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Impact of Coal Mining Subsidence on Sandy Geomorphology and Vegetation Habitat in Sandy Area

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Abstract [**Objectives**] To explore the problem of "secondary desertification" caused by coal mining subsidence in sandy area and its control countermeasures. [**Methods**] The collapse fissure changes, vegetation displacement and tilt, dry sand layer and wind erosion/aeolian deposit rate of the edge, middle and basin of subsidence area were studied in detail. [**Results**] The width and density of fissures at the edge of subsidence area were the smallest, followed by those in the center, and the width and density of fissures in the basin of the subsidence area were the greatest, while the staggering and surface damage showed the opposite trend. The average displacement length of vegetation in the subsidence area reached 60 cm, the slope was 5.67 -28.63, and the maximum wind erosion/aeolian deposit at the trunk roots was -30.52 cm/ +25.41 cm, most serious at the edge of subsidence. The changes in displacement length and slope of vegetation were positively linearly correlated with the height and surface damage of collapse fissures. The thickness of dry land layer at the edge of the subsidence area reached 14 cm, 4 -6 cm greater than that of the control, and the thickness of dry land layer in the middle and basin of the subsidence area was both about 11 cm, 1 -4 cm greater than that of non-subsidence area. The wind erosion rate at the edge of the subsidence area was up to 83.34%, followed by that (52.06%) in the middle. The aeolian deposit rate in the subsidence basin was 51.84%. [**Conclusions**] The subsidence edge has the strongest impact on the sandy geomorphology and vegetation habitat, and is a key area for ecological restoration. It is recommended that the coal mining subsidence should be treated in a timely manner to avoid the occurrence of "secondary desertification".

Key words Sandy area, Coal mining subsidence, Sandy geomorphology, Vegetation habitat

1 Introduction

The Mu Us Desert is located in the bordering area of Shanxi, Shaanxi, Ningxia and Inner Mongolia in northern China. It is a typical arid and semi-arid farming-pastoral transition zone along the Great Wall and a transition zone of combined wind and water erosion, and also one of the most important ecological control zones for the western source of the Beijing – Tianjin sandstorm source control project (phase II)[1-3], with very important ecological location. After more than half a century of control, the forest and grass coverage in the key management areas increased by more than 30%, the biodiversity became more and more abundant, and the local ecological environment had gradually improved, forming a savanna landscape dominated by fixed and semi-fixed sand dunes, and the expansion of desertification was basically controlled. However, this area which is also located in the hinterland of Shenfu Coalfield, one of China's eight largest coalfields, is the only national-level energy and heavy chemical industry base and super-large coal mining development zone in western China, and the typical coal-rich and arid and semi-arid ecologically fragile area in China, with prominent contradiction in resource development and utilization with ecological environment protection[4]. Especially for the acceleration of coal mining and development in recent years (the coal output exceeded 400 million t in 2018), "secondary desertification" phenomenon caused by coal mining subsidence occured gradually[1-2]. By 2018, the area of coal mined-out areas and subsidence areas had reached more than 3 000 km^2, accounting for 13.64% of the entire sandy area in Yulin. Among it, the area of obvious collapse fissures is about 2 000 km^2, and the area of activated fixed and semi-fixed dunes is more than 1 000 km^2, accounting for about 4.60% of the entire sandy area in Yulin. Surface collapse fissures, caused by coal mining (precipices, steep ridges and steep slopes have an overall downward displacement along some nearly vertical fracture surfaces) forced the ground surface to be distorted and the internal structure of the soil changes. A large amount of vegetation was shifted, withered and died, caused the "secondary activation" of sand dunes, severely restricting the progress and development of the economy and society. For many years, this area has been a key area for desertification research in northern China[5-12], to solve a series of ecological problems caused by the expansion of desertification. Although the ecological restoration and management of coal mining subsid-

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ence are concerned, it was still infant. In order to explore the "secondary activation" caused by coal mining subsidence in sandy areas and control measures, using statistical methods, the changes in the sandy geomorphology, the displacement and tilt of vegetation, the changes in the dry sand layer and the situation of wind erosion/aeolian deposit in the edge, middle and basin of coal mining subsidence were studied in detail, and the land degradation and vegetation habitat changes in the subsidence area were diagnosed and remedial measures were proposed. This study provided theoretical basis and technical support for ecological restoration and land reclamation projects in mining areas.

2 Overview of the study area

The study area is located in the bordering area of the north of Yulin, Shaanxi Province and the southeast of Ordos, Inner Mongolia. The tectonic structure belongs to the Ordos platform syncline of the North China platform. The main strata include Jurassic, Cretaceous mudstone, sedimentary sandstone and Quaternary aeolian sand layer that bear coal. The landform types are mostly fixed and semi-fixed star-moon dunes, with a relative height of 5 – 10 m. The vegetation types are mainly artificially planted *Salix*, *Poplar*, *Hedysarum mongolicum*, *Hedysarum scoparium* and *Caragana korshinskii*. The vegetation coverage before coal mining was 20% – 30%. The annual average temperature is 7.3 ℃. The average annual precipitation is 368.2 mm. The evaporation is 1 319 mm. The precipitation variability is large. In the spring, the precipitation with a guaranteed rate of 80% is only 12 mm, and the dryness is above 1.3. The annual average wind speed is 3.6 m/s, and the maximum wind speed is 24 m/s. The sand-blowing wind is mainly northwest wind and northerly wind. Especially in spring, the weather is dry and less rainy, the ground surface is dry, and strong winds are the most frequent, with maximum wind speed as high as 20 – 25 m/s.

At present, after years of coal mining, the surface subsidence is obvious in this area (Fig. 1). The maximum subsidence is more than 200 cm. The collapse fissures are staggered and widely distributed, with maximum width of 120 cm and minimum width of 1 cm. The height of the collapse staggers is 5 – 150 cm. The maximum displacement of vegetation is more than 100 cm, leading to the death of a large number of artificial vegetation and the decrease of bulk density of the sandy soil to 1.5 – 1.6 g/cm^3. The surface damage rate is 40% – 60%. The wind erosion area is more than 50%. The vegetation coverage has dropped to less than 20%. The blown sand activities are frequent. Nearly half of the sand dunes have been activated, and the phenomenon of "secondary desertification" in the sandy areas has become increasingly apparent.

3 Methods

3.1 Investigation of collapse-fissures From March, 2017 to November, 2018, a coal mining subsidence with age of 1 – 2 years was selected. In typical areas such as edge, middle, and basin (Fig. 2), five plots (10 m × 10 m) were arranged randomly for investigation on collapse fissure width (W), fissure stagger height (H), fissure density (P_{ss}) and surface damage rate (I_{ss}). Fissure density is expressed by the number of fissures per unit area, and the unit is strips/m; and surface damage rate is expressed by the percentage of surface damage area to unit area.

Fig. 1 The subsidence area studied

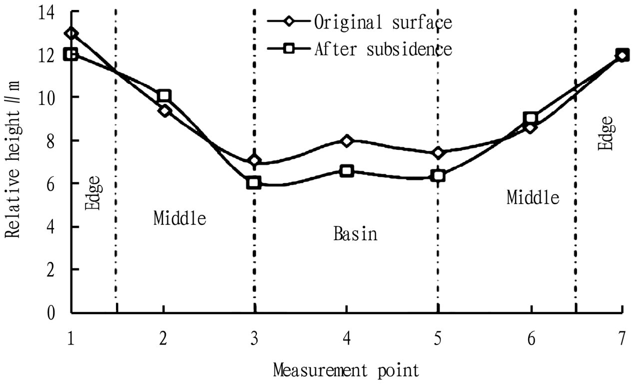

Fig. 2 Location of measurement points in the subsidence area

3.2 Investigation of vegetation displacement and tilt At the three typical positions, the surface displacement length (L), tilt degree (k) and wind erosion/aeolian deposit thickness of the trunk roots (G) of the representative tree *Poplar* and shrub *Salix* in the subsidence area were investigated. Wind erosion is represented by " – ", aeolian deposit is represented by " + ", and the degree of tilt is represented by slope (k).

3.3 Investigation of dry sand layer changes in the subsidence area In each plot, 3 measuring points were selected randomly. The thickness of the dry sand layer (D) was measured by the profiling method, with three replicates.

3.4 Investigation of wind erosion/aeolian deposit rate In each plot, the wind erosion/aeolian deposit rate after coal mining subsidence, that is, the percentage of entire wind erosion/aeolian deposit area in the total area, expressed by W_{ss}, was investigated, with three replicates.

4 Results and analysis

4.1 Impact of coal mining subsidence on micro-topography

After subsidence caused by coal mining, fissures crisscross, and the sandy surface has become fragmented, forming fissures of different sizes and layers (Fig. 3). According to the analysis, the width, staggering and position of the collapse fissures are greatly different. For the 4 collapse fissures randomly sampled, the width at the edge of the subsidence varied from (2.6 ±0.3) to (4.1 ± 0.2) cm, with an average of (3.9 ±0.25) cm; the width in the middle of the subsidence was (5.2 ±0.2) - (7.3 ±0.1) cm, with an average of (6.6 ± 0.15) cm; and in the basin of the subsidence, the width ranged from (9.3 ± 0.1) to (12.5 ± 0.2) cm, with an average of (10.9 ± 0.15) cm, increased by 2.75 times (Fig. 3A). Overall, the width of collapse fissures at the edge of the subsidence was the smallest, followed by that in the middle, and the width of collapse fissures in the basin was the greatest. The stagger height showed an opposite changing trend. From the basin to the edge of the subsidence area, the average staggering height of collapse fissures was increased by 6.23 times (Fig. 3B). The changes in the collapse fissures formed by coal mining subsidence may cause "secondary" wind erosion or aeolian deposit in the originally fixed and semi-fixed dunes, and even further disturb the growth environment of vegetation.

Similarly, the collapse fissure density and surface damage rate at different position of subsidence were different (Table 1). From the edge to the basin, the density of collapse fissures increased gradually, 0.29, 0.37 and 0.58 strips/m, respectively, while the surface damage rate per unit area continued to decrease, 0.60, 0.50 and 0.40, respectively. This is because that the gravitational potential energy was converted into kinetic energy when coal mining subsidence occurred, so that the edge was more likely to cause local landslides or collapses. Combined with the analysis results, it can be seen that although the width of collapse fissures at the subsidence edge was small, the staggering height was relatively large, and the internal structure of the soil had undergone serious changes, causing the most severe damage to the surface. This phenomenon often causes vegetation to shift and shear, and even strains the root system, causing the most serious damage to the growth of vegetation. In contrast, in the middle and basin of the subsidence, the width and density of the collapse fissures increased, while the staggering height and surface damage rate further reduced, leading to reduced impact on vegetation.

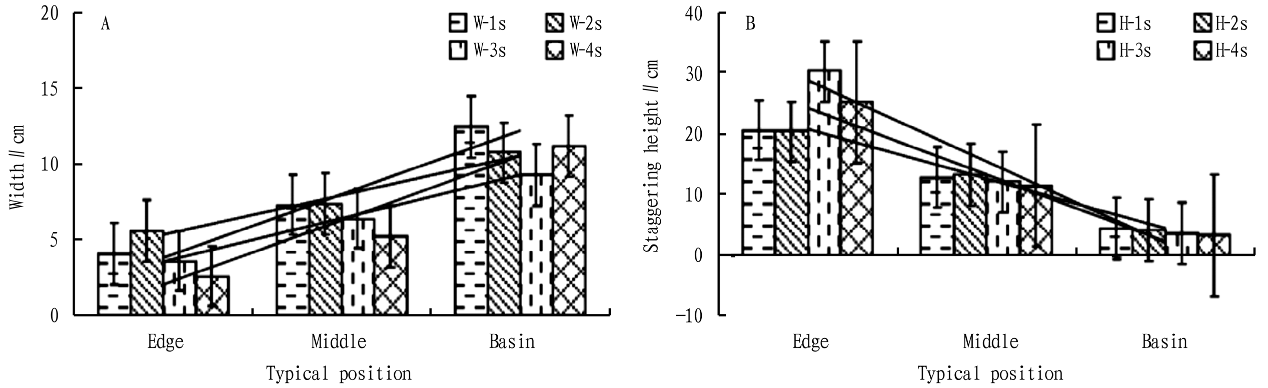

Fig. 3 Changes in collapse fissure

Table 1 Collapse fissure density and surface damage situation in plots (10 m ×10 m)

Position	P_{ss}//strips/m						I_{ss}
	X_1	X_2	X_3	X_4	X_5	Mean	
Subsidence edge	0.31	0.26	0.32	0.27	0.28	0.29	0.60
Subsidence middle	0.42	0.36	0.38	0.35	0.33	0.37	0.50
Subsidence basin	0.55	0.63	0.65	0.57	0.52	0.58	0.40

4.2 Impact of coal mining subsidence on vegetation From the above analysis, it could be seen that when coal mining subsidence occurs, collapse fissures and dislocations would form on the surface, causing displacement and tilt of the trees and shrubs in the area. Table 2 - 3 show the displacement length and tilt degree of *Poplar* and *Salix* populations at different positions of the subsidence area, as well as their wind erosion/aeolian deposit thickness around the trunk root after one year.

The displacement length and slope of *Poplar* and *Salix* were different at different position of the subsidence area. At the edge of the subsidence, the maximum displacement length of poplar reached 110 cm, and that of *Salix* was about 85 cm; in the middle of the subsidence, the maximum displacement length of *Poplar* and *Salix* was 53.35 and 42.11 cm, respectively; and in the basin of the subsidence, the maximum displacement length of *Poplar* and *Salix* was only 12.66 and 7.36 cm. Similarly, the slope of *Poplar* was the largest at the subsidence edge, reaching 1.73 -5.67; the slope of *Poplar* in the middle of the subsidence ranged from 3.73 to 11.43; while the *Poplar* in the subsidence basin basically did not tilt (Table 2). According to analysis, it could be concluded that the displacement length of vegetation has a positive linear relationship with the staggering height of collapse fissures. The greater the staggering height of collapse fissure, the greater the displacement length of vegetation, and the greater the tilt of vegetation.

After the ground collapses, the sandy surface becomes looser, and with the displacement and tilt of trees and shrubs, in the action of wind, wind erosion/aeolian deposit occurs to certain extent.

As a result, the root system is exposed or accumulated, which has a certain impact on the growth of vegetation (Table 2 - 3). Arbor and shrub species have different sand prevention characteristics, and *Poplar* trees are more prone to wind erosion at the roots of the trunk. The maximum wind erosion occurred at the edge of the subsidence, reaching about −30.52 cm, and the wind erosion of the subsidence basin was the smallest, about −5.36 cm (Table 2). According to on-site investigations, at the edge of the subsidence, the roots of most *Poplar* trees were seriously exposed within 2 m of the main roots, which had a great impact on their growth. In the middle and basin of the subsidence area, the impact was relatively little, and only part of the root system was exposed, bringing relatively small impact on the growth of the vegetation. *Salix* is multi-branched and prone to blocking wind and sand. Aeolian deposit occurred in all the three different locations, severest in the basin, followed by the middle, and mildest at the edge. The maximum aeolian deposit thickness was +25.41, +12.32 and +10.21 cm, respectively (Table 3). Aeolian deposit played a certain role in promoting the growth of *Salix* instead.

Table 2 Displacement length of *Poplar* trees in plots (10 m ×10 m) and impact

Position	L//cm			K//%			G//cm		
	L_{max}	L_{mid}	L_{min}	K_{max}	K_{mid}	K_{min}	G_{max}	G_{mid}	G_{min}
Subsidence edge	112.40	50.18	39.52	5.67	2.75	1.73	−30.52	−23.26	−10.32
Subsidence middle	53.34	42.64	30.45	11.43	5.67	3.73	−15.21	−10.56	−5.54
Subsidence basin	12.66	8.96	5.78	28.63	14.3	11.43	−5.36	−3.44	−2.17

Note: " − " represents wind erosion.

Table 3 Displacement length of salix trees in plots (10 m ×10 m) and impact

Position	L//cm			K//%			G//cm		
	L_{max}	L_{mid}	L_{min}	K_{max}	K_{mid}	K_{min}	G_{max}	G_{mid}	G_{min}
Subsidence edge	85.10	40.54	11.63	−	−	−	+10.21	+5.63	+3.60
Subsidence middle	42.11	33.56	10.33	−	−	−	+12.32	+8.25	+5.54
Subsidence basin	7.36	5.44	4.15	−	−	−	+25.41	+23.21	+22.50

Note: " + " represents wind erosion, and " − " represents "not observed".

4.3 Impact of coal mining subsidence on dry sand layer and wind erosion/aeolian deposit After coal mining subsidence occurs, the surface becomes fragmented, causing changes in the thickness of the dry sand layer on the sandy surface. Fig. 4 shows the contour changes of the dry sand layer of 18 sampling points at different locations of the subsidence area. When there was no subsidence, the sandy surface was basically a closed whole. The thickness change of the dry sand layer is directly related to soil evaporation. The usual influencing factors are soil structure, soil surface characteristics and topographic factors[1−2]. According to analysis, the dry sand layer thickness of the 18 profiles at 3 random sampling points was stable at 6 −10 cm (Fig. 4 B), following the rule that the dry sand layer on the top of the dune is thicker and the dry sand layer between the dunes is relatively thin. This is in line with the change law of the dry sand layer of the general dunes in the Mu Us Desert[1−2].

After coal mining subsidence occurs, the sandy soil becomes looser and the structure changes, collapse fissures and staggers form on the surface, promoting the general increase in the thickness of the dry sand layer at different locations of the subsidence area. The contour lines in the figure are very disordered, no longer in line with the changing law of dry sand layer in sandy area. The average thickness of the 18 profiles at the 3 random sampling points was 11.10 cm, increased by 37.05% compared with non-subsidence. This change was especially obvious at the edge of the subsidence, where the thickness of the dry sand layer was even more than 14 cm (Fig. 4 B), 4 −6 cm greater than the control. The thickness of dry sand layer in the middle and basin of the subsidence area was relatively small, around about 11 cm, increased by 1 −4 cm in comparison to non-subsidence.

These changes in the dry sand layer would directly lead to changes in wind erosion/aeolian deposit at different locations of the subsidence area (Table 4). The edge, middle and basin of the subsidence area showed different degrees of wind erosion/aeolian deposit under the action of wind. Overall, wind erosion/aeolian deposit were most obvious at the edge, where wind erosion was the main phenomenon, and the average wind erosion rate was as high as 83.34%. The average wind erosion rate of the subsidence middle ranked second, 52.06%. In the basin of the subsidence area, aeolian deposit was the dominant phenomenon, and the aeolian deposit rate reached 51.84% (Table 4). This shows that the collapse fissures and dislocations caused by coal mining subsidence have changed the local topography, indirectly increase the contact area with the air, and increase the soil evaporation, leading to further drought of sandy soil and gradual expansion of wind erosion/aeolian deposit area, affecting the growth of vegetation.

4.4 Diagnosis and control measures of "secondary desertification" From the above analysis, it could be seen that after coal mining subsidence occurs, it will cause a series of chain reactions. The first is that fissures and dislocations are generated on the surface under the influence of endogenic force collapse gravity, resulting in fissure crisscrossing and surface damage at different positions and displacement and tilt of vegetation. Under the action of exogenic force wind, wind erosion or aeolian deposit occurs around the plant body, promoting the exposure of the root system of the vegetation and making the vegetation gradually lose the ability to prevent wind and fix sand. This will cause further collapse, and expand the wind erosion/aeolian deposit area, directly affecting the growth of plants, resulting in the reactivation of fixed and semi-fixed dunes, eventually leading to "secondary desertification" in the subsidence area (Fig. 5).

Therefore, zoning ecological restoration should be carried out in time after coal mining subsidence, to avoid causing "secondary desertification" in the entire subsidence area. It is recommended to conduct land remediation (sand barrier) and restore and reconstruct the vegetation at the edge of the subsidence, proper reconstruction and promote artificial ecological restoration (flatting to form live sand barrier) in the middle of the subsidence, and appropriate transformation in the basin of the subsidence to promote self-ecological restoration.

Table 4 Changes in wind erosion/aeolian deposit rate at different positions of the subsidence area

Position	W_{ss} // %					Mean
	X_1	X_2	X_3	X_4	X_5	
Subsidence edge	-76.30	-91.80	-75.70	-82.10	-90.80	-83.34
Subsidence middle	-55.80	-60.60	-45.40	-43.60	-54.90	-52.06
Subsidence basin	45.70	52.60	45.80	60.60	54.50	51.84

Note: "+" represents aeolian deposit, and "-" represents wind erosion.

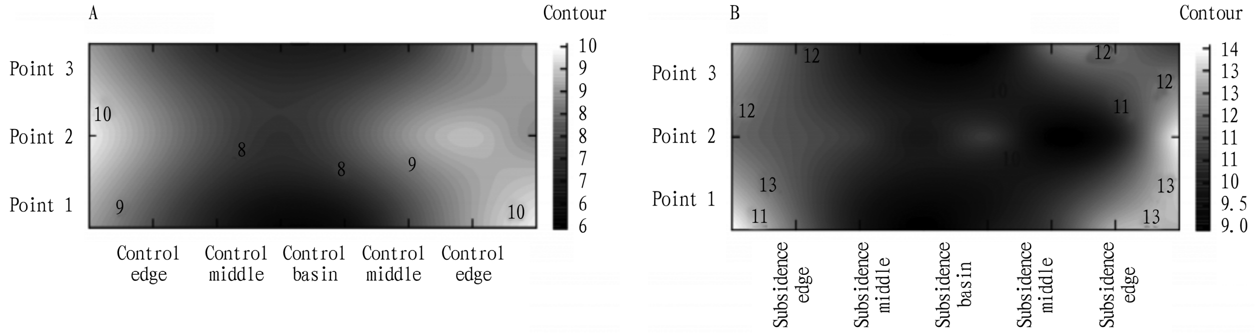

Fig. 4 Changes in dry sand layer at different positions of subsidence area

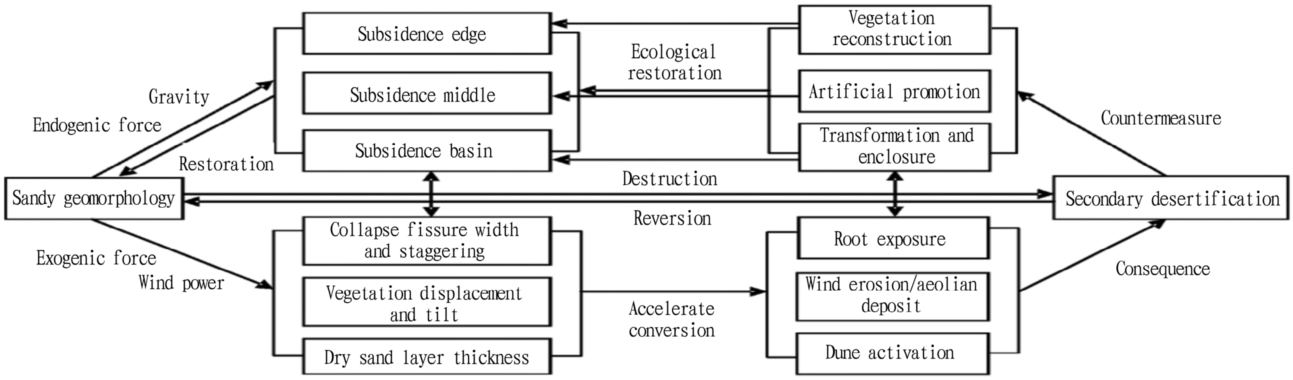

Fig. 5 Diagnosis and control measures of "secondary desertification" in subsidence area

5 Discussion and conclusions

(i) Among different locations of the subsidence area, the width and density of collapse fissures were both in the order as edge < middle < basin, while the staggering height and surface damage rate showed the opposite changing trend. Although the width and density of collapse fissures at the edge of the subsidence area were small, their staggering height and surface damage rate were great, resulting in exposure of a large area of ground and relatively prominent ecological risk. In addition, the average thickness of the dry sand layer in the subsidence area was 11.10 cm, and the dry sand layer at the edge of the subsidence was thicker, reaching more than 14 cm. Different degrees of wind erosion/aeolian deposit occurred after coal mining subsidence, most obvious at the edge, with an average wind erosion rate as high as 83.34%, followed by the middle of the subsidence. In the subsidence basin, wind erosion had turned into aeolian deposit, and the aeolian deposit rate was as high as 51.84%.

(ii) On the whole, the maximum displacement length of *Poplar* and *Salix* gradually decreased from the edge to the basin of the subsidence, and the maximum displacement length of *Poplar* was greater than that of *Salix*. The displacement length of the vegetation had a positive linear correlation with the staggering height of the collapse fissures. The greater the staggering height of collapse fissures, the greater the displacement length of vegetation, and the greater the tilt degree of vegetation. In addition, the severest wind erosion of the roots of the *Poplar* trunk occurred at the edge of the subsidence, reaching about -30.52 cm, while the subsidence ba-

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etc.[6], but they are not ideal for preventing severe frost damage below the critical temperature. (vii) When the cold wave comes, it is necessary to conduct smoking at the lowest temperature, 75 – 150 piles/ha, the smoke pile can be mixed according to the formula of 20% – 30% ammonium nitrate, 50% – 60% sawdust, 10% waste diesel, and 10% fine coal powder. It can also be mixed with combustible hay, shavings, fallen leaves and sawdust. The height of the smoke pile should be below 1 m, and there should be 75 – 120 piles/ha, smoke piles may be slightly denser in the upper wind area, such operation can increase the temperature in the orchard by 1 – 2 ℃[7]. (viii) It is feasible to spray water to prevent cold. Using the physical principle, spraying water in the orchard during the low temperature period, the water vapor will frost on the branches to alleviate the cold wave damage. (ix) Method of wearing tree clothes. This method is a primitive physical protection measure. The canopy of the tree canopy is enclosed or semi-enclosed with polyethylene color stripe cloth. During the occurrence of low-temperature frost damage on April 23, 2021, Mr. Zhang in Yining County used the method of interlacing and smoking and finally protected his entire orchard. (x) Once there is frost damage, remedy in time, spray 2 000 times 6% oligosaccharide solution or 7 000 times Bihu solution or 5 000 times 0.01% brassinolide solution promptly to promote recovery of fruit trees.

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sin was the mildest, about −5.36 cm. *Salix* showed aeolian deposit phenomenon in the three different positions of the subsidence area, severest in the basin, followed by the middle, and mildest at the edge. The maximum aeolian deposit thickness was +25.41, +12.32 and +10.21 cm, respectively. Wind deposit played a certain role in promoting the growth of *Salix* instead.

(iii) In short, the subsidence edge had the strongest impact on the sandy geomorphology and vegetation habitat, and is the key area of ecological restoration, followed by the subsidence middle, and the subsidence basin showed the smallest impact. Based on the analysis above, the following suggestions were put forward. After coal mining subsidence occurs, zoning ecological restoration should be carried out in time. At the edge of the subsidence, after land consolidation and engineering (sand barrier) measures, vegetation is restored and reconstructed; in the middle of the subsidence, after appropriate reconstruction, artificial ecological restoration will be carried out; and in the basin of the subsidence, after proper transformation, the self-ecological restoration can be carried out by enclosure.

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