Evaluation of Carbon Sequestration Benefits of Ecological Restoration in Open Pit Mines —— A Case Study of Tongluo Mountain Mine

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Abstract: The study takes Tongluo Mountain Mine in Chongqing as the test site, the plant and soil carbon sinks of different ecological restoration land use types were measured and the main influencing factors were analysed by means of plant investigation, plant biomass measurements, soil physicochemical property tests and model simulations. The main conclusions of the study are as follows:(1) The carbon sink per unit area of plant (4.65 kg C/m^2), the carbon sink per unit area of soil (4.36 kg C/m^2), the total carbon sink (574.39 t C), the carbon sink of vegetation (36.77 t C), and the carbon sink of soil (538.79 t C) are higher, but the carbon sink per unit area of vegetation is lower (0.29 kg C/m^2). The carbon sink of mine ecological restoration mainly comes from soil carbon sink, and the carbon sink per unit area of soil (4 kg/m^2) is 8 times higher than that of vegetation (0.5 kg/m^2).;(2) The main influencing factors of vegetation carbon sink are vegetation growth, and the main influencing factors of soil carbon sink are soil organic matter and soil fertility;(3) In the ecological restoration of open-pit mines, more local tree species such as *yellow camphor, cinnamomum camphor* and *acanthopanax* were planted, and measures such as increasing soil thickness and clay content in soil were taken to improve the regional soil ecological environment.

1 Introduction

Ecological restoration is an important way to achieve carbon sequestration and sink enhancement after the development of mineral resources [1-4]. After ecological restoration, the vegetation cover is improved, and a number of ecosystem services, such as soil and water conservation and water conservation, are improved [5-6], and at the same time, the restoration of vegetation cover can significantly increase the carbon sequestration in the ecosystem [7-8]. Vegetation carbon stock and soil carbon stock are not only the basic parameters to study the carbon cycle between the ecosystem and the atmosphere [9-10], but also an important indicator to reflect the structure and function of the community ecosystem characteristics, an accurate assessment of carbon stock is the key to estimate the carbon sequestration effect of ecological restoration, and is of great significance to the selection of ecological restoration species and the optimisation of the structure of the ecosystem after the ecological restoration [11-12].

Currently, studies on evaluating the carbon sink benefits of ecological restoration mainly focus on vegetation restoration and returning farmland to forests, watersheds and wetlands, karstic rocky desertification, and soil and water conservation [13-18], and the evaluations are mainly focused on a certain aspect of influencing the ecological environment, and few studies have been reported on comprehensively and systematically evaluating the benefits of ecological restoration of mine wastelands. The evaluation of the ecological restoration benefits of mine wasteland in a comprehensive and systematic way is rarely reported. The evaluation methods that have been used in the studies include comprehensive index method, fuzzy evaluation method, hierarchical analysis method, expert analysis method, grey system and system engineering analysis method, etc [19-20]. At present, studies on the carbon sequestration benefits of ecological restoration of open-pit mines mainly focus on the ecological effects of mine wasteland under different vegetation restoration types or vegetation configuration modes[9], and research has been carried out on the physical and chemical properties of soils, soil heavy metal contents, temperatures, and vegetation carbon stocks for different regions of mine wasteland and different types of mine wasteland with vegetation restoration [21-22]. There are fewer studies on the carbon sink benefits of restoration effects under different restoration modes of natural vegetation restoration and artificial vegetation restoration.

Tongluo Mountain mine is located in one of the four mountains of Chongqing main city, which has made excellent contribution to the development and

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construction of Chongqing as an important stone crushing base in the early days. In 2012, all the mines in the study area were closed to carry out ecological restoration, mainly including soil and water conservation measures and mainly including soil and water conservation and revegetation measures, using a combination of trees, shrubs and grasses, and after ecological restoration, a stable plant community was formed. There is no specific research on the carbon sink benefits of plants and soil after ecological restoration. In this study, we compared and analysed the ecological environment, microtopography, soil nutrient status and plant growth status of the ecological restoration soil of Tongluo Mountain mine through field investigation and indoor experiment, and focused on the carbon sequestration effect of plants and soil after ecological restoration, in order to provide technical support for the ecological restoration of open-pit mines, and the results of the research are of practical significance for evaluating the effect of ecological restoration of the mines and the reconstruction work.

2 Materials and methods

2.1 Study area

Tongluo Mountain (E 106°43′20″~106°48′14″, N 29°43′10″ ~ 29°49′12″) is located in Shichuan Town, Yubei District, Chongqing (Figure 1). The study area belongs to the subtropical monsoon climate zone, which is warm and humid, with four distinct seasons, mild climate, sufficient sunshine, abundant rainfall, with the characteristics of rainy summer and autumn, cloudy and foggy winter and spring, and significant continental monsoon climate characteristics. The average sunshine is about 1340 hours, and the average frost-free period is 319 days. The maximum annual rainfall of 1614.9mm (1993), the minimum annual rainfall of 828.8mm (2001), the average rainfall of 1206.04mm, rainfall is concentrated in May to September each year, the rainfall accounts for about 65% of the annual rainfall, the average maximum daily rainfall of 104mm, the maximum daily rainfall of 230.8mm (1 June 1971). The forest vegetation of Causeway Mountain belongs to subtropical humid evergreen broad-leaved forest area, and the primary vegetation is evergreen broad-leaved forest, with the main species of *camphor, heather, cypress, pine* and *fir*, etc., which has been damaged due to the exploitation of mineral resources and other activities, and has gradually become the present secondary forest.

Two typical restoration block in this area are selected as the research objects (Figure 2). The construction of the research area started in December 2018, was fully completed in December 2019, and the project was completed and accepted in April 2020. This area is mainly reclaimed for forest land and cultivated land, and the ecological restoration project is mainly laid in the cultivated land and woodland area. The site is first demolished and levelled, then covered with soil, and then equipped with stone retaining wall, field road, sump pond, sump pond, drainage ditch, sunken satang and agricultural culvert.

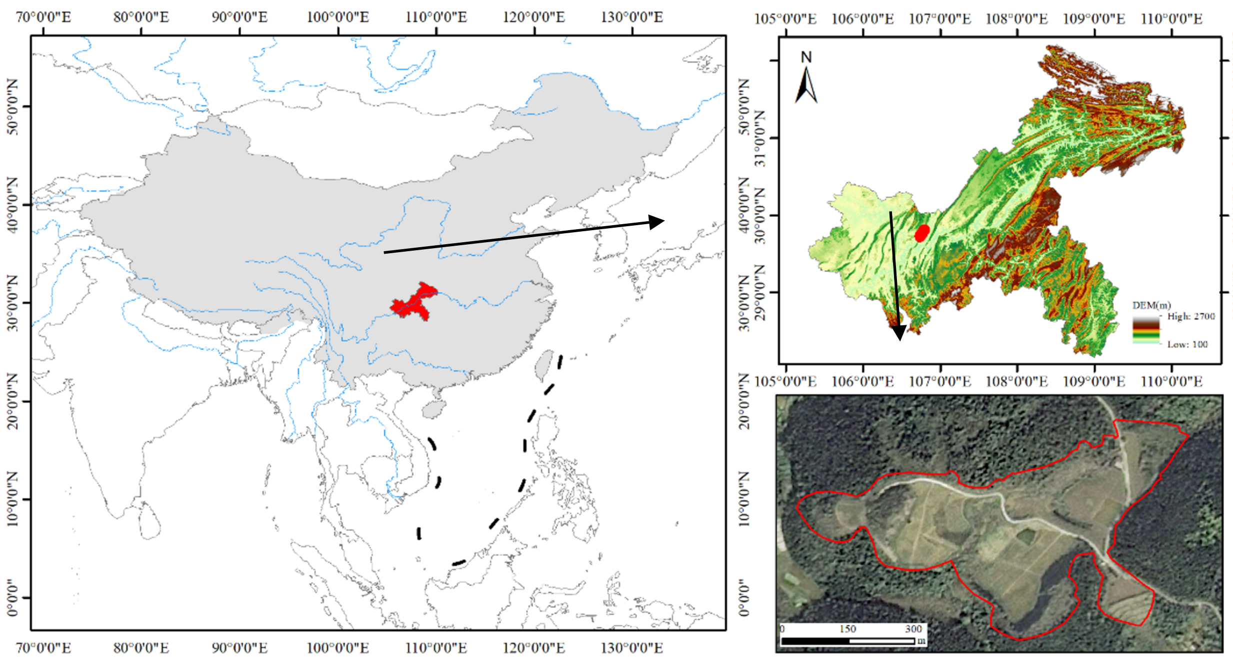

Figure 1. The study area location.

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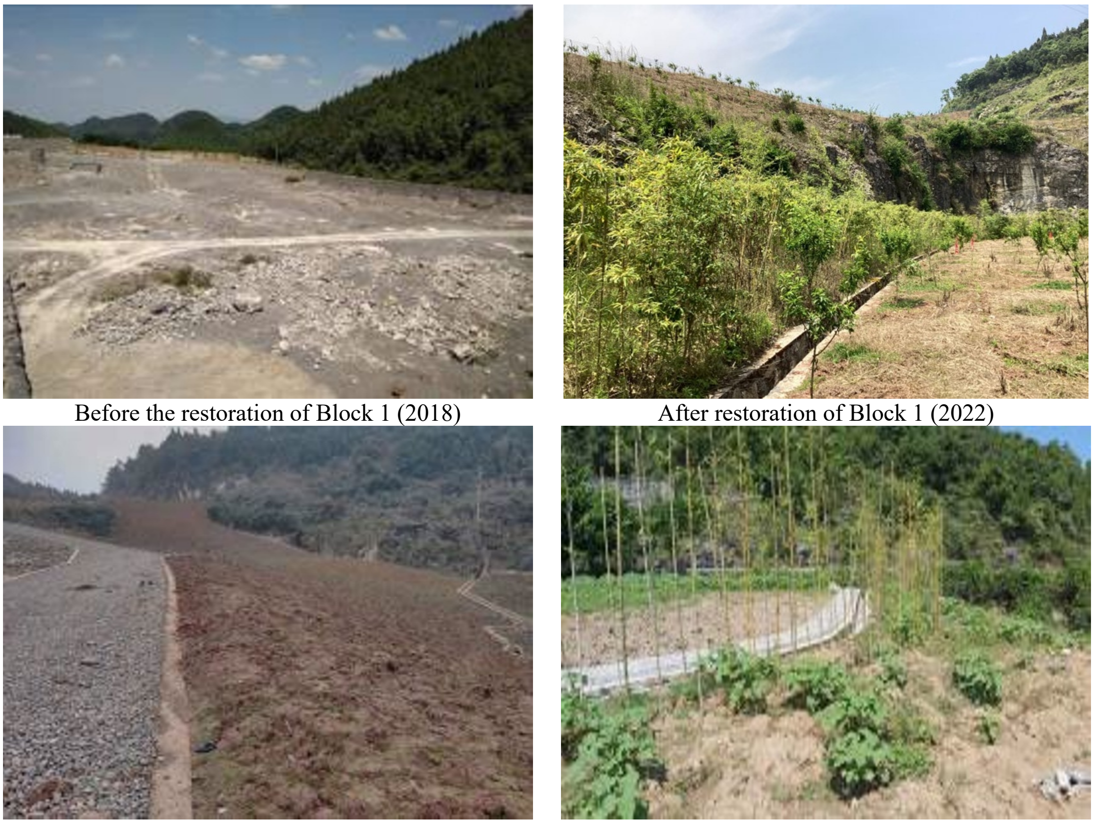

Before the restoration of Block 1 (2018) | After restoration of Block 1 (2022)

Before the restoration of Block 2 (2018) | After restoration of Block 2 (2022)

Figure 2. Comparison before and after ecological restoration in the study area.

2.2 Research Methods

2.2.1 Soil sample collection

Soil layers were divided into 0cm ~ 10cm, 10cm ~ 20cm and 20cm ~ 40cm in the soil sample block of two research block, and stratified sampling was conducted. Soil bulk density and soil moisture content were measured by ring knife method. The soil sample of 500g was directly put into plastic sealing bag by quartering method, numbered and brought back to the room to determine the content of soil organic matter. The content of soil organic matter was determined by potassium dichromate oxidation and external heating method.

2.2.2 Survey and collection of plant samples

In the study area, 10m×10m, 2m×2m and 1m×1m were set up for tree, shrub, and herbaceous block, respectively. The main survey indicators include mean age, mean DBH, mean tree height, origin, main vegetation type and coverage in the lower layer, soil type, geographical location, topography, landform, etc. For shrubs and herbs, the fresh weight of aboveground stems, branches, leaves and underground roots was determined by whole-plant harvesting method, and samples of stems, branches, leaves and roots (300g) were selected and brought back to the laboratory to determine their moisture content and dry matter quality.

2.3 Estimation of plant and soil carbon sinks

2.3.1 Measurement of plant carbon sink

The calculation of plant carbon sink includes the carbon sink of tree layer, shrub layer and herbaceous layer, in which the total carbon storage is the product of the sum of above-ground biomass and subsurface biomass of each layer and its carbon content. The carbon content of tree species was obtained by referring to literature. The default value of carbon content of shrub was 0.4672, and that of herbaceous layer was 0.3270.

$$C_{plants} = \sum_{i=1}^{n}(B_{iup} + B_{idown}) \times CF_i \tag{1}$$

C_{plants} are carbon storage of each layer; B_{iup} is the aboveground biomass of plants in each layer i. $B_{idown}$is the underground biomass of plants in each layer i. n is each layer of plants; CF_i refers to the carbon content of plant i. By consulting the reference value of carbon content of tree species (groups), the default value of carbon content of shrub is 0.4672 and that of herbaceous layer is 0.327.

2.3.2 Measurement of soil carbon sink

The formula for calculating soil organic carbon storage in the study area is as follows:

$$TOC = \sum_{i=1}^{n} A_i \times SOC_i \tag{2}$$

TOC is the soil organic carbon storage in the project area; A_i is the area of the i soil type; SOC_i is the soil organic carbon density of the i soil type, expressed in kg/m^2.

The formula for calculating soil organic carbon density is:

$$SOC = 0.58 \times C_{soil} \times SD \times SH \times \frac{(1-G)}{100} \tag{3}$$

SOC is the organic carbon density of soil (unit: kg/m2); C_{soil} refers to soil organic matter content, unit is g/kg, and its determination shall be carried out in accordance with LY/T 1237; SD is the soil bulk density, the unit is g/m^3, and its determination shall be carried out according to the provisions of NY/T 1121.4; SH is the soil thickness (unit: cm); G is the percentage of the volume of the gravel with a diameter ≥2mm, %.

3 Results and discussion

3.1 Land use type area of the study area

This paper extracts land use and cover in the study area based on the monitoring data of the geographical conditions of the year. Combined with the field investigation, the land use types and areas of the two block are shown in figure 3, including arbor forest land, bamboo forest land, shrub land, grassland and other areas. The ecological carbon sink benefits of this region are high.

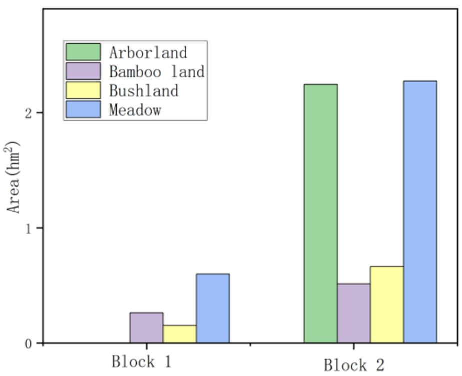

Figure 3. Statistics of plant area in different block.

3.2 Vegetation carbon sink in ecological restoration area

According to the quadrat survey, the main plant species in block 1 were: *corn, plum tree, green bamboo, bougainberry, wild carrot, ponderosa, beef sinew,* and *fragrant aconite,* while the main plant species in block 2 were: *corn, spotted bamboo, yellow kudu tree, cinnamomum camphor tree, bougainberry, artemisia annua, Humulus humulus, wild chrysanthemum, dragon sunflower*, and *Humulus humulus*. The vegetation carbon sink results of the two block were obtained by introducing the carbon density calculation formula. The vegetation carbon sink per unit area was 0.7091 kg C/m^2 and 0.2974 kg C/m^2, respectively, and the total vegetation carbon sink was 27.3768t C and 36.7694t C, respectively (Figure 4).

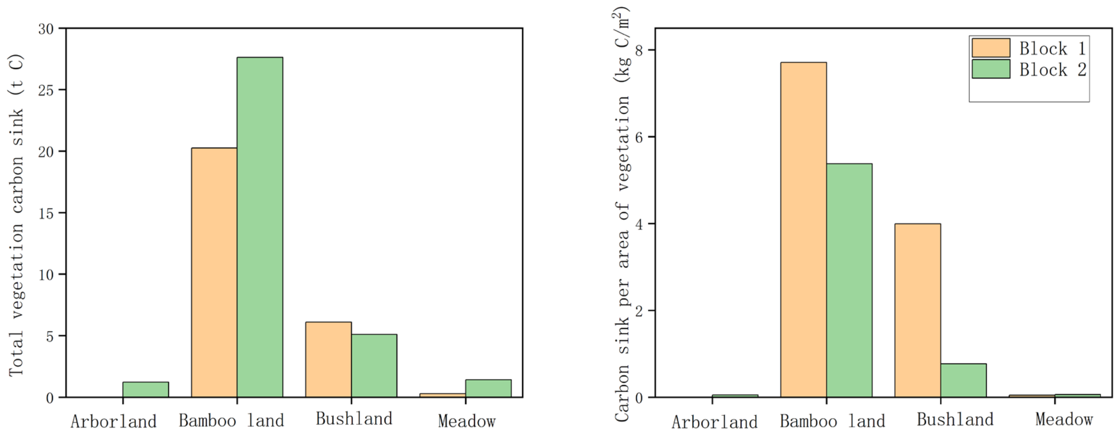

Figure 4. Total and unit carbon sink statistics of plants in different block.

3.3 Soil carbon sink in ecological restoration area

The soil carbon sink per unit area of block 1 and 2 in the study area was 3.6536 C kg/m^2 and 4.3583 C kg/m^2, respectively, and the total soil carbon sink was 141.0628t C and 538.7920t C, respectively (Figure 5).

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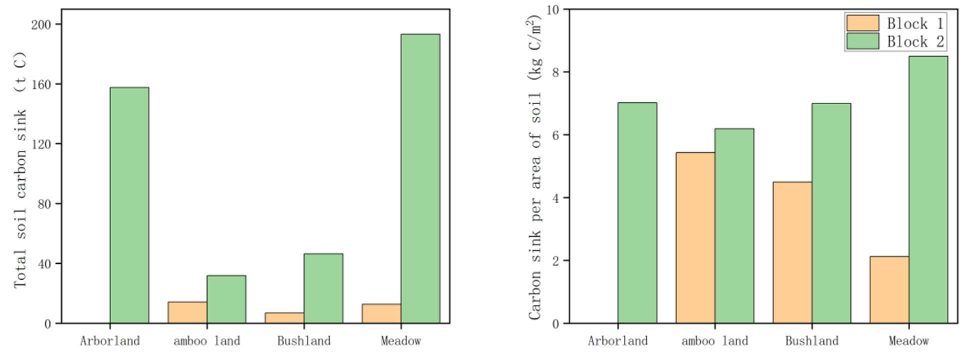

Figure 5. Soil carbon sink statistics of different land use types.

3.4 Ecological restoration plant and soil carbon sink composition

From the perspective of vegetation carbon sink and soil carbon sink, the carbon sink of mine ecological restoration mainly comes from soil carbon sink, and the carbon sink per unit area of soil (4 kg/m^2) is 8 times that of vegetation (0.5 kg/m^2), among which the bamboo forest has a higher carbon sink, accounting for about 38% of the total unit carbon sink (Figure 6).

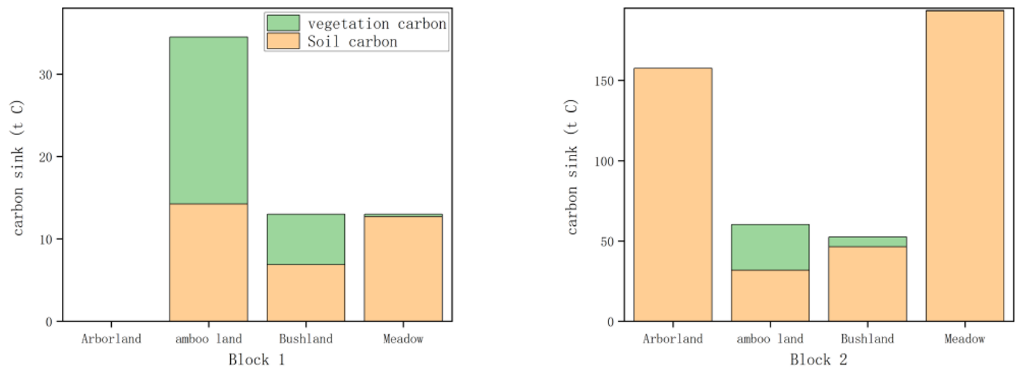

Figure 6. Analysis of carbon sink components in plants and soils.

From the perspective of different land types, farmland carbon sink, forest carbon sink and grassland carbon sink are the main parts of mine ecological restoration carbon sink. For farmland ecosystem, soil organic matter and soil carbon sink are maintained at a high level for a long time due to artificial tillage measures. For forest land, the higher carbon sink is due to the rapid accumulation of vegetation biomass, especially the increase of vegetation carbon density per unit area of bamboo forest land contributes to the higher carbon sink of forest land (Figure 7).

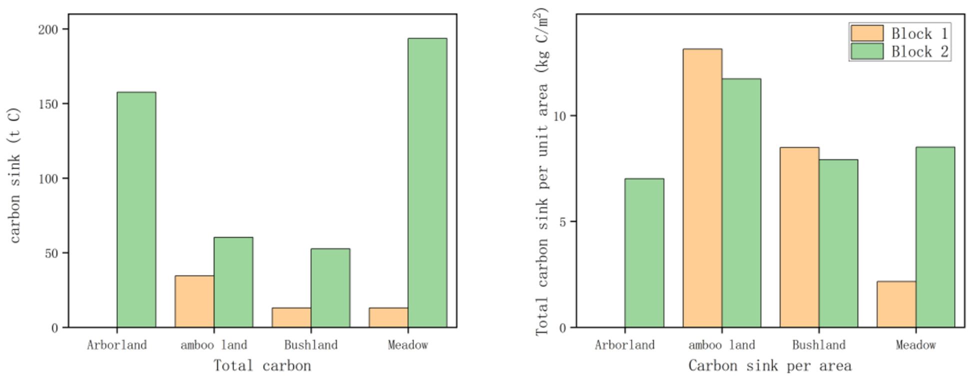

Figure 7. Analysis of total carbon sink and carbon sink per unit area of different land types.

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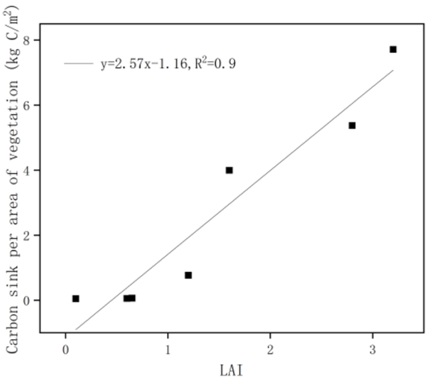

Figure 8. Relationship between Leaf area index and vegetation carbon sink.

3.5 Analysis of influencing factors of carbon sink change in ecological restoration

By analyzing the relationship between multi-stage leaf area index (Leaf area index, LAI) data and vegetation carbon sink, it was found that LAI increased with the increase of ecosystem vegetation. (Figure 8)

Comparative analysis of soil organic carbon, total nitrogen, available potassium, available phosphorus, bulk density, PH and other influencing factors showed that organic matter content, total nitrogen content and available potassium content could effectively improve soil carbon sink, and the increase of available phosphorus, PH and bulk density would inhibit the increase of soil carbon sink (Figure 9).

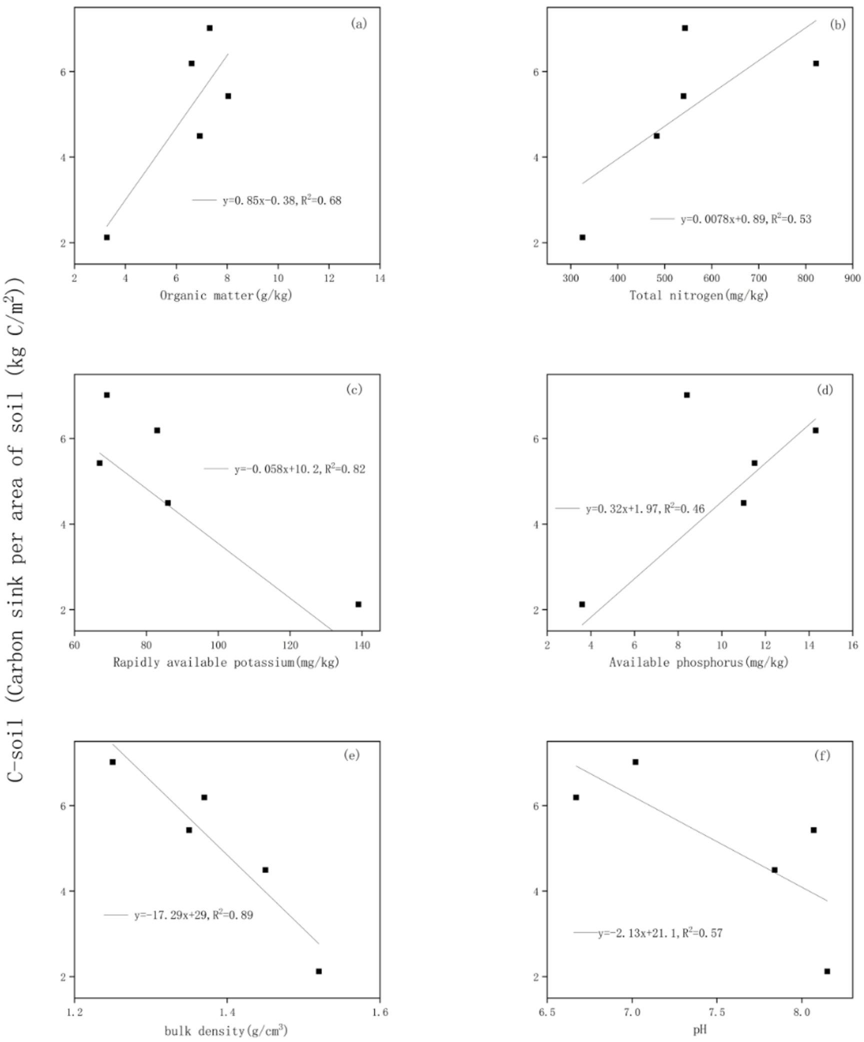

Figure 9. Relationship between soil properties and soil carbon sink.

4 Conclusion

In this study, the carbon sink per unit area (4.65kg C/m^2), soil carbon sink per unit area (4.36 kg C/m^2), total carbon sink (574.39t C), vegetation carbon sink (36.77t C), soil carbon sink (538.79t C) of the two block were higher. However, vegetation carbon sink per unit area was lower (0.29kg C/m^2). The main influencing factors of vegetation carbon sink are vegetation growth, and the main influencing factors of soil carbon sink are soil organic matter and soil fertility.

The carbon sink per unit area of soil (4 kg/m^2) is 8 times that of vegetation (0.5 kg/m^2), but the vegetation carbon sink is higher in bamboo forest, accounting for about 38% of the total carbon sink per unit area. For forest land, the higher carbon sink is due to the rapid accumulation of vegetation biomass. Especially, the increase in vegetation carbon density per unit area of bamboo forest land makes a higher contribution to the carbon sink of forest land. Arbor forest land and bamboo forest land are also the land types with the highest vegetation carbon sink potential. There was little difference between soil carbon sink potential and regional carbon sink potential for all restoration types.

Therefore, in the ecological restoration of abandoned land in open-pit quarry, the regional soil ecological environment can be improved by planting a variety of trees, increasing soil thickness and clay content in soil. In order to avoid the vicious cycle between soil nutrients and soil erosion, it is necessary to strengthen the maintenance of vegetation, increase the thickness of soil layer, plant more local tree species suitable for the local area, such as yellow caraway tree, cinnamomum camphor tree, and increase the proportion of herbaceous plants under the forest.

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References

1. Zhang Chengye, Li Jun, Lei Shaogang et al. Progress and prospect of the quantitative remote sensing for monitoring the Eco-environment in mining area [J]. Metal Mine,2022(3):1-27.
2. Li Fuping, Jia Ganfei, Xia Dong et al. Study status and development trends of ecological restoration techniques in abandoned quarry [J]. Metal Mine,2021(1):168-184.
3. Lei Shaogang, Bian Zhengfu, Yang Yongjun. Discussion on the guided restoration for mine ecosystem [J]. Journal of China Coal Society, 2022,47(2):915-921.
4. Bian Zhengfu, Yu Haochen, Han Xiaotong. Solutions to mine ecological restoration under the context of carbon [J]. Journal of China Coal Society,2022,47(1):449-459.
5. Portela M G T, Espindola G M D, Valladares G S et al. Vegetation biomass and carbon stocks in the Parnaíba River Delta, NE Brazil [J]. Wetlands Ecology and Management, 2020(1):1-16.
6. Yang Yongjun, Zhang Shaoliang, Hou Huping, et al. Resilience mechanism of land ecosystem in mining area based on nonlinear dynamic model [J]. Journal of China Coal Society,2019,44(10):3174-3184.
7. Zhang Peipei, Yu Yang. Effects of coal mining subsidence on soil aggregates and organic carbon [J]. Metal Mine,2020 (12):203-209.
8. Sun J, Wang Y, Lee T M, et al. Nature-based Solutions can help restore degraded grasslands and increase carbon sequestration in the Tibetan Plateau[J]. Communications Earth & Environment, 2024, 5(1): 154.
9. Zhu Y. F., Wang L.P., Ma J., 2024. Assessment of carbon sequestration potential of mining areas under ecological restoration in China. Sci Total Environ 921, 171179.
10. Bai, Z.; Zhang, D.; Wang, Z.; Harrison, M. T.; Liu, K.; Song, Z.; Chen, F.; Yin, X. Challenges and strategies in estimating soil organic carbon for multi-cropping systems: a review. Carbon Footprints. 2024, 3, 19. http://dx.doi.org/10.20517/cf.2024.15.
11. Ma Xuewei. Carbon Storage Features of High-efficiency Characteristic Forests and Carbon Sequestration Forestry Cultivation Techniques in the Karst Rocky Desertification Areas [D]. Guiyang:Guizhou Normal University,2020.
12. Guan, D.; Nie, J.; Zhou, L.; Chang, Q.; Cao, J. How to Simulate Carbon Sequestration Potential of Forest Vegetation? A Forest Carbon Sequestration Model across a Typical Mountain City in China. Remote Sens. 2023, 15, 5096.
13. Pan Ye, Zhang Yan. Ecological restoration of abandoned lands of mines - benefit evaluation research in nanjing shogun mountain, for example [J]. Journal of soil and water conservation in China, 2016 (5) :61-65.
14. Lei Min, Cao Mingming, Xi Jing. Comprehensive benefit evaluation and policy orientation of returning farmland to forests in Mizhi County [J]. Soil and Water Conservation Bulletin, 2007 (03): 151-156.(b).
15. Wu Houjian, Wang Xuelei. Research progress on the evaluation of wetland ecological restoration effectiveness in China [J]. Wetland Science, 2006 (04): 304 310.
16. Xiang Wusheng, Li Xiankun, He Chengxin, et al. Evaluation of the composite ecosystem of rocky desertification mountainous areas: A case study of the Longhetun Ecological Reconstruction Demonstration

Zone in Pingguo County, Guangxi [J]. Resources and Environment of the Yangtze River Basin, 2007 (06): 826-830.

17. Yang Zifeng, Yu Xingxiu, Ma Qian. Discussion on the Evaluation of Ecological Restoration Benefits of Soil and Water Conservation [J]. Soil and Water Conservation Research, 2006 (06): 175-177,181.
18. Lin Jiquan, Wang Boduo, Ma Junjie, et al. Study on the comprehensive evaluation index system of environmental quality for small watershed management [J]. Soil and Water Conservation Research, 2005 (01): 69-71.
19. Zhang Heyu, Peng Peng, Xiao Wu, et al. Evaluation of Ecological Environment Status in Mining Areas Based on AHP and GIS [J]. Coal Science and Technology, 2008 (09): 102-105.
20. Wu Dandan, Cai Yunlong. A review of the evaluation of ecological restoration effects in China [J]. Progress in Geographic Science, 2009,28 (04): 622-628.
21. Yuan Y, Zhao Y, Gao Y, et al. The effect of tree species on soil organic carbon recovery in a restoration project is associated with vegetation biomass: Evidence from the **shuo Mine reclaimed ecosystem, North China [J]. Land Degradation & Development, 2022, 33(18): 3870-3881.
22. Chen F, Zhu Y, Bi Y, et al. High-priority actions to improve carbon sequestration potential for mining ecological restoration in China[J]. Engineering, 2024.