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How would ecological restoration affect multiple ecosystem service supplies and tradeoffs? A study of mine tailings restoration in China

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ABSTRACT

Ecological restoration is becoming increasingly important in addressing the global crisis of ecosystem degradation. Ecosystem services, as a concept that connects people and natural ecosystems, can be incorporated into the design, practice and evaluation of restoration projects to promote both the socioeconomic and ecological effects of restoration. However, the full incorporation of ecosystem services in landscape-scale restoration projects is still greatly lacking. In this study, we used the Dashihe mine tailings restoration project in Hebei, China, as a case study and analyzed data from field surveys, remote sensing and literature reviews to study the following two questions: 1) How would multiple ecosystem service supply capabilities and their tradeoffs change after ecological restoration; 2) How can multiple ecosystem service supply capabilities be maximized while minimizing their tradeoffs? The supply capabilities of four important ecosystem services (i.e., soil retention, dust deposition, carbon sequestration and habitat maintenance) and their tradeoff intensities under six restoration scenarios were quantified and compared. The results showed that restored ecosystems outperformed unrestored and even the reference conditions in terms of ecosystem service supply enhancement. However, there is still much room for improvement compared to the recommended restoration scenario. The recommended scenario could result in both higher service supplies and lower tradeoff intensities among the services. On this basis, we call for more incorporation of ecosystem service supply and tradeoff analysis in future ecological restoration projects to reverse the declining trends of ecosystem services across the globe.

1. Introduction

The natural environment serves as the basis for human civilization's existence and development. Nevertheless, mounting evidence has demonstrated that humans are altering the natural environment upon which they depend at an unprecedented rate. Studies have shown that approximately 30% of the land area is degraded, directly affecting three billion people worldwide (Bergstrom et al., 2021; Brooks et al., 2019; Watson et al., 2014). In addition, the rate of biodiversity loss over the past three hundred years has also been hundreds of times higher than the

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long-term average (Mace et al., 2018; W. Wang et al., 2020). As a result, ecological restoration is becoming increasingly important and has been declared the theme of the decade of 2021 to 2030 by the United Nations to prevent, halt and reserve loss of nature (UNEP, 2022). Among the many causes of ecosystem degradation and biodiversity loss, mines and their tailing disposal sites, which are unique types of landscape following the disposal of processed mineral resources, present a series of particularly severe environmental challenges, including resource waste, pollution, land deterioration and biodiversity loss (Ahirwal and Pandey, 2021; Gairola et al., 2023). In China alone, the total area size of abandoned mines reached 2,267 million hm^2 at the end of 2018, with a rapid growth rate of 33,000 to 47,000 hm^2 per year (Yang et al., 2021). Due to both the magnitude and intensity of the problems, the restoration of mines and their tailing sites has been a long-standing major focus of various research fields, including restoration ecology, environmental science, and ecological technology.

Recent studies have advocated for incorporating the concept of ecosystem services, which refers to the contributions of ecosystems to human well-being, into ecological restoration design, practice and evaluation (Yang et al., 2018; Peng et al., 2022; Z. Wang et al., 2022). The concept of ecosystem services can bridge the gap between human civilization and natural ecosystems as its effect pathways cascade from ecosystem structure to function and further to human values and well-being (Haines-Young and Potschin, 2010). Therefore, they can be used as effective measures of the socio-ecological benefits created by the numerous restoration projects across the globe (Wortley et al., 2013; Ahirwal and Pandey, 2021; Xu et al., 2022). For example, del Río-Mena et al. (2020) studied the arid rural landscape of the Eastern Cape in South Africa and evaluated the effectiveness of ecological restoration interventions by quantifying the supply of six ecosystem services under different restoration scenarios; Goyette et al. (2021) also modeled the supply and demand of ecosystem services in wetlands in southern Quebec (Canada) to support the formulation of economic and effective wetland restoration policies; and Lü et al. (2021) reviewed the research on ecosystem services driven by ecological restoration and found that ecosystem services could be used to evaluate vegetation restoration and landscape management practices and as a key standard to promote the realization of sustainable development goals in dryland ecosystems.

Despite all these efforts and attempts, there remains a substantial lack of full and wide incorporation of ecosystem services in restoration projects, especially in landscape-scale mine and tailing restorations (Ahirwal and Pandey, 2021). One of the major challenges preventing such integration may be related to the complex relationships embedded between various ecosystem services (de Groot et al., 2010; He et al., 2020; Hua et al., 2022). Previous studies have shown that multiple ecosystem services found in the same ecosystem or region could exhibit tradeoff relationships (Howe et al., 2014; Wu and Li, 2019). For instance, Wang et al. (2020b) mapped and evaluated the cumulative impacts of long-term mining disturbance and gradual recovery on ecosystem services in Curragh mine, Australia, and found not only a synergy between carbon sequestration and air quality regulation but also strong tradeoffs between these two services and water production; Cueva et al. (2022) quantified the supply and tradeoffs between 23 ecosystem services in urban and peri-urban forests in southwest Germany and found that regions with higher supplies of supporting services had lower supplies of provisioning and regulating services; Ma et al. (2022) also found tradeoffs between provisioning services and regulating services were very common in the study results of forest restoration of monocultures. Nonetheless, current ecological restoration project designs and evaluation practices still lack consideration of the possible tradeoff relationships between ecosystem services, which may lead to biased and unfavorable restoration outcomes (Schirpke et al., 2019; He et al., 2020; Liu et al., 2020).

To address this key research gap and better promote both the socioeconomic and ecological effects of ecological restoration projects around the world, this study aims to evaluate both the supply capability of ecosystem services and their tradeoffs under different restoration scenarios. First, we used the restoration projects at a typical mine tailings site in Qianan, China, as a case study and identified its control and reference conditions by conducting field surveys and obtaining drone-based remote sensing data (Fig. 1). Then, based on the acquired data and extensive literature reviews, we delineated different stand types in the restoration, control and reference sites and established a species-level ecosystem service supply capability database to assess the average service supply in each stand. Lastly, we developed multiple potential restoration scenarios and analyzed their effects on ecosystem service supplies and tradeoff intensity. By doing so, we hope to answer the following two main research questions:

1) How would multiple ecosystem service supply capabilities and their tradeoffs change after ecological restoration?

2) How can multiple ecosystem service supply capabilities be maximized while minimizing their tradeoffs?

2. Methods

2.1. Study area

We selected the typical tailing sites of the Dasihhe iron ore mine, which is located in Qianan City, Hebei Province (39.99°N, 118.54°E), as our case study area (Fig. 2). The Dashihe mine tailings consists of two adjacent tailings ponds, namely Mengjiachong and Dacai, with a total area of 394 hm^2 (218 hm^2 for Mengjiachong and 176 hm^2 for Dacai, with 55.1 hm^2 of water area). The tailings area is located on the southern flank of the Yanshan Uplift Zone remnants, which has a sub-humid warm temperate continental monsoon climate, with an average annual precipitation of 611.0 mm, mainly from June to September, and a mean annual temperature of 10.8 °C (Qianan Goverment, 2023).

The Dashihe tailings ecological restoration project was implemented and managed by Hebei Shougang Qianan Iron & Steel Co., Ltd. The Mengjiachong tailings site was built and put into use in the 1960 s and was decommissioned in 2005, while the Dacai tailings site was formally opened in 2005. Since 2003, the Shougang company has been funding a series of ecological restoration projects in these two tailings sites of the Dashihe mine area, including the burial of the dump field, backfilling of guest soil, and vegetation planting. After 14 years of remediation and ecological restoration (by August 2017 when the first field survey was conducted), the vegetated area and vegetation coverage of the Dashihe tailings area had reached 243 hm^2 and 62% (155.4 hm^2 and 71% in Mengjiachong and 87.44 hm^2 and 50% in Dacai), respectively (Fig S1 to S2).

In order to accurately assess the effectiveness of the Dashihe tailings ecological restoration project, we also selected an undisturbed and unrestored area as the reference and control site, respectively. The reference site is located in the national nature reserve with the closest distance and the most similar natural conditions to the Dashihe tailings area, namely the Wuling Mountain National Nature Reserve in Hebei Province (40.55°N, 117.50°E). The reserve has a total area of 14,265 hm^2 with a forest coverage rate of 93%. The specific site we sampled in the Reserve has the most similar elevation and area size to the Dashihe restoration area (Fig. S3). The control site is another Shougang mine tailings area in Qianan (40.05°N, 118.54°E), which is still in operation and has not been actively restored (Fig. S4).

2.2. Vegetation survey and stand delineation

To obtain the soil, surface water and vegetation data required for ecosystem service supply assessment, we conducted three field surveys for the Dashihe tailings restoration area, the reference site and control site in the August of 2017 (5 to 14 vegetation sample sites were selected) (Fig S1 to S4). We also acquired high-resolution (~0.5 m) remote sensing data from unmanned aerial vehicle (UAV) for the restoration area, reference site and control site. In August 2018, a total of 14

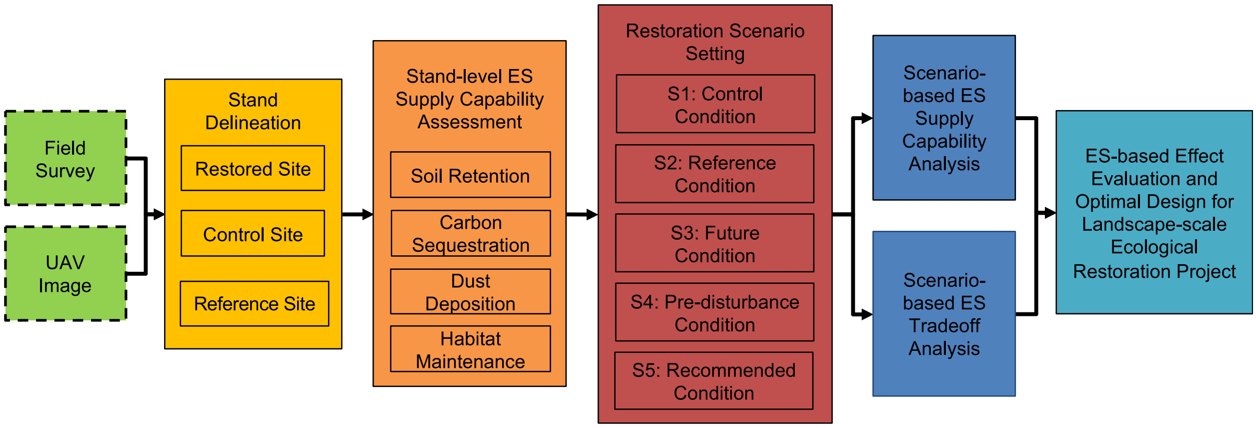

Fig. 1. Flowchart of the study design. ES and UAV stand for ecosystem services and unmanned aerial vehicle, respectively.

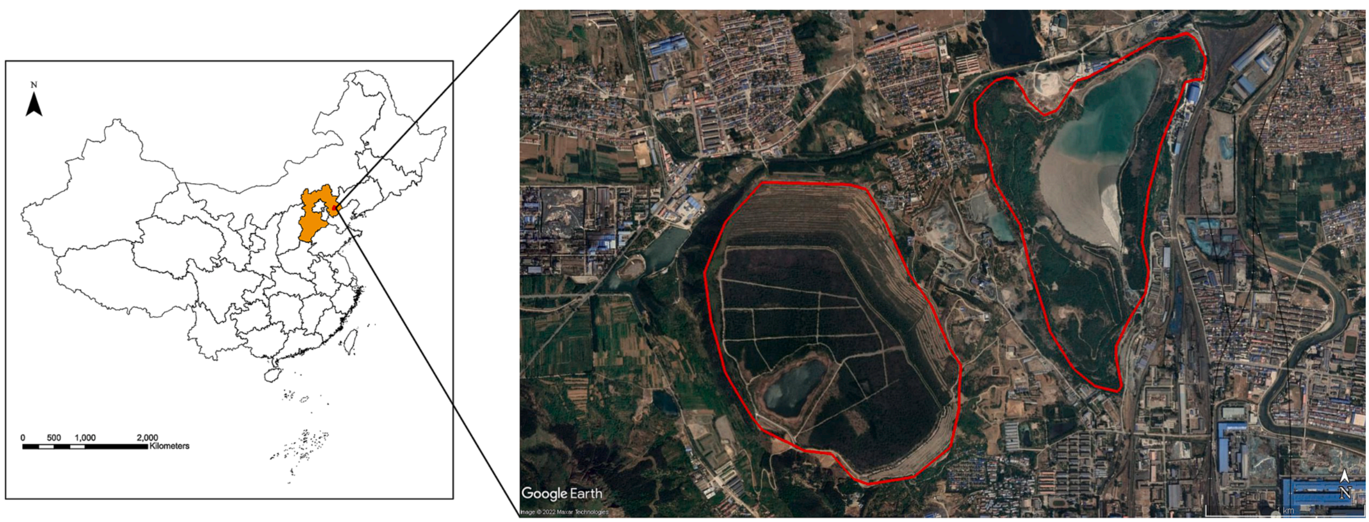

Fig. 2. Location map of Dashihe mine tailings restoration project (Mengjiachong area-left; Dacai area-right) in Qianan, Hebei Province of China. Image obtained from Google Earth.

additional ground truth sites were selected in the restoration area to verify the results of the UAV image analysis (Fig S1 to S4). The vegetation composition of each delineated stand type in the restoration area was also verified. The vegetation survey methodology refers to each tree and shrub survey quadrat being 10 m × 10 m, within which six additional 1 m × 1 m quadrats were selected for the herbaceous vegetation survey (Fang et al., 2009). All vascular plant species, species type (tree, shrub, or grass), invasive species status, and height and cover of each species were recorded.

Based on the acquired remote sensing and vegetation survey data, we classified the areas with vegetation cover in the Dashihe restoration area into different stand types and assessed the supply capability of ecosystem services within each type (Cummings et al., 2018; Simons et al., 2021). The specific steps of the stand type classification are as follows: 1) analyze the vegetation NDVI values calculated from UAV remote sensing images (Fig. S6 to S8), and extract the part of NDVI values greater than 0.2 to obtain the vegetation coverage area of the Dashihe tailings area (Guo et al., 2012); 2) combine the field data from two vegetation surveys, high-definition remote sensing images (UAV), historical remote sensing images (from Google Earth) for comparison and combined with topographic and geomorphological information to determine vegetation type distribution in the two tailings restoration areas of Mengjiachong and Dacai.

2.3. *Quantifying ecosystem service supply capability*

The core ecosystem services generated by the Dashihe tailings restoration project were screened by considering the planned restoration objectives, the realized restoration effects, the actual social demand and the service quantifiability. A total of four services were selected as the core ecosystem services for full evaluation: soil retention, carbon sequestration, dust deposition and habitat maintenance. Although water and soil purification services can be provided by the restored ecosystems in some mine tailings restoration projects (Wang et al., 2017; UNSD, 2021), the examination of the surface water quality in the Dashihe restoration area suggests a lack of demand for such services (Table S1). Consequently, we did not include these services in the further analysis. Since the Dashiehe restoration area was closed to neighboring communities for visiting and harvesting, no provisioning and cultural services were selected.

For the services of soil retention, carbon sequestration and dust deposition, there is mounting evidence suggests that the capability of species to provide these services vary with the environment and succession stages (Fricke et al., 2019; Oktavia et al., 2022; Rau et al., 2018). Therefore, we calculated the mean ecosystem service supply capabilities for every species found in Dashihe by using the data from a large number of published studies (all conducted in China) to represent the generalized service supply capacities in an ecosystem that is still heavily influenced by human activities and highly susceptible to change (Table S3 to S5).

2.3.1. Soil retention capability

Soil retention service is defined as the stabilizing effects of vegetation that reduce the loss of soil and support use of the environment (UNSD, 2021). The DEM maps showed that the Dashihe tailings area has slopy areas, which would result in severe soil erosion if unrestored (Fig. S6 and S7). Previous studies have shown that different vegetation species differ in their ability to retain soil (Wang et al., 2006; Wu and Li, 2019). Although it is impossible to precisely quantify these differences, we used the leaf area index (LAI) as the proxy, which is the major indicator of the ability of plant species to intercept and retain rainwater that causes soil erosion (Gao et al., 2020; Song et al., 2019; Zhang et al., 2014). The compiled database for leaf area index consists of 70 records from 22 studies and covers 32 out of the 33 species found in the Dashihe area (Table S3). If multiple sources of data values were available for a species, the average value was taken as its data value. If data values for a particular species could not be quantified, the mean value for the same type of species (trees or shrubs) in its area (restoration area, reference site, or control site) was used as the value.

2.3.2. Carbon sequestration capability

Carbon sequestration service represents ecosystem contributions to the regulation of the chemical composition of the atmosphere and oceans that affect the global climate (UNSD, 2021). This service was selected due to the strong demand to reduce greenhouse gas emissions through nature-based solutions like ecological restoration (Lu et al., 2022). As with the soil retention service, we compiled the carbon sequestration capability database for all species found in our study area and used the weighted mean value to assess the restoration effects. The compiled database for carbon sequestration capability consists of 56 records from 17 studies and covers 31 species (Table S4).

2.3.3. Dust deposition capability

Dust deposition represents the process of filtrating, fixing or storing dust particles that directly affect human health or infrastructure (IPBES, 2019). It is an important form of air quality regulation and was selected to acknowledge the contribution of the restored ecosystem in reducing the severe air pollution in the region (Yuan and Yang, 2019). The dust retention coefficient approach was used to measure the supply capability of dust deposition services (Gao et al., 2022). Details of the daily average unit area dust retention of species found in the restoration area, reference site, and control site, as well as their sources, can be found in the compiled database (Table S5). The database for dust deposition capability consists of 54 records from 14 studies and covers 29 species.

2.3.4. Habitat maintenance capability

Habitat maintenance services are defined as the continued production, by ecosystems, of ecological conditions necessary or favorable for living beings important to humans (IPBES, 2019). Although this service is generally viewed as a type of supporting or intermediate service, we learned that the main driver behind restoration investment in Dashihe was to restore the local biodiversity and believed that the strong local demand should be explicitly reflected through assessing the physical condition of the service. The supply capability of the service can be proxied by the level of biodiversity (i.e., α-diversity) (Liquete et al., 2016). We used the widely-used Shannon-Weiner diversity index as the indicator of local biodiversity (Gallardo et al., 2011), calculated as follows:

$$H = -\sum_{i=1}^{S} Pi\ln Pi \quad (1)$$

where H is the Shannon-Weiner diversity index, S is the total number of species in the sample pool, and Pi is the relative importance value of the i_{th} species. The importance values were calculated as follows (Fang et al., 2009):

$$P_{Tree} = (C_r + H_r + F_r)/3 \quad (2)$$

$$P_{Shrub/Herb} = (C_r + H_r)/2 \quad (3)$$

where the Cr is the percentage of the cover of the species to the total cover of all species, the Hr is the ratio of the height of the species to the total height of all species, and Fr is the percentage of the number of samples in which the species occurs to the total number of sample plots (14 in the restoration area and 5 in the reference and control sites).

2.4. Restoration scenarios setting

In order to identify potential conditions that can maximize multiple ecosystem service supplies while minimizing tradeoffs, we developed a total of five possible scenarios in the Dashihe restoration area (Table 1) (Y. Wang et al., 2022; Xiao et al., 2022; Xing et al., 2023). Specifically, Scenario 1 is based on the control ecosystem-based restoration scenario, which aims to understand the expected condition in the absence of restoration operations in the Dashihe tailings area. Scenario 2 is designed to understand the possible restoration outcome when the restoration project uses the reference ecosystem as the goal instead of the current plans. Scenario 3 aims to assess the likely future condition if the present ecosystem evolves to encompass the entire Dashihe tailings area. Scenario 4 is designed to simulate the conditions without human disturbance (i.e., mining) in the Dashihe tailings area. In addition, we also developed a recommended restoration plan that can theoretically improve the effectiveness of the Dashihe mine tailings restoration project by optimizing the supply capabilities of all core ecosystem services, i.e., Scenario 5.

For the recommended restoration scenario (Scenario 5), we followed four principles in designing the recommended restoration scenarios to

Table 1
Descriptions and goals of different restoration scenarios for the Dashihe mine tailings restoration project.

Restoration scenarios	Scenario descriptions	Scenario goals
Scenario 1: Control condition	Unrestored scenario with control area ecosystem structure and species replacement status	Understand the condition in the absence of restoration operations on the Dashihe tailings area
Scenario 2: Reference condition	Restoration using ecosystem structure and species from the reference area	Understand the possible restoration outcome when restoration of the Dashihe tailings area is restored with the objective of restoring the pre-human-disturbance ecosystem
Scenario 3: Future condition	Complete restoration* with existing ecosystem structure and species in the restoration area	Understand the likely future condition when the present ecosystem evolves to span the entire Dashihe tailings
Scenario 4: Pre-disturbance condition	Complete ecosystem species and structure in the reference area	Understand the likely condition of the tailings area if there is no mining disturbance
Scenario 5: Recommended condition	Restoration scenarios with recommended ecosystem structure paired with species design	Understand the potential ecological outcome when the results of the ecosystem service supply capacity analysis are used in the restoration

*Complete restoration: the area required to restore to 100% coverage after excluding the water area, the increased area of each forest stand is calculated according to the existing proportion, except for the area of the two types of forest stands (Grassland and *Vitex negundo* Mixed of Mengjiachong tailings pond) with distinct boundaries, which remains unchanged.

maximize the overall ecosystem restoration effect, namely:

1) Maintain or increase local biodiversity levels by utilizing the biodiversity levels of the reference site as a benchmark;
2) Prioritize tree species with the strongest ecosystem service supply capabilities found in the current restoration area or reference site;
3) Prefer shrub species in the reference area or those that can provide additional ecosystem services, such as those that can fix nitrogen, provide biological products, store carbon for a long period of time (i.e., long longevity), possess athletic value, etc.;
4) No invasive species shall be selected.

The species in the recommended scenario can be found in current restoration plans or reference sites to ensure the practicability of the design (Table 2). In designing the species composition, the species were first ranked in terms of their service supply capacity based on the compiled databases (Table S3, S4 and S5). The species with at least two capacity rankings in the top ten were then selected. It was found that *Larix principis-rupprechtii, Ulmus pumila, Platycladus orientalis* and *Populus tomentosa* were ranked in the top ten in all three rankings. They were

Table 2
Recommended restoration species composition based on the ecosystem service supply capacities for the Dashihe mine tailings restoration project.

Rank	Soil retention	Carbon sequestration	Dust deposition	Recommended species composition (ranks): %
1	*Larix principis-rupprechtii*	*Ulmus pumila*	*Larix principis-rupprechtii*	Tree species: *Larix principis-rupprechtii* (1, 3, 1): 20%; *Ulmus pumila* (9, 1, 7): 15%; *Platycladus orientalis* (10, 6, 2): 15%; *Populus tomentosa* (8, 7, 10): 15%; *Pinus tabuliformis* (3, -, 3): 10%; *Quercus dentata* (5, -, 5): 5%; *Morus alba* (-, 2, 9): 5%; *Salix matsudana* (-, 4, , 8): 5%; *Pistacia chinensis* (-, 8, 4): 5%; *Juglans mandshurica* (7, -, 6): 5% Shrub species: *Lespedeza bicolor* (nitrogen fixation): 10%; *Amorpha fruticose* (nitrogen fixation): 10%; *Hippophae rhamnoides* (nitrogen fixation): 10%; *Philadelphus schrenkii* (aesthetics): 10%; *Spiraea salicifolia* (aesthetics): 10%; *Weigela florida* (aesthetics): 10%; *Forsythia suspensa* (aesthetics): 10%; *Crataegus pinnatifida* (food): 10%; *Rubus crataegifolius* (food): 10%; *Vitex negundo* (long-living): 10%; Grass species: *Dendranthema erubescens*, *Cirsium leo*, *Asparagus cochinchinensis* and seven other local species, each account for 10%
2	*Philadelphus schrenkii*	*Morus alba*	*Platycladus orientalis*	
3	*Pinus tabuliformis*	*Larix principis-rupprechtii*	*Pinus tabuliformis*	
4	*Sambucus williamsii*	*Salix matsudana*	*Pistacia chinensis*	
5	*Quercus dentata*	*Robinia pseudoacacia*	*Quercus dentata*	
6	*Acer truncatum*	*Platycladus orientalis*	*Juglans mandshurica*	
7	*Juglans mandshurica*	*Populus tomentosa*	*Ulmus pumila*	
8	*Populus tomentosa*	*Pistacia chinensis*	*Salix matsudana*	
9	*Ulmus pumila*	*Rhus typhina*	*Morus alba*	
10	*Platycladus orientalis*	*Ailanthus altissima*	*Populus tomentosa*	

therefore allotted a higher proportion of the recommended species composition. Among the species, *Larix principis-rupprechtii* received the largest proportion due to its highest average ranking. Furthermore, the size and ecosystem structure in the recommended scenario used the maximum restoration area (area needed to reach 100% cover after restoration), the maximum patch connectivity, and the multi-layered structure of trees, shrubs, and grasses to maximize soil retention, carbon sequestration, and dust deposition services based on findings from Wu and Li (2019).

2.5. Ecosystem services tradeoff analysis

To quantify the strength of tradeoffs between ecosystem services, we applied the Root Mean Squared Error (RMSE) method, which calculates the amount of deviation of a given ecosystem service in a location relative to the average of all ecosystem services in that region (Bradford and D'Amato, 2012; Liu et al., 2019). The RMSE value reflects the distance of the ecosystem service from the no tradeoff state (1:1 line, Fig. S9). A larger RMSE value indicates a greater distance from the 1:1 line and a higher intensity of tradeoff, whereas a smaller value suggests a lower intensity of tradeoff. The particular formula for computing the RMSE value is shown in equations (4) to (5) (Liu et al., 2019).

$$RMSE = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} \left(ES_{istd} - \overline{ES}\right)^2} \tag{4}$$

$$\overline{ES} = \frac{\sum_{i=1}^{N} ES_{istd}}{N} \tag{5}$$

$$ES_{istd} = \frac{ES_i}{ES_{imax}} \tag{6}$$

where ES_{istd} is the standard value of the *ith* ecosystem service; $\overline{ES}$ is the average of the standard values of all ecosystem services in the study area; ES_{imax} is the maximum value of the ith ecosystem service in the study area; n represents the number of ecosystem services that need to be studied in terms of tradeoff intensity, and n is equal to 2 if the tradeoff intensity between two services needs to be studied; and N is the total number of all ecosystem services studied in the area.

3. Results

3.1. Stand delineation and ecosystem service supply capabilities

A total of nine stand types were delineated in the Dashihe mine tailings restoration area. The stand types were named after the dominant species in terms of coverage (if the coverage of the most common species is less than 60%, "Mixed" was added). They are *Hippophae rhamnoides*, *Vitex negundo* Mixed, *Populus tomentosa*, *Tamarix ramosissima*, Grassland (no dominant species), *Robinia pseudoacacia*, *Amorpha fruticosa* Mixed, *Ulmus pumila* Mixed, *Platycladus orientalis* Mixed (Fig. 3). Detailed species composition and representative picture for each stand type can be found in Table S2 and Fig. S5, respectively. Among the stand types, the type of *Hippophae rhamnoides* occupies the largest area (70.20 hm^2), followed by *Robinia pseudoacacia* (61.18 hm^2). Whereas, the *Platycladus orientalis* Mixed is the smallest (1.29 hm^2) stand type of all.

Compared to the unrestored control ecosystem, the supply capacities of soil retention, carbon sequestration, dust deposition and habitat maintenance of the nine forest types improved 383.63%, 193.71%, 134.36%, and 114.27% on average, respectively (Table 3). However, compared to the pre-disturbance reference stand type, the currently used stand types only outperform in carbon sequestration capability and underperform in the other three services. Compared to the recommended stand option, most currently used stand types underperform in all four ecosystem service supply capacities.

In Fig. 4a, we showed the standardized overall ecosystem service

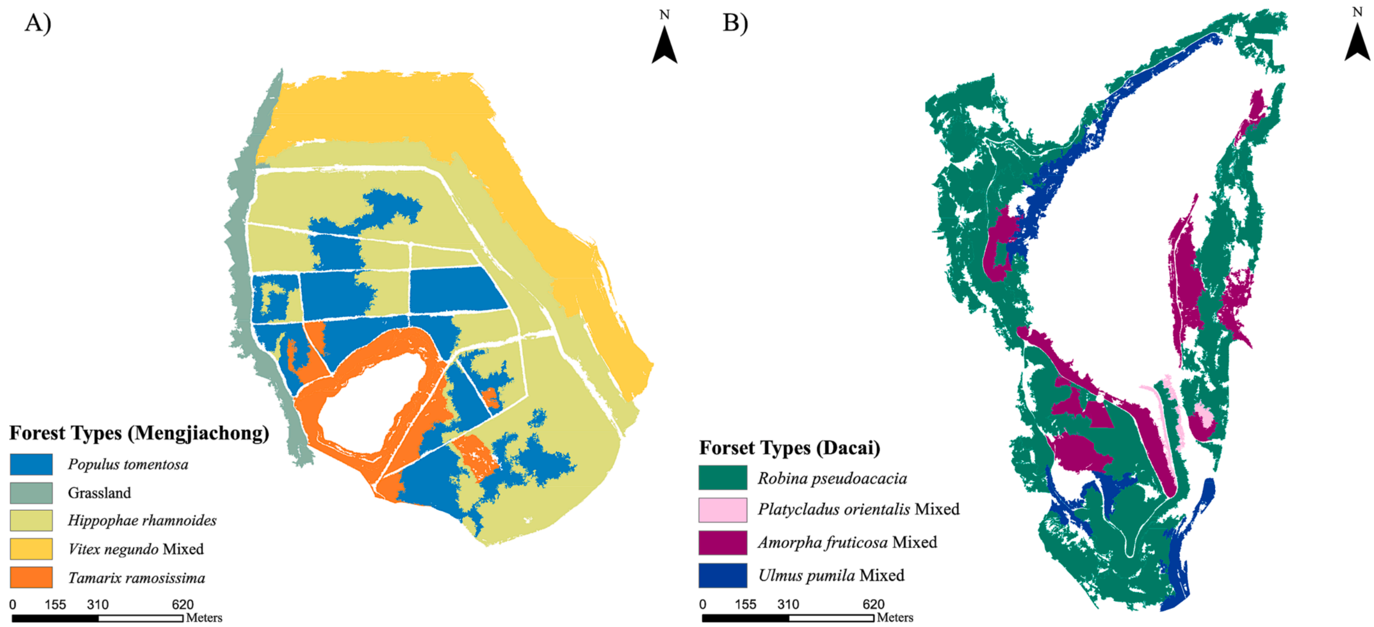

Fig. 3. Stand types of the Dashihe mine tailings restoration project found in Mengjiachong (A) and Dacai (B) areas.

Table 3
Supply capacities of carbon sequestration, dust deposition, soil retention and habitat maintenance of the stand types in the two tailing sites (Mengjiachong and Dacai) of the Dashihe mine tailings restoration project and the reference, control and recommended sites.

Stand types	Area (hm^2)	Carbon sequestration capability ($t/hm^2.a$)	Dust deposition capability ($kg/hm^2.d$)	Soil retention capability (Leaf Area Index)	Habitat maintenance capability (Shannon-Wiener Index)
Hippophae rhamnoides	70.20	33.66	78.59	5.05	3.47
Vitex negundo Mixed	36.05	25.69	64.31	4.31	2.99
Populus tomentosa	34.40	46.49	75.44	6.72	2.33
Tamarix ramosissima	10.05	47.19	96.56	4.67	3.04
Grassland	8.71	18.09	67.53	6.90	3.13
Robinia pseudoacacia	61.18	64.85	73.14	4.23	3.17
Amorpha fruticosa Mixed	15.40	80.17	114.18	7.79	4.16
Ulmus pumila Mixed	9.57	64.07	91.59	5.24	3.22
Platycladus orientalis Mixed	1.29	43.74	88.33	5.50	4.38
Reference	–	34.78	99.98	8.05	5.19
Control	–	9.74	28.36	2.39	1.55
Recommended	–	79.03	136.08	10.99	8.14

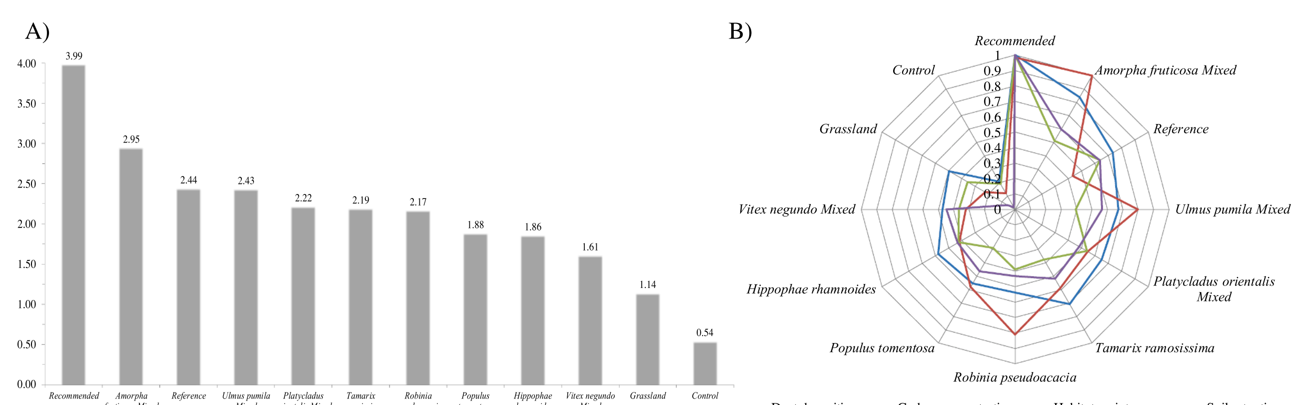

Fig. 4. Standardized overall (A) and individual (B) ecosystem service supply capacity of the 12 possible stand options for the Dashihe mine tailings restoration project.

supply capacities under the recommended, reference, control, and the nine existing stand types. Among them, the highest score (3.99) was obtained for the recommended stand option, and the lowest score (0.54) was obtained for the unrestored control stand option. For the individual ecosystem service supply capacity, we found that the recommended stand option was also better than the other stand options for all services except carbon sequestration (Fig. 4b). The *Amorpha fruticose* Mixed stand has the highest supply capability of carbon sequestration but has tradeoffs in other three services, especially in habitat maintenance (Fig. 4b).

3.2. Ecosystem service supply capabilities and tradeoffs under different scenarios

In Table 4, we showed the possible restoration effects under five scenarios and the status quo on the supply capabilities of the four ecosystem services. Compared with the unrestored control scenario (Scenario 1), the current restoration scenario (status quo) achieved satisfactory results for all core ecosystem services, with an average improvement of 66.78% in the supply capacities. Even when compared with the effects of the reference scenario (Scenario 2), the status quo still produced better results regarding carbon sequestration and habitat maintenance services. However, for the dust deposition service, Scenario 2 resulted in a significant improvement in the restoration this service. The comparison of the existing restoration effects with the complete restoration (i.e., Scenarios 3, 4 and 5) suggested that there is still room for improvement in the future. Among the three scenarios with complete restoration, Scenario 5 is more effective than Scenario 3 and 4 in improving the ecosystem service supply capabilities, except for dust deposition. Scenario 4 is the best choice for restoring the dust deposition supply capability among the three.

In Fig. 4, we showed the scatter plot of the two-by-two tradeoffs within the four ecosystem services among the five restoration scenarios and status quo (Fig. 5a) and the tradeoff intensity RMSE values (Fig. 5b). It was found that the scenarios based on the same species compositions (Scenario 2 and 4, Status quo and Scenario 3) were similar in terms of the tradeoff intensity of service restoration effects. The RMSE value thresholds for the various scenarios ranged from 0.06 to 0.40 (Fig. 5b). Among them, the service supply capabilities of dust deposition and carbon sequestration had the highest tradeoff intensity (RMSE = 0.40) in Scenarios 4 and 2, which indicates that these two services are more difficult to optimize simultaneously. However, the tradeoff intensity between soil retention and habitat maintenance service supply capabilities was the smallest (RMSE = 0.06), indicating that they are more likely to achieve synergy. Scenario 1 showed the smallest tradeoff intensity in the two-way comparison of dust deposition and carbon sequestration, dust deposition and soil retention, and dust deposition and habitat maintenance. Scenario 5 had the smallest tradeoff intensity between the service supply capabilities of carbon sequestration and habitat maintenance as well as carbon sequestration and soil retention. Lastly, the service restoration scatter plots showed that the dust deposition service achieved better results than the other three services when restoration scenarios other than Scenario 5 were used (Fig. 4a).

Last but not least, by comparing the overall tradeoff intensities of the four ecosystem services for each restoration scenario, we found that Scenarios 2 and 4 produced the highest tradeoff intensities (RMSE = 0.23) among the restoration effects, followed by the Status quo and Scenario 3 (RMSE = 0.18) (Fig. 6). A relatively small tradeoff intensity (RMSE = 0.14) among ecosystem services supplies could be achieved in Scenario 5. But the smallest overall tradeoff intensity (RMSE = 0.11) was found in Scenario 1.

4. Discussion

After comparing the effects of the 12 restoration stand options, we found that the Recommended option is optimal for all three core ecosystem services (Fig. 4). However, it is worth noting that the *Ulmus pumila* Mixed stand outperforms the Recommended alternative in terms of carbon sequestration capacity, which can be explained by the higher proportion (30%) of the fast-growing *Ulmus pumila* and *Populus tomentosa* trees found in this stand (Table S1) (Wang, 2009; Guo, 2015). In the future, if carbon sequestration becomes the most significant restoration objective of the Dashihe tailings restoration project, the restoration effect of this service can be strengthened by attempting to add *Ulmus pumila* mixed forest stands. Furthermore, we also found that the services of dust deposition and soil retention form a synergic relationship in general (Fig. 4). However, the services of carbon sequestration and dust deposition are more likely to have a tradeoff relationship (e.g., in the reference stand option) (Fig. 4). These results are highly consistent with the findings of Wu and Li (2019) on the formation of ecosystem services and can be explained by the different number of shared optimal ecosystem attributes (e.g., optimal size, structure, spatial configuration, etc.) that can maximize the service supply. In addition, we also found that both Scenarios 5 and 1 have a smaller tradeoff intensity (Fig. 6). However, when combined with the results in Table 4, it can be seen that the overall core ecosystem service supply generated by Scenario 5 based on the recommended restoration options is much greater than that generated by Scenario 1 based on the control site condition. Therefore, restoration designs that result in high synergy among multiple ecosystem services are not necessarily mean the optimal design that people should choose. To properly evaluate the effects of restoration designs on multiple ecosystem service supplies, it is vital to consider both the tradeoff intensity and the total effect strength simultaneously.

It is also worth noting that although the biodiversity level in the Dashihe restoration area exceeds the biodiversity level in the reference area (Table 4), the species composition between them still differs significantly (only four of the same species, Table S2). Therefore, it needs to be clarified that the Dashihe mine tailings restoration project is restoring and conserving a community with a different biodiversity composition from the reference ecosystem. Whether this difference will adversely affect the restored ecosystem and whether it is possible to restore the Dashihe area to biodiversity similar in composition and structure to the reference system in the future are still questions that need to be investigated (Huang et al., 2019). Moreover, since the number of survey samples in the restored and reference areas is still small relative to their areas and only plant species diversity was surveyed, the results may not fully reflect the biodiversity levels in both areas. In the future, it will also be necessary to use a larger sample size to

Table 4
Comparison of the effects of five restoration scenarios on ecosystem service supply capabilities for the Dashihe mine tailings restoration project.

Restoration scenarios	Carbon sequestration (t/a)-(change %)	Dust deposition (t/a)-(change %)	Soil retention (LAI)-(change %)	Habitat maintenance-(change %)
Status quo	11,408	3684	4.88	5.85
Scenario 1:Control condition	2408 (-78.9%)	1342 (-63.6%)	2.39 (-51.0%)	1.55 (-73.6%)
Scenario 2:Reference condition	8597 (-24.6%)	4732 (+28.4%)	8.05 (+65.1%)	5.19 (-11.2%)
Scenario 3:Future condition	16,162 (+41.7%)	5103 (+38.5%)	4.89 (+0.2%)	5.85 (0%)
Scenario 4:Pre-disturbance	11,788 (+3.3%)	6489 (+76.1%)	8.05 (+65.1%)	5.19 (-11.2%)
Scenario 5:Recommended condition	26,786 (+134.8%)	4612 (+25.2%)	10.99 (+125.4%)	8.14 (+39.1%)

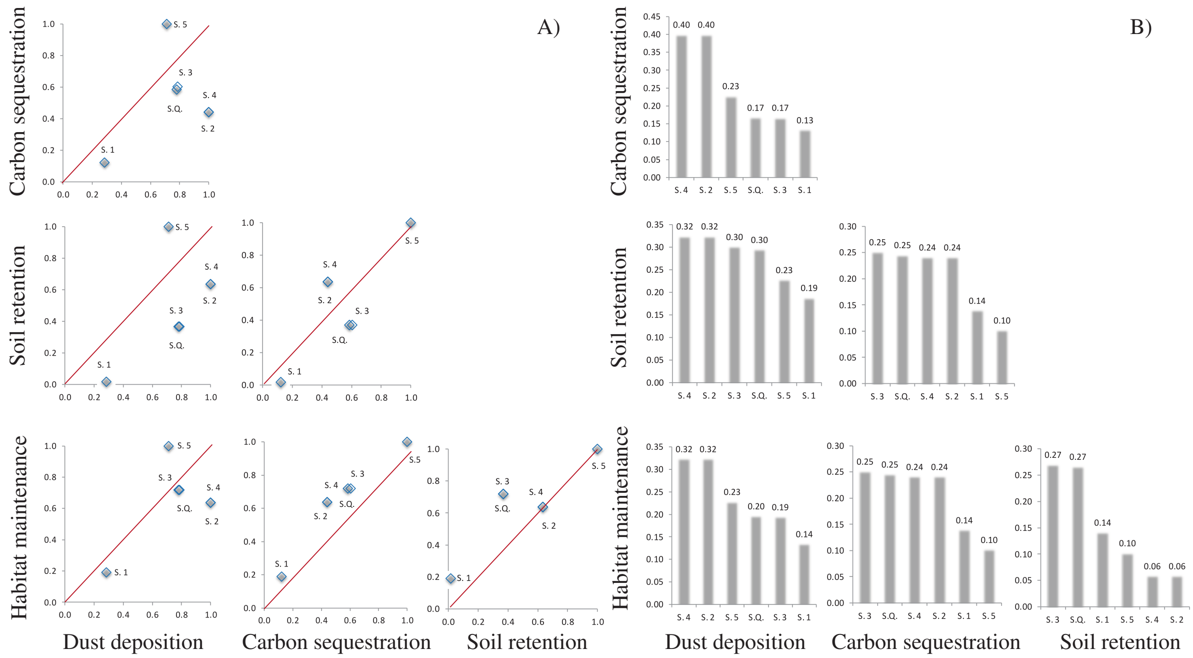

Fig. 5. Scatter plot matrices (A) and tradeoff intensity (RMSE values) (B) of paired ecosystem service supply capacities under six restoration scenarios (i.e., Status quo or S.Q. and S.1 to S.5) of the Dashihe mine tailings restoration project.

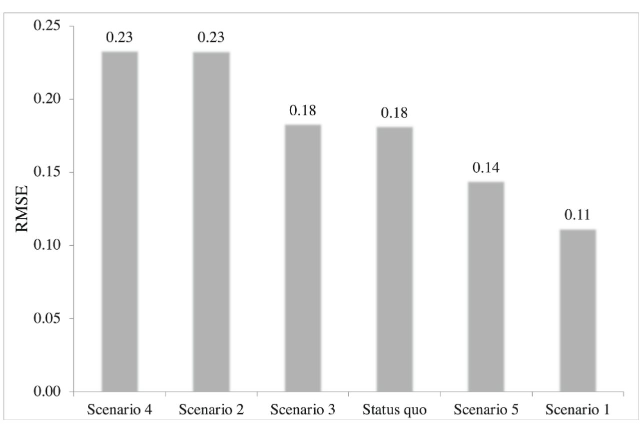

Fig. 6. The overall tradeoff intensity (RMSE values) of the ecosystem service supply capacities under six restoration scenarios in the Dashishe ecological restoration project.

draw dilution curves and to increase the diversity of other animals and insects to make a more reasonable comparison of biodiversity levels (Gotelli and Colwell, 2001).

In addition to biodiversity, the supply capability of carbon sequestration by species was also slower in the reference-ecosystem-based scenarios (Table 4). This finding is also in accordance with the studies comparing the productivity of planted and natural forests in China (e.g., Cao et al., 2013; Jia et al., 2013; Li and Ren, 2004), which may be related to the fact that restoration species are more often pioneer or early successional species (Boscutti et al., 2017; Wang et al., 2010). However, all of the ten most abundant species found in the reference area have an average lifespan of 50 to 150 years (i.e., *Betula chinensis, Acer truncatum, Crataegus pinnatifida, Vitex negundo, Lespedeza bicolor*) or more than 150 years (i.e., *Juglans mandshurica, Fraxinus chinensis, Larix principis-rupprechtii, Quercus dentata, Pinus tabuliformis*) (UFEI, 2023). Among the top most common species currently found in Dashihe, only *Ulmus pumila* and *Pinus tabuliformis* are long-lived species, and at least three species have an average lifespan of fewer than 50 years (i.e., *Ailanthus altissima, Salix matsudana, Rhus typhina*) (UFEI, 2023). Therefore, if the Dashihe mine tailings restoration project is unable to renew the stand in time for the existing species to reach a slow-growing maturity stage, the development of scenarios based on reference ecosystem species will reduce the differences in carbon sequestration service supply due to slowed growth rates and obtain higher total carbon sequestration in the long term.

Although Scenario 5 of the recommended condition significantly improves the restoration of all four core ecosystem services in the Dashihe tailings, it is still worth noting that due to the differences in growth conditions among species, some species may be unable to grow directly in the severely degraded areas. Therefore, the restoration design scenario needs to be implemented gradually, taking into account the ecological characteristics of each species and the corresponding silvicultural techniques to eventually reach the desired restoration state (Ashton and Kelty, 2018). In addition, the costs and budget of different restoration scenarios must be considered in practice (Kimball et al., 2015). In order to obtain more accurate and realistic analysis results, it will be necessary to estimate the input costs of different scenarios in future tradeoff and synergy analysis.

Last but not least, we must acknowledge that there are still some other limitations that can cause uncertainties in our conclusions. First, due to the lack of data on the pre-disturbance period of the Dashihe mine tailings restoration project, there is uncertainty as to whether the control area used in this study properly represents the background condition of the Dashihe area thus reflects the true restoration effects. Second, because this study used a coefficient database to assess carbon sequestration and dust deposition services, the data obtained from this method only represent the general supply capability of the ecosystem services provided by the species found in the study area, and actual future changes must be verified through return continuous tracking sampling. Finally, since the surrounding areas may also affect the supply of ecosystem services in the study area through species interactions and ecosystem services flows, the validity, accuracy and practicality of the assessment result in restoration projects similar to the Dashihe area could be further enhanced by obtaining data on the surrounding environment to quantify these potential interactions (Schröter et al., 2018; L. Wang et al., 2022).

5. Conclusion

In summary, by using the Dashihe mine tailings restoration project as a case study, we demonstrated how to incorporate ecosystem service supply and tradeoffs analysis into landscape-scale ecological restoration effect evaluation. More importantly, based on the analysis results, we also illustrated the possibility of achieving synergic improvement in multiple ecosystem service supplies by developing and testing multiple restoration scenarios. Although our assessment results suggest that the current Dashihe project can be viewed as a success from the perspective of enhancing the supply of ecosystem services, further improvement of service supplies and a decrease in tradeoffs among multiple services would still be possible if nature- and/or science-based planning were implemented. In the future, we call for more similar incorporation of ecosystem service supply and tradeoff analysis in more restoration designs and practices to promote the socio-ecological effects of restoration projects and reverse the declining trends of ecosystem service loss across the globe (Ruhl et al., 2021; Villarreal-Rosas et al., 2020).

CRediT authorship contribution statement

Weiyang Zhao: Writing – original draft, Writing – review & editing. **Shuyao Wu:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Xin Chen:** Writing – original draft. **Jiashu Shen:** Data curation. **Feili Wei:** Data curation. **Delong Li:** Data curation. **Laibao Liu:** Data curation. **Shuangcheng Li:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are attached in the supplementary material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110451.

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