

Article

Changing Coal Mining Brownfields into Green Infrastructure Based on Ecological Potential Assessment in Xuzhou, Eastern China

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Abstract: It is widely recognized that brownfield regeneration to green space is a sustainable form of urban development. However, it is essential to choose those brownfields that have the greatest potential to be integrated into urban green infrastructure (GI). This paper addresses how to quantitatively assess the ecological potential of coal mining brownfields at the city level, and looks at how these brownfields can be best adapted to enhance the GI system. Taking Xuzhou as an example, an ecological potential assessment method for brownfield regeneration to green space is established considering both its ecological importance and the capacity of maintaining GI connectivity. The results show that more than half of the coal mining brownfields have relatively higher ecological importance values, and only four patches play an important role in maintaining GI connectivity. The final ecological potential values of brownfield regeneration to green space are obtained by overlaying the values of ecological importance and the capacity values of maintaining GI connectivity. Then, all the brownfields are divided into five groups according to their ecological potential values, which are significantly different in each group. Around 51.35% of the brownfields have a high or very high potential for restoration to GI, which are distributed in the southeastern part of the western mining area and the central part of the eastern mining area. The presented method can assist reclamation scientists and urban planners in decision making based on quantitative analysis.

Keywords: mining brownfield; green infrastructure; coal mining city; brownfield greening; landscape connectivity; sustainable development

1. Introduction

China's coal production and consumption are among the highest in the world [1]. The intensive extraction of coal leads to large areas of coal mining brownfields. A coal mining brownfield refers to the land damaged, collapsed, occupied, or underutilized due to open-pit or underground mining, not only including abandoned mining operation systems, but also mining subsidence land and coal waste piles [2]. Coal mining brownfields are often viewed as a serious problem in resource-based cities [3], as they are associated with landscape fragmentation, economic degradation, and social conflict. Especially in eastern China, the underground coal mining caused a large proportion of subsided mining brownfields, which were accompanied by water accumulation [4]. Therefore, the mining brownfield regeneration is of significance to urban sustainable development. In most cases, these mining brownfields will be converted into construction land or reclaimed for agricultural land by deep-digging and shallow-filling [5]. However, the coal mining brownfield in eastern China is also thought to hold huge potential for greening the city due to its large areas of subsidence water [6].

In practice, urban wetland parks are regarded as one of the most common forms of coal mining brownfield greening. Such regeneration processes have been branded as a sustainable approach to urban land use [7]. It has been demonstrated that converting coal mining brownfields into urban green spaces can contribute to the enhancement of urban green infrastructure (GI), providing ecosystem services and supporting the health and well-being of the population [8–10].

A substantial amount of research has been conducted into linking brownfield and urban greenspace [11–13], and this has tended to concentrate on benefits, monitoring and evaluating the outcome of brownfield greening projects [14–17], as well as the planning process [18], the incentives, and the barriers regarding conversion from brownfield to greenspace [19]. However, the identification of brownfields for greenspace space regeneration has often been somewhat arbitrary, as this is usually determined by the will of the central government. There is less concerned on how to select those brownfields with the highest potential to be changed into greenspace in the total urban area. Some researchers put forward the assessment method of brownfield greening, but there is still a lack of a holistic view or quantitative analysis. For example, Altherr suggested that the distance to the city center, the involvement of the stakeholders, and the current legislation are important in determining the greening project location [20]. Mathey selected different types of urban brownfield samples to identify their potential for conversion in the GI system by creatively evaluating their ecosystem service function [21], although here he focused only on the ecological status of the land itself. Further research is needed in order to quantitatively assess the comprehensive potential of brownfield greening in an overall urban landscape context.

Green infrastructure (GI) refers to a continuous network of greenspace composed of patches, corridors, and stepping stones to support the natural ecosystems and bring benefits to human beings [22]. Changing brownfield to greenspace essentially means integrating brownfield into the GI network. The ecological potential of brownfield greening is not only determined by the ecological suitability and importance, but also by its position in GI networks [23]. Some brownfields in or close to key patches or corridors have special significance for improving the ecological structure and functions of GI [24]. The aim of this research is to explore how to assess the ecological potential of brownfield converted into GI in order to inform the planning and decision-making processes surrounding coal mining brownfields. An evaluation index system should be established considering both ecological status on site and the surrounding human activities, even the structure of GI. Taking Xuzhou City as an example, we finally identified the restoration priority of brownfields to be integrated into GI by assessing the ecological potential of each brownfield. For enhancing the connectivity and stability of GI, the ecological potential of coal mining brownfields is assessed from two aspects: the ecological importance of mining brownfields and the ability to maintain GI connectivity. At last, the brownfields that have relatively higher ecological potential are identified and ranked. Then, the suggestions about the land-use planning of coal mining brownfields and urban GI structure are put forward.

2. Coal Mining Brownfield in Xuzhou, Eastern China

Eastern China is an economically well-developed region, where the earliest large-scale industrial coal mines are located. After more than 50 years of coal mining, this region is on the verge of resource exhaustion [1]. Many cities have been built around the mines in this region, which has led to a large number of mining brownfields located in or at the edge of the urban area [25]. Xuzhou is located in the northwest of Jiangsu Province, southeast of the North China Plain. The landscape within and around the city is dominated by fluvial plains and hills, which account for 90.6% and 9.4% of the total land, respectively. The Huai River and the Old Yellow River as well as the Beijing–Hangzhou Grand Canal cut through the urban area. Xuzhou is rich in mineral resources and used to be an important coal production base for China. Our research is limited to the metropolitan urban area of Xuzhou, covering an area of 3126 km². The forest is mainly distributed in the surrounding mountain area. The GI includes main mountains and water within the urban area, with a typical wedge structure in Xuzhou. GI sources refer to large natural patches, and are the source of various ecological processes,

providing habitat or migration destinations for wildlife. In this paper, GI sources include large natural reserves, scenic spots, and large urban parks in Xuzhou (Figure 1).

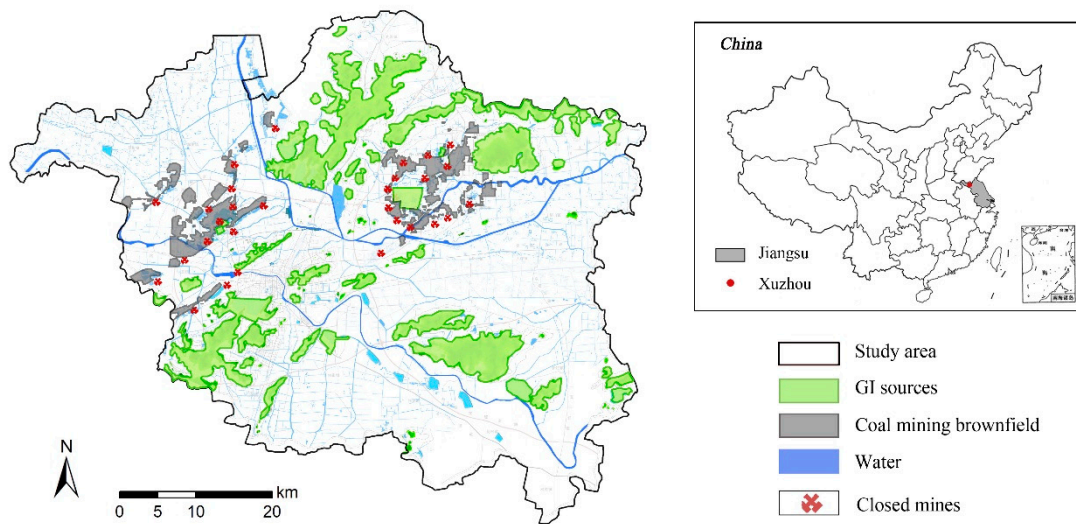


Figure 1. Location and description of the study area.

There used to be 29 coal mines in the area (Figure 1), which were gradually closed by 2012 due to resource exhaustion [26]. As a result, a large number of mining brownfields emerged, including large-scale subsided areas, waste dumps, and industrial squares (Figure 2). They are distributed in the urban fringe where ecological and social environments are fragile [27]. The mining brownfields, which were mostly concentrated in the east and west of the study area, had an area of $1.08 \times 10^8 \text{ m}^2$, and the subsided mining brownfields were close to $0.7 \times 10^8 \text{ m}^2$ by 2015. A large fraction of these are still not stable at present. Some brownfields with small subsidence depth were reclaimed as cultivated land. Some closed mines were reused as aquaculture areas and wetland parks, with new ecosystems formed by self-recovery and manual intervention. Although changing mining brownfields to urban parks can enhance biodiversity and urban ecosystem services [28,29], and plays an important role in improving the GI structure in Xuzhou, there has been a degree of randomness in selecting the mining brownfields that have been regenerated to GI. It is necessary to identify those mining brownfields with high ecological potential before recovering them to urban green spaces.

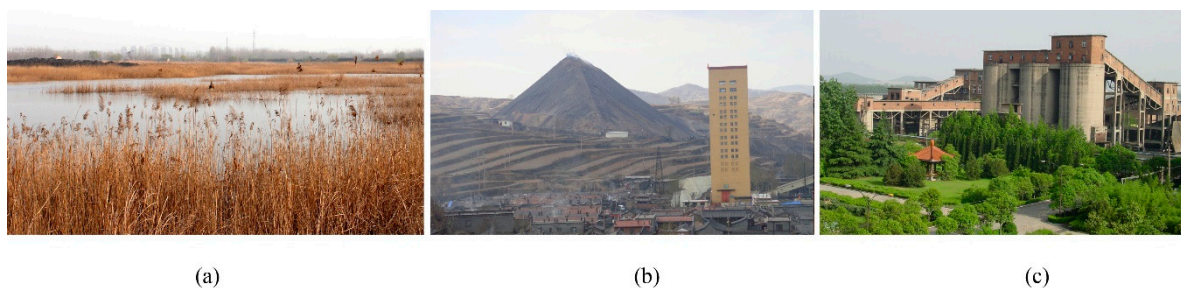


Figure 2. Different types of coal mining brownfields in Xuzhou. (a) Subsided land; (b) waste dump; (c) industrial square.

3. Methodology

The key of the study is to establish an ecological potential assessment method. Firstly, data was collected and analyzed for identifying the range of coal mining brownfields and GI sources. Then, two indicators describing the ecological importance (*EI*) and GI connectivity (*dPC*) of mining brownfields were assessed respectively at the local scale and urban scale, and the value of ecological potential (*P_{gi}*) was obtained by overlaying these two indicators. We selected the coal mining brownfields

with relatively high and very high P_{gi} values to integrate into the GI system. At last, a GI structure framework was proposed based on the results (Figure 3).

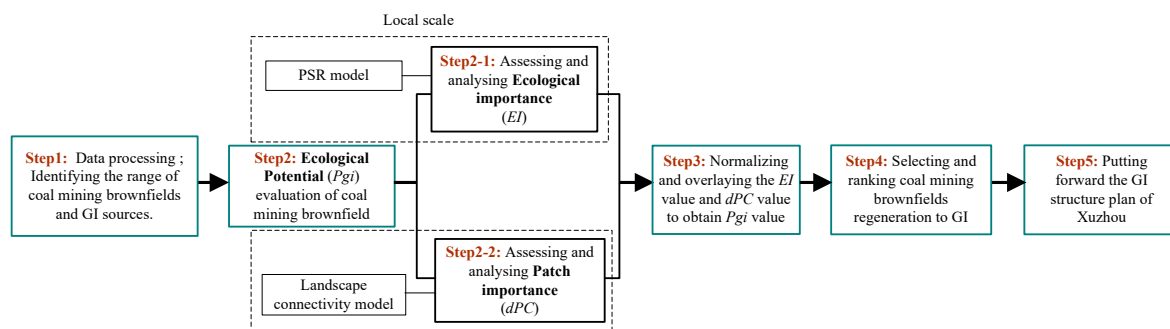


Figure 3. Methodological diagram.

3.1. Data Sources

Based on the Landsat-TM remote sensing image (spatial resolution 30 m) of Xuzhou City in June 2015, we divided land cover into five categories by human–computer interaction on the ENVI (The Environment for Visualizing Images) platform: water, forest, cultivated land, grassland, and built-up land (Figure 4). The interpretation result was modified by checking Google Earth high-precision images and a typical field survey. Then, we further produced the Normalized Difference Vegetation Index (NDVI) of Xuzhou. Combining the land-cover type map with the NDVI map, the important patches of GI sources in Xuzhou were obtained. Referring to the previous results of the GI network research [30], the criteria used for GI sources selection included: (1) most of the urban important ecological protection area; (2) an area greater than $0.5 \times 10^6 \text{ m}^2$; and (3) an NDVI greater than 0.3. The total area of GI source patches is nearly $3.03 \times 10^8 \text{ m}^2$. The border of the mining brownfields was identified based on the distribution map of coal mining subsidence in Xuzhou City (2015), referring to the Special Plan for Adjustment and Utilization of Industrial Wasteland Reclamation in Xuzhou (2012–2015). Those mining brownfields in the study area were divided into two concentrated areas: the eastern mining area and the western mining area, with a total area of about $1.08 \times 10^8 \text{ m}^2$, accounting for 3.5% of the study area.

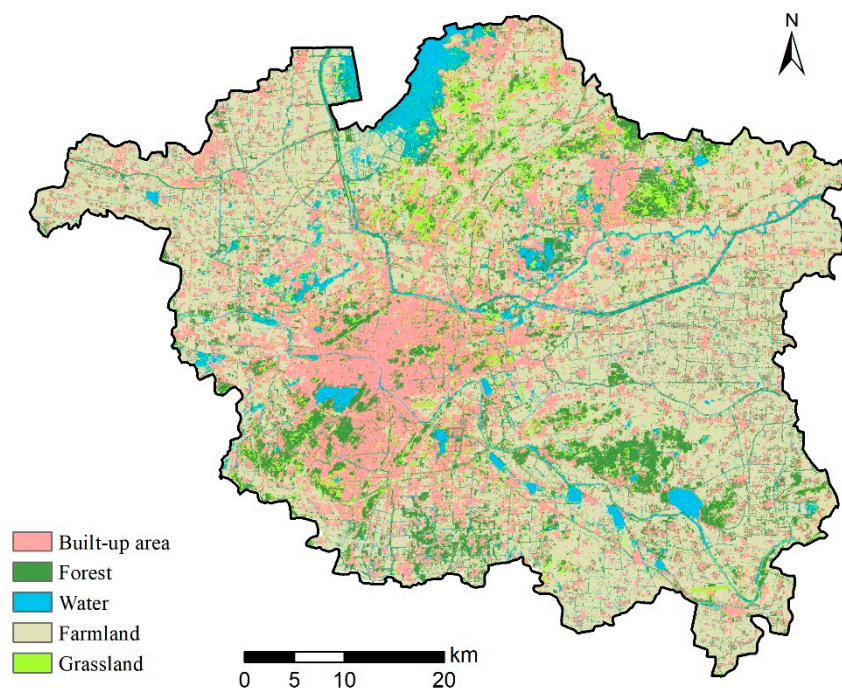


Figure 4. Land cover map of Xuzhou.

3.2. Analytical Method

There are two important factors in determining the ecological potential of mining brownfield regeneration to GI (Pgi). (1) The first is the suitability of mining brownfield itself as GI. Ecological importance (EI) is used to characterize the degree of GI suitability, which reflects the ecological status of the coal mining brownfield, and the suitability and limitation of GI. (2) The second factor is the importance of maintaining GI network connectivity. The patch importance (dPC) is applied to reflect the ability of the patch to maintain an ecological flow in the substrate landscape [31].

Both factors have equally important influences on judging the ecological potential of mining brownfields regenerated to GI. Therefore, the EI value and the dPC value were finally normalized and added to obtain the Pgi value.

$$Pgi = \sum_{i=1}^n W_i X_i \quad (1)$$

In the formula, X_i is the score of the EI and dPC , while W_i is the weight of each indicator.

(1). Ecological importance (EI)

Ecological importance refers to the potential of maintaining an urban ecological balance and preventing ecological deterioration or degradation [32]. In this study, we adopted the “Pressure–State–Response (PSR)” framework, which is often used to reflect the interaction between human beings and the environment, in order to establish the ecological importance index system by considering both the impacts of human disturbances and protections on the ecological state of brownfields. The index system includes eight indicators (Figure 5). Specifically, the “ P ” index represents the external pressure on the land system [33], including land-use type ($P1$), distance from major traffic routes ($P2$), distance from critical infrastructure ($P3$), and distance from pollution sources ($P4$). Among them, $P2$, $P3$, and $P4$ are reverse indicators, reflecting the degree of human interference in mining sites. The “ S ” index represents the change of natural resources, including NDVI ($S1$) and distance from rivers and lakes ($S2$). The “ R ” index represents human protective measures to improve adverse effects, including distance from historical and cultural heritage ($R1$) and distance from ecological protection red lines ($R2$).

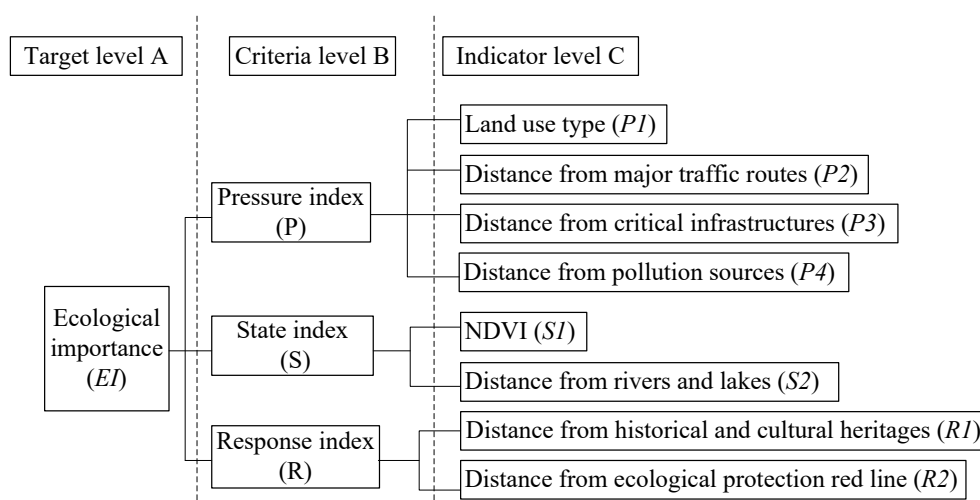


Figure 5. Index system of ecological importance (EI) evaluation of coal mining brownfield.

The classification of the indicators can be found in Table 1. Each indicator is set in a scale, where one means the lowest value, and five means the highest (Table 1). All the indicators were created on a 30 x 30 m grid map. The final ecological importance value of the mining brownfield is actually a weighted accumulation of indicator maps that can be obtained by spatially overlaying all the indicator maps in the environment of ArcGIS 10.2. The weights used in this research are shown in Table 2, which are calculated by using the analytic hierarchy method.

Table 1. Index criteria of *EI* evaluation of coal mining brownfield. NDVI: Normalized Difference Vegetation Index.

Index	Indicator	Class Condition	Value	References	
Pressure Index	Land-use type (P1)	Forest	5	According to the weight of each habitat type that characterizes the habitat quality index in the "Technical Specifications for Ecological Environment Assessment" (HJ192-2015), forest has the highest value, and construction land has the lowest value [34].	
		Water	4		
		Grassland	3		
		Cultivated land	2		
		Construction land	1		
	Distance from major traffic routes (P2)	Buffer larger than 1000 m	5	[32]	
		500–1000 m buffer	4		
		200–500 m buffer	3		
		100–200 m buffer	2		
	Distance from critical infrastructures (P3)	0–100 m buffer	1	Referring to the "power project status map of Xuzhou" (2014), power plants and high-pressure lines above 500 kv were selected. According to the "Urban Electric Power Planning Code" (GB/T 50293-2014), buffer division of high-pressure corridors were defined [35].	
		Buffer larger than 75 m	5		
		40–75 m buffer	3		
	Distance from pollution sources (P4)	0–40m buffer	1	According to the "environmental protection and sanitation status map of Xuzhou"(2014), pollution sources include industrial land (I class), coal gangue dump, landfill, sewage treatment plant [36].	
		Buffer larger than 800 m	5		
500–800 m buffer		3			
300–500 m buffer		2			
StateIndex	NDVI (S1)	0–300 m buffer	1	[32]	
		0.6 < NDVI < 1	5		
		0.4 < NDVI < 0.6	4		
		0.2 < NDVI < 0.4	3		
	Distance from rivers and lakes (S2)	1st order stream	0 < NDVI < 0.2	2	[32,37]
			0–500 m buffer	5	
			500–1000 m buffer	3	
		2nd order stream	1000–2000 m buffer	2	
			Buffer larger than 2000 m	1	
			0–100 m buffer	3	
Lake	Buffer larger than 100 m	1			
	0–500m buffer	3			
	Buffer larger than 500 m	1			
ResponseIndex	Distance from historical and cultural heritages (R1)	0–200 m buffer	5	[38]	
		200–500 m buffer	3		
		Buffer larger than 500 m	1		
	Distance from ecological protection red line (R2)	In the red line	5	Referring to the "Ecological Red Line Regional Protection Plan of Jiangsu Province" (2013), the ecological red line area includes various nature reserves, scenic spots, forest parks, and important water conservation areas. Buffer division standard referenced literature [39].	
		0–500 m buffer	4		
500–800 m buffer		3			
		800–1000 buffer	2		
		Buffer larger than 1000 m	1		

Table 2. Indicator weights of EI evaluation.

Criteria	Criteria Weight	Indicator	Indicator Weight	Sequence
Pressure index (P)	0.4934	P1	0.2951	1
		P2	0.0525	7
		P3	0.0525	7
		P4	0.0933	5
State index (S)	0.3108	S1	0.2072	2
		S2	0.1036	4
Response index (R)	0.1958	R1	0.0653	6
		R2	0.1305	3

(2). Patch importance (*dPC*)

The location of the mining brownfield in the GI network as well as its impact on landscape ecological processes is also an important factor for determining its suitability and potential as GI. In this study, mining brownfields were considered as potential GI in the evaluation of GI connectivity.

The change of GI connectivity with and without the integration of a mining brownfield into GI can reflect the importance of each mining brownfield patch in maintaining the connectivity of the GI network. The possible connectivity index (*PC*) was used to characterize the GI connectivity, and the patch importance of each mining brownfield to maintain the GI connectivity was calculated as follows [40]:

$$dPC(\%) = 100 \times \frac{PC_{add} - PC}{PC} \quad (2)$$

$$PC = \frac{\sum_{i=0}^n \sum_{j=0}^n a_i \cdot a_j \cdot P_{ij}^*}{A_L^2} \quad (3)$$

where *PC* represents the connectivity index value of all the GI patches, *PC_{add}* is the connectivity index value of the total patches after adding one coal mining brownfield patch, *n* represents the total number of patches, *a_i* and *a_j* represent the areas of patch *i* and patch *j*, *A_L* represents the total area of the study area, and *P_{ij}^{*}* is the probability of species directly spreading between patch *i* and patch *j*. According to the research area, patch distribution pattern, and existing research results [41], 10 km was selected as the threshold of patch connectivity.

The larger the *dPC*, the higher the patch importance, which means the stronger ability of the patch to maintain landscape connectivity, and its greater suitable for conversion from brownfield to GI.

4. Results

4.1. Ecological Importance Value (EI)

In this study, 42 GI source patches and 147 mining brownfield patches were identified. The evaluation results of each indicator were calculated (Figure 6), and the *EI* value of the coal mining brownfields are shown in Figure 7. It can be seen that the *EI* ranges between 1.21–4.82, which means that the suitability of coal mining brownfield conversion to GI are quite different for the different areas. The coal mining brownfield area with *EI* values greater than three is about 0.36×10^8 m², accounting for 34.15% of the total area of mining brownfield, and these brownfield patches have higher importance and potential for conversion to GI. Meanwhile, the area of the mining brownfield with *EI* values between 2–3 accounts for 54.17% of the total, which indicates that more than half of the mining brownfields have some ecological potential to be integrated into GI. Generally, the brownfields with relative high *EI* values have at least one of the following characteristics: they are in the buffer zones of an important ecological protection area; they are in the basins of urban important rivers; they

are far from important infrastructures such as transportation and power plants; they have high plant coverage; or they are far away from pollution sources.

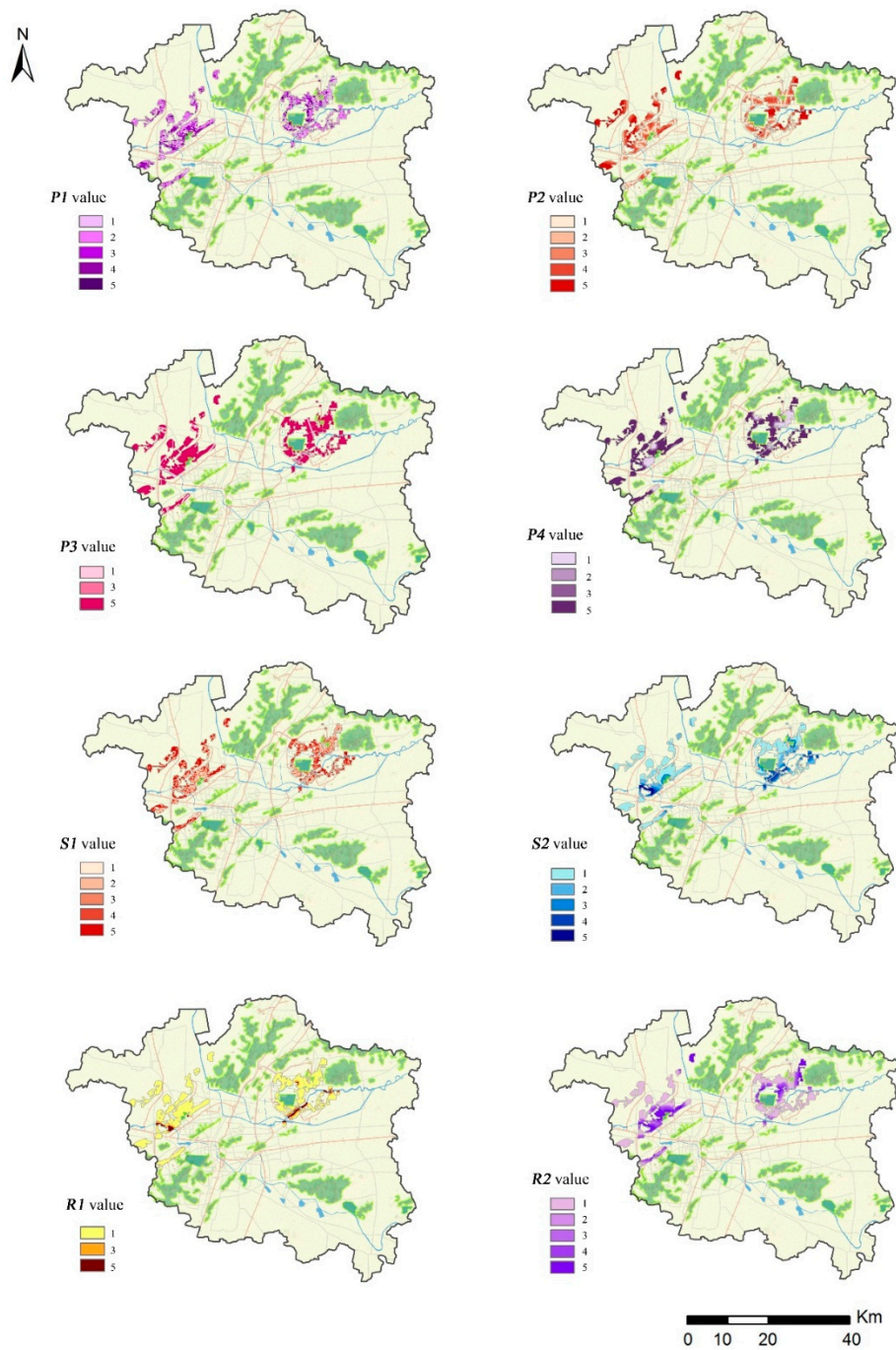


Figure 6. Each index result for EI evaluation of mining brownfields.

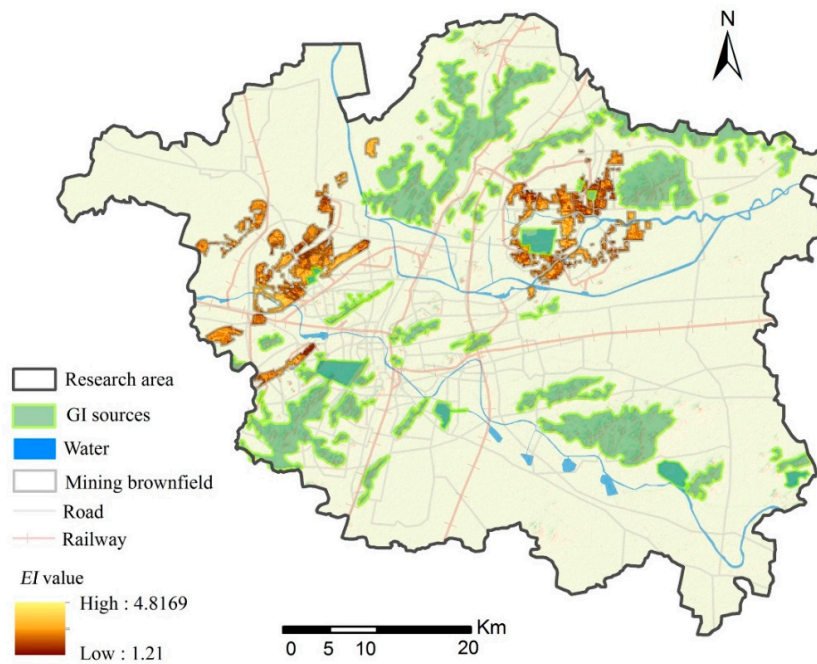


Figure 7. The EI value of coal mining brownfields.

4.2. Patch Importance Value (dPC)

The patch importance values of the mining brownfields in Xuzhou are between 0.00015–0.53845, but its distribution is extremely uneven (Figure 8). There are 70 brownfield patches (in total size of $0.09 \times 10^8 \text{ m}^2$) with scores below 0.025 (accounting for 47.62% of the total number of mining brownfield patches and 8.32% of the total area of mining brownfield), which have a lower effect on maintaining GI connectivity. There are 73 patches (in size of $0.82 \times 10^8 \text{ m}^2$) with scores between 0.025–0.1 (accounting for 49.66% of the total number of brownfield patches and 75.75% of the total area), which have a medium effect on maintaining the landscape connectivity. There are only four patches with scores above 0.3 (accounting for 2.72% of the total number of mining brownfields and 15.93% of the brownfield area), which play an important role in maintaining the GI connectivity.

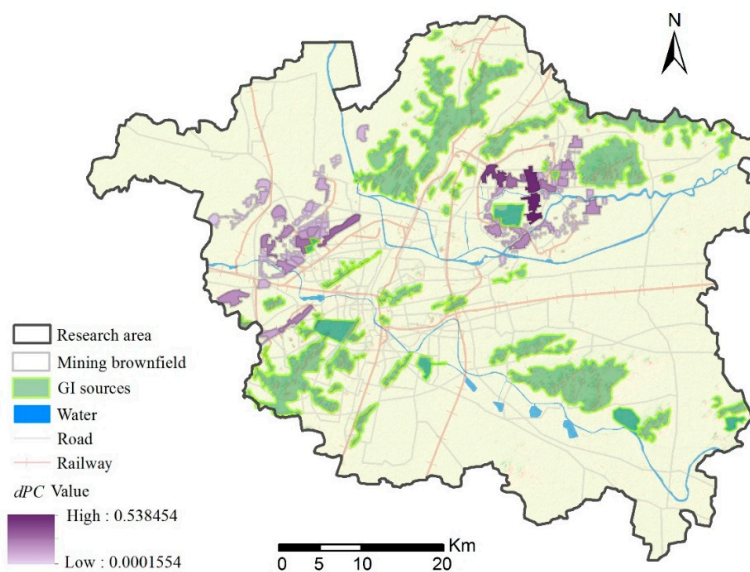


Figure 8. The GI connectivity (dPC) value of coal mining brownfields.

4.3. The Ecological Potential Value (*Pgi*)

According to Formula (1), the *Pgi* values of mining brownfields were calculated based on the *EI* and *dPC* values. Using the natural breakpoint method, the *Pgi* values were divided into five grades (very low, low, medium, high, and very high), showing the potential of coal mining brownfield conversion to GI (Figure 9). The higher the *Pgi* value, the more suitable the area was to be included in the urban GI system. The total area of the mining brownfields with “very high” and “high” *Pgi* values was $0.56 \times 10^8 \text{ m}^2$, accounting for 51.35% of the total brownfield area. These were located in the eastern part of the western mining area and the center of the eastern mining area. The mining brownfields with “medium” *Pgi* values occupied an area of $0.22 \times 10^8 \text{ m}^2$, accounting for 20.18% of the total, and the brownfields with “low” and “very low” *Pgi* values were nearly $0.31 \times 10^8 \text{ m}^2$, accounting for 28.47% of the total.

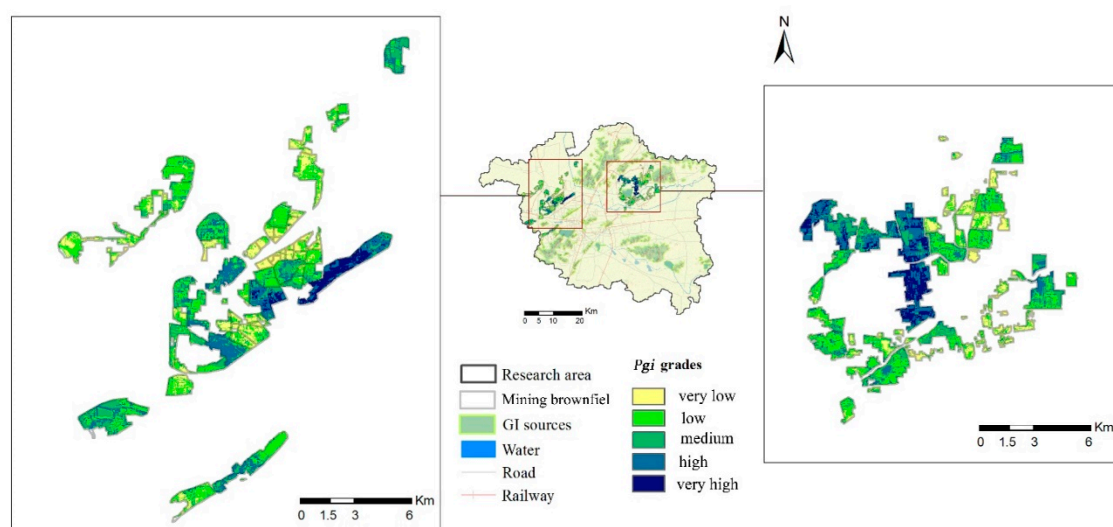


Figure 9. The grades of ecological potential of coal mining brownfields regeneration to GI.

5. Discussion and Conclusion

This paper proposes a quantitative method to identify the suitability of changing coal mining brownfields to GI, aiming at increasing the total GI area and strengthening the landscape connectivity. It considers not only the ecological importance on site, but also the locations of coal mining brownfields in the urban GI structure at the city level, namely the impact of “mining brownfield greening” on urban GI connectivity.

This GIS-based method allows decision makers and city planners to choose those coal mining brownfields with the greatest ecological potential, and integrate them into GI. We assumed that the mining brownfields with “very high” and “high” *Pgi* values can be considered for integration into the GI system. Based on the attribute extraction function and the grid turning function on the GIS platform, mining brownfields with the *Pgi* grades 4 and 5 were extracted, as shown in Figure 10a.

By integrating mining brownfields into the urban GI system, the structure of GI in Xuzhou presents a special wedge-shaped structure (Figure 10b), namely “one heart, four wedges, two corridors, and multiple points”. “One Heart” refers to Weishan Lake Protection Area; the “Four Wedges” are the Lvliang Mountain Scenic Area, Dadong-Panan Scenic Area, Yunlong Lake Scenic Area, and Jiuli Lake Scenic Area. “Two corridors” refers to the Old Yellow River and the Beijing–Hangzhou Grand Canal as well as the greenbelt alongside them. As shown in the above figure, brownfield greening will supplement the current green space system. For example, the mining brownfield in the eastern mining area will play a role in extending the Dadongshan green wedge, and bring the greenbelt deep into the urban area from the southwest–northeast direction. Also, the greening of coal mining brownfields around Pan’an wetland parks will increase the area of GI source patches. Lastly, the

mining brownfields in the western mining area will compensate for the lack of a large-scale green belt in the northwest of Xuzhou; and the mining brownfields along rivers will reconnect and strengthen the Old Yellow River green belt.

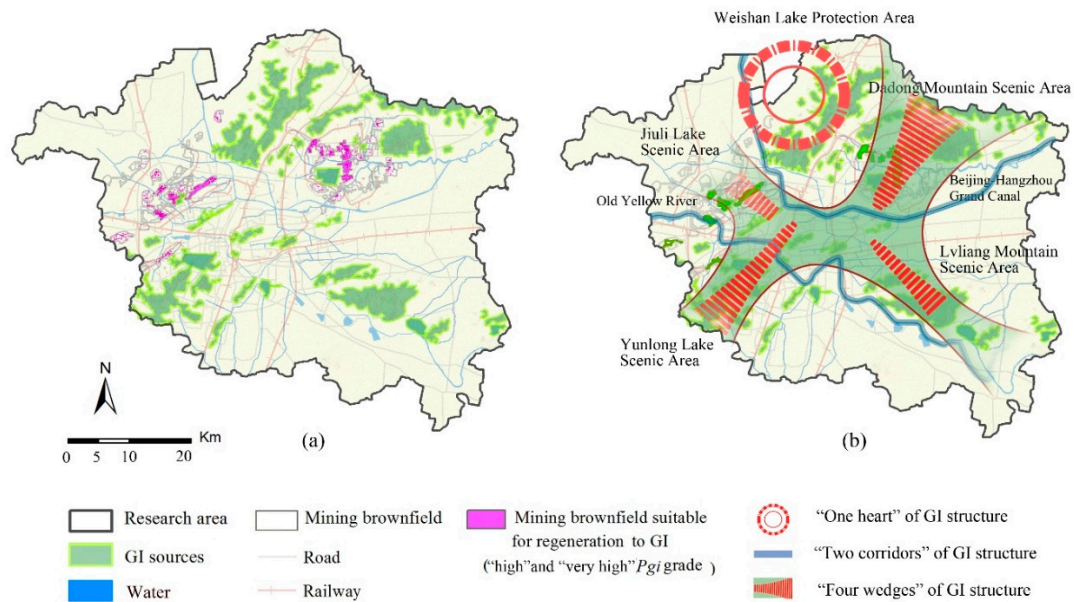


Figure 10. GI structure in Xuzhou based on coal mining brownfield greening. (a) The mining brownfields that should be integrated into GI ($P_{gi} \geq 4$); (b) GI structure planning in Xuzhou.

Coal mining brownfield greening will increase the area and landscape connectivity of urban GI. In this case study, there are 147 coal mining brownfield patches in the urban area of Xuzhou. With the objective of increasing the area and connectivity of GI network, the ecological potential values of coal mining brownfield regeneration to GI were divided into five grades based on evaluation of the ecological importance and patch importance. On the premise of restoring mining brownfields to urban GI, this paper suggests the integration of 51.35% of the mining brownfields into the urban GI system, which have the P_{gi} grades of high or very high. From the perspective of ecological importance, more than half of the mining brownfield is suitable to be regenerated to GI, as it has a greater potential to increase urban biodiversity. Regarding the effect on maintaining the stability of the GI network, most of the mining brownfields have a small effect, and only four mining brownfields hold a prominent role. Therefore, the ecological potential of each mining brownfield is significantly different.

This approach is a new attempt to improve the sustainable development of mining cities from “economic priority” to “ecological priority”. The approach focused on the ecological potential of coal mining brownfield regeneration to GI, which can provide an ecological basis for land-use decision making in brownfield regeneration and greenspace construction. However, it has limitations: the extent of the current research is not sufficient to consider the subsidence depth and damage degree, the plant and animal species in the brownfield, as well as the various economic and social factors. Additionally, the research is focused on coal mining brownfield, but did not consider the other types of brownfield, because the area of the coal mining brownfield accounts for a large proportion of the total brownfield in Xuzhou. Other factors may be necessarily considered in future research, such as ecosystem services, community residents’ wishes, and the costs and benefits of converting to GI. Furthermore, the evaluation method should be adapted according to the different characteristics of other types of brownfield. The subsidence of coal mining brownfield usually is a long-term process with dynamic change. Therefore, the subsidence prediction of coal mining brownfield should also be considered, and multi-period studies are needed.

Author Contributions: All the authors contributed equally to this work. S.F. and J.C. conceived, conceptualized, and designed the research plan; W.H. is responsible for the research methodology, software provision and key technology solutions. S.F. wrote the original draft, which was revised by W.H. and J.C. All the authors read and approved the final manuscript.

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