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Ecological rebuilding and land reclamation in surface mines in Shanxi Province, China

MIAO Ze-wei[1], BAI Zhong-ke[2], GAO Lin[1]

(1. Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China; E-mail: miaozewei@yahoo.com; 2. Department of Soil Science, Shanxi Agricultural University Taigu, 030801, China)

Abstract: It is well known that the mining industry produces a large amount of derelict land, and causes pollution of water loss and soil erosion as well as other environmental damage in China. As land is under pressure in China, it is now policy to restore or reclaim land despoiled by mining, the aim being to develop sustainable and healthy arable land ecosystems. This paper outlines the principles and approaches of ecological restoration, which have been adopted in Shanxi Province with reference to three typical surface mines. In the research, the principles of ecological engineering and ecological succession are considered as the critical theories of ecological restoration in mine degraded land. Meanwhile, the paper made a comparative research on main links of ecological rebuilding in three surface mines in Shanxi Province, which include new land construction, treatment of toxic substances, control of soil erosion, fertility management, irrigation, ecological planning and the establishment of legislation systems. As the research demonstrated, for successful restoration, new land construction is the fundamental framework, but it must be integrated with ecological engineering including ecological planning, the control of soil erosion and vegetation establishment and ecosystem creation in order to optimise land productivity and soil fertility. In addition, the establishment of the legislation systems and organization of administration are also indispensable aspects of ecological rebuilding in mined land.

Key words: ecological restoration; land reclamation; open-pit mine

Introduction

As a principle supplier of raw materials, th mining industry in China must increase its output to meet the ever-increasing demands for economic development and people′s expectations. However, a by-product of increased mining activity will be an increase in the amount of despoiled land. In China, land degraded by human activity amounts to about 3.3 million hm^2, and is growing at an unprecedented rate of 0.14 million hm^2 annually. The estimate for wetland produced in China by coal mining activities alone is ca. 20000 hm^2 every year, and is expected to exceed 33000 hm^2 annually by the end of this century. The waste land produces different types of despoiled land: stripped areas (59%), open-pit mines (20%), tailing dam (13%), waste tips (5%), and land affected by mining subsidence (3%). During surface mining, 2—11 times more land is destroyed compared to of that of underground mining. Some destruction of land by mining is inevitable even though the best pre-mining planning and land reclamation practices are undertaken.

These operations transfer fertile, cultivated land into wasteland or bog, and causes serious environmental pollution of land, air and water. The local status of water and landscape deteriorates, and some ecosystems will be totally destroyed. Recently, rapid advances in land reclamation have been made in China. By 1994 almost 400000 hm^2 had been rehabilitated throughout China, which is 13% of the total land area (3 million hm^2). Whilst this is an impressive achievement, clearly there is a large, and increasing, area of land which needs to be restored. Moreover, the quality of reclamation varies from region to region and mine to mine (Ma, 1995; Lin, 1998, Miao, 1997). In China, many papers and books on ecological restoration in mined land were published, which cover eco-planning, landscape design, institution construction, land reclamation and afforestation technologies in mine abandoned land (Zhao, 1993; Li, 1996; Miao, 1997; Qin, 1997, Ma, 1995). Other countries including America, British, Germany, Canada, France and so on also established a strict and perfect legislation and policy systems in

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ecological planning, design, ecosystems reconstruction and management as well as system evaluation(Marrs, 1993; Christensens, 1996; Dumker, 1992; Barnhisel, 1992; Kelliher, 1987). Much monograph on theory of ecological succession in degraded ecosystem studies was published as well(Bryan, 1984; Mitchell, 1997). To speak of, Australia's environmental protection agency had achieved environmental management in mining of world standard for effectiveness and efficiency. They issued a series of books and published lots of papers on ecosystems rebuilding in mined land. It is well known that the best practice modules, which were praised internaitonally, integrated environmental issues and community through all phases mining from exploration through construction, operation and eventual closure and began to be extended in the world.

The aim of this paper is to investigate the processes and driving mechanisms of ecological restoration of land affected by mining activities in the semi-arid(Shanxi Province) of Northern China so that best practice can be identified and used to guide future practice. Attention will be focused on methods to alleviate or eliminate damage, and to restore the soil fertility to provide sustainable production, which may even exceed pre-mining levels.

1 The theories and practicalities of ecological restoration and land reclamation

1.1 The practicalities of the respiration process

Although reclaimed mined land can support a variety of uses, the most common land use objectives in China are agriculture and forestry. It has been estimated that agriculture and forestry were suitable land use options on 2.7 million hm^2 of land or 80% of the total despoiled land. However, to achieve ecological restoration on such a large scale is a complex process and requires co-operation form a wide variety of organizations and professionals. Government at all levels must be involved and partnerships, which include engineers, landscape architects, soil scientists, agronomists, ecologists, and soil scientists, are needed(Kelliher, 1987). Moreover, it is also important to involve the local people who live in the areas surrounding the mines. This approach has just started to be initiated in China. Clearly the rehabilitation of mine wasteland is a complex process and ideally there should be an integrated planning, mining and restoration process (Christennsen, 1996; Qin, 1997). Some of the main linkages are illustrated in Fig. 1, emphasizing the complex relationship between the different disciplines. The key procedures in agro-ecological rehabilitation comprise:(1) new land reconstruction including backfilling the mines and dressing the surface with soil forming materials such as loess, (2) amelioration of soil toxicity, (3) irrigation engineering, and (4) biological restoration, which might screening of crop varieties, improving crop cultivation, and agro-ecosystem management, including integrated pest management. However, these are technical operations and we integrate them into a much wider restoration strategy. Central to this is the formation of a leadership group who administrate all aspects of the restoration process, including the optimization of decision making and strategies. This group must take into account governmental legislation and the public perception of the individual restoration projects(Dumker, 1992; Vastag, 1996). This may require the provision of education and promotional material as well as the establishment of horticultural training schemes. They also establish and strictly enforce appropriate legislation. We have found that successful schemes involve local people as partners, especially the women, in rural areas. Their involvement mobilizes the entire household(including husbands and children) in agricultural production, but also give added value to the economy as a result of sideline businesses, which increase the ecosystem's productivity.

The social, ecological and economic benefits of restored ecosystems are very high. From 1987 to 1996, a case study of ecological reconstruction was implemented in a pilot area at Antaibao Mine on an area of 430 hm^2. Average cost of land reclamation is as high as 1450 US \$ $h^{-1}m^2$, which was

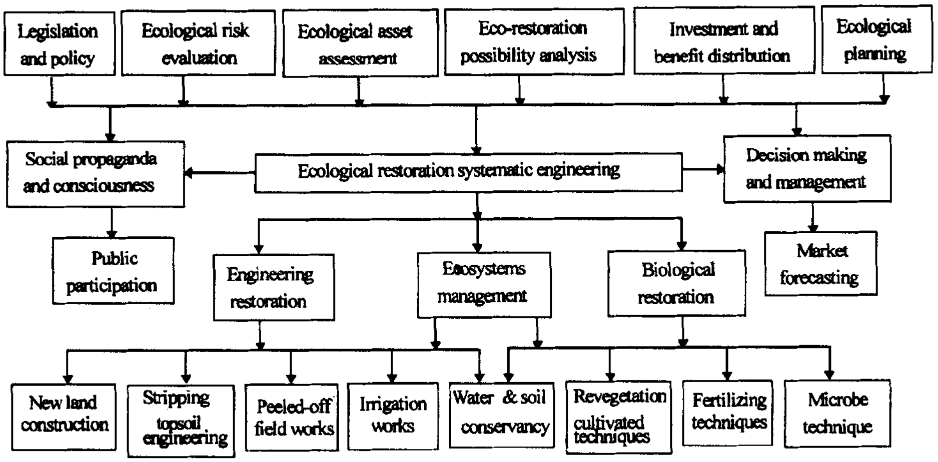

Fig. 1 The approaches and process of ecological restoration systematic engineering in mine in China

funded by the Antaibao Coal Mine. Table 1 shows the costs and benefits of ecological restoration. The economic benefit reached to 59 US $ after 5—6 year forage crop reclamation. If other crops such as *Avena nuda L*. (Naked oat), *Setaria italica* (*L*.) *Beauv*. (Foxtail Millet), *Solanum tuberosum L*. (Potato) and *Zea mays L*. (Maize), replaced forage crops, benefits could probably be greater. The land reclamation cost is mainly due to the costs of capital and materials, which include manure input and machinery. Although its economic benefits is not very high, its ecological benefit is very significant. The vegetation cover increased from 10%—30% to 60%— 80% water run-off was decreased from 45%—60% to 5%—10%, and the soil organic matter content was increased threefold, from 3% to 9%. The forage yield reached more than 4500kgh^{-1}m^{2}, crop yield increased from 103—106 to 1517—5535kgh^{-1}m^{2} (Table 2). Within 10 years the productivity of the restored ecosystem on this degraded mine spoils already exceeded that of the original ecosystems and had become much more sustainable in terms of water and nutrient conservation.

Table 1 Input-output analysis of restored herb ecosystem per hectare at Antaibao Mine(Li, 1996)

Items	Unit	1st year	2nd year	3rd year	4th year	5—6th years
Total input	RMB Yuan	332	480	636	636	636
Mateiral input	RMB Yaun	200	120	120	120	120
Labour	Workday	11	30	43	43	43
Input	RMB Yuan	132	360	516	516	516
Management fee harvest and transportation	Workday	10	10	14	14	14
Other	Workday	1	1	1	1	1
Output	RMB Yuan	666	900	990	1080	
Net output	RMB Yuan	186	264	354	444	
Soil conservation benifit	RMB Yuan	40	40	40	40	
Net benefit	RMB Yuan	−332	226	304	394	484

* The out of herbage production reaches to 3.7, 5.0, 6.0 and 6.0 th^{-1}m^{2} respectively with the price of 180 RMB Yuan per ton

Table 2 The ecological and social benefit of 9-year old restored herb ecosystems in degrade land(Ma, 1995)

Items	Local fragile ecosystems	Degraded ecosystem before restoration	Restored ecosystem for 9 years
Percentage of vagetative coverage, %	10—30	<10	60—80
Coefficient of run-off, %	10—15	45—60	5—10
Organic matter, mg/kg soil	6.0—10.0	3	8.8—9.3
Crop yield, kgh^{-1}m^2	690—1125	103—168	1517—5535
Herbage dry yield, kgh^{-1}m^2			

1.2 Theories of an ecological approach to mine restoration

1.2.1 Theories of ecological succession

Theories of ecological succession can be applied into mine reclamation. Moreover, it seems sensible to harness the principles of ecological succession within the restoration process(Reynolds, 1996). Succession is a natural process, and there usually is a sequential transition from simple ecosystems to more complex one on widely different scales in both space and time(Odum, 1969; Finegan, 1984; Bryan, 1993). Succession is nevertheless a most controversial issue, involving confrontation between holism (the view emphasizing unity and integration in nature), and reductionism(in which chance and Darwinian interpretation dominate). Natural succession change is often considered to occur in stages through wave-like invasions by groups of species or pioneer species, and so facititates successional change. Succession is interpreted teleologically as the process of development of an ecosystem of maximum stability and of maximum efficiency in the utilization of resources. For instance, a degraded grassland habitat gradually changes from a sparse herb grassland, to dense herb grassland, then to shrub-grass ecosystems, and finally to the forest. This process can take several decades or even centuries. However, human and social activities may interfere and accelerate the ecological development or even change their direction. Here we shall consider the social factors.

1.2.2 The principles of ecological engineering and sustainable development

Ecological restoration must be interdisciplinary and must cross traditional subject boundaries, for example: mining engineering, landscape architecture, agriculture, forestry, economics, social sciences and environmental management. In China, ecological engineering means an integrative study of material and energy metabolism and geo-chemical cycles in a social, economic and natural complex ecosystem, which should lead to the effective transformation and utilization of domestic and industrial wastes, and to sustain and safeguard the modern urban environment and to support modern agriculture. The fundamental task of ecological engineering is to develop sustainable ecosystems through integrative planning of their structure, function, and processes by encouraging totally functioning technology, systmatically responsible institute and ecologically vivid culture. So, the thoughts of Chinese ecological engineering were regarded as one of critical guidelines of ecological rebuilding in mine. In accordance with these principles, the following guidelines have been developed for restoring mine wastes in China: (1) the system analysis, and ecological planning of the structure and function of mine ecosystem pursuant to the local condition and landscape; (2) institution and legislation system construction of ecological building; (3) the scenario eco-design and implementation of ecological rebuilding and land relamation according to natural ecosystem principles of holism symbiosis, circulation and self-regulation, whose concrete technologies include: (a) select drought-resistant, fast-growing crop varieties to accelerate the agricultural production; (b) use inter-cropping, or rotations of grasses and leguminous crops to improve both the soil fertility and the physical structure of the spoil as quickly as possible; (c) rebuild a self-sustaining ecosystem by integrating the rational use of irrigation, fertilizer use and mycorrhiza; (d) plant diverse crops, including fruit trees, and integrate agriculture with forestry, animal husbandry and associated minor land-uses according to local landscape conditions so that restored mine wastes can be used to the full.

2 Case studies of ecological restoration in Shanxi Province of China

2.1 General condition of case study areas

Three sites that represent a range in size of surface mining operations were selected for the case studies: Yangquan Surface Bauxite Mine is the smallest, the Xiaoyi Surface Bauxite Mine is medium-sized and Antaibao Surface Coal Mine is the largest(Table 3). They are situated in the East, Middle and north of Shanxi Province respectively. In these areas, annual precipitation ranges from less than 450 at Antaibao to more than 550 mm at Yangquan and Xiaoyi. The frost-free period may be from under 114 days to over 180 days, and average annual temperature range between about 5.4—10℃. The dominant landform is of loess-covered hills, which results in severe water loss and soil erosion.

Table 3 Details of the surface mines used in this case study(Miao, 1997; Gao, 1998)

Site	Longitude & latitude	Type of mining	Ore production rates, 10^6t/a	Land take total, hm^2 Annual loss, hm^2/a
Yangquan	N37°82′ E113°65′	Bauxite	0—6	1.4hm^2
Xiaoyi	N37°19′	Bauxite	1—8 million	680hm^2
Antaibao	N39°31′ E112°23′	Coal	15	2000hm^2

2.2 Key procedures in the agro-ecological restoration

2.2.1 New land construction

Traditional mining activity designs its waste dumps with little regard to landform and its future use. However, an enlightened approach is now taking future landform and its future suitability for food and forest production, taken into account as part of the planning process before the start of the mining activity.

Usually, the solid waste is piled on the ground, filed into the gullies, or backfill into the abandoned open-pit. Fig. 2 illustrates the process of rebuilding new land within the mining operation, and Fig. 3 demonstrates how an improved methodology has been incorporated into the

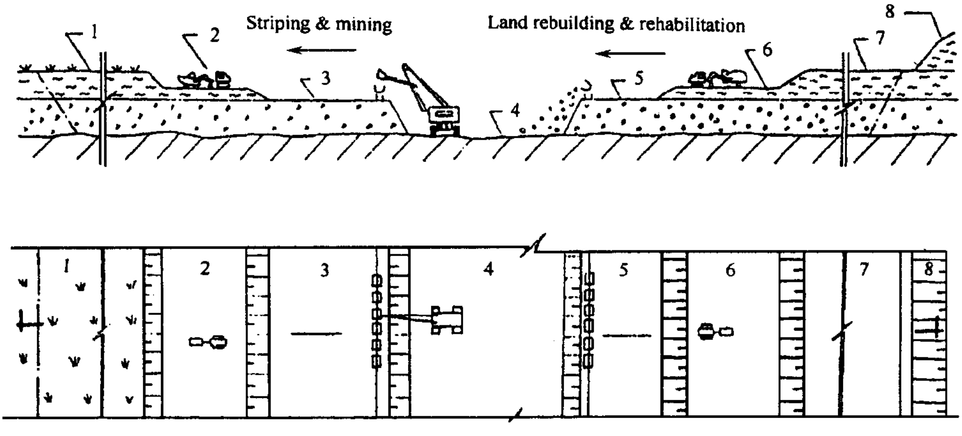

Fig.2 The diagram of striping, mining and land rehabilitation in open-pit mines in Shanxi (Zhao, 1993)
1. original farming field; 2. stripping area; 3. mining area; 4. degraded area; 5. backfilling area; 6. overburden(loess) topsoil area; 7. reclaimed field, and 8. temporal peeled-off field

working at Shanxi Mine. Care must be taken to prevent environmental hazards from uneven depression or subsidence, which results in soil coarseness, sloughing or clumping, denudation, unstable loose piles and debris erosion along water flow courses with some. Clearly environmental damage is likely to be more serious on large-scale mines than that on the small-scale ones, since the rate of land disturbance and waste dischrge from the large-scale mine are several orders of magnitude greater (Table 4). The following six factors should be taken into account when designing new waste dumps: (1) valley fill should be used where possible; (2) backfilling should be done to extend contour terraces to a larger area than the original landform; (3) the basal area of stability of the fill should be contoured; large-size and hard-weathered rocks should be filled on the basal area to increase the stability of the fill; (4) drainage culverts are needed of the longitudinal slope of the gully bottom exceeds 10°; (5) a protecting wall must be constructed at the gully bottom if the watershed area is large or funnelled; (6) the sub-layer should be compacted and levelled to prevent depressions forming, and to allow overing materials to be added easily (Fig.3)

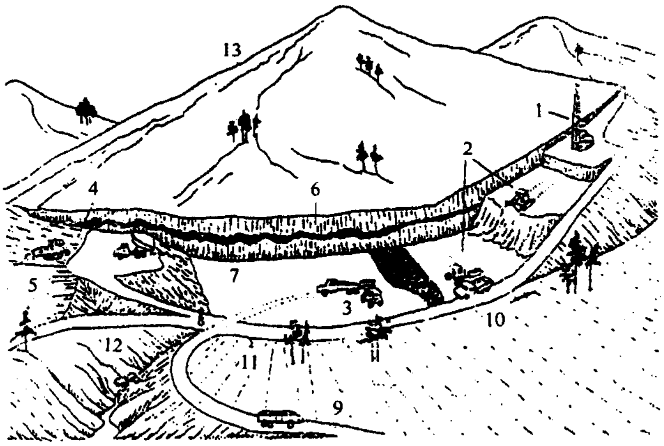

Fig.3 The valley backfilling, land rebuilding and mining in open-pit mine in Shanxi(Zhao, 1993)
1. Driller; 2. bulldozer and fork-lift truck load waste rock into trunk; 3. rock transportation by truck; 4. land levelling by bulldozer; 5. rebuilt field; 6. final slope; 7. degraded open-pit field; 8 and 9. road; 10. mining forward direction; 11. mineral deposit; 12. valley or gullies, and 13. mountain ridge

Table 4 Type of dumps, amounts and peeled-off rate at each of the three mines(Li, 1996)

Parameter	Mine(range of years data collected)					
	Yangquan (1966—1990)		Xiaoyi (1992—1995)		Antaibao (1985—1992)	
	Mean	Range	Mean	Range	Mean	Range
Land occupied rate, hm^2/a	1.4	0.8—1.6	23.2	20—26.7	80.5	—
Soil peeled-off rate, $\times 10^4 m^3/a$	35.7	9.0—70.8	—	—	2603.6	—
Type of dump	Valley-fill	Valley-fill	Valley-fill	Valley-fill	Continuous pile on valley fill	

2.2.2 Treatment of toxic chemicals in the mine wastes

An important consideration of dump design and new land reconstruction is the control and treatment of any toxic substances in the wastes. However, in some situations, for example at Antaibao(Table 5), the loess overburden wastes after irrigation and natural leaching had lower concentration of most potentially toxic elements than the local topsoil. Hence, on this site there should be little effect of soluble toxic substances affecting land revegetation and water quality. One way to help control the effect of toxic materials is to make sure that a large reserve of this loessic material is stored used to cap the wastes, essentially forming a new growing medium. For example, in the Shanxi mines 25%—30% of the loess has a high $CaCO_3$ concentration, a pH between 7.0 and 8.6, a strong adsorption capacity for heavy metals and a strong buffering capacity against low acidity. on these sites it is possible to mix these loess materials with waste materials, which are extremely acidic or have concentrations of toxic metals, to help reduce environmental damage. Experiments where *Hippophae rhamnoides L.* (Seabuckthorn), *Astragalus sinicus L.*

(Chinese Milkvetch), *Medicago sativa L*. (Alfalfa), *Crataegus pinnatifida Bunge* (Chinese Hawthorn), *Setaria italica*(*L*.) *Beauv*. (Foxtail Millet), *Zea mays L*. (Maize), *Festuca ovina L*. (Sheep Fescue), *Festuca arundinacea Schreb*. (Tall Fescue), *Bromus inermis Leyss* (Smooth Bromegrass), *Onobrychis viciaefolia Scop*. (Common Sainforn) and *Malus pumila Mill* (Apple) etc., have been grown on such mixture have demonstrated that soils with properties can be ameliorated and their fertility improved(Table 6).

Table 5 Concentration of potentially toxic metals in overburden at Antaibao Surface Coal Mine(Zhao, 1993; Ma, 1995; Lin, 1998) Unit: mg/kg

Overburden type	Elements							
	Cu	Pb	Cd	Cr	Hg	Ni	As	F
Topsoil	19.28	39.55	120	48.44	0.093	21.40	9.44	267.5
Mala loess	23.39	36.14	40	47.39	0.076	25.26	9.45	425.0
Lishi loess	25.80	38.68	70	73.08	0.048	27.58	23.75	403.8
Wucheng loess	12.38	26.66	210	27.76	0.107	14.82	6.67	68.00
Coal reuse	12.17	34.64	45	16.37	0.101	—	2.80	155.0
Other soils	27.61	33.49	215	48.12	0.126	—	10.89	416.3
Soil chromat.	0.01—	0.02—	0.00—	1.00—	0.00—	—	1.5—	0.85—
(eluviation, pH: 5.2—7.5, column 438 mm high)	0.10	0.03	0.90	4.00	14.10		6.8	1.47

Table 6 Improvement of soil fertility after 5-year forest planting in peeled-off field in Antaibao (Zhao, 1993)

Sampling site	Soil layer depth, cm	pH	Organic matter, %	N		P		K	
				Total, %	Available, ppm	Total, %	Available, ppm	Total, %	Available, ppm
Unreclai	0—20	8.26	0.32	0.026	15	0.033	3.93	1.48—2.00	53—100
Med soil	20—40	8.48	0.18	0.022	—	0.034	3.61	—	—
Forage	0—6	8.31	0.91	0.053	20	0.048	13.17	1.86	167
Planting	7—20	8.36	0.46	0.035	—	0.048	8.00	1.86	86
Soil	20—40	8.37	0.39	0.035	—	0.048	5.55	1.86	—

2.2.3 Stripping and recovering of loess topsoil before and after mining respectively

The usual procedure is to remove topsoil or subsoil, or both, from the land in a separated layer, store it, and then backfill it on the area after mining closure. The cost involved in topsoil removal, its storage and protection are high. Moreover, where topsoil is very infertile or is of poor quality for sustaining vegetation, as at the Shanxi mines, it is nor worth the effort or expense. Moreover, topsoil storage is often difficult because of erosion loss through both wind and water. In many instances loessal sub-soils, which have no toxic components are good soil-forming materials and are often more fertile for land revegetation than the available, poor-quality topsoil. Loessal soil or mixtures of topsoil, subsoil and loessal soil can, therefore, be spread over most surface mined wastes directly.

It is also important to note that the deleterious effects of earthmoving machinery (heavy truck, scraper, and bulldozer) on soil physical condition, especially for the reclamation of tailing fields(Fullen, 1995). Table 7 compares the effects of different compaction treatments at the different sized mines. Compaction was least in the small mine where levelling was done using manual tools and was worst in the large-scale mine, where a bulldozer or scraper was used for land levelling after discharging loess by "off-highway trucks" with a loading of 154—190t. Tillage loosened the tight surface and facilitated run-off in take and retention, but agricultural costs were increased by 4%—5%, and the loosened surface became hard and impervious quickly because of the low organic matter content of the loess.

Table 7 Comparison of physical conditions between new constructed surface soils and undisturbed original surface soils (Zhao, 1993; Ma, 1995)

Parameter	Newly constructed lands			Undisturbed original soil (ave. of the three fields)
	Yangquan	Xiaoyi	Antaibao	
Methods for land levelling	Manual tools	Manual tools after bulldozer	Bulldozer or scraper	
Bulk density, g/cm^3	1.2—1.3	1.3—1.4	1.5—1.9	1.40
Initial permeability coefficient, mm/min	>10	<10	<10	>10
Stability permeability	>10	0.4—1.0	0.16—0.28	0.4—1.0
Resistance coefficient, kg/cm	—	—	>30.00	2.13—6.21
Runoff coefficient, % *	—	—	68.84	11.20—23.69

* Simulated value using the needle-type artificial rainfall device with precipitation duration of 60 min and precipitation intensity of 0.75—0.81 mm/min

2.2.4 Control of soil erosion

Loess has a very poor structure, it is very loose and is susceptible to water and wind erosion. When it is used as covering materials splash, sheet, rill, and gully erosion can easily erode it. Land slides and other mass movements of debris are found on many steep and unstable slopes. Thus, newly constructed land on mine sites is vulnerable to erosion (Table 8), with loss of much material. Great attention must be paid to erosion control on the larger dump, which are often huge loose piles, constructed at a rapid rate. On such sites it is of more difficult for mechanical treatment, since there is often severe and uneven sibsidence for at least 4—10 years after the restoration is finished. One way to reduce erosion is to use biological methods by creating a diverse vegetation as soon as possible. Early establishment of a plant cover is usually possible on fresh spoils to help control erosion even in arid climates. A planting mixture should preferably include herbs, shrubs and trees, and the following species might be suitable in our sits in China: (1) herbs, *Astragalus adsurgens Palls*. (Erect Milkvetch), *Onobrychis Mill*. (Sainfoin), *Vicia amoena Fisch* (Broadleaf Vetch), *Medicago sativa L*. (Alfalfa), *Milium effusum L*. (American Milletgrass), *Bromus inermis Leyss* (Smooth Bromegrass); (2) Shrubs, *Festuca arundinacea schreb*. (Tall Fescue), *Hippophae rhamnoides L*. (Seabuckthorn), *Lycium chinense Mill*. (Chinese Wolfberry), *Caragana korshinskii Kom*. (Korshinck Peashrub) and (3) trees, *Populus nigra var. italic Koehne* (Lombarby Poplar), *Populus alba L*. (White Aspen), *Populus X xiaozhuanica*, *Robinia pseudoacacia L*. (Black Locust), *Ulmus pumila L*. (Siberian Elm), *Pinus tabulaeformis Carr*. (Chinese Pine), *Pinus sylvestris var. mongolica Litvin* (Mongolian Scotch Pine), *Salx matsudana Koidz* (Hankow Willow), *Picea meyeri Rehd. et Wils* (Meyer Spruce).

2.2.5 Fertility management

It is essential to assess monitor the soil gentility of degraded land, since it is rare to be able to use high quality topsoil as a covering material. Techniques, which might be needed, include acceleration of the weathering of the material used, artificially raising the fertility and eliminating other constraints. Two techniques, which yield rapid results, are the application of fertilizers and encouraging the growth of appropriate forage plants. Moreover, a high yield and an impressive financial return can be obtained using these techniques (Table 9), and soil fertility can be improved by planting forage species (Table 10).

Table 9 **The effects of a various fertilizer combinations on the growth and profit margin on restored land at Yangquan between 1987—1989. Treatment code: N = nitrogen, P = phosphorus, O = farmyard manure; N_1, N_2 means 75 and 150kgNh^{-1} m^2(82 and 165 RMB Yuan Nh^{-1}m^2); P_1, P_2 represents 75 and 150 kgPh^{-1}m^2 as P_2O_5(102 and 204 RMB Yuan Ph^{-1} m^2); O_0, O_1 illustrate without and with 7500kgh^{-1}m^2(450 RMB Yuanh^{-1}m^2) of dired sheep manure. The millet and corn economic output and profit are respectively discounted with the constant price in 1989 respectively, 0.50 RMB Yuan per kilogram and 0.40 RMB Yuan per kilogram (Zhao, 1993; Ma, 1997; Lin, 1998)**

Treatment code	Millet 1987 kgh^{-1}m^2	Millet 1988 kgh^{-1}m^2	Corn 1989 kgh^{-1}m^2	Fertilizer input RMB Yuan/hm^2	Crop output RMB Yuan/hm^2	Profit RMB Yuan/hm^2
$N_0P_0O_0$	1.94	2.87	2.57	0	2955.0	
$N_0P_0O_1$	2.57	2.35	4.37	1350.0	4209.0	−96.0
$N_0P_1O_1$	2.89	3.16	4.03	1655.6	4640.3	+29.7
$N_0P_0O_1$	2.41	4.66	5.87	1597.5	5885.3	+1332.8
$N_1P_1O_1$	1.96	5.20	5.25	190.31	5680.5	+822.4
$N_1P_2O_0$	2.97	5.68	4.72	2208.2	6213.8	+1050.6
$N_1P_0O_1$	2.83	3.39	4.07	247.5	4737.8	+1535.3
$N_1P_1O_0$	1.94	4.45	4.08	553.1	4827.0	+1318.9
$N_2P_2O_0$	1.36	3.94	3.85	858.2	4193.3	+380.1
$N_2P_1O_1$	3.30	5.73	6.01	2150.6	6921.0	+1815.4
$N_2P_2O_0$	2.66	6.13	5.85	2455.7	6686.3	+1275.6

Table 10 **Effects of planting forage at Yangquan (1987—1989) and at Antaibao (1991—1995) on selected aspects of soil fertility (Zhao, 1993; Li, 1996)**

Sampling site	Organic matter, g/kg	Total N, g/kg	Bacterium, numbers/g	Fungi, numbers/g	Actinomyces, numbers/g	Average crop yields, th^{-1}m^2
Yangquan	2.2	0.3	6.17×10^5	2.08×10^5	0	
Reclaimed	8.3—9.9	0.5—0.7	3.71—7.2 $\times10^{10}$	3.75—6.89$\times10^6$	1.14—7.76$\times10^5$	20.55
Antaibao	3.2	0.3	4.50×10^6	4.0×10^2	0	
Reclaimed	6.4—7.2	0.4—0.5	1.26×10^7	3.43×10^4	3.49×10^5	17.76

3.2.6 Use of mycorrhiza

Other techniques, which can assist reclamation, are to amend the soil with an inoculum of VA-mycorrhizal fungi (Endogenous fungi, *Glomus mosseae* and *Glomus veriforme*). At the Xiaoyi Bauxite Mine, mycorrhiza inoculation with strains of *Glomus mosseae* and *Glomus versiforme* adapted to the alkali soil in the northern of China have given good results. Experiments have shown that inoculum with these fungi have produced significantly better growth of three test crops (*Solanum Tubersum L.* (potato), *Glycine max* (L.) *Merr.* (soybean) and *Zea mays L.* (maize), when these species have been grown on mine spoil. The percentage of potato and maize plants infected by mycorrhiza reached 90% and 75% respectively, and potato yield was as much as 25% higher than uninoculated plants (Table 11).

Table 11 Experiments for effects of inoculated VA mycorrhizal fungi on various parameters of soybean at Xiaoyi Bauxite Mine (Lin, 1998)

Treatments	VA—1	VA—2	CK
Total numbers of buds per pot	5.7	6.4	4.4
Plant height, cm	21.68	21.68	11.79
Root fresh weight, g/plant	2.81	3.37	1.51
Fresh weight per plant, g/plant	18.03	19.27	11.59
Dry weight per plant, g/plant	4.20	4.20	2.80
Comparison of phosphorus content, %	173	189.5	100
Stained extant	+	+	Slightly stained

2.2.7 Irrigation

The establishment of vegetation in the dry climate of northern China, means that agricultural production in restored mine areas is largely dependent upon irrigation, both its quantity and quality. In the three mines discussed here the potential water supply has been increased because of abundant wastewater. In Antaibao Mine, for example, the waste water supply ranges from 360000 to more than $600000m^3$ per year. Clearly, there is great potential to increase agricultural production if efficient irrigation schemes can be designed.

We tested the effects of different after sources for crop irrigation: (1) irrigation with clean, fresh groundwater; (2) water from a coal washing plant and (3) water produced as industrial waste. Irrespective of source of water, irrigation increased yield of *Onobrychis viciaefolia Scop*. (Common Sainfoin), *Avena nuda L*. (Naked oat), *Oryza sativa L*. (Rice), *Robinia pseudoacacia L*. (Black locust), *Toona sinensis* (A. Juss.) *Roem* (Chines Toona) (Table 12). The clean water produced a bigger increase than that produced by either of the contaminated waters (Table 12). Thus, through a combination of advanced drip (or spray) irrigation with high efficient fertility management, it is rather possible that soil fertility of reclaimed lands may be more productive than that before mining.

Table 12 Effects of irrigation effect on crops grown on reclaimed land at Antaibao (Li, 1996; Miao, 1997)

Species	Irrigation treatment								
	Fresh water			Discharge from coal washing			Discharge from industrial wastes		
	Plant height,cm	Biomass yield, g/m²		Plant, height,cm	Biomass yield, g/m²		Plant height, cm	Biomass yield, g/m²	
Oryzopsis munroi stapf(Sainfoin)	25.08	300		25.5	240		22.3	230	
	Plant height	Spike length	Numbers of spikelet	Plant height	Spike length	Numbers of spikelet	Plant height	Spike length	Numbers of spikelet
Avena nuda L. (Naked oas)	85.6	23.2	11.2	82.9	21.9	9.4	83.8	21.9	11.1
Oryza sativa L. (Rice)	98.7	49.2	11.9	89.9	19.7	11.5	—	—	—
	Plant height, cm			Plant height, cm			Plant height, cm		
	Before irrigation	After irrigation	Annual increase	Before irrigation	After irrigation	Annual increase	Before irrigation	After irrigation	Annual increase
Roninia pseudoacacia L. (locust tree)	30.5	86.4	55.9	34.6	84.5	49.9	80.4	130.5	50.1
Toona sinesis (A. Juss.) *Roem* (Chinese toon)	17.5	35.5	180	14.4	32.1	17.7	37.6	61.8	24.2

3 Decision making, design optimization and ecological planning

It is well known that rational decision-making and design optimization are extremely important in land reclamation. In fact, after the initial investigations of geology and the decision to mine, systematic planning is the most important part of ecological restoration. Decision making for reclamation must take into account government policies (local, regional and national), financial investment, site factors, agricultural status, public requirement and availability of restoration techniques. Moreover, if scientific decision making and ecological planning are included at the concept and design stage, i.e., before the land is stripped, reclamation targets for mine wasteland are easier to achieve, and many of the usual problems associated with reclamation will be avoided. Nevertheless, problems do occur where this integrated view is not taken. As an example of problems caused by ignoring the importance of restoration is provided by the restoration procedures at the antaibao Mine carried out in the 1980s. The disposal of spoil from the primary pit was based solely on geotechnical and economic information. The fill area had been designed to minimize the amount of land take, with the steepest possible slope gradient, which would remain stable. The consequence is that restoration of the land after mining land(over 300 hm^2) has been severely limited by these steep slope. The only way to improve the post-mining crop productivity for this land is to go back and re-structure the tip to increase its basal area, a huge and expensive task with significant disturbance to the substructure of mine land area under the fill. Therefore, it is essential to realize that the cost-benefit analysis must take into account both the economic productivity of the mining operations and the costs associated with restoring productive land use. Mine planners, local regulatory and political officials will need to make a joint decision on this matter if they desire to change the post-mining management pattern in these fill areas.

4 The establishment of legislation systems and organization of administration

The three mines discussed here have come together and established a leadership group for mine production. This group is now in charge of approving all aspects of the mining operations: mining, stipping, ore dressing, the construction of tailing dams, environmental protection, and restoration of a sustainable land use. This was established in Shanxi Province in 1985 and included local government at various levels and any other management agencies, including those responsible for land management, mining management and water and soil conservation. Their mission is to guide mine production and ecological restoration in the right direction.

This has been done against a background of changing legislation implemented by the State Council of China, these include: The Land Management Law, Water and Soil Conversation Law, Forestry Conservation Law, Mineral Resources Law and Environmental Protection Law. The local municipality formulated 15 local rules and regulations in 1992 and subsequently mining, dressing and refining sites run by individuals have been eliminated. Moreover fees for land restoration, forest conservation, and prevention of water and soil erosion are gathered before the land is assigned for mining use in order to guarantee that environmental protection can be paid for. Restoration of the damaged areas is carried out by a designated organization or by the polluters themselves. The reclamation contract must be signed by the Municipal Land Bureau, The Mining Group and the Department of Land Expropriation. At this point an advance fee for land reclamation must be paid to the appropriate agencies in advance of mining. Once the restoration on the despoiled land meets an agreed state assessment standard, the advance will be reimbursed to mines. At the Antaibao Mine the mine land has been integrated with the local villages. Farmers in these villages restore the land and grow crops, and the mines pay the cost of land reclamation. However, the ownership of the discarded land still belongs to the state and mines. In other words, only the right of to farm the land is given to villages or farmers. These strategies allow control over the management of the restored land, yet promote appropriate development.

5 Conclusions

An ecological restoration approach is beneficial for land reclamation on land degraded by mining in China. At present, most reclaimed land is use for agriculture and forestry. Ecological restoration should include: (1) legislation systems; (2) ecological risk evaluation; (3) ecological assessment; (4) ecological planning; (5) financial investment and benefit distribution; (6) clean production techniques; (7) resource regeneration, and (8) restoration and rebuilding of ecosystems on mine waste land. Among them, ecological planning, engineering restoration and land reclamation are the basic links.

For successful restoration, new land construction is the fundamental framework, this should, however, involve ecological planning, contour terrace building, the control of soil erosion, the prevention and treatment of toxic substances, and covering spoil with loess. This must be integrated with ecological engineering aimed at vegetation establishment and ecosystem creation in order to optimize land productivity and soil fertility. Effective decision making processes aimed at optimizing design is a key step to successful practice and will require consulation with all involved including the local people. In order to make ecological restoration successful emphasis must be placed on the use of fiscal policies (both rewards and penalties) through a legally binding system with strict enforcement.

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References:

Christensen N L, Bartuska A M, Brown J H *et al.*, 1996. Ecological Applications[J], 6: 665—691.

Dumker R E, Barnhiser R I, Darmody R G, 1992. Prime farmland reclamation [M], Illinois Agricultural Experimental Station. Urbana, University of Illinois Press.

Fullen M A, Fearnehough W, Mitchell D J *et al.*, 1995. Soil use and management[J], 11:77—83.

Finegan Bryan, 1984. Nature[J], 11:77—83.

Kelliher G G, Jennison B, 1987. Transactions of the Institution of Engineering[J], 11: 70—74.

Li W Y, Wang Z G, Cai J Q, 1996. Water conservation in mines[M]. Beijing: Science Press. 162—170.

Gao L, Miao Z W, Bai Z K *et al*, 1998. Ecological Engineering[J], 11:221—229.

Ma Z B, 1995. Research on reclamation of surface-mine land in the loess plateau(No.1)[M]. Beijing:China Scientific & Technical Press. 199.

Marrs R H, Bradshaw A D, 1993. Primary succession on land (Ed. by Miles J and d W H Walton)[M]. Oxford: Blackwells Scientific Publications. 221—248.

Miao Z W, Gao L, Zhou X Y, 1997. Proceedings of 25th anniversary and 15th annual national meeting of the American Society for Surface Mining and Reclamation(ASSMR)[C]. 512—520.

Mtchell R J R, R H Marss, M G Le Duc *et al.*, 1997. J. of Applied Ecology[J], 34: 1426—1444.

Odum E P, 1969. Science[J], 164:262—269.

Qin P, An S Q, Yan J S, 1997. The sciences of ecological engineering[M]. Nanjing: Nanjing University Press. 60—65.

Reynolds J F, Tenhumen J D, 1996. Ecological Studies[M]. Berlin, Heidelberg: Springer Verlag. 304—310.

Vastag G, Kerekes S, Rondinelli D A, 1996. International Journal of Production Economics[J], 43:193—211.

Zhao J K, 1993. The technologies for land reclamation and their management in mine[M]. Beijing: Chinese Agricultural Press. 195—214.

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