Selection and evaluation of suitable tree species in dry and dusty mining areas of Northwest China

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Abstract To select drought-resistant and dust-tolerant native species suitable for use in the rehabilitation of major coal bases in northwest China, nine tree species were identified for growth rates, biomass, harm index, and physiological indices under drought and high dust stress conditions. The results showed that, in the dust resistance index system, the order was Caragana korshinskii > Amorpha fruticosa > Sabina vulgaris > Hedysarum scoparium > Tamarix chinensis > Ammopiptanthus mongolicus > Ulmus pumila > Caryopteris mongholica > Elaeagnus angustifolia. In a comprehensive drought and dust resistance index system, 14 indices (such as shoot length, stomatal conductance, and peroxidase) had the larger weight indices. The drought and dust resistance order of the tree species was Caragana korshinskii > Ulmus pumila > Amorpha fruticosa > Sabina vulgaris > Caryopteris mongholica > Ammopiptanthus mongolicus > Hedysarum scoparium > Tamarix chinensis > Elaeagnus angustifolia. This study provides effective strategies and references for selecting suitable tree species for arid mining sites in China, and also for the revegetation of coal mining sites worldwide.

Keywords Coal mining · Species selection · Drought resistance · Dust resistance · Evaluation index system

Introduction

Northwest China is a large arid region with a dry atmosphere, deserts, sandstorms and fragile ecology (Zhu et al. 2016; Roy et al. 2020). Drought is the major factor limiting plant growth and productivity due to climate change, rapid industrialization, as well as the over-exploitation resources in northwest China (Li et al. 2010; Nezhadahmadi et al. 2013; Na and Jiang 2018; Zhao et al. 2018; Roy et al. 2020). Annual precipitation varies from 410 mm in the east, 230 mm in the west and in some places, below 50 mm, while evaporation may vary from 1500 to 3600 mm per year (Yi and Li 2011). The low precipitation and high evaporation produce dry air and dehydrated soils, resulting in water deficits for plants and affecting their normal growth and development (Sun et al. 2003; Li et al. 2010; Wang et al. 2015). Most cropland is dryland rain-fed farming, and water scarcity is the biggest challenge for local agriculture development in this region (Li et al. 2010).

Drought-resistant plants can generally tolerate long-term water shortages by developing natural mechanisms, from enhanced deep root growth to control of water loss in leaves (Hu and Kang 2005; Li et al. 2010; Tirado and Cotter 2010; Chang et al. 2018). Drought resistance mechanisms...
are usually studied from the morphological structure, and physiological and biochemical indices of plants (Faroq et al. 2009; Li et al. 2010; Tirado and Cotter 2010; Anjum et al. 2011; Nezhadahmadi et al. 2013). In northwest arid regions, soil-water deficiency is one of the major factors restricting plant establishment and survival (Ji et al. 2006; Li et al. 2010; Wang et al; 2015; Roy et al. 2020). An et al. (2007) found that leaf area and the growth rate of new branches were the lowest under severe drought compared with those under adequate water conditions. Pan et al. (2003) reported that drought stress decreased plant biomass. Water deficiencies caused a notable reduction in growth-associated parameters (e.g., maximum height, stem diameter, root length and dry biomass) (Roy et al. 2020). Therefore, the selection of drought-resistant species has always been an important subject for vegetation introduction in northwest China (Li et al. 2010; Wang et al. 2015; Na and Jiang 2018; Zhao et al. 2018).

Coal mining has considerable impact on local ecosystems due to severe environmental and ecological problems, like vegetation damage, soil water contamination and air pollution at the mining sites and in the surrounding areas (Rocha-Nicoleite et al. 2018; Pietrzykowski 2019). Increasing demand of coal has led to adverse impacts on the natural environment and air quality, especially in north-western China (Li et al. 2010; Zhao et al. 2018). There have been numerous studies on dust resistance of plants (Wang et al. 2014; Aliya et al. 2015; Zhang et al. 2015a; Nurmamat et al. 2017; Shah et al. 2018). Most of these studies have focused on the dust retention of urban tree species (Joshi et al. 2007; Wang 2011b; Wang et al. 2014; Li et al. 2016; Tang 2017), and some research has focused on air pollutant adsorption in urban settings by different types of roadside vegetation, and found that plants with needles adsorbed more airborne particulates than broad-leafed plants with the same leaf area (Beckett et al. 1998; Prajapati and Tripathi 2008; Zhang et al. 2015a, 2015b; Shah et al. 2018). Only a few studies have looked at the selection of tree species for highly dusty, arid coal mine spoils (Grant et al. 2002; Pietrzykowski 2019). Coal mining sites in arid areas require species to be drought-resistant because of the shortage of water, and growth of trees has been seriously harmed because of dust and other pollutants caused by mining. Tree species need not only withstand water shortages but also the hazards of particulate matter such as severe dust (Schleicher et al. 2011; Wang 2011a; Losfeld et al. 2015; Zhang 2016). These two factors are critical since species with enhanced drought resistance may not show strong dust resistance. The success of revegetation depends on the species and their adaptation to newly formed reclaimed mining soils. In this study, species were evaluated for their drought and dust resistance. There have been no studies on species selection for these attributes. We have hypothesized that (1) strong drought resistance species have strong dust resistance, (2) strong drought resistance species have weak dust resistance and (3) tree species with moderate drought resistance have strong dust resistance.

Nine native species (Caragana korshinskii, Tamarix chinensis, Amorpha fruticosa, Hedysarum scoparium, Ammopiptanthus mongolicus, Caryopteris mongolica, Sabina vulgaris, Ulmus pumila, and Elaeagnus angustifolia) were selected to determine their relative drought and dust resistance. These species are widely planted in northwest China. Due to extreme arid and cold environment, introduced or exotic species may not adapt to the local climate. Native species, like nine species we selected in the research, may be suitable for the local arid environment. However, these species showed different adaptations under different mining and dusty environments. Species in field pots were used to monitor growth, physiology and biomass. Principal component analysis (PCA) and membership function methods were applied to evaluate and compare drought and dust resistance of species.

Materials and methods

Study area

Dust resistance experiments were carried out in Ningxia at the Yangchangwan Coal Mine (106°35′–106°38′ E, 37°59′–38°03′ N) of the Shenhua Ningxia Coal Industry Group, and drought resistance tests were monitored at a nearby farm (105°49′–106°22′ E, 38°26′–38°38′ N). The distance between the drought and dust resistance test sites is 68 km. Climate of the two sites are similar. Ningxia has a temperate, arid climate, with an average annual temperature of 8.8 °C. Annual maximum and minimum temperatures were 41.4 °C in 1953 and -28.0 °C in 1954. The average frost-free period is 167 days. Precipitation mostly occurs from July to September with an annual average of 206.3 mm, accounting for 76% of the annual rainfall. Average annual evaporation is 1470.1 mm. The main wind direction is west-northwest, and the average wind speed is 3.1 m/s; the maximum is up to 20 m/s. Soil texture is sandy loam and annual average soil moisture content is 8.4% in 0–300 cm depth. Soil pH was between 8.4 and 9.2, and total salt content was 0.13–1.04 g/kg. Soil organic matter ranged from 0.15 to 1.47%. Total nitrogen, alkali-hydrolyzable nitrogen, and available phosphorus and potassium ranged from 0.3 to 1.0 g/kg, 25.0 to 88.6 mg/kg, 1.3 to 32.9 mg/kg, and 73.3 to 190.0 mg/kg, respectively.

The experiment was carried out from April 2018 to October 2019. One-year old potted seedlings of Caragana korshinskii, Tamarix chinensis, Amorpha fruticosa, Hedysarum scoparium, Ammopiptanthus mongolicus,
Caryopteris mongholica, Sabina vulgaris, Ulmus pumila, and Elaeagnus angustifolia were selected. The size of the pots was upper diameter 580 mm, lower diameter 450 mm and height 520 mm. The potting soil was simulated soil of waste rock from the Lingwu Yangchangwan Coal Mine site. In April 2018, the selected seedlings were planted on the site for drought resistance and dust retention tests (Fig. 1).

In the drought resistance test, a progressive water stress treatment was carried out using a pot-water control method and single-factor design was adopted. A natural drought treatment group and control group were established. All plants were fully irrigated three days before the test to ensure that the soil in each pot was saturated. Watering in the treatment group ceased after three days and renewed after 30 days of drought stress. The seedlings in the control group were watered every seven days. The PCA method was used to calculate the weight of each index and to establish the tree drought resistance evaluation index system (Xie and Hu 2016; Guo and Wang 2018). For the dust resistance test, we selected the dust-contaminated coal-mining site (waste rock field) for the pot experiment. Dust retention per unit area was 1.08–2.76 g/m²/week; the plants were watered every seven days. After rainfall (> 15 mm), the relevant indices were monitored. We replicated the test with 10 pots of each seedling species.

**Measurement indices**

**Growth indices and biomass**

At the beginning and end of the two tests, growth indices (height, ground diameter, shoot length, and crown breadth) were measured to calculate the net growth (growth index value at the end – growth index value at the beginning). Three whole seedlings were removed from each pot to measure biomass of the stems, leaves, and roots. Leaf biomass ratio (leaf dry mass/plant dry mass), root biomass ratio (root dry mass/plant dry mass), stem biomass ratio (stem dry mass/plant dry mass), root shoot ratio (root dry mass/upper ground dry mass), and the length of the main root system were calculated (Ma et al. 2010).

**Physiological indices**

Physiological growth parameters influence the growth of plants, and this study consisted of photosynthetic and water physiological indices. Twenty-eight drought-resistant physiological indices were measured, including photosynthetic parameters, water consumption, leaf water saturation and deficit values, superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and other enzyme activities. Twenty dust-resistant physiological indices were recorded.
including stomatal conductance, plant water content, leaf relative water content (RWC), relative water deficit (RWD), transpiration rate, photosynthetic rate, intercellular CO₂ concentration and water use efficiency.

At the beginning, middle, and end of the test, with the TARGAS-1 portable photosynthesis analyzer (PP Systems, Amesbury, MA, USA), three leaves of different plants on the sunny side from 9:00 to 11:00 a.m. were randomly selected to measure physiological indices of the different species. Leaf water content [(leaf fresh mass-leaf dry mass)/leaf fresh mass], plant water content [(fresh plant mass-dry plant mass)/fresh plant mass] were calculated. Soil moisture content was measured every half hour using a Multi-point Soil Temperature and Humidity Recorder (TZS-2XG). Leaf relative water content (RWC; Eq. 1) and relative water deficit (RWD; Eq. 2) were determined by the drying method. Fresh plant leaves were cut, weighed fresh (Wx) and soaked in ionized water. After 24 h, leaves were removed, surface dried, weighted saturated (Wb), and transferred to an oven for 15 min at 105 °C and 90 °C until constant weight (Wh).

\[
\text{RWC}\% = \frac{(W_x - W_h)}{(W_b - W_h)} \times 100\% 
\]

\[
\text{RWD}\% = 1 - \text{RWC}\% 
\]

Leaf water retention capacity was measured by the in vitro leaf weighing method. Ten effective leaves (with some leaf sheaths) were cut every seven days after fully watering, weighed fresh immediately, and then dried in an oven at 105 °C for 15 min and again for 48 h at 90 °C to obtain the dry weight. The calculation of leaf water retention capacity was fresh weight-dry weight and was calculated in six consecutive weeks for each species to analyze water retention capacity.

**Dust retention**

Thirty leaves were randomly sampled on day 7 after rainfall and the amount of dust retained measured by the cleaning method (Guo et al. 2007; Aliya et al. 2015). Leaf area (cm²) was measured with a portable leaf area meter, and recorded as S₁, S₂, …, S₃₀. The washed leaves were dried and weighed. Dust retention was calculated using the following equation (Baidourela et al. 2015):

\[
\text{Dust retention per unit leaf area (g/m²/week)} = \frac{M_1 - M_2}{\sum S_i (i = 1, 2, \ldots, 30)} \times 10^4 
\]

\[
\text{Dust retention per unit fresh leaf weight (g/g)} = \frac{M}{W_f} 
\]

where, \(d_i\) is the amount of dust retained per unit fresh leaf weight (g/g); \(W_f\) is the total leaf fresh weight of the sample (g); and, \(M\) is the total dust retention of all leaves of the samples (g).

**Harm index**

Plant harm index is a way to reflect and evaluate the leaf damage degree caused by diseases and insect pests (He et al. 2007). To observe the impact of dust retention on morphology, a classification standard for leaf damage caused by dust retention was established (Table 1). In the dust resistance test, we investigated and classified 10 leaves of different orientations (east, west, south, north) and parts (upper, middle, and lower) of each species according to the following harm degree indices (Panda and Kush 1995; He et al. 2007):

\[
\text{Harm index} = \frac{\sum (\text{Harmgradeleaves} \times \text{Harmgraderepresentativevalue})}{(\text{Totalinvestigatedleaves} \times \text{Highestharmgradevalue})} \times 100\% 
\]

**Survival rate**

The survival rate represents the adaptability of seedlings. Wilting or dead plants were recorded every seven days since the drought test began. At the end of the experiment, the survival rate (number of dead plants/total plants) was calculated.

**Table 1** Evaluation standard for leaves under dust resistance stress

| Classification of harmed leaves (value) | Harmed symptoms |
|----------------------------------------|-----------------|
| 0                                      | Leaves were green and normal |
| 1                                      | The leaves were green with individual discolored spots or slight wrinkles and curls |
| 2                                      | The fading area of the leaf reached 1/3 of the leaf area, and the leaves were obviously curled |
| 3                                      | Above 3/4 area of the leaves were withered and severely curled |
| 4                                      | The leaves were all withered or completely curled and easily broken |
| 5                                      | Leaves fell off |

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Results

Experimental micro-environment and leaf damage characterization

Soil physical and chemical properties in the pot experiments are shown in Table 2. Table 3 shows the air particle concentrations in the drought resistance and the dust resistance experiment site.

Table 4 shows the harm symptoms and grades of leaves from different species after dust retention, and the grades of the harmed leaves from left to right are 0, 1, 2, 3, 4, and 5. *Sabina vulgaris* was less affected by dust retention and only showed grade 0 and grade 1 harm symptoms.

Screening and evaluation of drought resistance of species

Establishment of evaluation index system for drought resistant species

Table 5 shows the weight of each index and drought resistance evaluation index system. The greater the weight, the

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Table 2  Physicochemical properties of potted soil

| Soil      | pH  | Conductivity (ms·cm⁻¹) | Organic matter (g·kg⁻¹) | Total Nitrogen (g·kg⁻¹) | Total Phosphorus (g·kg⁻¹) | Alkaline Nitrogen (g·kg⁻¹) | Available Phosphorus (g·kg⁻¹) | Rapidly available potassium (g·kg⁻¹) |
|-----------|-----|------------------------|--------------------------|--------------------------|---------------------------|----------------------------|-------------------------------|-------------------------------------|
| Content   | 8.81| 1.50                   | 1.97                     | 0.09                     | 0.11                      | 41.9                       | 7.69                          | 120.30                              |

Table 3  The ambient air parameters in the drought resistance experiment site (farm) and the dust resistance experiment site (mining site)

| Site          | TSP (mg·m⁻³) | SO₂ (mg·m⁻³) | NOₓ (mg·m⁻³) | PM₂.₅ (µg·m⁻³) | PM₁₀ (µg·m⁻³) |
|---------------|---------------|--------------|--------------|----------------|---------------|
| Farm          | 0.2           | 0.01         | 0.01         | 42.7           | 117.3         |
| Mining areas  | 0.8           | 0.03         | 0.02         | 198.4          | 3055.2        |

Note: TSP represents total suspended particulate

Table 4  Harm symptoms of leaves after dust retention

| Grades of harmed leaves | 0 | 1 | 2 | 3 | 4 | 5 |
|-------------------------|---|---|---|---|---|---|
| *A. fruticosa* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *E. angustifolia* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *U. pumila* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *A. mongolicus* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *S. vulgaris* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |

| Grades of harmed leaves | 0 | 1 | 2 | 3 | 4 | 5 |
|-------------------------|---|---|---|---|---|---|
| *C. korshinskii* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *T. chinensis* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *C. mongholica* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
| *H. scoparium* | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] | ![Image] |
greater the importance of the index. Among these indices, root biomass ratio, root/shoot ratio, water consumption, proline (PRO) content, CAT content and SOD content had relatively large weight index (> 0.05), which were the main indices for the comprehensive evaluation of drought resistance of the species.

**Comprehensive evaluation of drought resistance of tree species**

Table 6 shows the drought resistance coefficients of 28 indicators of nine species. The contribution rates of the first seven indices were 26.6%, 19.1%, 17.0%, 12.6%, 10.9%, 7.1%, and 4.8%. Their cumulative contribution rate reached 98.1%.

### Screening and evaluation of dust resistance of tree species

**Establishment of evaluation index system for dust resistance**

In a dusty environment, species reflect their adaptability through changes in morphology and biomass allocation. The amount of dust retained on the leaves directly reflects the pollution of the surrounding air, and the harm indices of the leaves reflect the harm situation of the species. Dust retention per unit leaf area and per unit leaf weight, stomatal conductance, main root system length, transpiration and photosynthetic rates, harm index, water use efficiency, and root biomass ratio had a relatively high weight index (> 0.05) and could be used as the main indices to evaluate the dust resistance of different species (Table 7).

| Target layer                  | Criterion layer | Weight index | Index layer           | Weight index |
|------------------------------|-----------------|--------------|-----------------------|--------------|
| Drought resistance of species | Growth status index | 0.2844       | Plant height          | 0.0357       |
|                              |                 |              | Ground diameter       | 0.0022       |
|                              |                 |              | Shoot length          | 0.0092       |
|                              |                 |              | Crown breadth         | 0.0352       |
|                              |                 |              | Main root length      | 0.0433       |
|                              |                 |              | Leaf biomass ratio    | 0.0085       |
|                              |                 |              | Stem biomass ratio    | 0.0401       |
|                              |                 |              | Root biomass ratio    | 0.0564       |
|                              |                 |              | Root shoot ratio      | 0.0538       |
| Water physiological index    |                 | 0.2541       | Soil water content    | 0.0209       |
|                              |                 |              | Leaf water content    | 0.0343       |
|                              |                 |              | Plant water content   | 0.0165       |
|                              |                 |              | Water consumption     | 0.0826       |
|                              |                 |              | RWC                   | 0.0491       |
|                              |                 |              | RWD                   | 0.0427       |
|                              |                 |              | Water retention capacity of leaves | 0.0079 |
| Adaptability index           | Growth status index | 0.0433       | Survival rate         | 0.0433       |
| Stress resistance index      |                 | 0.1134       | Conductivity          | 0.0420       |
|                              |                 |              | MDA content           | 0.0158       |
|                              |                 |              | PRO content           | 0.0556       |
| Photosynthetic physiological index |             | 0.1454       | Transpiration rate Tr | 0.0112       |
|                              |                 |              | Stomatal conductance Gs | 0.0334     |
|                              |                 |              | Photosynthetic rate Pn | 0.0333      |
|                              |                 |              | Intercellular CO₂ concentration (Ci) | 0.0317 |
|                              |                 |              | Water use efficiency WUE | 0.0358 |
| Biochemical index            |                 | 0.1594       | CAT content           | 0.0516       |
|                              |                 |              | SOD content           | 0.0644       |
|                              |                 |              | POD content           | 0.0434       |
**Table 6** Eigenvectors and contribution rates of principal components in drought-resistant experiments

| Indices                                | Eigenvectors and contribution rates of principal components indices |
|----------------------------------------|-------------------------------------------------------------------|
|                                        | Principal component 1        | Principal component 2        | Principal component 3        | Principal component 4        | Principal component 5        | Principal component 6        | Principal component 7        |
| Growth status index                    | Plant height: −0.0254        | −0.0338                      | 0.1576                       | 0.0406                       | 0.1891                       | −0.0068                       | −0.0199                       |
|                                        | Ground diameter: 0.0868       | −0.0267                      | −0.1157                      | 0.0107                       | −0.0089                       | −0.2266                       | 0.1678                       |
|                                        | Shoot length: −0.0136         | 0.0483                       | 0.1380                       | 0.0184                       | −0.2046                       | −0.1384                       | 0.0714                       |
|                                        | Crown breadth: −0.0360        | 0.0661                       | 0.1374                       | 0.1567                       | −0.0589                       | −0.0602                       | −0.0962                       |
|                                        | Main root system length: −0.0099 | 0.1279                     | 0.0361                       | 0.1579                       | 0.0256                       | −0.2112                       | 0.0056                       |
|                                        | Leaf biomass: 0.0241          | 0.0678                       | 0.0486                       | −0.1044                      | −0.0947                       | −0.3293                       | −0.1088                       |
|                                        | Stem biomass: −0.1113         | 0.0392                       | 0.0353                       | −0.1325                      | −0.0172                       | 0.0208                       | 0.0908                       |
|                                        | Root biomass: 0.0940          | 0.0053                       | −0.0348                      | 0.1892                       | 0.0119                       | 0.0032                       | 0.0821                       |
|                                        | Root shoot ratio: 0.0916      | −0.0011                      | −0.0377                      | 0.1931                       | 0.0080                       | −0.0018                       | 0.0977                       |
| Water physiological index              | Soil water content: 0.0786    | −0.0165                      | −0.0994                      | −0.1775                      | −0.0329                       | −0.0159                       | −0.0681                       |
|                                        | Leaf water content: −0.0117   | 0.1468                       | −0.0667                      | −0.0118                      | 0.0234                       | 0.1730                       | 0.2852                       |
|                                        | Plant water content: −0.0350  | 0.1210                       | −0.1445                      | −0.0021                      | −0.0064                       | −0.0161                       | −0.0553                       |
|                                        | Water consumption: 0.1152     | 0.0545                       | 0.0415                       | 0.0567                       | 0.0659                       | 0.1120                       | −0.0043                       |
|                                        | RWC: 0.1066                  | −0.0247                      | 0.0378                       | 0.0372                       | 0.0945                       | 0.0613                       | −0.3291                       |
|                                        | RWD: −0.1037                 | 0.0466                       | −0.0946                      | 0.0694                       | −0.0795                      | 0.0260                       | 0.0604                       |
|                                        | Water retention capacity of leaves: −0.0731 | −0.0512         | 0.0092                       | 0.1221                       | 0.1671                       | 0.1334                       | 0.2407                       |
| Adaptability index                     | Survival rate: 0.0799         | 0.1346                       | −0.0296                      | −0.0470                      | 0.0112                       | −0.1218                      | −0.0240                       |
| Stress resistance index                | Conductivity: −0.0187         | 0.1474                       | 0.0608                       | 0.0431                       | 0.1034                       | −0.1098                      | −0.2060                       |
|                                        | PRO content: −0.0199          | 0.0877                       | 0.0899                       | −0.0333                      | −0.2095                      | 0.1531                       | 0.1016                       |
| Photosynthetic physiological index     | MDA content: 0.0309           | 0.0861                       | 0.0515                       | −0.0920                      | 0.2031                       | 0.0590                       | 0.3032                       |
|                                        | Transpiration rate Tr: 0.0230 | 0.0683                       | −0.1295                      | 0.1491                       | −0.1241                      | 0.0639                       | 0.0938                       |
|                                        | Stomatal conductance Gs: −0.0399 | 0.0683                     | −0.1390                      | −0.0958                      | 0.0612                       | 0.0924                       | −0.2285                       |
|                                        | Photosynthetic rate Pn: −0.0940 | 0.0508                     | −0.0885                      | 0.1251                       | −0.0126                      | −0.0473                       | −0.1464                       |
|                                        | Intercellular CO2 concentration (Ci): 0.0776 | 0.0258                     | 0.0364                       | 0.0069                       | −0.2091                      | 0.2174                       | −0.0581                       |
|                                        | Water Use Efficiency: −0.1288 | 0.0235                       | 0.0161                       | 0.0226                       | 0.0278                       | −0.0103                      | −0.0340                       |
| Biochemical index                      | CAT content: 0.0433           | 0.1361                       | 0.0089                       | −0.1048                      | 0.1020                       | −0.0315                      | 0.2430                       |
|                                        | SOD content: 0.0488           | 0.0817                       | 0.1329                       | −0.0545                      | −0.0478                      | 0.2320                       | 0.0484                       |
|                                        | POD content: 0.0069           | 0.1338                       | −0.0100                      | 0.0032                       | 0.1147                       | 0.1954                       | −0.3342                       |
|                                        | Characteristic root: 7.4521   | 5.3453                       | 4.7614                       | 3.5173                       | 3.0666                       | 1.9922                       | 1.3449                       |
|                                        | Contribution rate (%): 26.6148 | 19.0905                     | 17.0049                      | 12.5617                      | 10.9521                      | 7.1148                       | 4.8032                       |
|                                        | Cumulative contribution rate (%): 26.6148 | 45.7053                     | 62.7103                      | 75.2719                      | 86.2240                      | 93.3389                      | 98.1420                       |

**Comprehensive evaluation of dust resistance of tree species**

Dust resistance coefficients were calculated, and the results show that the contribution rates of the first six comprehensive indices were 30.5%, 18.8%, 16.1%, 13.4%, 9.3%, and 7.1%, and the cumulative contribution rate reached 95.2% (Table 8). Thus, we transformed 20 individual indicators into new and independent comprehensive indicators CI1–CI6. Table 9 shows the D value of the comprehensive evaluation of dust resistance: *Caragana korshinskii* > *Amorpha fruticosa* > *Sabina vulgaris* > *Hedysarum scoparium* > *Tamarix chinensis* > *Ammopiptanthus mongolicus* > *Ulmus pumila* > *Caryopteris mongholica* > *Elaeagnus angustifolia*. *Caragana korshinskii* and *Amorpha fruticosa* had the best dust resistance and their D values were 0.5782 and 0.5139, respectively. The least dust resistant species were *Caryopteris mongholica* and *Elaeagnus angustifolia.*
Comprehensive evaluation of drought and dust resistance

Drought and dust resistance indices included seven primary indices and 48 secondary indices. Among these, shoot length (dust retention), stomatal conductance (dust retention), crown breadth (dust retention), POD content (drought resistance), stem biomass ratio (dust retention), and transpiration rate (drought resistance), SOD content (drought resistance), dust retention per unit weight (dust retention), photosynthetic rate (dust retention), water consumption (drought resistance), malondialdehyde (MDA) content (drought resistance), intercellular CO₂ concentration (drought resistance), CAT content (drought resistance), leaf water content (drought resistance) and survival rate (drought resistance) had a relatively large weight (> 0.03). These indices were used to evaluate and select drought and dust resistant tree species. The contribution rates of the first eight comprehensive indices were 22.3%, 18.5%, 14.9%, 13.3%, 10.4%, 9.9%, 6.4%, and 4.2%, and their cumulative contribution rate reached 89.0% (Support Table S1). Thus, we transformed 48 individual indicators into new and independent comprehensive indicators $CI_f-CI_p$.

Table 10 shows that, in arid areas with high dust levels but under irrigation, species may be selected based on the order of dust resistance: Caragana korshinskii > Amorpha fruticosa > Sabina vulgaris > Hedysarum scoparium > Tamarix chinensis > Ammopiptanthus mongolicus > Ulmus pumila > Caryopteris mongholica > Elaeagnus angustifolia. In the high dust areas without irrigation, tree species can be chosen for both their drought resistance and dust resistance: Caragana korshinskii > Ulmus pumila > Amorpha fruticosa > Sabina vulgaris > Caryopteris mongholica > Ammopiptanthus mongolicus > Hedysarum scoparium > Tamarix chinensis > Elaeagnus angustifolia (Table 10).

Discussion

The selection of tree species for afforestation and reforestation purposes is an important subject in forestry research. It is generally believed that, because of water shortages and large-scale mining activities in northwest China, species with good drought and dust resistance are key to survival under the harsh environment. Mining dust contributes to global climate change due to its role in the air and soils.
Heavy metals from mining sites cause serious water and soil contamination. In some cases, trees may grow normally with dust pollution but cannot and even may die in certain cases of severe air pollution, even if irrigation is sufficient. Stomatal conductance was heavily blocked by dust caused by mining activities (Singh et al. 2021). Therefore, the capacity of a tree species to withstand soil and air pollution needs to be given priority.

This research introduced multiple variables while incorporating complex factors into several principal components, which simplified the problem and obtained scientific and effective data. As a result, this study overcame the subjectivity of artificially determined weight index (Zhou et al. 2016). The D value is a dimensionless comprehensive evaluation constant of each species. This evaluation was relatively objective and reliable. The PCA method and membership function offer advantages for the selection of suitable tree species for planting in complex environments. These two methods have been used in numerous fields, such as theoretical physics, meteorology, psychology, biology, chemistry and engineering (Loska and Wiechula 2003; Collard et al. 2010; Giuliani 2017; Koo et al. 2021). It is beneficial to apply them in the selection of drought-resistant and dust-resistant species in arid areas with high air and soil pollution. Based on these results, drought-resistant species might not have the capacity

| Indices                                | Eigenvectors of the principal component indices |
|----------------------------------------|-------------------------------------------------|
|                                        | Principal component 1   | Principal component 2   | Principal component 3   | Principal component 4   | Principal component 5   | Principal component 6   |
|                                        | 0.025   | −0.097   | 0.222   | −0.016   | −0.189   | −0.237   |
| Growth status index                    | −0.114   | 0.041   | 0.191   | −0.046   | 0.124   | −0.086   |
| Ground diameter                        | 0.121   | −0.033   | 0.115   | −0.129   | −0.221   | 0.044   |
| Shoot length                           | −0.007   | 0.098   | 0.144   | −0.202   | −0.116   | 0.385   |
| Crown breadth                          | −0.011   | −0.087   | 0.119   | 0.126   | 0.419   | 0.013   |
| Specific leaf weight                   | 0.09   | −0.021   | −0.045   | 0.064   | 0.168   | 0.454   |
| Main root system length                | −0.058   | −0.038   | 0.156   | 0.251   | −0.048   | 0.106   |
| Leaf biomass                           | 0.124   | −0.106   | 0.003   | −0.158   | −0.08   | 0.074   |
| Stem biomass                           | −0.034   | 0.241   | 0.079   | 0.035   | 0.079   | −0.115   |
| Root biomass                           | −0.056   | 0.226   | 0.065   | −0.004   | −0.019   | −0.175   |
| Root: shoot ratio                      | −0.01   | 0.215   | −0.101   | −0.039   | −0.131   | 0.19   |
| Leaf water content                     | −0.003   | 0.136   | −0.188   | −0.143   | 0.073   | −0.184   |
| Water physiological index              | Dust retention per unit leaf weight              | 0.117   | 0.15   | 0.043   | 0.114   | 0.047   | 0.046   |
|                                        | Dust retention per unit leaf area                | 0.123   | 0.122   | 0.034   | 0.095   | 0.146   | 0.176   |
| Stress resistance index                | Harm index                                       | 0.005   | 0.071   | 0.11   | 0.277   | −0.224   | 0.081   |
| Photosynthetic physiological index     | Transpiration rate                               | 0.149   | 0.014   | 0.017   | −0.006   | 0.135   | −0.23   |
|                                        | Stomatal conductance                             | 0.107   | 0.068   | 0.205   | −0.07   | −0.057   | −0.106   |
|                                        | Photosynthetic rate                              | 0.085   | 0.017   | 0.145   | −0.186   | 0.26   | −0.024   |
|                                        | Intercellular CO₂ concentration                  | 0.127   | −0.02   | −0.08   | 0.172   | −0.133   | −0.111   |
|                                        | Water use efficiency                             | −0.136   | −0.037   | 0.096   | −0.12   | 0.002   | 0.2   |
|                                        | Contribution rate (%)                            | 30.5   | 49.316   | 65.43   | 78.821   | 88.166   | 95.24   |
to also be resistant to dust, and even under irrigation in highly polluted areas, drought-resistant species may have poor growth. How to find suitable species is a major issue faced by local governments in vegetation restoration and environmental protection in coal mining areas.

The results of this study confirmed the third hypothesis: tree species with moderate drought resistance are also more resistant to air pollution. Drought resistant species should be planted in environments with light dust in coal mining areas; those with better dust resistance could be selected for sites with severe pollution and irrigation, and those with good drought resistance and dust resistance could be planted in areas with high pollution and water shortages. This study was not only the first time to select tree species with strong drought and dust resistance in coal mining areas, but also had wide applications in semi-arid areas of China. In addition, different indices of tree species under different growth conditions (high dust, drought, irrigation and non-irrigation), were discussed and which has important value for multi-objective tree species selection under complex growth environments. Although this study was completed under the polluted conditions of arid coal mining, it also has application value for the selection of tree species under polluted environments of other mining areas with the same aridity. Therefore, this study provides scientific basis for tree species selection in vegetation restoration of coal bases in arid and semi-arid environments across the world.

Conclusions

According to the results of this study, the following conclusions may be made: (1) Water consumption, relative leaf water content, relative water deficient, conductivity, and the levels of superoxidase and peroxidase had a relatively larger weights (>0.05) and could be used as indices for the evaluation index system of drought resistance. (2) Dust retention per unit leaf area and per unit leaf weight, stomatal conductance, main root system length, transpiration and photosynthetic rates, harm index, water use efficiency, and root: shoot biomass ratios had a relatively high weight (>0.05) and could be used as the indices to evaluate dust resistance of tree species. The order was Caragana korshinskii > Amorpha fruticosa > Sabina vulgaris > Hedysarum scoparium > Tamarix chinensis > Ammopiptanthus mongolicus > Ulmus pumila > Caryopteris mongholica > Elaeagnus angustifolia. (3) Shoot length (dust retention), stomatal conductance (dust retention), crown breadth (dust retention), peroxidase content (drought resistance), stem biomass ratio (dust retention), transpiration rate (drought resistance), superoxide dismutase content (drought resistance), dust retention per unit weight (dust retention), photosynthetic rate (dust retention),

| Variety                  | C1   | C2   | C3   | C4   | C5   | C6   | D value | Order | U(X1) | U(X2) | U(X3) | U(X4) | U(X5) | U(X6) | W(X) |
|--------------------------|------|------|------|------|------|------|---------|-------|-------|-------|-------|-------|-------|-------|------|
| Ulmus pumila             | 3.0031 | 1.8346 | 3.6003 | −1.3468 | 1.0000 | 0.3948 | 0.3987 | 1.0000 | 0.3948 | 0.3987 | 0.3619 | 0.1573 | 0.3948 | 0.2148 | 0.4026 | 1.3104 |
| Caragana korshinskii     | 5.2477 | 1.7848 | 5.7658 | −1.0303 | 1.0000 | 0.3948 | 0.3987 | 1.0000 | 0.3948 | 0.3987 | 0.3619 | 0.1573 | 0.3948 | 0.2148 | 0.4026 | 1.3104 |
| Tamarix chinensis        | 2.3143 | 1.9958 | 2.4664 | −0.2903 | 0.2400 | 0.2224 | 0.2243 | 0.2006 | 0.2067 | 0.2006 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Hedysarum scoparium      | 2.1347 | 1.3665 | 2.4808 | −0.3326 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Sabina vulgaris          | 1.5349 | 0.8630 | 2.4808 | −1.3730 | 0.2400 | 0.2224 | 0.2243 | 0.2006 | 0.2067 | 0.2006 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Amorpha fruticosa        | 1.7574 | 1.4906 | 2.5960 | −0.3326 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ammopiptanthus mongolicus| 3.4645 | 1.7662 | 3.8878 | −1.1339 | 0.2400 | 0.2224 | 0.2243 | 0.2006 | 0.2067 | 0.2006 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ulmus pumila             | 1.7080 | 1.6452 | 3.1189 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

Table 9 Comparison of comprehensive index values in dust resistant experiments
Comparison of the order of dust resistant and comprehensive drought and dust resistant for nine tree species

| Dust resistance          | Caragana korshinskii | Amorpha fruticosa | Sabina vulgaris | Hedysarum scoparium | Tamarix chinensis | Ammopiptanthus mongolicus | Ulmus pumila | Caryopteris mongholic | Elaeagnus angustifolia |
|--------------------------|----------------------|-------------------|-----------------|---------------------|-------------------|--------------------------|--------------|-----------------------|------------------------|
| Drought and dust resistance | Caragana korshinskii | Ulmus pumila | Amorpha fruticosa | Sabina vulgaris | Caryopteris mongholic | Ammopiptanthus mongolicus | Hedysarum scoparium | Tamarix chinensis | Elaeagnus angustifolia |

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References

Aliya B, Umut H, Tayierjiang A, Kailibinuer N (2015) Maximum dust retention of main greening trees in arid land oasis cities, Northwest China. Sci Silvae Sin 3:57–64 (In Chinese)

An YY, Liang ZS, Han RL, Liu GB (2007) Effects of soil drought on seedling growth and water metabolism of three common shrubs in Loess Plateau, Northwest China. Front Forest China 2:410–416

Anjum SA, Xie XY, Wang LC, Saleem MF, Man C, Lei W (2011) Morphological, physiological and biochemical responses of plants to drought stress. Afr J Agric Res 6(9):2026–2032

Baidourela A, Halik U, Aishan T, Abiliz A, Welp M (2015) Dust retention capacities of urban trees and the influencing factors in Aksu, Xinjiang, China J Desert Res 35(2):322–329 (In Chinese)

Beckett KP, Freer-Smith PH, Taylor G (1998) Urban woodlands: their role in reducing the effects of particulate pollution. Environ Pollut 99(3):347–360

Chang QS, Zhang LX, Wang JZ (2018) Effects of drought stress and rewatering on physiological indexes of four Paeonia lactiflora cultivars and evaluation of their drought resistance. J Nanjing Forestry Univ (nat Sci Ed) 42(06):44–50 (In Chinese)

Collard AD, McNally AP, Hilton FI, Healy FD, Atkinson NC (2010) The use of principal component analysis for the assimilation of high-resolution infrared sounder observations for numerical weather prediction. Q J R Meteorol Soc 136(653):2038–2050

Farooq M, Wahid A, Kobayashi N, Fujita D, Basra S (2009) Plant drought stress: effects, mechanisms and management. J Sustain Agric 29:185–212

Giuliani A (2017) The application of principal component analysis to drug discovery and biomedical data. Drug Discov Today 22(7):1069–1076

Grant CD, Campbell CJ, Charnock NR (2002) Selection of species suitable for derelict mine site rehabilitation in New South Wales, Australia. Water Air Soil Poll 139:215–235

Guo XQ, Wang YC (2018) Quality of Lycium barbarum in east hexi corridor region: comprehensive assessing index construction. China Agric Sci Bull 34(22):66–71 (In Chinese)

Guo EG, Wang C, Peng ZH (2007) Woody landscape plants selection in urban accessory greenlands of branches in semi-arid areas—an example of Shendong mining area. Sci Silvae Sin 7:35–43 (In Chinese)

He CG, Wang SS, Cao ZZ, Wei ZW, Feng HW (2007) Field evaluation on resistance of 40 Medicago cultivars (lines) to thrips. Cao Ye Xue Bao 16(5):79–83 (In Chinese)

Hu TT, Kang SZ (2005) The compensatory effect in drought resistance of plants and its application in water-saving agriculture. Acta Ecol Sin 4:885–891 (In Chinese)

Ji KS, Sun ZY, Fang Y (2006) Research advance on the drought resistant in forest. J Nanjing Forestry Univ (nat Sci Ed) 30(6):123–128 (In Chinese)

Joshi SC, Chandra S, Palni LMS (2007) Differences in photosynthetic characteristics and accumulation of osmoprotectants in saplings of evergreen plants grown inside and outside a glasshouse during the winter season. Photosynthetica 45:594. https://doi.org/10.1007/s11099-007-0102-5

Koo S, Shin D, Kim C (2021) Application of principal component analysis approach to predict shear strength of reinforced concrete beams with stirrups. Materials 14(13):3471
Li L, Jia ZQ, Zhu YJ (2010) Research advances on drought resistance mechanism of plant species in arid area of China. J Desert Res 5:1053–1059 (In Chinese)

Li H, Wang GH, Zhang Y, Zhang WK (2016) Morphometric traits capture the climatically driven species turnover of 10 spruce taxa across China. Ecol Evol 6(4):1203–1213

Losfeld GL, Huillier L, Fogliani B, Jaffré T, Grison C (2015) Mining in New Caledonia: environmental stakes and restoration opportunities. Environ Sci Pollut Res 22(8):5592–5607

Loska K, Wiechula D (2003) Application of principal component analysis for the estimation of source of heavy metal contamination in surface sediments from the Rybnik Reservoir. Chemosphere 51(8):723–733

Ma W, Shi P, Li W, He Y, Zhang X, Shen Z, Chai S (2010) Changes in individual plant traits and biomass allocation in alpine meadow with elevation variation on the Qinghai-Tibetan Plateau. Sci China Life Sci 53:1142–1151

Na Z, Jiang DM (2018) Study of the drought resistance of thirteen sand-fixing plants in Horqin Sand Land, China. Int J Agric Biol 20:1717–1724

Nezhadahmadi A, Prodhani ZH, Faruq G (2013) Drought tolerance in wheat. The Sci World J. https://doi.org/10.1155/2013/610721

Nurmamat K, Halik Ü, Baidourela A, Nasirdin N (2017) Characterization and valuation of dust retention of the main species of streets trees in Aksu City. Sci Silvae Sin 53(1):101–107 (In Chinese)

Panda N, Khush GS (1995) Host plant resistance to insects. CAB International, Wallingford

Pietrzykowski M (2019) Tree species selection and reaction to mine soil reconstructed at reforested post-mine sites: central and eastern European experiences. Ecol Eng 142:100012

Prajapati SK, Tripathi BD (2008) Seasonal variation of leaf dust accumulation and pigment content in plant species exposed to urban particulates pollution. J Environ Qual 37(3):865–870

Rocha-Nicoleite E, Campos ML, Colombo GT, Overbeck GE, Mueller SC (2018) Forest restoration after severe degradation by coal mining: lessons from the first years of monitoring. Braz J Bot 41(3):653–664

Roy R, Wang J, Golam M, Fornara D, Sikdar A, Sarker T, Wang X, Shah M (2020) Fine-tuning of soil water and nutrient fertilizer levels for the ecological restoration of coal-mined spoils using Elaeagnus angustifolia. Environ Manag 270:110855

Schleicher NJ, Norra S, Chai F, Chen Y, Wang S, Cen K (2011) Temporal variability of trace metal mobility of urban particulate matter from Beijing—a contribution to health impact assessments of aerosols. Atmos Environ 45(39):7248–7265

Shah K, Ul Amin N, Ahmad I, Ara G (2018) Impact assessment of leaf pigments in selected landscape plants exposed to roadside dust. Environ Sci Pollut Res 25(23):23055–23073

Singh S, Pandey B, Roy LB (2021) Tree responses to foliar dust deposition and gradient of air pollution around opencast coal mines of Jharia coalfield, India: gas exchange, antioxidative potential and tolerance level. Environ Sci Pollut Res 28:8637–8651

Sun B, Zhou S, Zhao Q (2003) Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma 115(1/2):85–99

Tang M (2017) Primary research on dust retention effects of landscape plants in industrial mining area of Tangshan City. Hubei Agric Sci 56(19):3664–3668 (In Chinese)

Tirado R, Cotter J (2010) Ecological farming: drought-resistant agriculture. Greenpeace Research Laboratories, Exeter, UK

Wang X (2011a) Coal mining environmental impact and treatment methods of mine. Coal 20(5):60–61 (In Chinese)

Wang YC (2011b) Carbon sequestration and foliar dust retention by woody plants in the greenbelts along two major Taiwan highways. Ann Appl Biol 159(2):244–251

Wang F, Xiong SG, Li HY, Li LL, Zhang QM (2014) Study on dust-retention ability of major afforestation tree species in new industrial zone. Adv Mater 838:2433–2438

Wang X, Zhu D, Wang Y, Wei X, Ma L (2015) Soil water and root distribution under jujube plantations in the semiarid Loess plateau region. China Plant Growth Regul 77(1):21–31

Xie DB, Hu MX (2016) Research on the classification index system design of the state-owned forest farms based on correlation analysis and principal component analysis. J Cent South Univ Technol 36(8):141–146 (In Chinese)

Yi X, Li X (2011) Characteristics of soil resources and development and protection in the Northwest region. J Earth Sci Environ 26(4):85–89 (In Chinese)

Zhang YX (2016) Effects of coal mining on soil environment and microbial restoration in western area of China. China Univ Min Technol, Beijing In Chinese

Zhang VK, Wang B, Niu X (2015a) Study on the adsorption capacities for airborne particulates of landscape plants in different polluted regions in Beijing (China). Int J Environ Res Public Health 12(8):9623–9638

Zhang WK, Wang B, Niu X (2015b) Adsorption capacity of the air particulate matter in urban landscape plants in different polluted regions in Beijing (China). Environ Sci 36(7):2381–2388 (In Chinese)

Zhao TN, Zhang YX, Cao B, Xiao HJ, Zhang CL (2018) Eco-security technology for coal mining bases in the northwestern arid desert regions of Beijing. J Earth Sci Environ 32(1):1–5

Zhou DW, Dong B, Liu J (2016) Method of comprehensive evaluation on soil fertility on the basis of weight analysis. J Irrig Drain 35(6):81–86 (In Chinese)

Zhao Y, Chen Y, Ren L, Li H, Zhao W, Yuan F, Xu M (2016) Ecosystem restoration and conservation in the arid inland river basins of Northwest China: problems and strategies. Ecol Eng 94:629–637

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