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ARTICLE

Vegetation Changes in Alberta Oil Sands, Canada, Based on Remotely Sensed Data from 1995 to 2020

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ABSTRACT

There are rich oil and gas resources in Alberta oil sand mining area in Canada. In the 1960s, the Canadian government decided to increase the mining intensity. However, the exploitation will bring many adverse effects. In recent years, more people pay attention to the environmental protection and ecological restoration of mining areas, such as issues related to changes in vegetated lands. Thus, the authors used the Landsat-5 TM and Landsat-8 OLI remote sensing images as the basic data sources, and obtained the land cover classification maps from 1995 to 2020 by ENVI. Based on the NDVI, NDMI and RVI, three images in each period are processed and output to explore the long-term impact of exploitation. The results show that from 1995 to 2020, the proportion of vegetation around mining areas decreased sharply, the scale of construction land in the mining area increased, and the vegetated land was changed to land types such as tailings ponds, oil sand mines and other land types. In addition, three vegetation indexes decreased from 1995 to 2020. Although the exploitation of oil sand mining areas brings great economic benefits, the environmental protection (especially vegetation) in oil sand mining areas should be paid more attention.

1. Introduction

As the world economy grows, so does the population, and energy demand is increasing. In order to meet human needs, the intensity of energy development is also increasing, which will inevitably have many negative impacts on the ecological environment [1]. For example, the impact of oil sands mining on the environment has always been a serious problem, mainly as follows: (1) The mining of oil sands requires removal of surface vegetation to destroy the original forest ecosystem; (2) The hot washing of oil sands requires a lot of water resources; (3) The oil sands mining process has adverse effects on the atmospheric environment.

Oil sands resources in Alberta province are mined mainly by open-air and gas injection mining according to the depth. In the process of gradually opening this, it

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has brought many effects to the mining area and its surrounding environment and ecology, such as air pollution, massive damage of vegetation forest, vegetation health damage, and regional temperature rise, etc. Among them, vegetation is an important indicator in ecological environment monitoring [2]. Besides, an important goal of monitoring vegetation status is to provide data to assess and predict the effects of the combined effects of various factors. The long-term impact on an ecosystem is caused not only by mining areas, but also by their combined effects [3]. Remote sensing technology has the advantages of speed, accuracy and economy in obtaining large-scale and periodic land, ocean and atmospheric data, the access to land and high-level technical means to obtain information also play an important role in vegetation research [4,5]. Therefore, in this study, USGS Landsat-5 TM and Landsat-8 OLI remotely sensed images were used as the basic data sources; three vegetation indexes (NDVI, NDMI and RVI) of Alberta oil sand mining area from 1995 to 2020 are processed and output to explore the long-term impact of the vegetation in the mining area and its surrounding areas.

2. Materials and Methods

The time series of this paper spans 25 years from 1995 to 2020. Landsat-5 TM and Landsat-8 OLI/TIRS remote sensing data are used according to the year basic data source. Landsat-8 OLI/TIRS remote sensing data are used for 2015 and 2020 data, and Landsat-5 TM remote sensing data are used for other time nodes. Landsat images covering the study area in summer of 1995, 2000, 2005, 2010, 2015 and 2020 are obtained from these data sources. The spectral values of the images are functions of the current phenological conditions, especially for broad-leaved forest ecosystems. In order to limit the impact, we choose the image time to tilt up in the same season [6]. All image requirements are of high quality and have little cloud or mist to hinder the atmosphere.

This paper selects remote sensing geological images of Alberta province from 1995 to 2020 to understand the changes of the research area and the development and mining process of the mining area in 25 years. Among them, Landsat-5 TM data from 1995, 2000, 2005 and 2010 were used before 2013, while Landsat-8 TM/OLI data could be used in 2015 and 2020. The remote sensing image data involved in this paper are detailed in Table 1. All of the data were preprocessed.

3. Study Area

The northeastern Alberta province has a storage area of about 14,000 square kilometers, the world's second largest oil store in the world after Saudi Arabia. This paper selects the core area of oil sand mining area, and the land area is about 4687 square kilometers. The three main areas of oil sands in Alberta province are Athabasca, Cold Lake and Peace River. About 80% of the available asphalt is located in the Athabasca oil sands mine [7].

3.1 Geographic Settings

The geographical area of the Alberta is located at 57°-58°N, 111°-112°W. As Figure 1 shows, Alberta Province is located in the west of Canada, and the oil sands deposit is the largest around the world [8]. The three main areas of the Alberta oil sands are Athabasca, Cold Lake and Peace River. Athabasca is the largest and most widely developed region in the world [9].

Table 1. Remote sensing image data in the study area.

Satellite name	Date	Time	Cloud	Latitude	Longitude
Landsat-8	20200818	18:34	0.36	57°19’18.62”N	112°18’23.91”W
Landsat-8	20150602	18:33	0	57°19’16.27”N	112°02’23.36”W
Landsat-5	20100722	18:24	9	57°19’24.31”N	111°16’25.33”W
Landsat-5	20050530	18:15	0	57°19’19.81”N	111°14’17.02”W
Landsat-5	20000615	18:06	0	57°19’22.41”N	111°23’34.37”W
Landsat-5	19950804	17:29	0	57°19’19.34”N	111°02’38.12”W

Figure 1. Map of Alberta Province, Canada [10].

3.2 Geologic Settings

The study area is located in the Alberta province of western Canada, and its main oil sands resources are distributed in the Western Canada Basin, occurring in the lower Cretaceous Mannville group McMurray formation Wabisca member, belonging to the typical craton basin. Alberta basin tectonic evolution overall is the passive continental edge stage-early orogenic stage-foreland basin stage-orogenic zone landform formation stage. The mining of oil sand mining area mainly consists of three parts, specifically, Athabasca oil sand mining area, Cold Lake oil sand mining area and Peace River oil sand mining area. Among them, Athabasca oil sand mining area is the largest in scale.

3.3 Oil Sands

Oil sands are oil-soaked rock, because it contains natural asphalt sand or other rock, so also called asphalt sand. It contains two main meanings: one is the mixture of oil in sand and other rock-forming minerals; the other is the crude oil in the blend [11]. When indicating this meaning, oil sands and asphalt sands are the same [12]. The first project in the world was processed by Great Oil Sands Company, which was licensed to operate the oil sands as early as 1964. But because the technology was relatively backward, mining capacity was limited. Until the 1990s as oil sands resources were paid more and more attention [13], conventional oil and gas had not met the needs of human, because of the innovation of oil sands mining technology, Alberta province gradually established a perfect oil sands open pit mining process.

The current more used mature mining methods include open pit mining and in-situ mining [14], which mining method mainly depends on the depth of oil sands deposit. Generally speaking, buried less than 75 meters using open pit mining, buried more than 75 meters of oil sand ore belt needs to peel off the thick cover layer and often use in-situ mining [15].

For Alberta province oil sand mining area, the open-pit mining method is mainly used in the early stage of mining, and the surface oil sand mine is mined in the simplest way. With the mining, to obtain a deep layer of oil sand ore resources, it is necessary to combine the in-situ mining method.

4. Methodology

4.1 Method of Vegetation Change

In order to compare the changes of land vegetation area around Alberta oil sands mining area from 1995 to 2020, we adopted the supervised classification method in ENVI to judge the types of land cover in the study area according to previous research results and prior knowledge, which can be divided into five parts: vegetation, water body, settling ponds, oil sands mine and other land types. Images of vegetation areas circled by Region of Interest (ROI) in Figure 2.

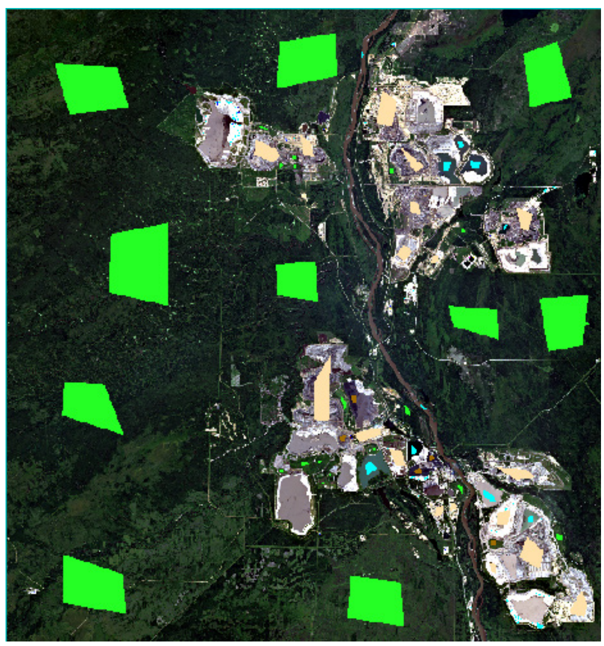

Figure 2. Visual interpretation of the study area.

We used Support Vector Machine (SVM) classification, which is a machine learning method based on Statistical Learning Theory. SVM can automatically find those support vectors that have a large discriminative ability for classification, thus constructing a classifier that can maximize the interval between classes. Therefore, it has good generalization and high classification accuracy.

4.2 Method of Spatiotemporal Variations

The most common method in the application of the vegetation index is to combine the reflectance of the wavelength with the characteristics of the vegetation [16]. The health of vegetation can be assessed by analyzing different vegetation indices, and then assess the environment [17]. Vegetation coverage can be fully reflected by the NDVI and other vegetation indexes inverted by the remotely sensed image, and is positively associated with them. Generally speaking, the better the vegetation coverage, the greater the vegetation index NDVI and RVI values, and then explore the vegetation water changes around the oil sands mining area combined with the NDMI value [18]. To clearly reflect the changes in vegetation cover in the oil sands area, we used the computer statistics tool in ENVI software to derive mean NDVI, NDMI and RVI values.

4.2.1 Normalized Vegetation Index (NDVI)

NDVI is defined as the difference between the reflectance of NIR band and visible red band divided by the sum of the reflectance of the two bands. For Landsat 8 OLI data [19], the calculation formula of NDVI is as follows:

$$NDVI = \frac{b_4 - b_5}{b_4 + b_5} \tag{1}$$

b_4 and b_5 are the reflectance of band 4 and band 5 of Landsat 8 OLI, respectively. The value of NDVI is in the range of [–1, 1]. Generally, the value of NDVI in non-vegetative areas (bare, aquifer, etc.) is low or negative, so is the city. The NDVI value of cultivated land and forest land with high vegetation coverage is higher [20]. NDVI can partially remove or weaken the influence of satellite observation angle, solar elevation angle, topographic relief, a small amount of cloud shadow and atmospheric radiation on the imaging [21]. Therefore, NDVI is widely used in vegetation research based on remote sensing images, and it is the best indicator of plant growth and coverage.

4.2.2 Normalized Vegetation Water Index (NDMI)

Due to the influence of water absorption band in mid-infrared band, vegetation index NDMI is very sensitive to humidity and water content information, and has a strong reflection on vegetation leaves in near infrared band. Therefore, NDMI is highly related to water content of vegetation (especially canopy and stem), which has been widely used in environmental protection and agricultural production, especially in the monitoring of surface humidity and crop growth [22]. The calculation formula of NDMI is as follows:

$$NDMI = \frac{b_5 - b_6}{b_5 + b_6} \tag{2}$$

b_5 and b_6 are the reflectance of band 5 and band 6 of Landsat 8 OLI, namely, the reflectance of near infrared and short wave infrared.

4.2.3 Ratio Vegetation Index (RVI)

As the vegetation coverage in the study area is generally high, RVI is more sensitive to the vegetation coverage area than other vegetation indexes, and has the best correlation with biomass. The RVI is the ratio of near infrared band (NIR) to visible red band (R):

$$RVI = \frac{b_5}{b_4} \tag{3}$$

b_4 and b_5 are the reflectance of band 4 and band 5 of Landsat 8 OLI, respectively. The range of RVI value is 0 - 30, the range of general green vegetation area is 2 - 8, and the RVI value of non-vegetation covered ground (mining land, water body, tailings pond, oil sand mine, etc.) is near 1. RVI has a high correlation with Leaf Area Index (LAI), leaf dry biomass and chlorophyll content, and is often used to analyze and estimate the vegetation coverage. The relationship between RVI and vegetation coverage is as follows: in areas with high vegetation coverage, vegetation has a great influence on RVI; in areas with low vegetation coverage, vegetation has little influence on RVI. In addition to the influence of vegetation coverage, atmospheric conditions also affect the RVI value, hence the remote sensing data can only be solved after atmospheric correction to obtain more accurate RVI value [23].

5. Result and Discussion

5.1 Results of Vegetation Change

The changing analysis of vegetation area is as follows:

(1) 1995

Figure 3 shows the interpretation image of the study area in 1995, and the changes of each type of areas are shown in Table 2. Most of the study area is covered by vegetation, and only Cold Lake oil sand mining area has been developed very much. Vegetation accounts for

95.636% of the whole area, water body accounts for 0.688%, settling ponds accounts for 0.247%, oil sand mine accounts for 0.021%, and other land types account for 3.408% of the total area. The area of vegetation removal in the study area is about 204.54 square kilometers, and the vegetation area is about 4482.46 square kilometers. In summary, the original landform is well preserved, and the impact of oil mining on the environment is limited.

(2) 2000

Figure 4 is the land cover image of the oil sand mining area in 2000, and the data of each type of areas are shown in Table 3. Athabasca oil sand mining area has been preliminarily developed, and Cold Lake oil sand mining area has become a new extended oil mine in the east part of the original mining area. The vegetation area accounts for 93.373% of the total area, water body accounts for 0.910%, settling ponds accounts for 0.713%, oil sand mine accounts for 0.032%, and other land types in the mining area account for 4.972%. The area of vegetation is 4376.39 square kilometers, which is 106.07 square kilometers less than that in 1995; the vegetation coverage rate in the study area is 93.373%, which is 2.263% less than that in 1995. Thus, the exploitation of oil sand mining area in Alberta province increased from 1995 to 2000, and new oil sand mining area was developed.

(3) 2005

Figure 5 is the interpretation image of the study area in 2005, and the data of specific mining area are shown in Table 4. During the period from 2000 to 2005, Athabasca oil sand mining area ushered in the peak period of mining, and Cold Lake oil sand mining area has also been widened very much. The vegetation area decreased from 93.373% in 2000 to 89.597%, the water area decreased from 0.910% in 2000 to 0.721%, the settling ponds increased from 0.713% in 2000 to 0.923%, and the oil sand mine increased from 0.032% in 2000 to 0.123%. During this period, with the development of the oil sand mine, a large number of vegetation continued to be removed, and the area of the oil sand mine doubled.

(4) 2010

Figure 6 is the interpretation image of the study area in 2010, and the changes of each type of areas are shown in Table 5. Compared with 2005, Athabasca has developed a new mining area in the east part of the original mining area, Cold Lake has basically completed the mining work, and Peace River has been opened up in the northwest of the study area. The proportion of vegetation area decreased from 89.597% in 2005 to 85.367%, water area increased from 0.721% to 0.833%, settling ponds increased from 0.923% to 1.459%, and oil sand mine increased from 0.123% to 0.206%.

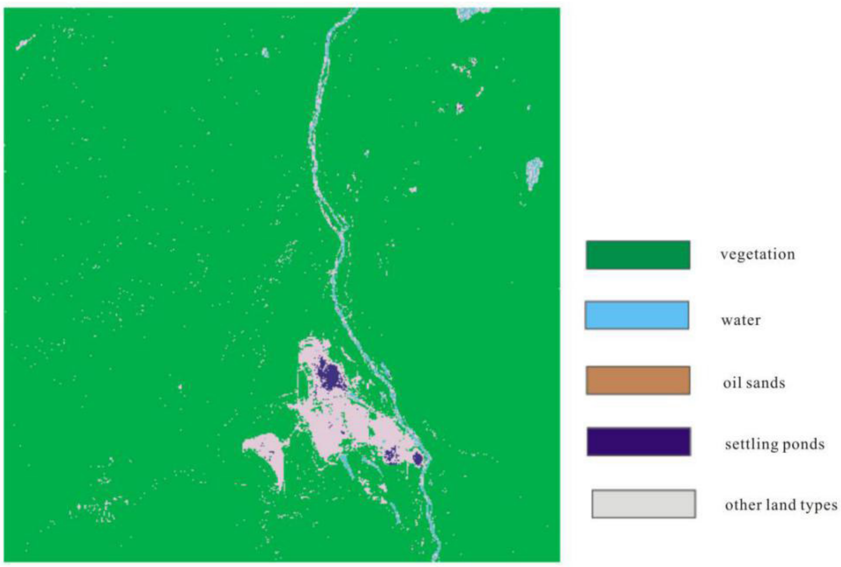

Figure 3. Land cover map of Alberta oil sand mining area in 1995.

Table 2. Areas of each type of Alberta oil sand mining area in 1995.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	4482.46	32.25	0.98	11.58	159.73	4687
Proportion/%	95.636%	0.688%	0.021%	0.247%	3.408%	100%

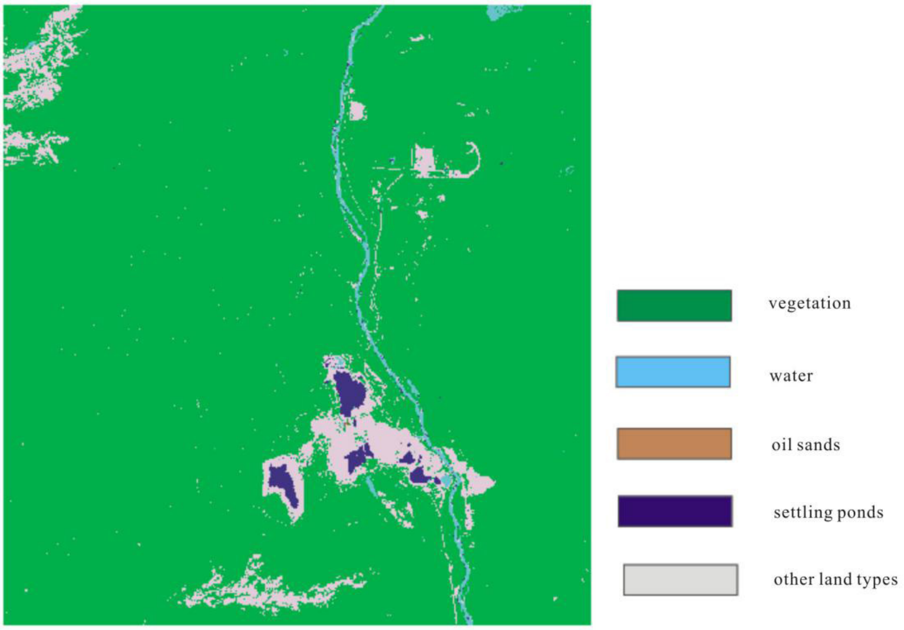

Figure 4. Land cover map of Alberta oil sand mining area in 2000.

Table 3. Areas of each part of Alberta oil sand mining area in 2000.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	4376.39	42.65	1.50	33.42	233.04	4687
Proportion/%	93.373%	0.910%	0.032%	0.713%	4.972%	100%

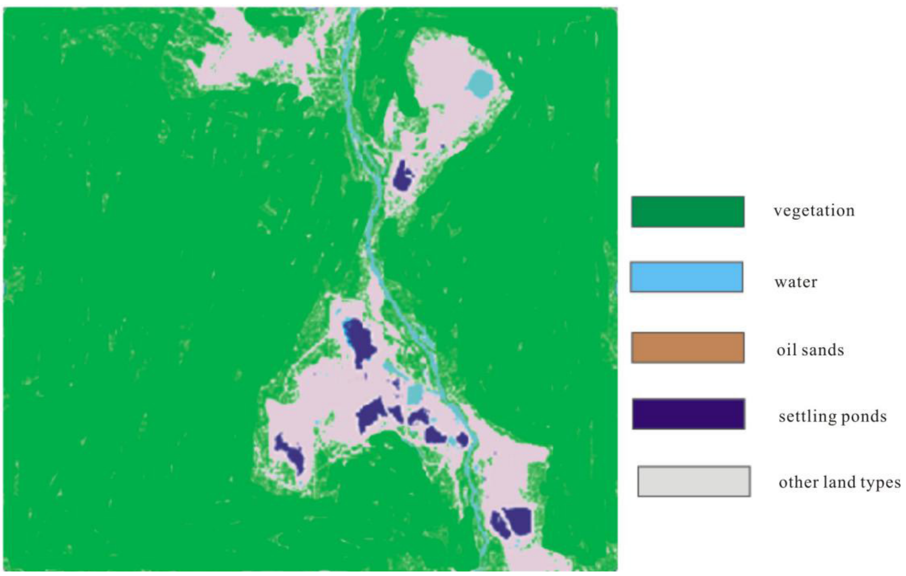

Figure 5. Land cover map of Alberta oil sand mining area in 2005.

Table 4. Area of each type of Alberta oil sand mining area in 2005.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	4199.41	33.79	5.76	43.26	404.77	4687
Proportion/%	89.597%	0.721%	0.123%	0.923%	8.636%	100%

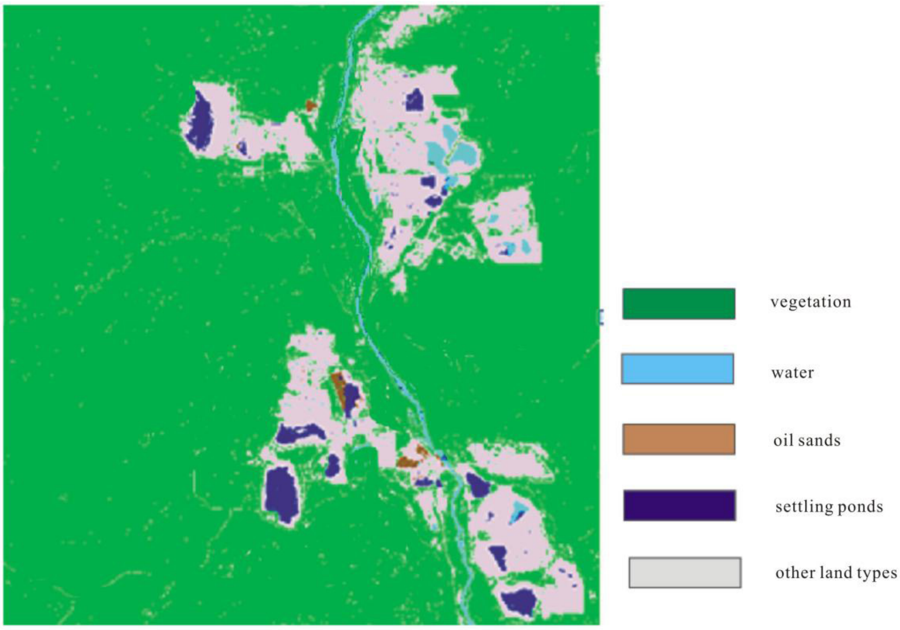

Figure 6. Land cover interpretation map of Alberta oil sand mining area in 2010.

Table 5. Area of each part of Alberta oil sand mining area in 2010.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	4001.15	39.04	9.66	68.38	568.77	4687
Proportion/%	85.367%	0.833%	0.206%	1.459%	12.135%	100%

(5) 2015

Figure 7 is the interpretation image of the study area in 2015, and the changes of specific mining area are shown in Table 6. Athabasca continued to develop, but the growth rate of Cold Lake slowed down from 2010 to 2015. The proportion of vegetation changed from 85.367% to 82.982%, water area increased from 0.833% to 0.964%, settling ponds increased from 1.459% to 1.513%, and oil sand mine increased from 0.206% to 0.234%.

(6) 2020

Figure 8 is the interpretation image of the study area in 2020, and the changes of each mining area are shown in Table 7. The areas of the three oil sand mining areas tend to be stable from 2015 to 2020, with less mining and less change in other land use areas. The proportion of vegetation in the whole study area decreased from 82.982% to 82.672%, the water area increased from 0.964% to 0.973%, the area of settling ponds increased from 1.513% to 1.521%, and the area of oil sand mine increased from 0.234% to 0.243%. The overall area of each type of the oil sand mining area changes very little and the overall environment of the mining area tends to be stable.

In summary, from 1995 to 2020, the proportion of vegetation decreased from 95.636% to 82.672%; water body increased from 0.688% to 0.973%; settling ponds increased from 0.247% to 1.521%; oil sand mine increased from 0.021% to 0.243%; other land use types increased from 3.408% to 14.591%. Only vegetation was reduced in the whole study area, and the removed vegetation was developed into settling ponds, oil sand mine, and so on. The change of the proportion of each land type in 25 years is shown in Figure 9.

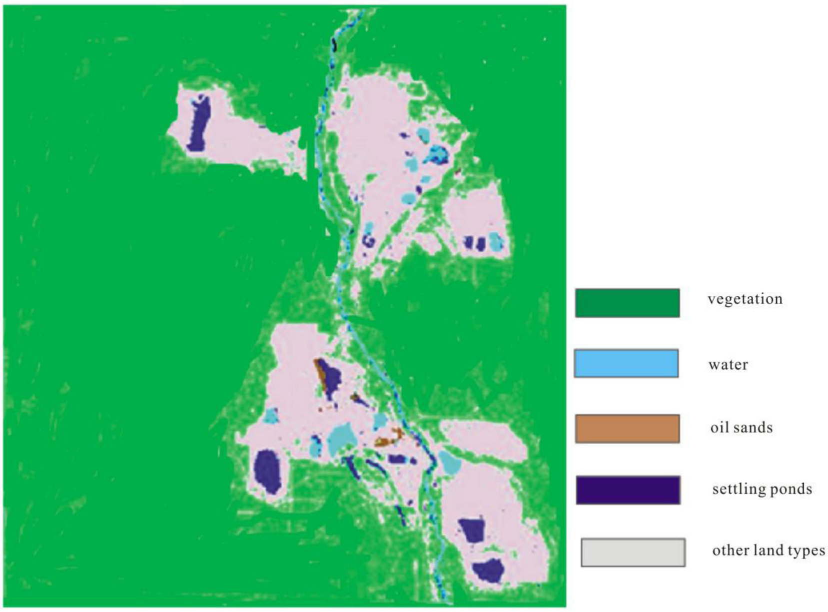

Figure 7. Land cover interpretation map of Alberta oil sand mining area in 2015.

Table 6. Areas of each type of Alberta oil sand mining area in 2015.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	3889.94	45.18	10.97	70.91	670.57	4687
Proportion/%	82.982%	0.964%	0.234%	1.513%	14.307%	100%

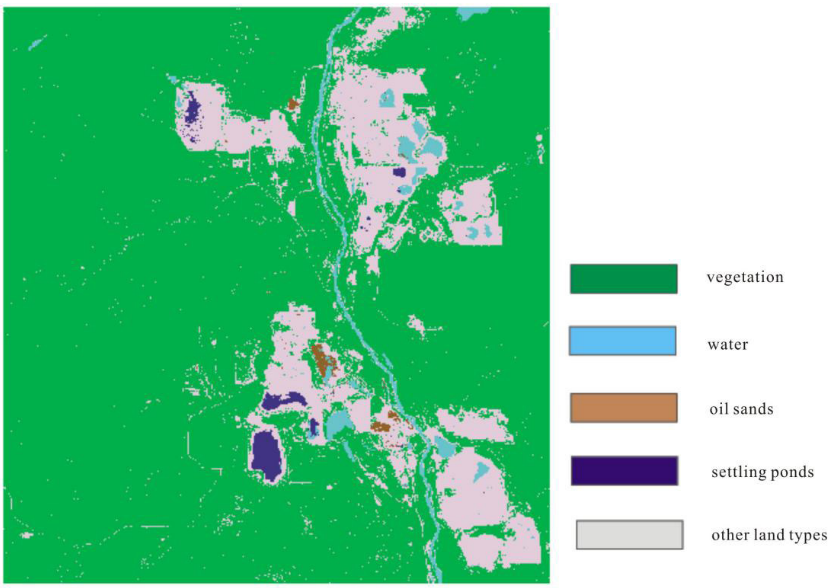

Figure 8. Land cover interpretation map of Alberta oil sand mining area in 2020.

Table 7. Area of each part of Alberta oil sand mining area in 2020.

Land use types	Vegetation	Water	Oil sands	Settling ponds	Other land types	Total
The measure of area/km²	3874.84	45.60	11.39	71.29	683.88	4687
Proportion/%	82.672%	0.973%	0.243%	1.521%	14.591%	100%

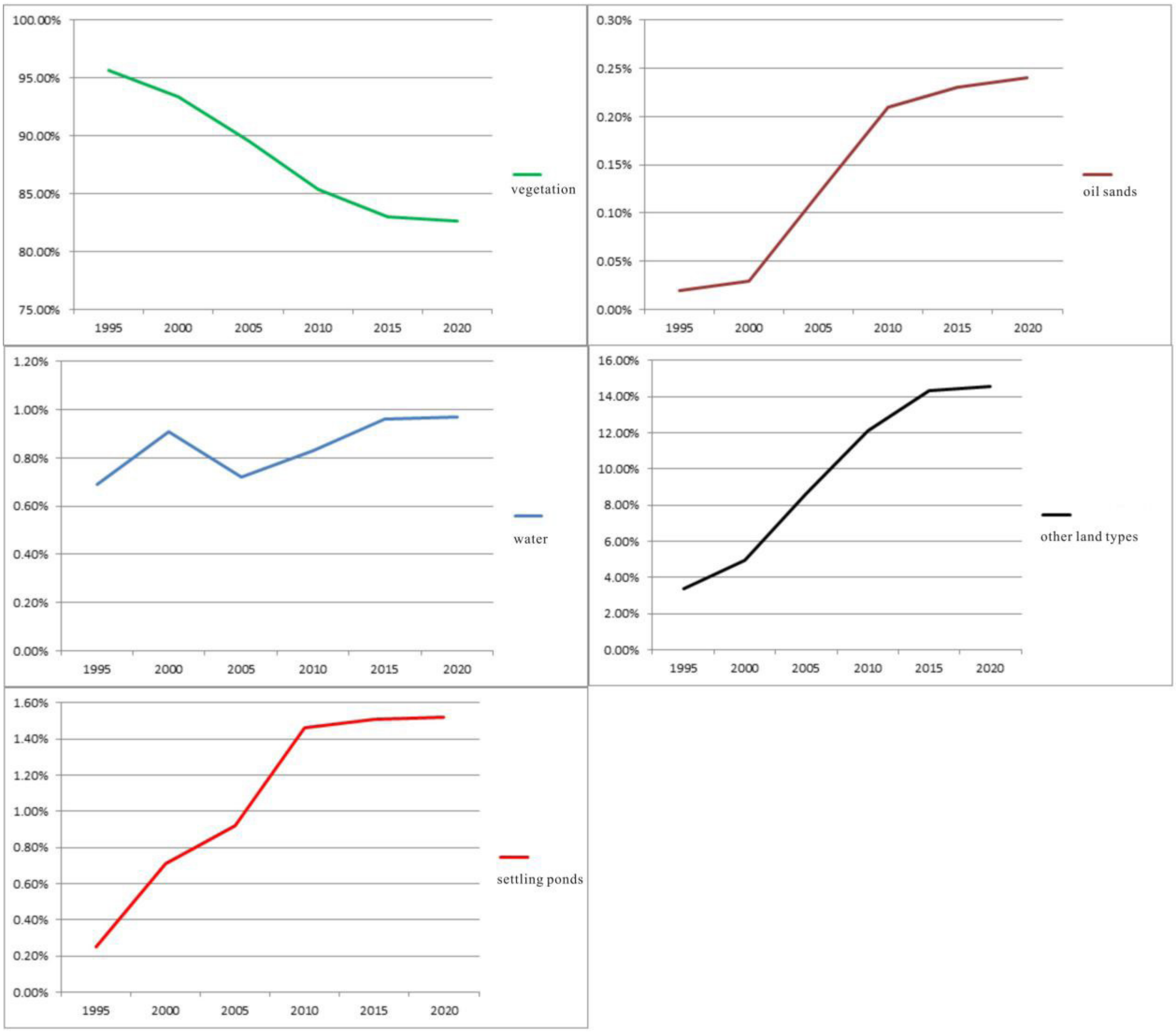

Figure 9. Proportion of different land types from 1995 to 2020.

From Figure 9, it can be seen that the proportion of vegetation in the study area decreases gradually from 1995 to 2020; the proportion of settling ponds, oil sand mine and other land types in the mining area shows an upward trend; the proportion of water body fluctuates up and down. Especially in 2000-2015, the change is particularly obvious, which indicates that the development and mining of oil sand mining area ushered in the peak during this period. In 2015-2020, the change of land cover type in the study area has been basically completed, and the change of land type is smaller than that in previous periods.

In order to show the change of vegetation in the study area from 1995 to 2020 more intuitively, we classify the land except vegetation as the area of oil sand mining area. The vegetation area of the study area was 4482.46 square kilometers in 1995, 4376.39 square kilometers in 2000, 4199.41 square kilometers in 2005, 4001.15 square kilometers in 2010, 3889.94 square kilometers in 2015 and 3874.84 square kilometers in 2020. The proportion of vegetation coverage is from 95.64% in 1995, 93.37% in 2000, 89.60% in 2005, 85.37% in 2010, 82.98% in 2015 to 82.67% in 2020. Figure 10 depicts the change of vegetation proportion in the study area from 1995 to 2020. From the result, it can be observed that the vegetation coverage in the oil sand mining area decreased more from 2000 to 2015, with a total of 375.24 square kilometers less. The vegetation proportion in the study area changed less from 1995 to 2000 and from 2015 to 2020.

From the above, we can obtain the results as follows:

(1) From 1995 to 2000 and from 2015 to 2020, the proportion of vegetation in and around the oil sand mining area changed little; from 2000 to 2015, with the peak period of oil sand mining area development, a large number of vegetation in the study area was removed, and the pro-

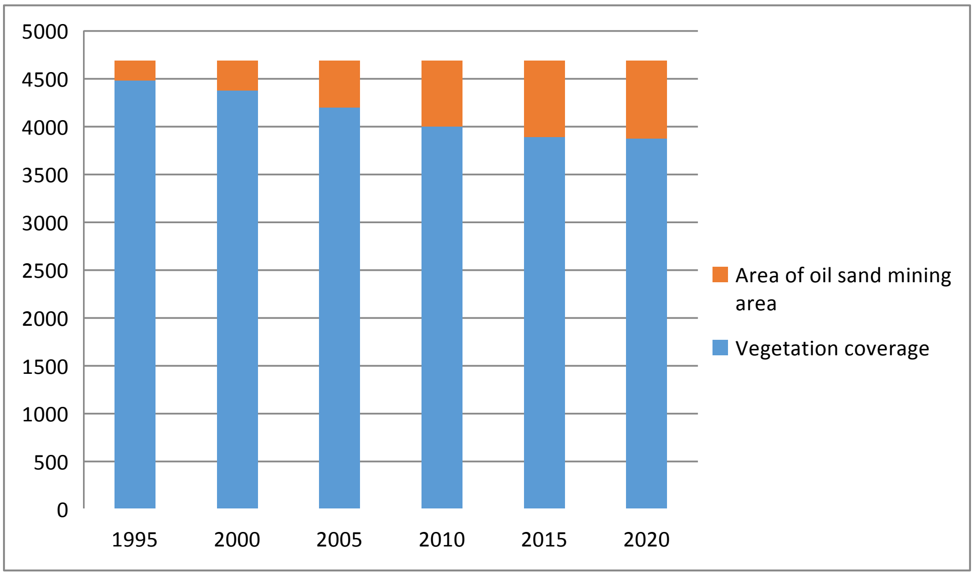

Figure 10. The change of vegetation areas from 1995 to 2020.

portion of vegetation decreased rapidly.

(2) The proportion of vegetation in the study area showed a downward trend; the proportion of settling ponds, oil sand mine and other land types in the mining area showed an upward trend; the proportion of water body fluctuated up and down. Especially in 2000-2015, this change is particularly obvious. During the period of 2015-2020, the development of oil sand mining area is basically completed, and the change of vegetation proportion in the study area is very small.

(3) From 1995 to 2020, only vegetation was reduced in the study area, and the original vegetation land was converted to tailings pond, oil sand mine and other land types in the mining area.

5.2 Results of Spatiotemporal Variations

The followings are the long-time change characteristics and analysis of the three vegetation indexes in the study area from 1995 to 2020.

5.2.1 Normalized Vegetation Index (NDVI)

Six remotely sensed images from 1995 to 2020 in Alberta oil sand mining area were preprocessed, parameter band operation and vegetation index were calculated, and the distribution maps of NDVI and time correlation index of oil sand mining area in 1995, 2000, 2005, 2010, 2015 and 2020 were obtained as shown in Figures 11-16.

According to the image analysis, the NDVI value in the north of the study area generally increased and the vegetation coverage increased from 1995 to 2000, while the NDVI value in the mining area decreased due to the development; with the rapid development of new mining areas from 2000 to 2005, 2005 to 2010 and 2010 to 2015, the NDVI value in the newly developed mining area de-

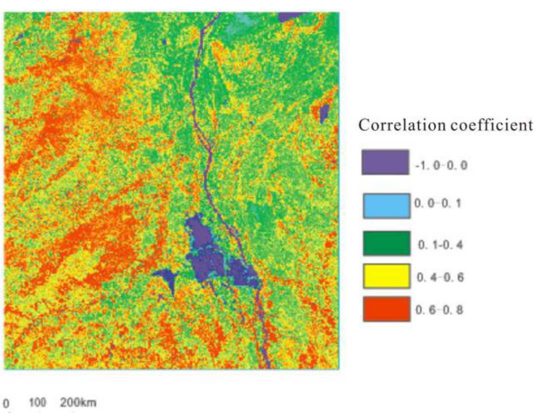

Figure 11. NDVI map in 1995.

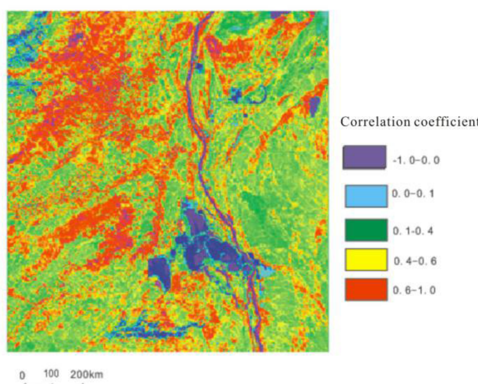

Figure 12. NDVI map in 2000.

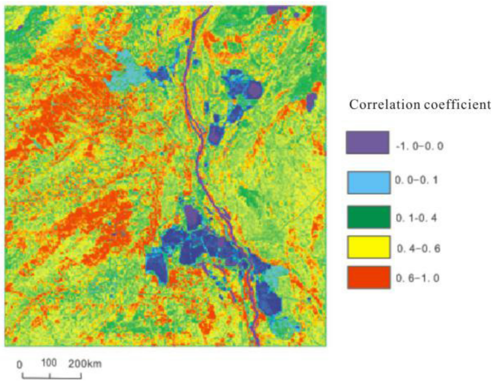

Figure 13. NDVI map in 2005.

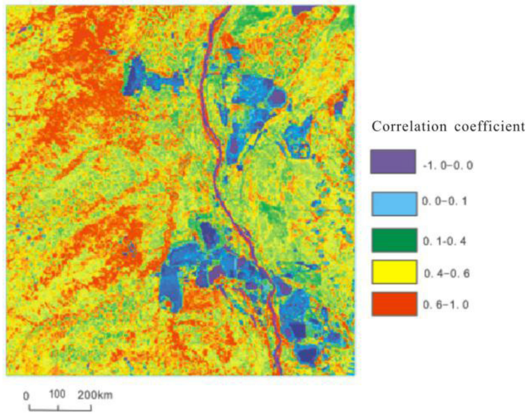

Figure 14. NDVI map in 2010.

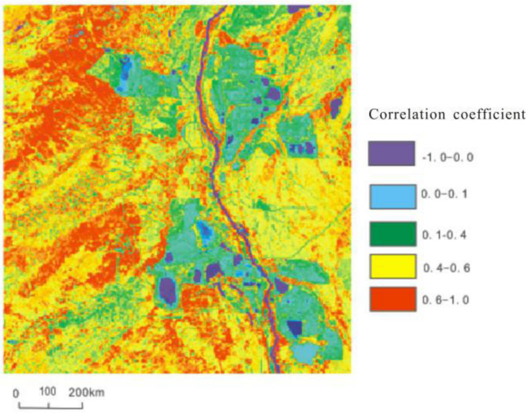

Figure 15. NDVI map in 2015.

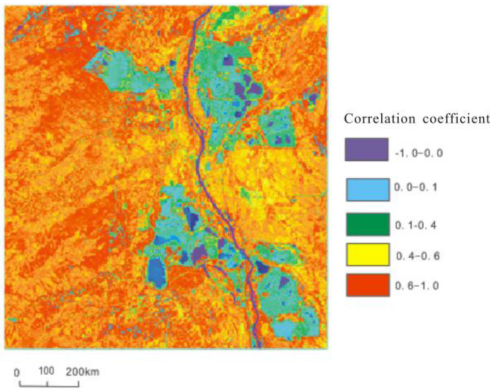

Figure 16. NDVI map in 2020.

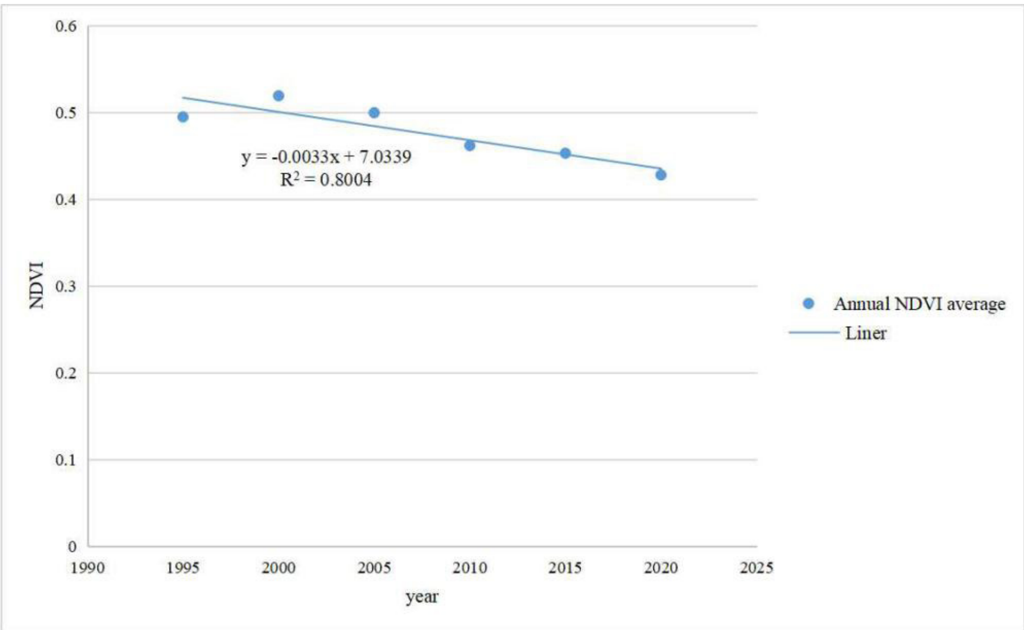

Figure 17. Change of NDVI mean values from 1995 to 2020.

creased and the vegetation was removed; the mining area was basically completed from 2015 to 2020, Combined with the policies of the local government of Canada, the forest around the oil sand mine is effectively protected, and the overall NDVI value around the mining area becomes larger. In order to further study the long-term correlation of NDVI value in the study area from 1995 to 2020, the average NDVI value in the study area is obtained by using the tool of compute statistics in ENVI software, and a long-term trend is observed. Figure 17 is the correlation between NDVI value and the related years. It can be clearly observed that the NDVI average value of the study area is decreasing from 1995 to 2020.

5.2.2 Normalized Vegetation Water Index (NDMI)

The distribution of NDMI and time correlation index in 1995, 2000, 2005, 2010, 2015 and 2020 are obtained by using band math tool after pretreatment and error elimination, which is the same as NDVI part (Figures 18-23).

From the above figures, it can be clearly observed that

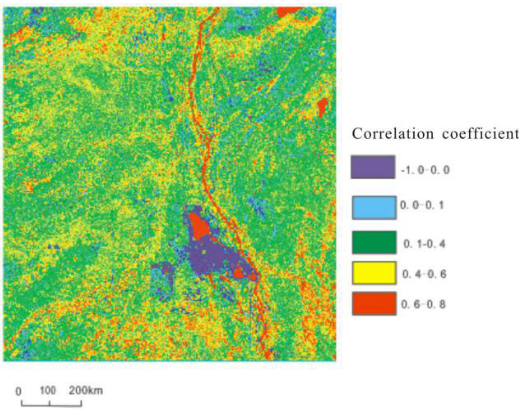

Figure 18. NDMI map in 1995.

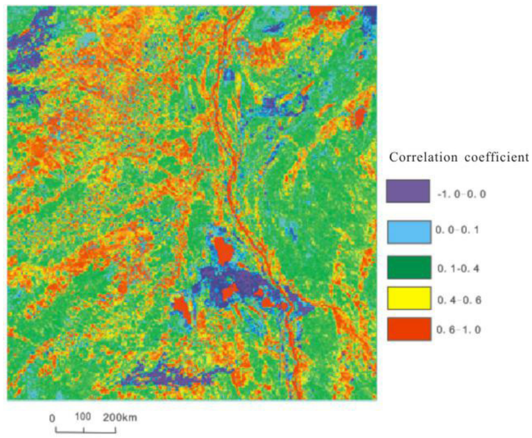

Figure 19. NDMI map in 2000.

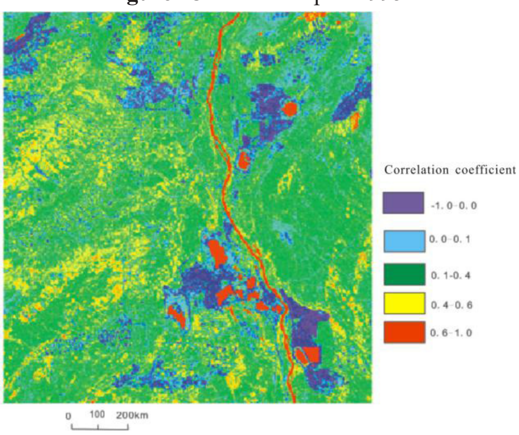

Figure 20. NDMI map in 2005.

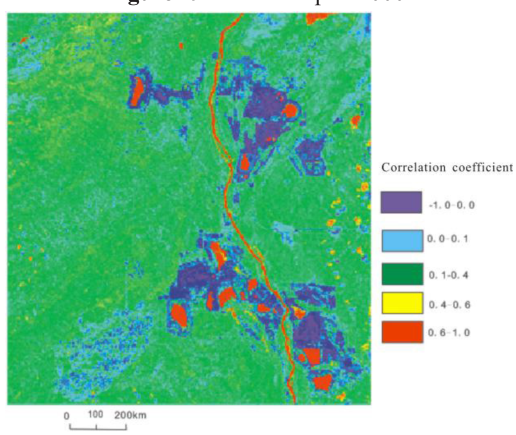

Figure 21. NDMI map in 2010.

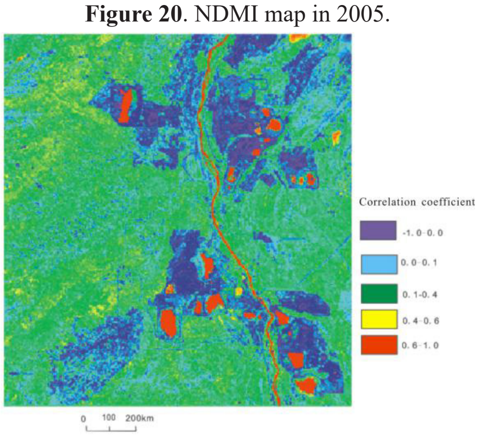

Figure 22. NDMI map in 2015.

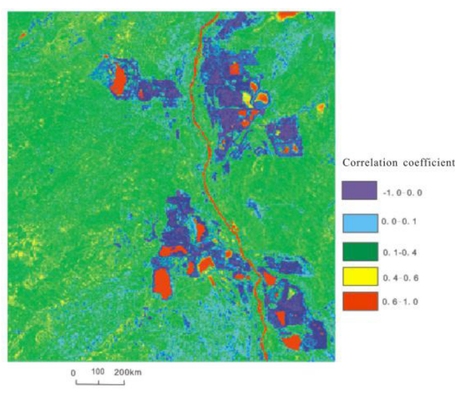

Figure 23. NDMI map in 2020.

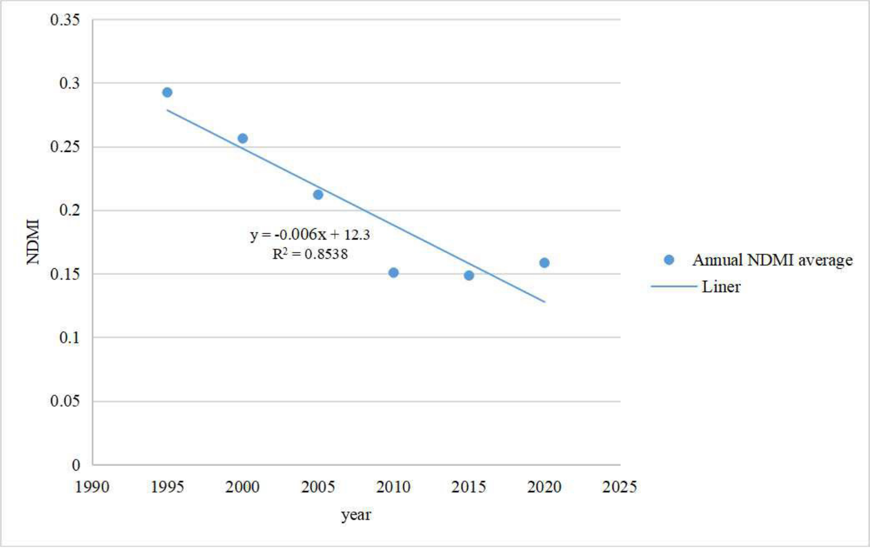

Figure 24. Change of NDMI mean values from 1995 to 2020.

there were more yellow and red in the forest area in 1995 and 2000, which proved that the NDMI value was larger and the water content of vegetation was higher in this period; 2000-2015 was the most rapid stage of the mining area, and in 2005, there were some yellow areas and some green areas in the forest area. In 2010, 2015 and 2020, most of the forest areas are green, and the NDMI value is small. Combined with the change of NDVI value in the previous part, it fully shows that with the development and mining of the mining area, although the vegetation coverage rate outside the mining area is still high, the water content of vegetation decreases seriously, and the health status of vegetation is greatly affected. In addition, because there are sand settling ponds and water bodies in the mining area, there are large red areas in the mining area from the images, and the NDMI value is high.

In order to further study a correlation of long-term changes of NDMI value from 1995 to 2020, the average NDMI value of the study area is obtained by using the tool of compute statistics in ENVI classic, and a long-term trend is observed. Figure 24 is the correlation between NDMI value and the related years. It can be clearly observed from the images that the average NDMI of the study area is decreasing from 1995 to 2020, especially from 1995 to 2010.

5.2.3 Ratio Vegetation Index (RVI)

After preprocessing and error elimination, band math tool is used to calculate the RVI and time correlation index distribution in 1995, 2000, 2005, 2010, 2015 and 2020 (Figures 25-30).

In order to further study the long-term change of RVI

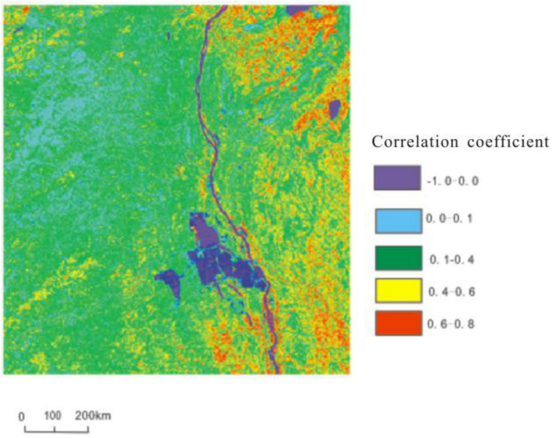

Figure 25. RVI map in 1995.

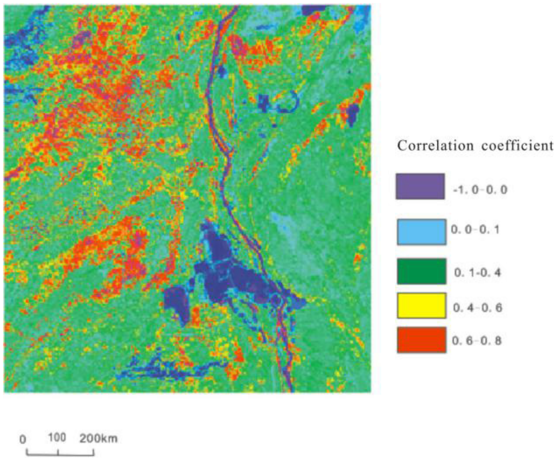

Figure 26. RVI map in 2000.

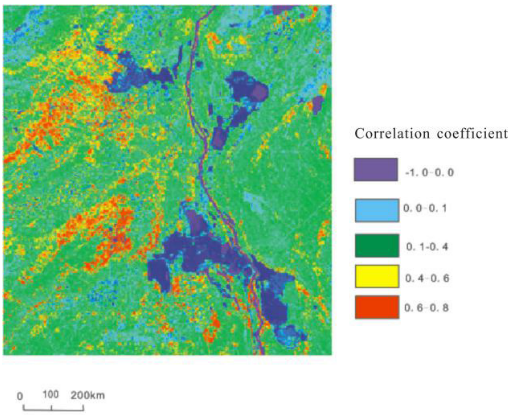

Figure 27. RVI map in 2005.

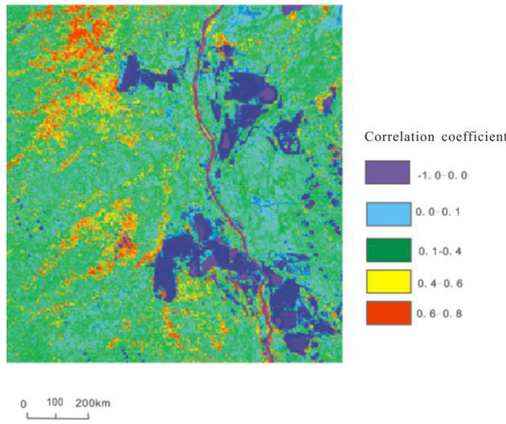

Figure 28. RVI map in 2010.

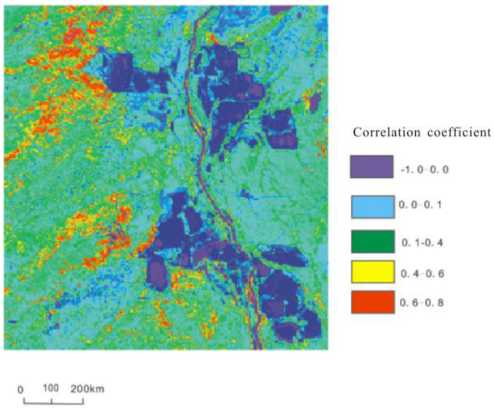

Figure 29. RVI map in 2015.

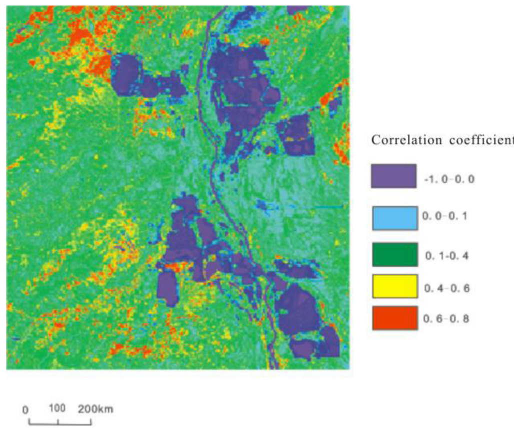

Figure 30. RVI map in 2020.

value in the study area from 1995 to 2020, the average RVI value is obtained by using compute statistics tool in ENVI software and a long-term trend is observed. As shown in Figure 31, the relationship between RVI value and the related years is shown. It can be clearly observed from the images that the RVI mean in the study area is decreasing from 1995 to 2020.

Finally, in order to understand the changes of three indexes in 25 years and the impact of development and exploitation of oil sand mining area on the environment (especially on vegetation), we list the average annual mean of three vegetation indexes (NDVI, NDMI and RVI) in Table 8.

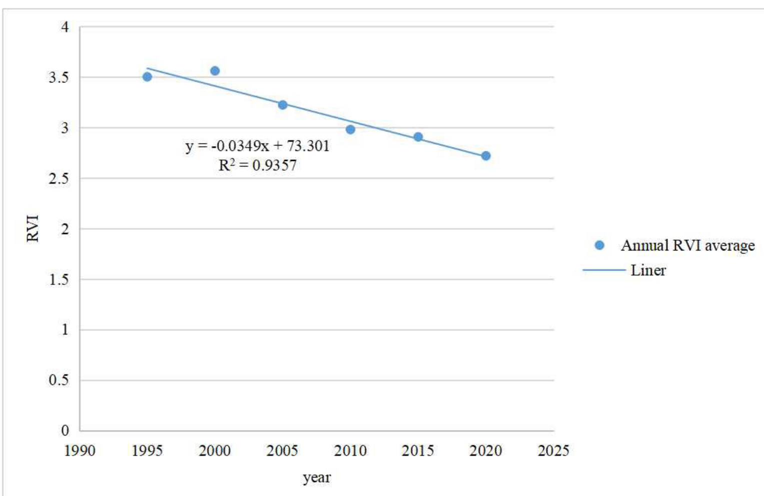

Figure 31. Annual variation of RVI mean values from 1995 to 2020.

Table 8. Corresponding lists of years and vegetation indexes.

Indexes \ Years	1995	2000	2005	2010	2015	2020
NDVI	0.494788	0.519125	0.499578	0.461666	0.452805	0.427828
NDMI	0.292505	0.256337	0.212075	0.150779	0.148542	0.158529
RVI	3.501492	3.559949	3.222617	2.979133	2.9065	2.71917

The results can be obtained from the above:

(1) From 1995 to 2020, with the development and exploitation of oil sand mining area in Alberta, the three vegetation indexes (NDVI, NDMI and RVI) showed a downward trend.

(2) From 2000 to 2010, the development of oil sand mining area is the fastest, and the corresponding vegetation index is also the fastest decline, especially RVI.

(3) From 1995 to 2005, the decrease of NDMI was much faster than that of NDVI, indicating that the development and exploitation of the mining area had a significant impact on the vegetation water content.

(4) The changes of NDVI and RVI are very similar, NDMI decreased significantly from 1995 to 2010, and tended to be stable from 2010 to 2020. It shows that the vegetation coverage decreased in the early mining period from 1995 to 2010, and the vegetation water content also decreased rapidly; after 2010, with the gradual improvement of mining area development, the vegetation coverage decreased slowly, and the change of NDMI tended to be stable.

6. Conclusions and Future Directions

Through the processing of USGS Landsat-5 TM and Landsat-8 OLI remotely sensed images, the distribution of vegetation in and around Alberta oil sand mining area and the long-term changes of three vegetation indexes (NDVI, NDMI and RVI) in 1995, 2000, 2005, 2010, 2015 and 2020 were obtained. Several conclusions and suggestions can be drawn as follows:

(1) The proportion of vegetation in the study area decreased sharply from 1995 to 2020, and the scale of construction land in the mining area increased. The development of the mining area led to the reclamation of vegetation and the proportion of vegetation decreased. Especially in 2000-2015, the period is the fastest stage for oil sand development; from 1995 to 2000, the development of oil sand mining area is slow, while that of Cold Lake oil sand mine increases slightly, and the development of Athabasca oil sand mine is just in the initial stage; from 2015 to 2020, the development of oil sand mining area is basically bound, which mainly involves mining and vegetation protection around the study area.

(2) From 1995 to 2020, with the development and exploitation of oil sands mining area in Alberta, the NDVI, NDMI and RVI are all declining. The period of 2000-2010 is the fastest stage of development of oil sand mining area, and the corresponding vegetation index is also the fastest, especially RVI. The decrease of NDMI in 1995-2005 was much faster than NDVI, which indicated that the development and exploitation of the mining area had a significant impact on vegetation water content. NDVI and RVI are similar in trend, and NDMI has declined significantly from 1995 to 2010, and tends to be stable from 2010 to 2020. It shows that the vegetation coverage decreased in the early mining period from 1995 to 2010, and the vegetation water content also decreased rapidly; after 2010, with the gradual improvement of mining area development, the vegetation coverage decreased slowly, and the change of NDMI tended to be stable.

(3) The Canadian government took some protection measures around 2015. While the oil sand mining area continues to start, the protection of vegetation around the study area is increased. It can be proved from the analysis of vegetation indexes. In 2015-2020, due to the implementation of various environmental protection, the vegetation coverage rate is basically unchanged, and NDMI even rises slightly, thus the vegetation protection has achieved initial results. Although the exploitation of oil sand mining area can bring great economic benefits, the environmental protection (especially vegetation) in and around oil sand mining area should be paid more attention.

Conflict of Interest

Authors declare no conflict of interests.

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