Long-term remote sensing monitoring coal mining activity in resource-based cities: a case study of Qitaihe City, Northeastern China

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Abstract: Mining activity has strongly impacted the sustainable socioeconomic development of resource-based cities. The systematic monitoring of the change in mining activity can provide evidence for the transition and future development of resource-based cities. This paper chose Qitaihe, one of the four coal mining cities in northeastern China as the study area. Remote sensing and Geographical Information Systems (GIS) technique, as well as methods on landscape pattern analysis were used to study the evolution of mining activity from 4 different periods over 58 years’ time. Results showed that the area of land used in mining increased by about six times during the study period with cultivated land the main type that contributed to this increase. Mining activity showed an eastward trend, developing from one concentration circle to four circles, from a disordered system to a relatively integrated system. It was also suggested that differentiated policies should be adopted in different mining circles. This study also provides a framework for future city planning and sustainable development.

1. Introduction

Mining activity has made a significant contribution to regional and national economics, creating new job opportunities and revenue flows. Despite the contribution of the resource sector to economic growth, questions are frequently raised about the concomitant negative social, economic and environmental impacts [1]. Over these years, these questions have become a worrying subject in resource-based cities all around the world. Thus, it is of great significance to monitor the change of mining activity and its impact on the city and the country as a whole.

Remote sensing data provides an objective, reliable, safe, and cost-effective way to monitor mining activities and their environmental and societal impacts [2]. In recent times, remote sensing monitoring mainly focused on the land use and cover change caused by mining activities [3], or specific environmental problems such as land subsidence as a result of mining activity [4]. Few studies focused on the dynamic change of mining activity and its spatial variation. Focusing on Qitaihe city in northeastern China’s Heilongjiang province; this paper tracks the changes mining activity has brought to the city over the years. These changes can be seen as representative of the wider impact to mining on northeastern China, specifically the four coal cities which comprise Longmei mining holding group. Remote sensing conducted in this area included landscape pattern change from 2000-2010 [5], vegetation coverage change from 1993-2011[6], and landscape ecological security monitoring from 1984-2014 [7]. However, most of these studies concentrated mainly on land cover change of the
overall area; no studies have focused on the evolution of mining activity or on a relatively long period
high temporal frequency and spatial resolution.

In this paper, we combine a topographic map of the year 1957 and 1979 with Landsat images from
1985, 2000 and 2015 to study the temporal and spatial process of mining activities in Qitaihe city over
58 years. Methods including dynamic indexes, transfer matrix, landscape pattern indexes and
centroid algorithm are used to present the evolution of mining activity in the city.

2. Study area
Located in the east of Heilongjiang province, Qitaihe city is one of the four famous coal cities together
with Jixi city to the south, Shuangyashan city and Hegang city to the north (see the Figure. 1). The city
is also in the belt of northeast economic zone with an easy access to Russia in the north.
Geographically, it is located between longitude 130°06′-131°58′E, latitude 45°16′-46°37′N, and lies in
the narrow convergence of Zhangguangcai range and Wanda range. Qitaihe has a semi-humid
continental climate, and the average annual temperature is 4.0℃.

Figure 1. Location of the study area
The city is rich in coal with the proven reserves exceeding 1.7 billion tons. Complete types and
high quality make it one of the three rare coal fields that need protective mining in China and the
largest coking coal production base in northeastern China. Mining started in 1958 and expanded at a
rapid pace. Over the past few decades, mining activity caused changes in the population, economy, society and landscape of the area and also contributed to a series of geological disasters and environmental problems which hindered regional development. Covering an area of 6223 km², Qitaihe city is divided administratively into 3 districts and 1 county, this paper makes the central urban area of Qitaihe city as the area of interest.

3. Materials and methods

3.1. Data sources
The remote sensing data used to derive the temporal and spatial evolution of the mining activity and land cover type resulting from the mining activity comprised Landsat TM, and OLI images with a 30m spatial resolution. We acquired TM images for the year 1985 and 2000, and OLI images for the year 2015. In addition, the topographic map with 1:50.000 resolution of the year 1957/1979 as well as land use map with 1:100.000 of the year 2014 were used for geometry correction and verification. The details of data used were given in Table 1.

| Data Path/row | Data of acquisition | Scale or Resolution | Number |
|---------------|---------------------|---------------------|--------|
| Topographic map | 1957/1979 | 1:50000 | 2 |
| Land use map | 2014 | 1:100000 | 1 |
| Landsat5 | 150/28 | 1985-10-14 | 30 | 1 |
| Landsat5 | 150/28 | 2000-9-1 | 30 | 1 |
| Landsat8 | 150/28 | 2015-9-15 | 30 | 1 |

3.2. Visual interpretation
In this study, a classification system for the land use/cover in the region has been introduced according to national land use classification standard and previous studies on this field [8] as well as the research need (Table 2).

| Type | Description |
|------|-------------|
| Cultivated land | Dry farmland, irrigable land |
| Forest | Trees, shrubs, sparse vegetation, and other forested lands |
| Grass land | High coverage grassland, medium coverage grass land, low coverage grass land |
| Water area | River, lake, reservoir or pond, Urban area, rural residential area, other built-up area |
| Construction land | |
| Mining land | Open-pit area, overburden-dump area |
| Unused land | Sandy land, saline land, bare land, bare rock, other unused land, swamp |

Before interpretation, false-color composite images were used according to the characteristics of different bands and statistical characteristics, band 8,5, and 3 were used for Landsat OLI 8 in 2015; band 7,4,2 were used for Landsat TM 5 in 1985 and 2000.

The geometry rectification of the topographic map of 1957 and 1979 were conducted using Erdas 2014. Then the rectified topographic map of 1979 was used to check the Landsat 5 TM data of 1985.
More than 10 control points were selected with the mean location error less than 1 pixel. The resolution with 30m was adopted to ensure the matching of the spatial data. Finally, the rectified TM image of the year 1985 was used to check other Landsat TM images.

Visual interpretation was based on image characteristics such as size, shape, tone, texture, site association and pattern [9]. Visual interpretation work was done using GIS 10.X. During interpretation, the following principles were adopted: (1) the minimum mapping patch was 6*6 pixels; (2) indoor validation work was done to the interpretation results using the land use map of 2014; (3) the overall accuracy interpretation was greater than 90%.

3.3. Models

3.3.1. Dynamic index of mining land The dynamism of a land use class represents change in quantity of a certain land use class in a unit time [9], so is a key index for evaluating spatial change of a land class. The dynamism of mining land can be calculated according to the following formula:

\[ R = \frac{U_a - U_b}{U_a} \times \frac{1}{T} \times 100\% \]

Where \( U_a \) and \( U_b \) denote areas of a certain land use class at time a and time b respectively; \( T \) denotes the length of time from time a to time b. When \( T \) is in a unit of year, then \( R \) is the annual rate of change in area for this land use class.

3.3.2. Transfer matrix of mining land Transfer matrix can reflect the interconversion relationship between different land use types in the same area at different time, including unchanged part, transfer part, transfer direction, newly increased part and so on [10]. Cross tabulation is often used in transfer matrix to calculate quantities of conversions from a particular land cover to another land cover category at a later date. It is defined as follows:

\[ S = \begin{pmatrix}
S_{11} & \cdots & S_{1n} \\
\vdots & \ddots & \vdots \\
S_{n1} & \cdots & S_{nn}
\end{pmatrix} \]

\( S_{1n} \) refers to the transfer area of land type 1 to land type n; \( S_{n1} \) refers to the transfer area of land type n to land type 1. The transfer variation of mining land area and other land types can be calculated by transfer matrix. All the area can be calculated through ArcGIS 10.X.

3.3.3. Landscape pattern indexes Landscape indexes has become one of the main methods to quantify the landscape patterns. Some indices are with the same ecological meaning, while others have the opposite and even some have no specific one [11]. In this study, landscape indexes PD, MPS, LPI and DIVISION were chosen to quantify the dominance and fragmentation degree of mining land and the diversity variation change of the landscape under the disturbance of mining activity [12-14] (Table 3).

| Landscape index          | Description                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| Percentage of Landscape (PD) | The percentage the landscape comprised of the corresponding type.            |
| Mean Patch Size (MPS)    | The total area of a certain land cover type divides by the total number of patches. |
| Largest Patch Index (LPI) | Defines the percentage of the largest patch area accounting for the total area and reflects the dominance of the patch level |
| DIVISION                 | The length of the landscape boundary per unit area. Reflects the exchange potential and the influence strength of the material, energy and species between patches. |
3.3.4. **Centroid algorithm**  The spatial change of land use can be reflected by the change of gravity centre [15]. Similarly, the centroid algorithm was employed to study the rule of spatial change of mining land. It is defined as follows:

\[
X^t = \frac{\sum_{i=1}^{n} (S_{ti} \times X_i)}{\sum_{i=1}^{n} S_{ti}} \quad Y^t = \frac{\sum_{i=1}^{n} (S_{ti} \times Y_i)}{\sum_{i=1}^{n} S_{ti}}
\]

\(X^t\) and \(Y^t\) refers to the centroid coordinate of mining land in time \(t\). \(S_{ti}\) refers to the area of patch \(i\) in mining land. \(X_i\) and \(Y_i\) is the centroid coordinate of patch \(i\). All the centroid coordinate and its area can be calculated by ArcGIS 10.X.

4. **Results**

4.1. **Area change of mining land**

4.1.1. **Land use and cover change**  The land use and cover change in the study area from 1957 to 2015 were shown in Figure 2. In 1957, 1398.31\(\text{km}^2\) being 80.29% of the total area was covered with forest; the study area remained undeveloped. From 1957 to 1985, cultivated land increased quickly, reached 649.15 \(\text{km}^2\) being 37.27% of the total area, and became the dominant land type thereafter (866.92\(\text{km}^2\), 49.78% in 2000; 862.51 \(\text{km}^2\), 49.53% in 2015). At the same time, forest kept declining, from 1398.31\(\text{km}^2\) in 1957 to 615.54\(\text{km}^2\) in 2015. Likewise, the unused land declined from 276.32\(\text{km}^2\) in 1957 to 14.99\(\text{km}^2\) in 2015 (see Table 4).

In general, except for grass land and water area, which remained basically unchanged, cultivated land, construction land and mining land increased largely, which implied that human activity played an important role. With the expansion of mining activity, population flowed in and became the main driving force of the total region.

**Table 4.** Land use/cover change in the study area from 1957 to 2015

| Land use/cover type | 1957 | 1985 | 2000 | 2015 |
|--------------------|------|------|------|------|
| Area \(\text{km}^2\) | AreaPercent age % | Area \(\text{km}^2\) | AreaPercent age % | Area \(\text{km}^2\) | AreaPercent age % | Area \(\text{km}^2\) | AreaPercent age % |
| Cultivated land    | 3.41 | 0.20% | 649.1 | 37.27% | 866 | 49.78% | 862.5 | 49.53% |
| Forest             | 1398.31 | 80.29% | 849.8 | 48.80% | 627.9 | 36.06% | 615.5 | 35.35% |
| Grass land         | 36.91 | 2.12% | 92.07 | 5.29% | 80.16 | 4.60% | 30.11 | 1.73% |
| Water area         | 10.12 | 0.58% | 1.05 | 0.06% | 18.53 | 1.06% | 28.91 | 1.66% |
| Construction land  | 7.6 | 0.44% | 84.15 | 4.83% | 82.02 | 4.71% | 138.5 | 7.96% |
| Mining land        | 8.92 | 0.51% | 19.33 | 1.11% | 36.94 | 2.12% | 50.87 | 2.92% |
| Unused land        | 276.3 | 15.87% | 46 | 2.64% | 28.81 | 1.65% | 14.99 | 0.86% |
4.1.2. Speed of mining land change

The dynamic degree of land use can quantitatively describe the speed of land use change, and play an important role in predicting the future trend of land use change [16]. The mining land area, its proportion in the built-up area in the corresponding year and its dynamic index are shown in Table 5. It was obvious that the area of mining land kept increasing during the study area (8.92 km² in 1957; 19.33 km² in 1985; 36.94 km² in 2000; 50.87 km² in 2015). In 1957, mining land took up 54% of the built-up area, which proved that it was a city built and developed by coal mining activity. With the large expansion of mining activity in 1958, a lot of people flowed in and the built-up area expanded dramatically. In 1985, the population reached 309,912, about 10 times as that in 1957. The proportion of mining land in built-up area declined to 18.68% as the living area was built near mining deposits. From 1985-2000, after the implementation of reform and opening-up policy, mining activity entered into its golden period, representing a dynamic index of 6.15% which was the highest among the three indexes. Meanwhile, due to low access threshold, a lot of small and irregular deposits occurred, causing a series of problems such as surface subsidence and tailing stacking. From 2000-2015, after entering into the new century, the increase rate declined, representing a 2.51% dynamic index. Problems as environmental pollution, resource depletion were the main causes.

**Figure 2.** Land cover map in 1957, 1985, 2000 and 2015 in the study area
Table 5. The dynamic change of mining land from 1957 to 2015 in Qitaihe city

| Item                        | 1957  | 1985  | 2000  | 2015  |
|-----------------------------|-------|-------|-------|-------|
| Mining land area (km$^2$)   | 8.92  | 19.33 | 36.94 | 50.87 |
| % of total built-up area    | 54%   | 18.68%| 31.05%| 26.85%|
| Increased area of miningland (km$^2$) / R(%) | /     | 10.46 | 17.89 | 14.06 |
| /                           | /     | 4.19  | 6.15  | 2.51  |

4.1.3. Type of mining land change  Mining activity can cause the change of other types of land cover. In a mining city, different types of land cover have different ability to protect the ecological environment. Thus, it is significant to monitor the land cover changes caused by expansion of mining activity. Table 3 presented the main types of land cover transferring to mining land during 58 years. Here, we define a ratio, equal to the size of each land type transferring to mining land divided by the total size of mining regions in corresponding period, as a quantitative parameter shown in Table 2.

As was shown in Table 6, one can see that from 1957-1985, forest was found to be the most contribution to the mining land (18.17km$^2$, 94%), which indicated that mining activity expanded at the cost of deforestation at the early stage of Qitaihe’s development. From 1985-2000, the gain in mining land area was largely from cultivated land (12.36 km$^2$, 33.16%), then urban land (12.28 km$^2$, 32.95%) and mining land itself (7.96 km$^2$, 21.36%). Cultivated land was severely spoiled by expansion of mining activity during this period. From 2000-2015, cultivated land (23.21 km$^2$, 45.21%) continued playing a dominant role in the increase of mining land, then mining land (14.55, 28.35%) and forest land (7.93km$^2$, 15.45). So the conclusion could be drawn that the increase in mining land was largely taken from cultivated land, especially in the last 30 years. Forest land and construction land were affected by the mining expansion too. Besides, the rate of mining land transferring to mining land kept increasing (3.97% from 1957-1985, 21.36% from 1985-2000, and 28.35% from 2000-2015), indicating that the mining activity expanded on the basis of its own scale.

Table 6. Transfer matrix of the mining region from the six land cover types in 58 years.

| Type of land cover    | 1957-1985 | 1985-2000 | 2000-2015 |
|-----------------------|-----------|-----------|-----------|
| Area (km$^2$)         | Rate (%)  | Area (km$^2$) | Rate (%)  | Area (km$^2$) | Rate (%)  |
| Cultivated land       | 0         | 0         | 12.36     | 33.16       | 23.21     | 45.21     |
| Forest                | 18.17     | 94%       | 3.77      | 10.12       | 7.93      | 15.45     |
| Grass land            | 0.23      | 1.19%     | 0.80      | 2.15        | 0.56      | 1.09      |
| Construction land     | 0.04      | 0.21%     | 12.28     | 32.95       | 5.07      | 9.88      |
| Mining land           | 0.77      | 3.97%     | 7.96      | 21.36       | 14.55     | 28.35     |
| Unused land           | 0.17      | 0.88%     | 0.1       | 0.27        | 0         | 0         |
| Water area            | 0         | 0         | 0         | 0           | 0         | 0         |

4.2. Landscape pattern change of mining land  Landscape indexes including PD, MPS, LPI and DIVISION were calculated using Fragstats 4.2 (see Table 7) to analyze the dominance, fragmentation and division degree of mining land.

Largest patch index (LPI) was a measure of dominance. The rising curve indicated that mining land became more and more important in the study area. The rising trend was more obvious from 1957 to 1985. Patch density (PD) and Mean patch size (MPS) were indicators for fragmentation and heterogeneity. Fragmentation means breaking up of habitat, ecosystem or land cover types into smaller parcels [17]. Figure 3 showed that PD increased from 1957 to 1985 and then declined from 1985 to 2015, while MPS showed an opposite trend. This implied that in 1985, the mining land was the most dispersed distributed. After 1985, some related mining regulations were enacted to limit the small mines and regular the large ones, so the fragmentation degree declined and the mining land became more integrated than that in 1985.
DIVISION (Landscape division index) referred to the dispersed degree of spatial distribution for different land types. The division degree kept declining through the study period. The highest decline rate was seen from 1985 to 2000, indicating that mining land become more integrated during this period.

So the conclusion can be drawn that the large expansion of mining activity made the mining land more and more important in the study area. The year 1985 had seen the largest fragmentation degree, which showed that mining activity was conducted disorderly at the first stage of exploitation, but then the situation improved in the following 30 years. As mining land become more integrated and industrialized, more policies should be constituted to promote its further development.

|        | 1957 | 1985 | 2000 | 2015 |
|--------|------|------|------|------|
| LPI    | 0.13 | 0.22 | 0.28 | 0.33 |
| PD     | 3.36 | 5.84 | 3.6  | 2.77 |
| MPS    | 29.73| 17.26| 27.77| 36.08|
| DIVISION | 1.28 | 1.15 | 0.65 | 0.49 |

4.3. Spatial change of mining land

The evolution of mining activity can be also found in spatial distribution. Centroid algorithm was employed to better present the change trend (see Figure. 3).

Figure 3. The centroid change of mining land during 1957-2015.

In general, as was shown in Figure 3, centroids of mining land showed an eastward trend as time went by. But centroids shifted 0.01° westward from 1957-1985, showing that mining activity expanded at its own scale during this period. Mining activities started to shift eastwards after 1985, and the trend became more obvious during 2000-2015. The whole process transferred about 0.18° eastward, and 0.02° northward. To better present the spatial distribution of mining activity, four concentration circles were drawn using ArcGIS 10.X (see Figure.4). Circle 1 was the earliest concentration point that was formed in the city. In 1957, there was some small and scattered mining sites, and then the mining activity expanded quickly at its own scale, but until 1985, all the mining activity in the city gathered in circle 1, the west part of the city. Five large deposits were included in circle 1, including Xinjian, Xinxing, Taoshan, Xinli, and Dongfeng deposit. These five deposits are the...
earliest to be explored, and had the longest development period. Circle 1 was also where the former central urban district - Xinxing district located, but then the central district moved due to serious subsidence caused by large scale of mining activity.

Figure 4. Four mining circles in Qitaihe city

Mining activity moved eastward with the founding of new resources. After 1985, Circle 2, 3 & 4 occurred constantly. Circle 2 included Tiedong, Fuqiang and Longhu deposit. These deposits had the relatively long development period only second to the deposits in circle 1, and higher development level as well. On the contrary, the eastern circle 3&4 were not well developed yet, including Lushan coal deposits and Beixing farm mining sites. These deposits were the main object of future mining activity.

The spatial transfer of mining activities was closely linked with the condition of coal resources, especially the occurrence condition of coal seams. The coal field in the city showed an arched structure, with more stable and simpler structure in the west flank than in the east [18], so the deposits in Circle 1, as located in the west flank, was the easiest to explore and had the longest development period.

The second point that matters was the problem caused by coal mining. Mining subsidence was the important factor that largely hindered the development of the city. The expansion of mining activity accelerated the surface collapse. In 1985, the collapse appeared in circle 1, and then in Circle 2 in the year 2000. The collapse area accounted for 10.3% of the total coal field area at the beginning of new century. In 2011, 30.7% of the main urban area was mine-out and subsidence areas. Large area of subsidence in Xinxing district caused damages to roads and houses as well as city’s infrastructure, disturbing resident’s daily life, so the central urban district removed twice, once from Xinxing to Beishan district, and finally to Taonan district [19]. The frequent removal of the main central area also caused a lot of resource waste to the city.
5. Discussion
Since the city of Qitaihe was listed as the transition pilot city in 2009, a series of polices have been enacted to promote its future development, among these, the coordination between economic development and environmental protection were highly emphasized. However, as the coal deposits in the city are differing in their development stages, policies were not applicable to all areas. Suggestions were given that an integrated layout of mining activity is needed, and different mining areas should adopt different development policies.

First at all, reclamation work was highly recommended in the western subsidence region. Reclamation of these sites in the vicinity of mining areas plays an important and significant role in regenerating ecosystem health and regional ecological security [20]. According to the mining plan of Qitaihe city (2009-2015), the reclamation work remained a tough one. About 3.63 km² deserted land needed to be reclaimed, including abandoned stones, stacking tailings and surface subsidence. Different subsidence areas were supposed to adopt different reclamation methods. In Xinxing district, the subsidence area is mostly surrounded by cultivated land, so it could be reclaimed as cultivated land, while In Taoshan district, the subsidence had an easy access to the main urban area, so reorganizing the land for construction should be the reclamation object.

Environmental protection should also be emphasized in the process of building the eastern coal mining base in the city. Efforts must be made to regulate mining activity and develop large-scaled mines while limiting small ones. To avoid wasting resources, living areas should be separated from mining areas. Furthermore, intensive exploitation was supposed to replace the former extensive way in the future mining work.

In addition, attention should be paid to the fact that the city is also characterized by a large area of forestry, as it has the world’s largest artificial Korean pine forest. The expansion of mining activity has also destroyed the forest, resulting in the loss of biological diversity and a rise in ecological vulnerability. Though the extent of the damage to the ecological processes due to mining activity is not well estimated from this paper, future work should be conducted in this area.

6. Conclusions
This study analyzed mining land in Qitaihe city over a period of 58 years. This analysis was based on remote sensing data, as well as their dynamic spatial and temporal distribution variation. Results showed that mining activity expanded at a fast pace. The area of mining land increased by about 6 times its original area with the fastest increase happening between 1985 and 2000. Cultivated land, as the crucial land cover type for northeastern China, contributed most to the increase of mining regions.

The large increase in mining activity made the mining land more and more important in the study area. Mining activity was largely carried out in a disorganized fashion before 1985, but then become more integrated and industrialized in the following 30 years with the implementation of related regulations. Moreover, the spatial location of mining activity transferred eastward and developed from one concentration circle to four circles. Mining activity also directly contributed to a series of socioeconomic problems, such as subsidence and stacking of tailings, the relocation of urban centers and a direct and detrimental effect on urban development. The monitored results provide evidence for managers to evaluate the effects of mining activity in order to constitute new planning for the continued sustainable development of mining activity.

The study further showed that dynamic monitoring of the mining activity by means of multi-temporal remote sensing images was a highly efficient and feasible technique, which provides scientific criteria for reasonable planning and decision-making in urban management.

Despite the promising results, there are also limitations on the accuracy of the remote sensing data. The main constraints are the long time interval and a lack of experienced visual interpreters. We believed that if more images are used at a shorter time interval, and more quantitative methods are employed in the analytical part, monitoring of mining activity will become more objective and effective.
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