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A study of sustainable design for abandoned coal mines' ecological remediation

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Abstract. To explore ecological remediation plans for abandoned coal mines in line with the sustainable development perspective, this paper, based on the sustainable development theory, sets Wangshi'ao coal mine as an example and studies application models and ecological elements allocations of abandoned coal mines' ecological remediation. Through investigations and calculations, this paper finds out that in ecologically remediating abandoned coal mines, sustainable designs can facilitate abandoned coal mines evolving into zonal nature ecosystem and accelerate nutrient accumulation of abandoned soil, which can improve abandoned coal mines' ecosystem services value. Research results can provide references to studies on theory and practice of ecological remediation planning and design of abandoned coal mines.

Key words. Abandoned coal mine, ecological remediation, sustainable design, Wangshi'ao coal mine.

1. Introduction

Coal is the largest and most widely distributed conventional energy in the world, accounting for 25 % of the world's primary energy consumption. For a long time, coal mining has been damaging the original ecosystem stability and natural landscape homogeneity, which leads to environmental degradation and lots of abandoned coal mines. Abandoned coal mines refer to lands that are damaged and cannot be used without remediation because of the exploitation of coal resources. After mining for a long time, abandoned coal mines will re-pollute and destroy the surrounding environment through dust, collapse, landslide and erosion, which will further deteriorate the surrounding environment [1].

Environmental hazards and social contradictions caused by coal mining have attracted wide attention. Long before World War II, in the mining areas, the United States and some developed countries had begun ecological remediation after mining. For example, in 1920s, the United States conducted re-planting experiment in Indi-

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ana's coal gangues and German afforested the Lignite mine in open pit coal mine etc. China's ecological remediation of abandoned coal mines embarked on a legal track in the late 1980s, beginning an organized land reclamation stage, such as land reclamation in Huaibei coal mine subsidence area in Anhui province. At present, with the development of world economy and coal industry, abandoned coal mines' ecological remediation has become a serious problem, waiting to be solved during social and economic development.

2. Literature review

Recently, domestic and foreign scholars have conducted massive researches on ecological remediation in coal mine areas. Coal mines' ecological remediation refer to comprehensive restore surface damage caused by coal resources mining, and improve ecological system's structure and function in the coal mine area, so that the ecosystem can maintain itself and reach a new ecological balance. Because of long-term coal mining and grazing activities, similarities between remediation areas' soil seed bank and nearby control mountain's surface vegetation are relatively high [2], so using these indigenous species to ecologically remediate abandoned lands in coal mines can reduce costs and avoid ecological risks associated with non-native species [3]. In coal mining areas, there is a correlation between plant species' diversity and soil's physical and chemical properties [4], and different tree species have varying functions in improving rhizosphere soil quality, which provides an important basis for selecting suitable tree species used for ecological remediation in abandoned coal mine areas [5].

Compared with undisturbed soil, after coal mining and soil reclamation, soil's microbial diversity and biomass decrease significantly [6]. To promote soil amelioration and comprehensive land management in abandoned coal mines, there have been massive studies in spatial distribution and variation characteristics of soil heavy metals in abandoned coal mines [7], soil reconstruction, fertility management and microbial flora regulation in reclamation and ecological remediation of abandoned coal mines [8], and soil's physical and chemical properties changes in abandoned coal mines under different remediation modes [9], results from which provide scientific basis for vegetation restoration in abandoned coal mines.

Existing studies are focusing on plant species preference and soil matrix improvement, and the planning and design practice of abandoned coal mines' ecological remediation have not been widely touched upon, which results in demonstration projects' lead and radiation. Therefore, this paper applies the sustainable design concept to abandoned coal mines' ecological remediation, and combines practice procedures in ecologically remediating Wangshi'ao coal mine to the sustainable design model and its application rules in ecologically remediating abandoned coal mines.

3. Research methodology

Sustainable design, based on ecology, builds a sustainable ecological structure suitable for a variety of environments by following the natural patterns of development. In recent years, sustainable design has gradually been applied to agricultural park planning, urban and rural landscape planning and other fields, which proves its certain universality.

Sustainable design, which takes natural aesthetics as the standard, relies on ecosystem's self-succession and is supplemented by artificial remediation methods, is the integration of artificial restoration and natural restoration mode, with the premise of no large-scale engineering remediation for constructing abandoned coal mines' ecosystem. From the perspective of ecological ethics, sustainable design belongs to an alternative theory of abandoned coal mines' ecological remediation, and has a set of sustainable ecological design concepts.

In accordance with labor intensity or frequency of visits, sustainable design, from the inside to the outside, zones abandoned coal mining areas into five parts (as shown is Fig. 1). Selecting diversified species is to increase niche by vertical planting, marginal cultivation and other models; the disposition of biological elements is dominated by perennial plants, considering the functional diversity of each organism and the functional synergy between organisms.

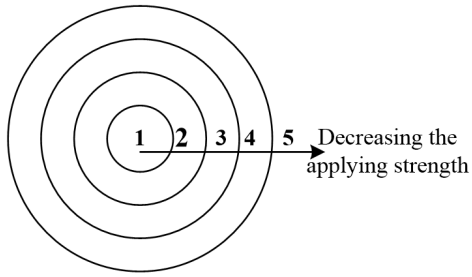

Fig. 1. Sustainable design's zoning plan

Sustainable design emphasizes the use of parks, lawns, residential areas, roads, and other marginal areas as well as not reasonably utilized open lands for growing grain crops with landscape function. It also focuses on organic combination of production, living elements and biological elements.

The value orientation of sustainable design advocates harmonious development of man and nature, with ecological perspective to observe things, which reflects sustainable development concepts, that is people's demands are fundamental and the needs of people for the people, and symbiosis between man and nature. It can promote the transformation and upgrading of traditional culture to ecological culture.

4. The application of sustainable design in abandoned coal mine's ecological remediation

Wangshi'ao coal mine locates in 12.5 kilometers east suburb of Tongchuan city in Shaanxi Province, which is one of the 156 key projects built by the Soviet Union during the first Five-Year-Plan. It started construction in December 1957 and applied into use in November 1960 with an annual production capacity of 120 tons, the largest mechanized shaft in Northwest China at that time. The rise and fall of Wangshi'ao coal mine is a microcosm of the development of China's coal industry.

4.1. The application model of sustainable design

Planning according to different zones. In practice, sustainable design does not concern every zone, and each zone are not divided equally from the inside to the outside area. According to Wangshi'ao coal mine's location, surrounding environment and the intensity of land use, it is divided into four zones from the inside to the outside (as shown in Fig. 2). The first zone is the main area for people's activities, so it requires the most amount of energy and management. From the first zone to the fourth zone, the biological elements gradually decrease so there are different ecological construction goals, which means the time for management and maintenance is gradually reduced. The planning principle for each zone can be seen in Table 1.

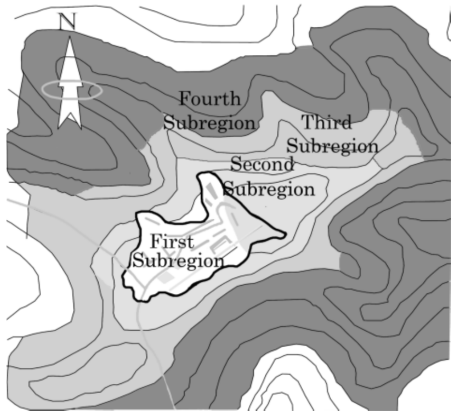

Fig. 2. Zoning diagram of the ecological restoration in Wangshi'ao coal mine

Sector analysis. Sustainable design focuses on the application of natural energy flow patterns, creating a regional microclimate environment by human, as shown in Fig. 3. In Wangshi'ao coal mine, a low water tank is at the southwest side in the first zone, connecting with drains in other zones, which can cool the hot air from the southwest during summer; there is a degradation tank in the shade at the second zone and a firewood storing area at the sun exposure area; a hedge is set at northeast side of the fourth zone to fend off dry and cold monsoon during winter, etc.

Cyclic layout. Sustainable design emphasizes zoning across areas and mobilizing ecological elements as much as possible to participate in material recycling. Wang-

shi'ao coal mine ecosystem makes full use of the symbiotic relationship between animals and plants, forming the industrial chain of material recycling as shown in Fig. 4. In addition, drains are excavated from natural gullies in each zone. During the rainy season, surface water, through the third zone, is injected into catchments in the second or even the first zones, which can be served as breeding grounds for aquatic animals and plants or used for irrigation.

Table 1. Principle of zoning plan of the ecological restoration in Wangshi'ao coal mine

Subregion	Construction objectives	Visiting frequency
1	Industrial heritage tourism area, ecological vegetable garden	Several times per day
2	Food forest, orchard, fowl	Daily
3	Grain crops, Chinese herbal medicines	Once every several days
4	Gullies, forested area, steppe area	Once every several weeks

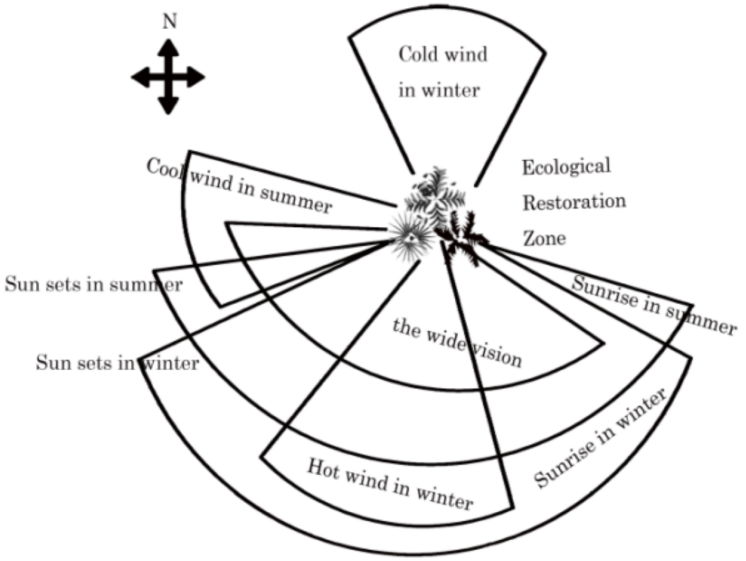

Fig. 3. Sector analysis of sustainable design

4.2. Configuration of biological elements in sustainable design

Creating niche. In the first zone of Wangshi'so coal mine, we plant ornamental fruits and vegetables in marginal areas at sides of the pond, near the building, and along the path, achieving ecosystem stability through plant density and biodiversity.

A mixture of apple, cherry, walnut and other economic forest is planted in the second zone with beans, peppers and potatoes scattered among them and the lowest layer is strawberries, vegetables, mint and other low plants to construct an uneven and spreading plant forest.

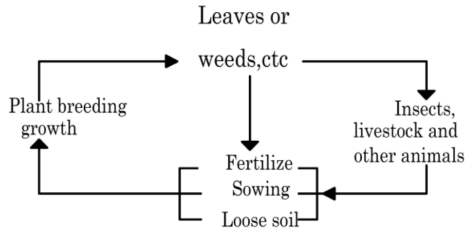

Fig. 4. Material cyclic use layout in sustainable design

Prioritizing local plants. Local perennial plants are preferred in sustainable design, and grain and forage crops such as wheat, rape, alfalfa etc. are planted at the third zone with cumin, pepper, dandelion and other spices scattered among them. In the fourth zone, there are natural secondary forest of Pinus, poplar, oak etc. and wild herbs including bupleurum, forsythia, rhizoma atractylodis, scutellaria etc. In addition, temperate deciduous broad-leaved forest mixes with grasses and shrubs, within which there are small animal groups of partridge, pheasant, deer and sheep etc.

Utilizing Synergistic relations between biological elements. At the first zone of Wangshi'ao coal mine, vines are planted among rose plants where vine roots absorb chemical material released from roses roots to fend off pest white flies; clover and other nitrogen fixing and cold resistant species are planted in the grassland; under fruit trees, there grow vegetables, such as legumes and peppers for nitrogen fixation and pest control and at the edge area there are beekeeping farms and small dairy farms, etc.

4.3. Measurement of ecosystem service value in Wangshi'ao coal mine

To evaluate the application of sustainable design in abandoned coal mines' ecological remediation, it is necessary to estimate the value of ecosystem services in Wangshi'ao coal mine in recent years and understand its trend of change.

The ecosystem types in Wangshi'ao coal mine are mainly forest, farmland and grassland. The ecological function service types are food production, material supply, gas regulation, climatic regulation, water conservation, soil protection and waste treatment and biodiversity as well as entertainment culture [10]. In the ecosystem of Wangshi'ao Coal Mine, the calculation formula of production service value of food produced by per hectare of the farmland ecosystem is [11]

$$V_{\mathrm{e}} = \frac{1}{7}\sum_{j=1}^{n}\frac{A_j P_j Y_j}{T}, \quad j = 1, 2, 3, \cdots, n\,. \tag{1}$$

In formula (1), V_e denotes the service value of food produced by per hectare of the farmland ecosystem, yuan/hm^2, A_j is the planted area of the grain crop j in the farmland ecosystem, P_j is the national average price within the calculation period of the grain crop j, yuan/t, Y_j is the yield of the grain crop j, t/hm^2, T is the total area of the grain crop n, hm^2. 1/7 is the ecological function service value that the farmland ecosystem can offer under natural conditions with human factor intervention fully eliminated. The crops of the farmland ecosystem in Wangshi'ao coal mine are wheat, corn and rapeseeds (Table 2).

Table 2. Crop planting in the farmland ecosystem of Wangshi'ao coal mine

	Name	2014	2015	2016
Planted area (hm^2)	Wheat	26	31	36
	Corn	17	25	25
	Rapeseed	9	13	27
	Total	52	69	88
Yield per unit (t/hm^2)	Wheat	2.15	2.29	2.55
	Corn	3.16	3.50	3.78
	Rapeseed	0.98	1.39	1.35
Unit price (yuan/t)	Wheat	2.507	2.513	2.360
	Corn	2.243	2.241	1.903
	Rapeseed	5.080	3.726	3.910

Note: the data is available from the Propaganda Department of Wangshi'ao Coal Mine, Yearbook of Tongling City and www.cngrain.cn.

According to formula (1), it was calculated that the service values of food produced by per hectare of the farmland ecosystem in Wangshi'ao coal mine ecosystem during 2014–2016 were 839.12 yuan/hm^2, 914.73 yuan/hm^2 and 875 yuan/hm^2.

According to the Unit Area Ecological Service Value Equivalent Scale of Terrestrial Ecosystem in China of the scholars XIE Gaodi et al., the unit area ecological service value equivalent scale of Wangshi'ao coal mine ecosystem was obtained (Table 3). According to formula (2) below, the ecological service value per hectare of the ecosystem types in Wangshi'ao coal mine was calculated (Table 4).

$$V_{mi} = c_{mi} V_e \,. \tag{2}$$

Here, V_{mi} is the value of the type m ecological service provided by per hectare of type i ecosystem, yuan/hm^2, c_{mi} is the coefficient of value equivalent of the type m ecological service provided by per hectare of type i ecosystem versus the functional service of food produced by per hectare of the farmland ecosystem; V_e is the service value of food produced by per hectare of the farmland ecosystem, yuan/hm^2.

According to the area of ecosystems in Wangshi'ao coal mine (Table 5) and based on the annual ecosystem service value in Table 4, the ecological service function values of ecosystems in Wangshi'ao coal mine could be calculated (Table 6).

Table 3. Unit area ecological service value equivalent scale of Wangshi'ao coal mine ecosystem

	Forest	Grassland	Farmland
Food production	0.1	0.3	1
Material supply	2.6	0.05	0.1
Gas regulation	3.5	0.8	0.5
Climatic regulation	2.7	0.9	0.89
Water conservation	3.2	0.8	0.6
Soil protection	3.9	1.95	1.46
Waste treatment	1.31	1.31	1.64
Biodiversity protection	3.26	1.09	0.71
Entertainment culture	1.28	0.04	0.01

Table 4. Ecological service value per-hectare of Wangshi'ao coal mine ecosystem from 2014 to 2016

	Forest	Grassland	Farmland
Food production	0.1	0.3	1
Material supply	2.6	0.05	0.1
Gas regulation	3.5	0.8	0.5
Climatic regulation	2.7	0.9	0.89
Water conservation	3.2	0.8	0.6
Soil protection	3.9	1.95	1.46
Waste treatment	1.31	1.31	1.64
Biodiversity protection	3.26	1.09	0.71
Entertainment culture	1.28	0.04	0.01

5. Discussion

Combined with the ecological remediation of Wangshi'ao coal mine and calculation results of its ecosystem's service function value, it is found that the main roles of sustainable design in abandoned coal mines' ecological remediation are as follows.

5.1. Promoting the remediation of abandoned coal mines' biodiversity to achieve evolution to regional natural ecological systems

Sustainable design establishes a pioneer plant community by simulating natural ecosystems and maximizing the use of resources and topographic conditions in abandoned coal mines. With successive regional species' invasion, abandoned coal mines have more similarities with regional natural ecosystem, along which there are improvements in ecological system's self-maintenance ability, stability, ecological carrying capacity and anti-risk ability.

Table 4. Ecological service value per-hectare of Wangshi'ao coal mine ecosystem 2014 to 2016

	2014			2015			2016		
	Forest	Grass-land	Farm-land	Forest	Grass-land	Farm-land	Forest	Grass-land	Farm-land
Food pro-duc-tion	83.91	251.73	839.12	91.47	274.42	914.73	87.5	262.5	875.00
Material supply	2181.71	41.96	83.91	2378.30	45.74	91.47	2275	43.75	87.50
Gas regula-tion	2936.92	671.30	419.56	3201.56	731.78	457.37	3062.5	700	437.50
Climatic regula-tion	2265.62	755.21	746.82	2469.77	823.26	814.11	2362.5	787.5	778.75
Water conser-vation	2685.18	671.30	503.47	2927.14	731.78	548.84	2800	700	525.00
Soil protec-tion	3272.57	1636.28	1225.12	3567.45	1783.72	1335.51	3412.5	1706.25	1277.50
Waste treat-ment	1099.25	1099.25	1376.16	1198.30	1198.30	1500.16	1146.3	1146.25	1435.00
Biodi-versity	2735.53	914.64	595.78	2982.02	997.06	649.46	2852.5	953.75	621.25
Enter-tain-ment culture	1074.07	33.56	8.39	1170.85	36.59	9.15	1120	35	8.75
Total	18334.76	6075.23	5798.33	19986.86	6622.65	6320.8	19118.8	6335	6046.25

Table 5. Land use area of the ecosystems in Wangshi'ao coal mine from 2014 to 2016, hm^2

	2014	2015	2016
Forest	62	70	84
Grassland	76	89	113
Farmland	57	73	91

5.2. Speeding up the accumulation of soil nutrients in abandoned coal mines and promoting ecological remediation systems integrating into biogeochemical cycles

Each zone of derelict land in the Wangshi'ao coal mine grows clover, soybean, locust tree, sea-buckthorn, oleaster, lespedeza, and other nitrogen fixing plants, while animal manure, leaves, straw and alfalfa are good sources for soil nutrients such as nitrogen, phosphorus, potassium, calcium, iron, magnesium and zinc. Sustainable

design is to promote abandoned coal mines' ecosystem to integrate with biogeochemical cycles by means of nutrient retention and loss, and organic matter synthesis and degradation.

Table 6. Ecological service value of the ecosystems in Wangshi'ao coal mine from 2014 to 2016

	2014	2015	2016
Forest ecosystem	1.14×10^6 (59%)	1.40×10^6 (57%)	1.61×10^6 (56%)
Grassland ecosystem	0.46×10^6 (24%)	0.59×10^6 (24%)	0.72×10^6 (25%)
Farmland ecosystem	0.33×10^6 (17%)	0.46×10^6 (19%)	0.55×10^6 (19%)
Total value of biological services	1.93×10^6 (100%)	2.45×10^6 (100%)	2.88×10^6 (100%)

5.3. Enhancing abandoned coal mines' ecosystem service function value and speeding up the ecological balance construction

The ecosystem service value of Wangshi'ao coal mine shows an increasing trend year by year. Although the annual increment is very low, each ecosystem function service value basically maintains balanced change condition, which means that sustainable design can help maintain a relatively stable change in species composition and proportion of ecosystems, and promote the ecosystem to move towards dynamic equilibrium.

5.4. 5.4 Promoting the coordinated development of ecological, economic and social subsystems in abandoned coal mines

While constructing ecosystem, sustainable design also considers planting agricultural plants with edible and landscape functions, and taps coal mines' social and cultural values to incorporate abandoned coal mines' ecology, economy and social elements into one ecosystem and promote coordinated development among abandoned coal mines' subsystems: ecology, economy and society.

6. Conclusion

To explore ecological remediation plans for abandoned coal mines in line with the sustainable development perspective, this paper, based on the sustainable development theory, analyzes ecological remediation patterns for abandoned coal mines and configuration of ecological elements. This paper finds that sustainable design has four stages in abandoned coal mines' ecological remediation. The first is to establish a diversified pioneer plant community, promoting abandoned coal mines to evolve into regional natural ecological systems. The second is to accelerate soil nutrients' accumulation in abandoned lands by using biological elements. The third is to enhance abandoned coal mines' ecosystem service function value, and promote sustainable development of ecosystems' structure and function. The fourth is to incorporate economic and social elements into ecological remediation and promote

coordinated development among abandoned coal mines' subsystems: ecology, economy and society.

Up to now, there is no universal evaluation system for ecosystem services value [12], and the ecosystem services value per unit area is affected by its biomass and its spatial location [13]. Those uncertainties will lead to calculating deviations of ecosystem's service function, influence environmental economic accounting of abandoned coal mines, and increase difficulties in controlling abandoned coal mines' ecological mechanism and ecological function zoning.

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