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Suitability evaluation model for the land reclamation of coal mines in the northern foot of tianshan mountain, Xinjiang

Introduction

Western China is rich in coal resources with good quality, mainly hard coal, and large-scale exploitation of hard coal resources is bound to cause changes in the ecological

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environment. Ecological environment in western China, e.g., western Helan Mountains and northern Kunlun Mountains as well as part of the Qaidam Basin, has been experienced substantial damage by local large-scale coal mine activities, such as land and surface vegetation covering by coal gangue heaps, and destruction of land resources due to ground collapses. To prevent land destruction caused by coal mining and protect local ecological environment as well as restore damaged land resources, and due to the scarce soil resources and difficulty in the efforts of land reclamation in western China, an effective evaluation method to analyze suitability level of land reclamation for coal mine lands therein is in particular important.

Approaches to assess impact of coal mine activities on ecological environment are needed to investigate land reclamation strategies. Shi (2013), Wang et al. (2012), Moosavirad and Behnia (2017), Pereira and Duckstein (1993) using the limit method to evaluate land reclamation suitability, Kalogirou (2002), Reshmidevi et al. (2009), Ye (2012) et al. using the limit method, Wang et al. (2015) using the extenics-based method, Yu et al. (2012), Tian et al. (2014), Zhang and Lu (2014), Kubit et al. (2015), Kim et al. (2016) using the development of index systems method, Du and Li (2001) et al. using the fuzzy evaluation methods, Cengiz and Akbulak (2009), Bagheri et al. (2013) using the analytical hierarchy process methods, Jafari and Zaredar (2010) using the neural network model to evaluate. The studies thus far have focused on the system index, which were determined based on the different characteristics of the assessed regions; however, literature provides few researches on the evaluation of land reclamation based on discriminant analysis.

In addition, with regard to land reclamation, Chen et al. (2015) repaired abandoned coal mine land polluted by erosion and acid mine drainage through FGD products; Lottermoser et al. (2009) carried out land reclamation through Mitchell grasses and added improvers as a waste management strategy; Ioannis et al. (2017) proposed a method to select the best land-use for reclamation of mining areas, considered several multi-attribute criteria and constraints, and combined the will function and evolutionary search algorithm to select the best recovery scheme; Amirshenava and Osanloo (2022) developed a new strategic planning method for post mining land use based on SWOT analysis and IE (internal external) matrix, and defined 32 strategies for all 8 Post-Mining Land-Use (PMLU) selection.

The evaluation of the suitability level for coal-mine land reclamation in cold and arid regions of China was implemented in accordance with a relevant standard specification (TD/T 1036-2013), in which the suitability degree for land reclamation is classified into four categories: (1) excellent, (2) average, (3) poor, and (4) fail. The evaluation index in this specification mainly includes the topographic slope, soil quality, irrigation and drainage conditions, and contamination levels. However, quantification of some of the index, for example, the disturbance to the land surface, still poses a challenge. Moreover, two different results of classified categories may be generated which are confined by the same evaluation index. Therefore, without the consideration of original soil types, land planning, and field investigation, the conclusion yielded from the specification is insufficient to provide information about the reclamation strategies and even the measurement of workloads. Generally, the areas with

cold and arid climates where the ecological environment is substantially vulnerable to coal mine activities exhibit a challenge for the evaluation of land reclamation strategies on the local environment.

With the above points in mind, specific research questions addressed in this work include: (1) Which factors have the contributions to impact land reclamation in cold and arid regions in western China? (2) Can we use a solid but simple model to assess the suitability level of coal-mine land reclamation in cold and arid climates? The objective of this study was to answer the above questions by taking into account: (1) the characteristics of the ecological environment in western China; (2) the impact significance of coal mine activities on land reclamation; (3) the possibility of index quantification for evaluation into considerations based on the evaluation index in the specification (TD/T 1031-2011; TD/T 1007-2003). Ten indexes (for example, terrain slope of destructed mine land, depth of ground collapse and excavation or flatness of the deposited debris.) were applied in the evaluation, based on which, a comprehensive evaluation index for cold and arid regions in western China was established. Finally, we present an evaluation model to assess the suitability level for land reclamation employing Bayes discriminant analysis based on the quantified data of each index that was obtained from measurements and literature (DucInskas et al. 2012; Chen et al. 2020).

1. Methods

1.1. The basic ideology of the Bayes discriminant

The multivariate statistical method, Bayes discriminant analysis (BDA), was employed to the development of the evaluation model in this study. Bayes discriminant is a probability discriminant analysis and various types of distribution density functions should be obtained before proceeding. Priori distribution was used to describe the level of awareness of the study collectivity before extracting samples, and then the posterior distribution was obtained by modifying the priori distribution based on extracted samples, followed by a variety of statistical inference. BDA is widely used for the analysis of data in event classification (Irhamah et al. 2019; Wang and Gu 2010), and many researchers have used the classification method in various practical areas (Chen et al. 2020; Irhamah et al. 2019; Wang and Gu 2010; Yao and Cheng 2016; Hamsici and Martinez 2008).

To estimate the reliability of discriminant criterion, the re-substitution method was used to calculate the mis-discriminant rate (Gustavo de Araújo Carvalho et al. 2019; Efthymia and Panos 2020). All the training samples were regarded as the new samples and re-substituted into the discriminant criterion. The rate of misjudgment can be evaluated as the value of the number of mis-discrimination samples divided by the total number of samples.

1.2. Impact factors influencing land reclamation

A set of independent and complementary variables under the assumptions of multivariate normality and equal covariance was selected to evaluate land-reclamation strategies. Three factors were considered in the selection of evaluation indexes:

- ◆ measurability of the evaluation index;
- ◆ the ability of the quality of land reclamation to be represented by the index;
- ◆ the fact that the indexes should not overlap each other.

Land reclamation is influenced by many factors, which can be divided into several aspects, including land disturbance, soil conditions, irrigation and drainage conditions. The change of the dominant slope of the ground after open-pit mining or collapse will affect the degree of land damage, and the average depth of the ground relative to the surrounding ground after land collapse or excavation or the amount of deposits occupied by the soil and ground pressure will have a greater impact on the degree of land damage. Land damage will reduce productivity. The greater the value, the more serious the land damage is, and the worse the suitability of land reclamation is. After land collapse or excavation, the buried depth of underground water level is shallow, which is easy to cause salinization of surface soil, which is not conducive to the growth of surface vegetation, and the worse the suitability. In the process of land reclamation, whether the soil source is sufficient and the soil thickness are important factors that determine the difficulty of reclamation. In addition, the content of soil clay particles will affect the aeration, water and fertilizer retention of soil, which have a great impact on the survival and production of vegetation. Organic matter can provide necessary nutrients for plant growth, promote plant development, and improve the physical and chemical properties of soil. The climate in Xinjiang is arid, water resources are extremely scarce, and there is basically no ponding on the surface. Therefore, this index selection does not consider drainage conditions, but only irrigation conditions. Xinjiang is a vast region with large rainfall difference. Although the rainfall difference is small for a single mine, it is very different for different mines. Therefore, the irrigation conditions include the annual average rainfall and the runoff of surface rivers available for irrigation in the mining area and nearby areas. After comprehensive analysis, ten specific indexes influencing land reclamation were considered in the evaluation (Table 1): the dominant terrain slope after excavation, ground surface collapse, or the deposition of other types of debris (X_1), depth of collapse and excavation, or the flatness of the deposited debris (X_2), decline in production caused by, e.g., excavation, deposition of other types of debris, or ground surface collapse (X_3), the depth of the phreatic surface after ground surface collapse or excavation (X_4), soil resources ensurence rate (X_5), percentage of clay particles in the soil (X_6), percentage of organic matter contents in the soil (X_7), thickness of the topsoil (X_8), mean annual precipitation (X_9), and surface runoff which is available for irrigation around the mining area (X_{10}).

Table 1.   Coefficients of discriminant function based on Bayes discriminant analysis

Tabela 1.   Współczynniki funkcji dyskryminacyjnej na podstawie analizy dyskryminacyjnej Bayesa

| Evaluation indicator	Linear discriminant function expressions			
	$W_1(X)$	$W_2(X)$	$W_3(X)$	$W_4(X)$
Surface slope after excavation, deposition of other types of debris, or ground-surface collapse (X1)	−0.306	−0.255	0.214	0.604
Depth of ground-surface collapse and excavation or flatness of the deposited debris (X2)	0.102	0.054	0.005	−0.008
Yield reduction caused by land disturbance (X3)	−0.174	0.009	−0.018	0.115
Depth of phreatic surface after ground-surface collapse or excavation (X4)	0.540	0.234	0.307	0.192
Assessed quality of soil (X5)	0.527	0.356	0.112	−0.215
Clay-particle contents in soil (X6)	0.092	0.185	0.166	0.353
Organic matter contents in soil (X7)	−0.008	−0.005	−0.029	−0.057
Thickness of topsoil (X8)	−0.323	−0.322	−0.061	0.108
Mean annual precipitation (X9)	0.017	0.016	0.007	−0.006
Surface runoff for irrigation around mines (X10)	0.633	0.621	−0.041	−0.410
Constant	−26.532	−16.395	−7.947	−17.213
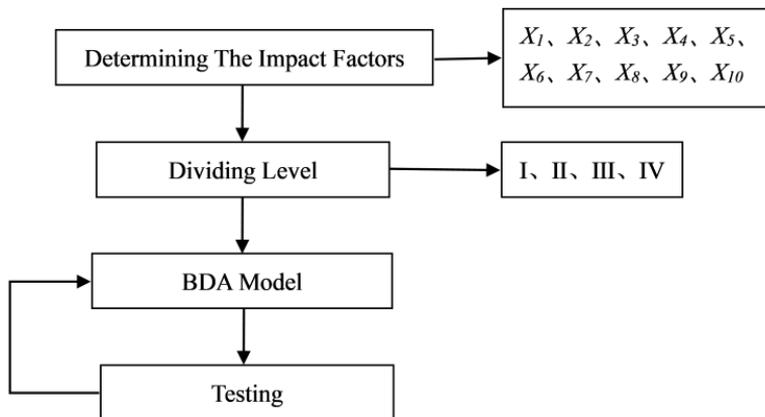
Fig. 1. Plot of the process to build the Bayes discriminant model

Rys. 1. Wykres procesu budowy modelu dyskryminacyjnego Bayesa

1.3. Development of the Bayes discriminant model

The process to build the Bayes discriminant model can be divided into four steps: 1) determining the impact factors influencing land reclamation; 2) dividing the suitability level of land reclamation; 3) developing the BDA model by using training samples; 4) testing of the BDA model. A flow chart of the building model is presented in Figure 1.

Grassland and baren land are the two main land types that are subject to damage by coal-mining activities in western China. As such, whether the grassland reclaimed from damage is appropriate will be the primary task in the evaluation. If the evaluation grade is "Fail" as described above, then the baren land can be laid down as the reclamation strategy. Based on Table 2, the eighty-four land reclamation units from sixteen coal mining areas in Xinjiang, China were used as training samples to establish a Bayes analysis model to evaluate the suitability level. Four levels were classified corresponding to the categories shown in the specification as described above. Land use, land management and environmental policy, environmental policy, and the deterioration level of land use were taken into account in the development of the model.

The ten indexes described in Section 2.2 were applied as independent variables and the evaluation grades of suitability for land reclamation were distinguished as grouping variables according to a set of independent variables. The analysis was performed using SPSS 2.0 software based on eight hundred and forty items of data relating to eighty-four samples. The linear discriminant functions were established as follows:

$$\begin{cases} W_1(X) = -0.306X_1 + 0.102X_2 - 0.174X_3 + 0.540X_4 + 0.527X_5 + 0.092X_6 - 0.008X_7 - 0.323X_8 + 0.017X_9 + 0.633X_{10} - 26.532, (a) \\ W_2(X) = -0.255X_1 + 0.054X_2 + 0.009X_3 + 0.234X_4 + 0.356X_5 + 0.185X_6 - 0.005X_7 - 0.322X_8 + 0.016X_9 + 0.621X_{10} - 16.395, (b) \\ W_3(X) = 0.214X_1 + 0.005X_2 - 0.018X_3 + 0.307X_4 + 0.112X_5 + 0.166X_6 - 0.029X_7 - 0.061X_8 + 0.007X_9 - 0.041X_{10} - 7.947, (c) \\ W_4(X) = 0.604X_1 - 0.008X_2 + 0.115X_3 + 0.192X_4 - 0.215X_5 + 0.353X_6 - 0.057X_7 + 0.108X_8 - 0.006X_9 - 0.410X_{10} - 17.213. (d) \end{cases}$$

✎ $W_1(X)$, $W_2(X)$, $W_3(X)$, and $W_4(X)$ are the discriminant functions representing four evaluation grads for land reclamation as grassland: (1) Excellent, (2) Average, (3) Poor, and (4) Fail. The grads were determined by quantifying the above functions in accordance with certain criteria.

2. Results and discussion

2.1. Test of BDA model

The linear correlation of the samples was 0.957, confirming that the distribution density of training samples were the normal distribution. The data were input into the BDA model and discriminant functions can be obtained. The misdiscrimination of the model was 0.02.

For example, a subsidence site in the No. 2 Zhundong Coal Mine area should be classified as level "Poor" or "Fail". If the impact factors (e.g., the topographic slope and depth of the subsidence) are taken into account, this site could be categorized as "Poor". However,
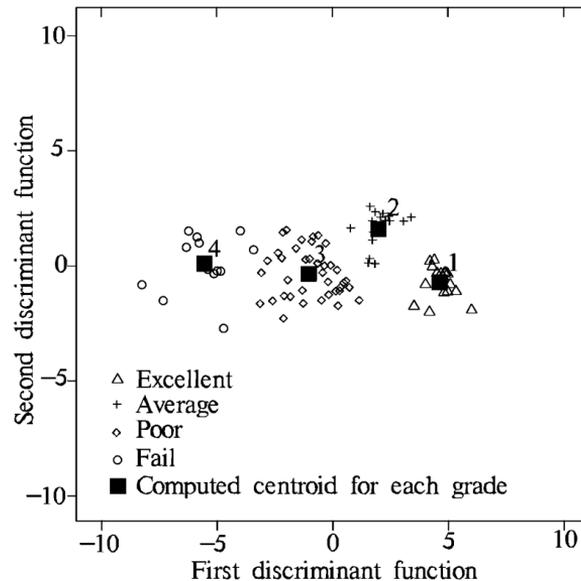

Fig. 2. Plot of distribution of distance between sites and centroids

Rys. 2. Wykres rozkładu odległości między lokalizacjami a centroidami

considering the site was originally bare and irrigation water was not available therein, land reclamation to grassland would be a challenge. Evaluation grade for land reclamation at this site was therefore classified as "Fail". It can be observed in Figure 2 that most of the sample points are clustered around the centroid (evaluation grades) with a minority of them scattered away from grades "Poor" and "Fail", indicating that the BDA model was verified and it can be applied to evaluating land reclamation for coal mines.

2.2. Index system and classification

The average values of the ten indexes in each evaluation grade were used to verify the correlation between the indexes and evaluation grades for land-reclamation suitability. It can be seen from Table 2 that the variation in average values change with the evaluation grade. As the evaluation grades reduced, X_1 and X_3 gradually increased while X_5, X_8, and X_6 decreased. The results suggest that the indexes dominate the evaluation grades for land reclamation.

Table 2.   The average value of the ten evaluation indicators in each evaluation grade

Tabela 2.   Średnia wartość dziesięciu wskaźników ewaluacyjnych w każdej ocenie ewaluacyjnej

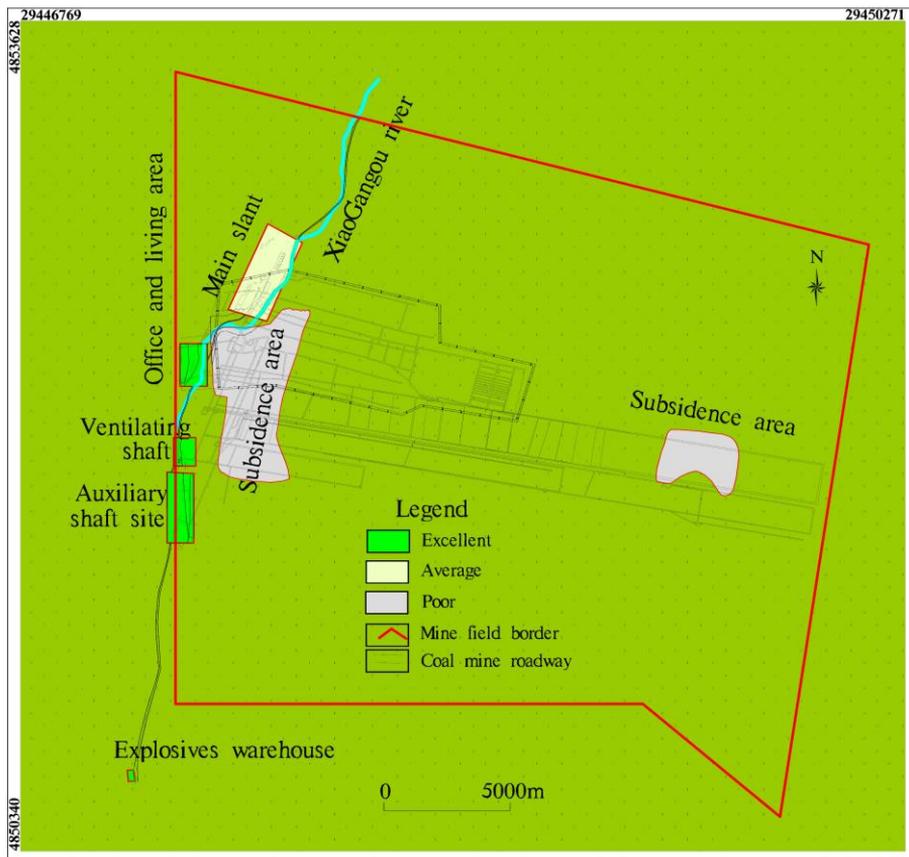| Evaluation grades	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
I	3.94	1.18	8.88	10.94	92.06	12.82	25.56	32.53	31.70	4.00
II	13.06	6.29	66.25	8.48	86.88	13.25	37.12	33.38	35.27	3.51
III	21.82	9.45	47.89	8.30	46.66	8.68	23.95	18.44	28.64	1.80
IV	36.54	32.73	85.00	9.06	5.08	2.54	1.28	1.39	20.21	0.91

Fig. 3a. Land reclamation suitability evaluation results for sites
of Xiaogangou Coal Mine, Hutubi County, Xinjiang

Rys. 3a. Wyniki oceny przydatności rekultywacji terenów kopalni węgla Xiaogangou,
okręg Hutubi, Xinjiang

As shown in Table 2, thirteen of the eighty-four sites were categorized as level "Fail", i.e., in comparison to grasslands, baren lands are more suitable to be reclaimed for these sites due to substantial land disturbance, lack of irrigation, and poor soil quality. Thirty-eight sites were classified as level "Poor" (not very suitable to be reclaimed as grassland) due to land disturbance. By contrast, the sites that were classified as levels "Excellent" or "Average" have only slight changes, thus grassland is recommended to be reclaimed. Generally, the intensity of land disturbance poses significant effects on the evaluation level of land reclamation.
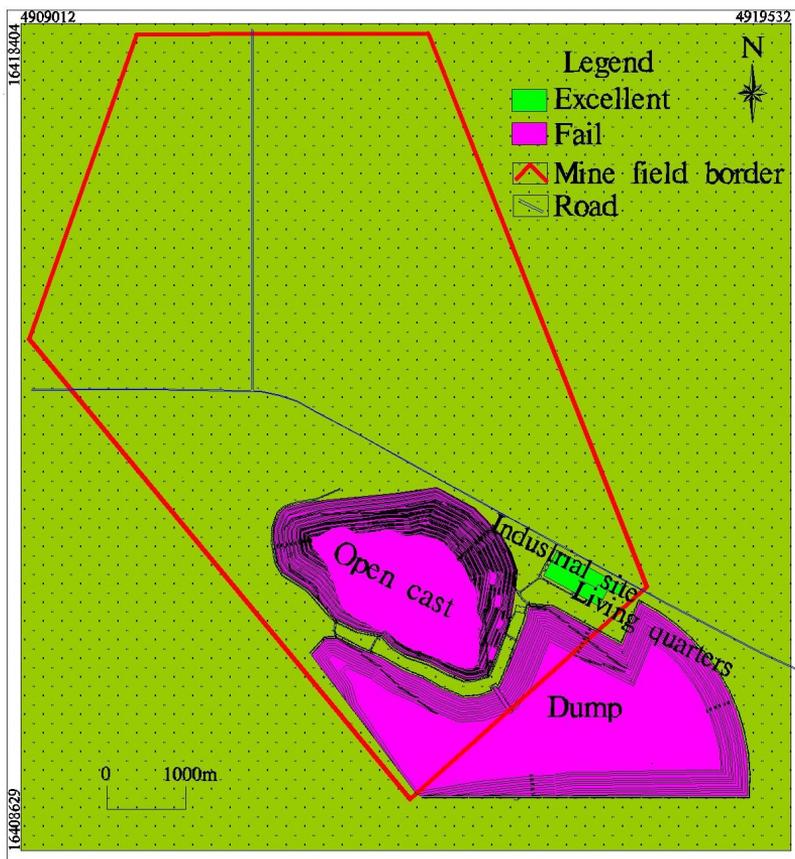

Fig. 3b. Land reclamation suitability evaluation results for sites
of Bisikuduke mine (open-cast mine), Xinjiang

Rys. 3b. Wyniki oceny przydatności rekultywacji terenów kopalni Bisikuduke
(kopalnia odkrywkowa), Xinjiang

2.3. Engineering application of the BDA model

After the BDA model is established, the open-pit coal mine and underground coal mine are selected to verify the model. The underground coal mine takes Xiaogangou coal mine as an example, and the open-pit coal mine takes Bisikuduke coal mine as an example. The suitability levels for land reclamation in the Xiaogangou coal-mine field (Figure 3a, 1.3 km^2), Xinjiang, China and the Bisikuduke mine field (an open-cast mine, Figure 3b, 12.1 km^2), Xinjiang, China were evaluated employing the BDA model developed in the study. The Xiaogangou coal-mine field and the Bisikuduke mine field were divided into seven and four sites, respectively, based on land destruction degree, soil conditions and irrigation conditions (Table 3). In reality, land surface in the western parts of the Xiaogangou mine field has land disturbance caused by human engineering activities. In the eastern part, land subsidence has occurred accidentally due to mining activities. For the Bisikuduke mine field, in the south-

Table 3.　　Measured indicator values of sites for land reclamation

Tabela 3.　　Zmierzone wartości wskaźników terenów do rekultywacji

Site no.	Mine field	Site name	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
1	Xiaogangou coal mine, Hutubi County, Xinjiang	No. 1 subsidence area	30.0	8.9	55.0	0.29	60.0	4.0	6.8	4.2	411.88	0.05
2		No. 2 subsidence area	35.0	16.2	70.0	0	50.0	4.0	7.2	4.4	412.88	0.05
3		Office and living quarters	6.0	0.0	0	11.20	100.0	6.0	7.6	5.1	413.88	0.05
4		Main slant	20.0	11.0	35.0	9.19	75.0	4.0	7.2	4.4	414.88	0.05
5		Auxiliary shaft site	15.0	0.0	0	12.10	100.0	5.0	7.6	4.8	415.88	0.05
6		Ventilating shaft	10.0	0.0	0	12.50	100.0	5.0	7.6	4.8	416.88	0.05
7		Explosives warehouse	5.0	0.0	0	10.80	100.0	5.0	7.5	4.8	417.88	0.05
8	Bisikuduke mine (open-cast mine), Xinjiang	Open cast	35.0	180.0	100.0	0	0	0	0	0	150.00	0
9		Dump	22.0	120.0	100.0	28.00	0	0	0	0	150.00	0
10		Industrial site	5.0	0.4	20.0	25.00	100.0	3.8	7.4	48.0	150.00	0.02
11		Living quarters	2.0	0.0	10.0	25.00	100.0	3.9	7.6	50.0	150.00	0.02

The data in this table are the comprehensive results mainly sourced from field investigations and measurements, related experiments, land reclamation reports, environmental assessment reports, mineral resource development and utilization schemes, and mine geological environment protection schemes.

east of the mining area, the pile of coal gangue caused land occupancy. In the central part, open-cast mining caused land excavation.

Table 4 and Figure 3 show the calculated evaluation results for the two mine fields. Therefore, the actual suitability degree of land reclamation at the No. 1 subsidence site for the Xiaogangou mine field is at the level "III" or "IV", which is identical to the BDA model evaluation results. The actual suitability degree of the remaining sites are also consistent with the model evaluation results. For the Bisikuduke mine field, the actual suitability degree and the model evaluation results of land reclamation are consistent. Compared with the suitability level in specifications, the overall prior probability of every collectivity was fully considered in the BDA model. The BDA model has a fixed structure and the training process is simple and the training is quick.

The model was developed with consideration to the characteristics of geology and ecological environment in western Tianshan, Xinjiang, China. Whether or not grassland or baren land are suitable to be reclaimed for the damage were evaluated in this paper. Furthermore, in comparison with the samples collected from mine lands with opencast mining, the samples employed in the research are mainly from mine lands that have been experiencing underground mining activities. Therefore, the limitations existed in both the reclaimed land use types and the sample diversity. Future research may focus on the diversified collection of samples from coal mine areas and examine if other land use types are suitable to be reclaimed for cold and arid regions in western China using the BDA model.

Table 4.   Evaluation results of sites

Tabela 4.   Wyniki oceny lokalizacji

Site	Value of the determinant function				Evaluation result based on model	Evaluation result according to standardized method
	$W_1(X)$	$W_2(X)$	$W_3(X)$	$W_4(X)$		
1	–6.49	4.50	7.36	–6.69	III	III or IV
2	–15.37	0.07	6.96	0.09	III	III or IV
3	36.45	26.54	11.28	–33.23	I	I or II
4	12.98	14.39	10.00	–16.59	II	II
5	34.22	24.40	13.35	–28.02	I	I or II
6	35.99	25.79	12.41	–30.97	I	I or II
7	36.62	26.68	10.83	–34.31	I	I or II
8	–33.81	–12.24	–0.42	13.14	IV	IV
9	–20.80	–5.60	5.12	11.14	IV	IV
10	22.11	11.71	10.12	–23.39	I	I or II
11	24.09	11.74	9.55	–26.11	I	I or II

Notes: I Excellent; II Average; III Poor; IV Fail.

Conclusions

Based on the Bayes discriminant analysis theory and actual characteristics of land use in mining areas, a Bayes discriminant analysis (BDA) model for evaluating the suitability level of land reclamation for coal-mine lands in western China was presented. Ten factors that are capable of impacting land reclamation were selected as the indexes. The indexes were quantified based on the data acquired from literature and field measurements. The results show that the BDA model has high precision and can be used in practical engineering. Compared with other prediction methods (Kim et al. 2012; Amiri and Shariff 2012; Cheng et al. 2017), the BDA model has a stable structure and the discriminant process is simple and convenient.

It is the preliminary attempt that Bayes discriminant analysis theory is applied to evaluate the suitability level of land reclamation, in particular in western China, for coal mine areas. In future work, it will be necessary to collect diversified samples and other land-use types will be examined to analyze the degree of suitability.

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SUITABILITY EVALUATION MODEL FOR THE LAND RECLAMATION OF COAL MINES IN THE NORTHERN FOOT OF TIANSHAN MOUNTAIN, XINJIANG

Abstract

The ecological environment is significantly vulnerable to coal-mining activities in western China due to the cold and arid climate. The evaluation of land reclamation is therefore a key process that has to be known for the sustainable use of coal resources. A Bayes discriminant analysis method to evaluate the suitability level of land reclamation for coal mine lands in cold and arid regions of western China is presented. Ten factors influencing the suitability of land reclamation were selected as discriminant indexes in the suitability analysis. The data of eighty-four land reclamation units from sixteen coal-mining areas was used as training samples to develop a discriminant analysis model to evaluate the suitability level of land reclamation. The results show that the discriminant analysis model has high precision and the misdiscriminant ratio is 0.02 in the resubstitution process.

The suitability levels of land reclamation for eleven sites in two coal mine lands were evaluated by using the model and the evaluation results are identical with that of the practical situation. Our method and findings are significant for decision makers in similar regions who want to prepare for possible strategies for land reclamation in the future.

MODEL OCENY PRZYDATNOŚCI DO REKULTYWACJI TERENU KOPALŃ WĘGLA KAMIENNEGO W PÓŁNOCNYM PODNÓŻU GÓRY TIANSHAN, XINJIANG

Słowa kluczowe

rekultywacja gruntów, analiza dyskryminacyjna Bayesa,
region zimny i suchy, poziom przydatności, indeksy

Streszczenie

Środowisko ekologiczne jest bardzo wrażliwe na działalność wydobywczą węgla w zachodnich Chinach z powodu zimnego i suchego klimatu. Ocena rekultywacji gruntów jest zatem kluczowym procesem, który powinien być znany dla zrównoważonego wykorzystania zasobów węgla. W artykule przedstawiono metodę analizy dyskryminacyjnej Bayesa do oceny stopnia jej przydatności w rekultywacji gruntów kopalni węgla w zimnych i suchych regionach zachodnich Chin. Jako wskaźniki dyskryminacyjne w analizie przydatności wybrano dziesięć czynników wpływających na przydatność rekultywacji terenu. Dane z osiemdziesięciu czterech jednostek melioracyjnych z szesnastu obszarów górniczych wykorzystano jako próbki szkoleniowe do opracowania modelu analizy dyskryminacyjnej w celu oceny stopnia przydatności do rekultywacji terenu. Wyniki pokazują, że model analizy dyskryminacyjnej jest wysoko precyzyjny, a współczynnik błędnej dyskryminacji wynosi 0,02 w procesie resubstytucji. Poziomy przydatności rekultywacji dla jedenastu miejsc na dwóch terenach kopalni węgla zostały ocenione za pomocą modelu, a wyniki oceny są identyczne jak w praktyce. Model BDA ma wysoką precyzję i może być stosowany w praktyce inżynierskiej. W porównaniu z innymi metodami predykcji model BDA ma stabilną strukturę, a proces dyskryminacyjny jest prosty i wygodny. Jest to wstępna próba zastosowania teorii analizy dyskryminacyjnej Bayesa do oceny poziomu jej przydatności w rekultywacji gruntów, w szczególności w zachodnich Chinach, dla obszarów kopalń węgla. Wypracowania metoda i wyniki są istotne dla decydentów w podobnych regionach, którzy chcą przygotować się do możliwych strategii rekultywacji gruntów w przyszłości.