogen-fixing bacteria, DEB denitrifying bacteria*

The majority of physiochemical properties (bulk density, soil water content, pH, soil organic carbon, and total phosphorus) pointed to the positive side of the axis, and most biological properties (urease, sucrase, polyphenol oxidase, denitrifying bacteria, actinomycetes, bacteria, nitrogen-fixing bacteria) pointed to the negative side, thus showing a clear division: plot 1, plot 2 and plot 3 with high values of physiochemical properties, and plot 7, plot 8, and plot 9 with high values of biological properties. Alkaline phosphatase activity and soil total nitrogen were located close to the second principal component axis, which accounted for 29% of the variance (*Table 3*). Plot 4, plot 5, and plot 6 were the nearest to alkaline phosphatase, which indicates the soil in these plots have high alkaline phosphatase activity; similarly, plot 1, 2 and 3 was the closest to soil total nitrogen, indicating high total nitrogen content of the soil in these plots.

Growth variables and leaf nutrient concentrations

With the exception of P, there were significant differences in leaf nutrient concentrations (P<0.05) among the nine plots (*Table 4*). The concentrations of leaf C, N, Fe, Mn, and Zn were higher in plot 7 to 9, but lower in plot 1 to 3. The concentrations of leaf K ranged from 3.39 g kg^{-1} in plot 9 to 11.96 g kg^{-1} in plot 3. The leaf Ca and Mg contents were the highest in plot 6, with 55.92 and 2.97 mg kg^{-1}, respectively. The leaf Cu content ranged from 6.51 mg kg^{-1} in plot 9 to 7.29 mg kg^{-1} in plot 5. The growth variables of black locust were higher in plot 4 to 6, with the highest values of DBH (9.78 cm), CD (13.95 m^2), and H (7.21 m), and the lowest DR (19.11%). Furthermore, the DBH (5.32 cm) and H (4.16 m) were the lowest in plot 8, while the DR (38%) was the highest in plot 1, which showed the lowest value of CD (3.51 m^2).

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Table 3. *Contribution rate of principal components and scores of variables. Abbreviations: SWC soil water content, FMC field moisture capacity, BD bulk density, SOC soil organic carbon, TP total phosphorus, AP available phosphorus, TN total nitrogen, AN available nitrogen, POP polyphenol oxidase, ALP alkaline phosphatase, ACT actinomycetes, NFB nitrogen-fixing bacteria, DEB denitrifying bacteria*

Axis	Eigenvalue	% of variance	Cum.% of variance	Variables	Eigenvector	
					Axis 1	Axis 2
1	12.887	67.828	67.828	FMC	-0.9944	-0.0833
2	5.564	29.287	97.114	SWC	0.9941	-0.0069
				Fungi	0.9936	0.1068
				Urease	-0.9828	-0.1809
				BD	0.9826	0.0548
				DEB	-0.9689	-0.2191
				Catalase	0.9485	0.2333
				Sucrase	-0.9441	-0.3246
				AN	-0.9342	-0.3500
				pH	0.9321	-0.3596
				AP	-0.8674	0.4942
				SOC	0.7690	-0.6381
				POP	-0.7580	-0.2281
				TP	0.7354	-0.6743
				NFB	-0.6791	0.7261
				ACT	-0.5271	-0.8451
				Bacteria	-0.5163	-0.8562
				TN	0.2192	-0.9733
				ALP	-0.0855	0.9853

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Table 4. *Leaf nutrient concentration and growth variables of black locust in the different plots. Data are shown as the mean ± SE, n=3. a, b, c, and d indicate that there is a significant difference between the nine plots (P<0.05)*

Plant performance	Plot								
	1	2	3	4	5	6	7	8	9
C (g kg^{-1})	448.50±0.02a	448.51±0.01a	448.49±0.01a	450.46±0.01b	450.44±0.02b	450.44±0.02b	460.93±0.02c	460.93±0.02c	460.91±0.01c
N (g kg^{-1})	15.56±0.02a	15.50±0.05a	15.51±0.06a	16.23±0.03b	16.15±0.06b	16.16±0.08b	18.63±0.07c	18.44±0.12c	18.49±0.16c
P (g kg^{-1})	2.29±0.05	2.26±0.07	2.21±0.03	2.25±0.06	2.19±0.10	2.13±0.06	2.21±0.07	2.22±0.06	2.14±0.03
K (g kg^{-1})	11.08±0.30b	11.81±0.77b	11.96±0.66b	4.43±0.02a	4.50±0.05a	4.49±0.06a	3.57±0.06a	3.42±0.16a	3.39±0.14a
Ca (g kg^{-1})	48.50±0.50b	48.19±0.72b	47.66±0.35b	55.07±0.63c	55.22±0.75c	55.92±0.29c	46.06±0.12a	45.83±0.28a	45.73±0.21a
Mg (g kg^{-1})	2.44±0.03a	2.44±0.02a	2.41±0.01a	2.94±0.03c	2.95±0.02c	2.97±0.01c	2.55±0.04b	2.59±0.01b	2.54±0.03b
Fe (mg kg^{-1})	243.33±3.33a	240.00±5.77a	236.67±3.33a	450.00±5.77b	453.33±3.33b	446.67±3.33b	583.33±3.33c	580.00±5.77c	576.67±3.33c
Mn (mg kg^{-1})	156.68±0.44a	156.70±0.42a	156.20±0.16a	380.93±0.44b	380.76±0.57b	380.28±0.24b	400.24±0.16c	400.19±0.19c	400.01±0.08c
Cu (mg k-^{1})	6.94±0.03b	6.93±0.03b	6.90±0.01b	7.25±0.02c	7.29±0.01c	7.26±0.05c	6.52±0.02a	6.53±0.02a	6.51±0.01a
Zn (mg kg^{-1})	17.36±0.25a	17.37±0.24a	17.09±0.09a	20.02±0.08b	19.85±0.19b	19.79±0.15b	22.27±0.26c	22.19±0.33c	21.90±0.13c
DBH (cm)	6.99±0.10b	6.85±0.21b	6.76±0.14b	9.30±0.16c	9.70±0.42c	9.78±0.36c	5.63±0.15a	5.32±0.26a	5.48±0.15a
CD (m^2)	3.51±0.08a	3.74±0.20a	3.74±0.12a	13.95±1.12b	13.82±1.22b	12.55±0.46b	5.07±0.45a	4.61±0.79a	4.15±0.46a
H (m)	4.84±0.21c	4.92±0.15c	4.68±0.10bc	6.95±0.23d	7.21±0.09d	6.94±0.23d	4.33±0.15abc	4.16±0.27ab	4.18±0.17a
DR (%)	38.00±2.00c	36.00±3.46c	34.00±2.00bc	24.44±1.94ab	19.11±3.64a	20.44±4.64a	19.33±2.91a	25.33±6.96abc	27.33±5.46abc

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MDS, which was used to analyze similarities between changes in soil properties, leaf nutrient concentration and growth variables, grouped the variables DBH and H with soil water content, bulk density, soil total phosphorus, total nitrogen, soil fungi and catalase (*Fig. 3A,C*). Moreover, DBH correlated positively with soil water content (r=0.737; P<0.05), bulk density (r=0.714; P<0.05), fungi (r=0.703; P<0.05) and catalase (r=0.695; P<0.05), while DBH and H correlated negatively with soil total nitrogen. CD was grouped with soil alkaline phosphatase, leaf Mn, and leaf Fe (*Fig. 3B*), in addition, CD correlated significantly positively with soil alkaline phosphatase (r=0.703; P<0.05). DR was grouped with leaf K, soil organic carbon and total nitrogen (*Fig. 3D*), which were positively related to DR.

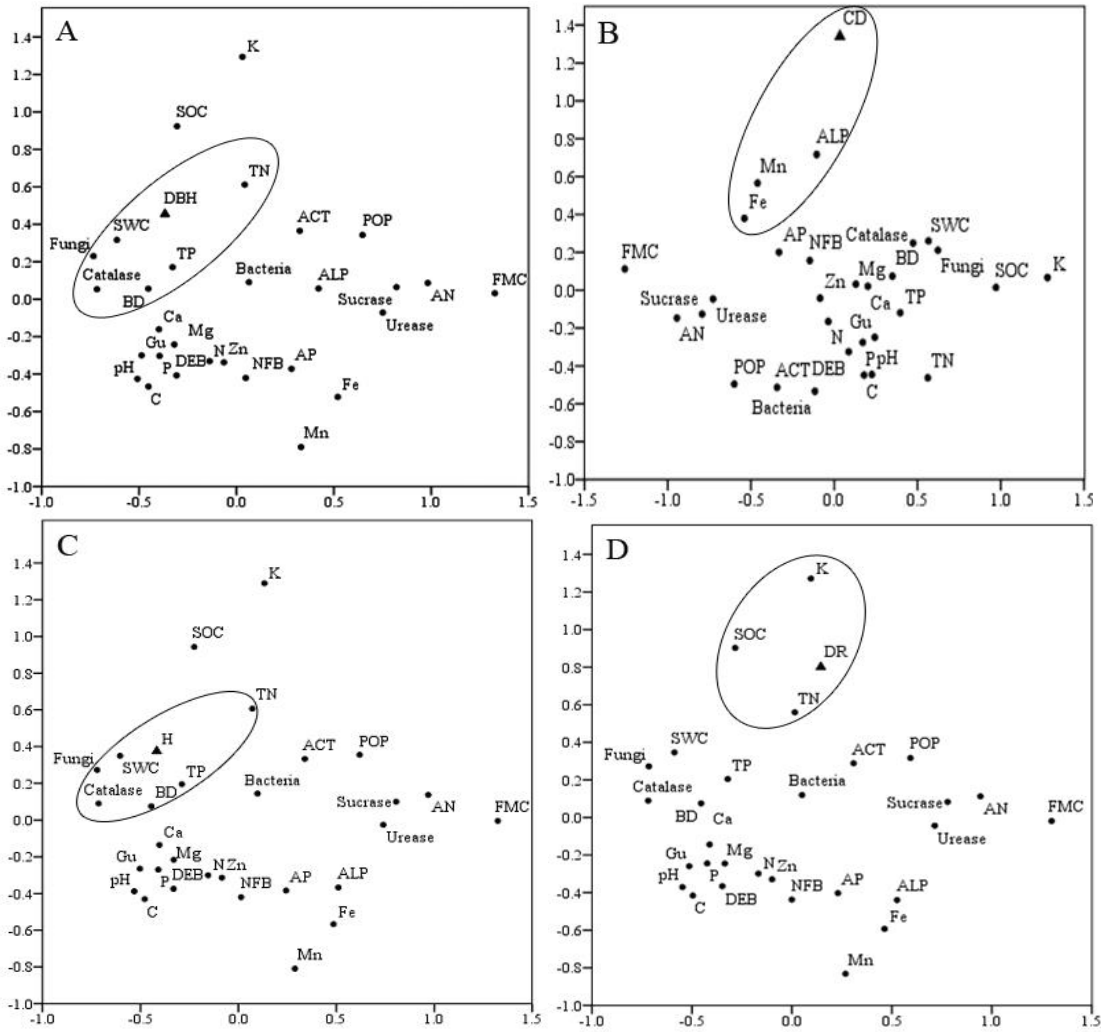

Figure 3. *MDS analysis based on similarity matrices between soil physicochemical properties, biological properties, leaf nutrient content, and DBH (A), CD (B), H (C), and DR (D)*

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Discussion

There were significant differences in soil properties between different plots. In plot 1 to 3, soil water content was higher, which promoted the degradation of organic matter (Berger et al., 2015), and the soil contained higher organic carbon, total nitrogen and total phosphorus. This was related to their higher stand density and more litter. At the same time, the soil bulk density and pH were also higher, which limited the growth of soil microorganisms (Hu et al., 2010), and the soil enzymes involved in minerals decomposition, nutrient transformation and circulation were lower, resulting in lower nutrients that could be directly absorbed by black locust. In plot 7 to 9, higher field moisture capacity, lower soil bulk density and soil pH provided favorable conditions for the growth of soil microorganisms (Shao et al., 2020). Under the action of a large number of soil microorganisms and soil enzymes, soil minerals were well decomposed and transformed (Lanuza et al., 2019), and the soil available phosphorus and available nitrogen contents were higher. However, due to the higher altitude, the soil water content was lower (Sternberg and Shoshany, 2001; Liu and Wang, 2013), which limits the growth of black locust to a certain extent. In plot 4 to 6, the soil organic matter and mineral contents were lower, due to the lower stand density and less litter. Appropriate soil bulk density, water content and pH were beneficial to the growth of soil fungi (Wang et al., 2015), resulting in the higher content of soil catalase and alkaline phosphatase. The nutrient content of leaves also reflected that the soil promoted the growth of black locust.

Soil properties have a significant effect on the growth of black locust (Calvaruso et al., 2011; Vondráčková et al., 2014; Miatto and Batalha, 2016). Soil water content, bulk density, soil fungi and catalase affected DBH and H of black locust. Soil water content influences plants through affecting the transpiration and photosynthesis as well as root growth (Chen et al., 2021), while soil bulk density, indicative of soil tightness, influence on field moisture capacity and soil pores (Lü et al., 2006), thus affects the stretching of plant roots (Wang et al., 2011; Ma et al., 2012). Compared with bacteria or actinomycetes, fungi are more tolerant to adverse environments. Mycelia of fungi loosen the soil structure and improved soil aerobic conditions (Sinegani et al., 2005). Fungi help the root to absorb nutrients, but also improve the tolerance of black locust to non-environmental environmental factors (Jahromi et al., 2008). Catalase is an important enzyme that is activated under stress, which reduces the hazard of black locust from hydrogen peroxide (Keshavarz et al., 2022). The CD was significantly related to alkaline phosphatase activity: a high alkaline phosphatase activity is predominantly due to rich macro vegetation, which is mainly forest vegetation in alkaline soils (Dick et al., 2000; Fierer et al., 2003). There were many factors that caused the death of black locust, and the correlation between mortality and soil factors was not significant. Further research is still to be done.

Conclusion

Evaluation of black locust performance and soil properties in different plots showed that soil water content, soil bulk density and soil fungi had important effects on performance of black locust. Therefore, attention must be paid to soil water content of black locust plantation in the reclamation area and ensure that each individual plant can absorb necessary water. At the same time, suitable soil bulk density and fungal inoculation may promote black locust's growth.

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Author Contributions. Chunyan Guo planned the experiments, analyzed the data and wrote the manuscript. Jinhua Zhang revised the manuscript. Yuzhen Wu and Yingui Cao completed the soil microorganisms experiment. Hao Qin helped data analysis.

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