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REMOTE MONITORING DATA ON OPENCAST MINING AND DISTURBED LAND ECOLOGY IN THE BAKAL IRON ORE FIELD

Currently in the Middle and South Ural in Russia, opencast mining operations are being closed in many iron ore fields. Opencast iron ore mines are closed in the Magnitogorsk, Goroblagodat, Vysokogorsky, Bakal and Tukan fields. The Bakal siderite ore reserves total 1 billion tons, which governs inclusion of the deposit in the group of the world's largest iron ore provinces. At the closing stage of the Bakal field development (2007–2013), overburden dumping and iron ore haulage to processing plant were carried out using dump trucks with a capacity of 40–55 t. Mining equipment included excavators EKG-5A for overburden excavation and drill rigs SBSH-250 for drilling-and-blasting.

The long-term remote ecological monitoring of the mining-disturbed lands in the territory of the Bakal iron ore field estimates the rate of expansion in the area with vegetation ecosystem as 7.9 ha yearly. It is found that overburden dumps show the first signs of revegetation 2–3 years after dumping termination, and the mature grass cover appears on the surface of dumps in 5–6 years. Later on, in 10–12 on these dumps, young mixed forest shows itself and then becomes the mature forest in 16–18 years. All these facts confirm ecologically admissible rates of the planting ecosystem restoration in the course of self-planting of aboriginal wood and shrub species from the native areas adjoining the closed overburden dumps and open pits.

The total area of the disturbed lands occupied by the industrial landscape formed in the course of the Bakal iron ore mining totals 2065.9 ha in 2018. The areas containing all types of vegetation cover, including the areas showing revegetation, make 1588.7 ha. By the end of the monitoring period, the reestablishment of vegetation cover in the mining-disturbed lands is at the high level of 79.8 %.

Key words: *South Ural, Bakal iron ore field, opencast iron ore mines, truck-and-railroad car-piled dumps, earth remote sensing, ecological monitoring, vegetation ecosystems*
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Introduction

At the present time, many opencast iron ore mines are being closed in the Middle and South Ural, for example, in the Magnitogorsk, Goroblagodat, Vysokogorsky, Bakal and Tukan fields. Opencast mining leaves behind an industrial landscape with pits and waste heaps. One of such deposits, namely, the Baikal field being developed for 200 years, deserves paying a particular attention. Over the whole period of mining, the area of disturbed lands has exceeded 2000 ha. Extraction of iron ore has resulted in large-scale disfigurement of the natural landscape. This situation inspired interest of basic and applied researchers in long-term monitoring and valuation of ecological restoration efficiency in the industrial landscape area of opencast mining in the Baikal iron ore field in the conditions of a continental climate of the Ural.

Recently the restoration of the ecological balance in large-scale mining areas attracts close attention at mineral deposits of any type. Rehabilitation and reclamation of disturbed lands is in spotlight, which is duly reflected in the dedicated literature [1–16]. At the same time, the publications lack the research of open pit mining ecology using diverse resources of the remote sensing monitoring. Actually, the latter is a framework of revealing long-term trends in formation and development of ecosystems anywhere on the Erath, including regions of developed opencast hard mineral mining.

This gap in the scientific knowledge is bridged by our science school on remote sensing analysis of opencast mining areas disturbed lands.

Research results

All proven iron ore deposits in the territory of Russia can conditionally be grouped with respect to ore types, and a specific place will belong to the group of siderite ore deposits. Commercial fields of siderite ore lie in the west of the Chelyabinsk Region—Bakal field in the Satka district and Akhte field in the Kusa district. The Bakal iron ore field is located 70 km southwards of the Bakal town, Satka district, Chelyabinsk Region. The Bakal group is the world's largest group of siderite deposits [17]. The field is being under mining for more than 200 years, and high-grade bog iron ore reserves are almost depleted. In-place siderite makes 1 billion tons, which places the Baikal field amongst the largest iron ore provinces in the world. The field with an area of 150 km^2 holds more than 20 independent deposits composed of more than 200 ore bodies. The deposits are bounded by large tectonic dislocations. Siderite deposits are sheetlike and lenticular. The ore bodies reach 2 to 3 km in length, maximum thickness of 80 mm and occur at both gentle and steep angles. Siderite is iron carbonate ($FeCO_3$) with an isomorphous admixture of magnesium at 5–12% (up to 19%) and belongs in the isomorphic sideroplesite–pistomessite row of minerals. Admixture of sulfur and phosphorus is under 0.05%. The basic ore minerals are sideroplesite and pistomessite containing Fe (25–40%), Mg (7.5–19%), CaO (to 1.5–3%) and MnO (to 2%) making 80–95% of the total. The rest 5–20% are dolomite, ankerite and barite.

Large-scale development of the field was started in the 1950s when the USSR starved for iron ore. In the 1980s–90s the infrastructure of Bakal Mining and processing Plant (hereinafter Bakal GOK) included a sintering plant and 7 opencast mines. Overburden was removed using railway and road transport. Two dumps made using railroad cars had some layers piled using dump trucks [17].

Fig. 1. Satellite image fragment with the infrastructure and industrial landscape of opencast mining at Bakal GOK

For a period over 50 years, eight pits have been formed in the field. The pits are marked by figure 1 to 7 in **Fig. 1** as two pits are united under the same figure 2 in the curse of remote sensing [18, 19].

In 2007 Bakal GOK was shut down. Iron ore mining was restarted at opencast mines 1 and 3 in 2008–2013 and at opencast mine 5 in 2007–2009. The operations were stopped cold in 2011 as the exposed reserves were mined out.

OCM 1 reached the depth of 170 m, or 250 m including an upland part, OCM 3 and 5 were 230 and 169 m deep, respectively. At the late mining stage in the Bakal field (2007–2013), overburden dumping and iron ore haulage to processing plant was performed by dump trucks with a capacity of 40–55 t. Mining equipment involved excavators EKG-5A for mining and drill rigs SBSH-250 for drilling-and-blasting.

Disturbed land ecology

A maximum reliability estimate of the industrial landscape ecology is provided by different-time earth remote sensing (ERS). Prior to presenting ERS estimation results, it is decided to describe ecological influences such as climate, soil and natural vegetation cover. In the Satka district of the Bakal iron ore field occurrence, are temperature shows the absolute maximum at +36 °C and absolute minimum at 56 °C. Thus, the temperature amplitude is 92 °C. The annual average precipitation makes 652 mm. The great majority of annual precipitation, i.e. 84%, falls on the warm seasons (April–October), 60% out of which is in summer. In winter fall-out is low and ranges from 13 to 20 mm. The annual deficit of humidity is small: 1.2–4.4 mm in war seasons and 0.2–09 mm in cold seasons [20].

The territory under study is widely covered by softwood forest represented mainly by pine and larch with small addition of birch and aspen. Under the cover there is raspberry and black-fruit cotoneaster. In wetter shady forest, dense brushwood of fern is often met. Furthermore, the ground in pinery forest is covered with red grass, moss and lichens. In mixed forest, cowberry, blackberry and strawberry grow. Grass in this forest is often wintergreen, pipsissewa, red fescue, bluegrass and mountain melick. Taiga liana — Atragene sibirica — can also be met here. Uralian orchids registered in the Red Book are preserved in some nooks, namely, Cypripedium macranthon, Cypripedium calceolus and Cypripedium guttatum. Meadows and forest openings are sometimes covered with very popular vulnerary plants of marjoram and John's wood. The soil in the softwood forest is podsol.

The spatiotemporal analysis of change in the selected areas of the industrial landscape resulted from the Bakal iron ore field development as well as revegetation on the surface of overburden dumps and open pits was carried out using Landsat 5 and 8 images obtained over the period from 1995 to 2016. The types of the industrial landscape, soil structure and areal characteristics were determined with ArcGIS software package. At the preliminary stage, the objects were selected for the long-term monitoring with ERS.

Within the industrial landscape under analysis, eight opencast mines are delineated, with two of them united under the same figure, and ten overburden dumps (see Fig. 1). For the general understanding of the long-term trends in the formation and development of plant ecosystem on the surface of the dumps and mined-out pits, the industrial landscape is divided into five classes of the mature vegetation cover clearly seen in the satellite images: mature forest — forest crop; young forest—immature wood; areas showing revegetation; areas with grass cover and areas with grass and shrub vegetation.

The types of the vegetation are determined based on the spectral data obtained in the infrared, red and green ranges of long waves, which corresponds to the combination of channels RGB 4 3 2 for Landsat 5 TM and RGB 5 4 3 for Landsat 8 OLI. The choice of these channels in Landsat 5 TM and Landsat 8 OLI is governed by a considerable difference in reflectivity of different vegetation types.

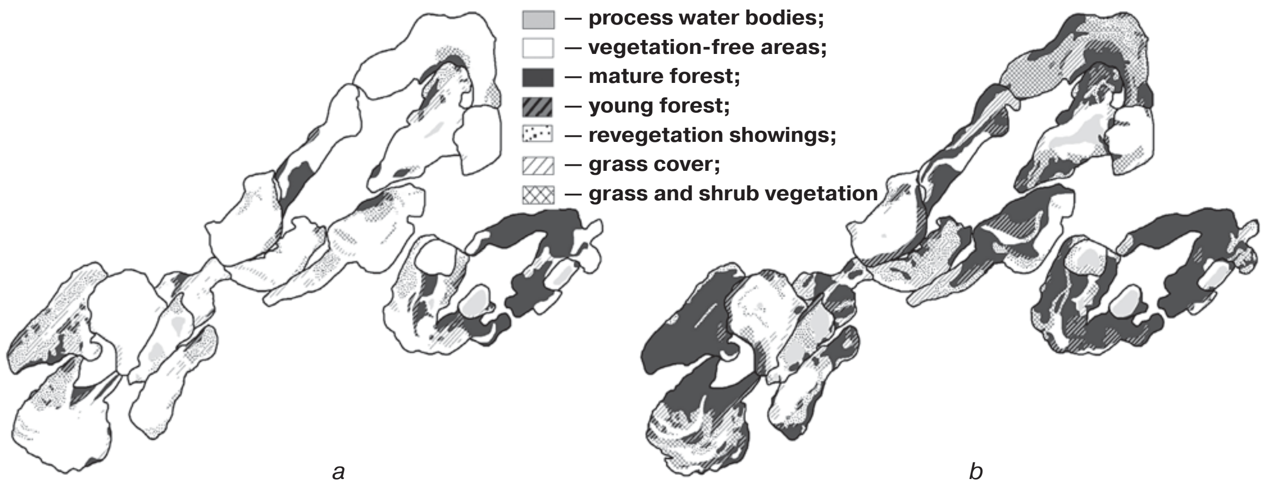

Fig. 2. Delineated objects of industrial landscape in Bakal field in satellite images with interpretation:
***a* — July 1995; *b* — July 2016**

Fig. 2 shows 1995 and 2016 images with the delineated objects of the industrial landscape resulted from operation of Bakal GOK, with the decoded data on the studied areas in accordance with the above classes.

All in all, in the territory of the mined-out opencast mines, seven classes of the industrial landscape are identified: areas with no vegetation cover; mine process water bodies; areas showing revegetation and four areas with stable plant formation. Total area of the opencast iron ore mines in the period of monitoring was 543.5 ha. The vegetation-free areas gradually shrank by more than 2 times, from 435.3 to 202.8 ha. The trends in the change in the areas with the other landscape classes are described below.

In the areas showing revegetation, the alternation of two downward trends and one upward trend is detected. From the orbital survey evidence, such areas were 27.3 ha in 1995. Starting from 1996, the areas reduced to 20.1 ha in 2007. Later, on, since 2008, the areas grew up to 50.5 ha. Then, starting from 2011, the size of the areas with revegetation decreased to 43.6 ha in 2016.

The areas with grassland vegetation also showed the alternating downward and upward trends. By the satellite data in 1995, such areas made 32.3 ha. Since 1996, the areas reduced a little to 32.1 ha in 2001. Then, a gradual increase in the areas was observed to 42.4 ha in 2016.

The change in the young mixed forest areas shows an alternation of two upward trends and one downward trend. This class vegetation covered the area of 6.6 ha in 1995. Starting from 1996, the areas grew almost 5 times up to 30.2 ha in 2007. Afterwards, since 2008 the figure jumped 2 times down to 16.3 ha in 2010. However, in 2011 at the final stage of mining operation, the young forest areas began expanding up to 58.2 ha in 2016.

The change in the areas with the mature mixed forest shows an upward trend. By the satellite survey evidence of 1995, this type of vegetation covered the area of 12.6 ha. Since 1996, such areas started continuously expanding. By 2016 the areas grew by 6.6 times up to 84.3 ha.

The areas with the grass and shrub vegetation changed with the alternating upward and downward trends. According to the satellite images in 1995, these areas were merely 1.7 ha. Starting from 1996 such areas increased more than 23 times and reached 40.4 ha in 2010. Later on, a gradual decrease was observed in the areas down to 32.4 ha in 2016.

In the change in the area occupied y the mine process water bodies, a single upward trend is detected. By the satellite survey data, such area was 27.7 ha in 1995. Since 1996 the areas started gradually growing and reached 71.4 ha by 2016.

In 2018 the structure of the disturbed lands represented by the areas free from vegetation cover, with vegetation and water ecosystem in the territory of mined-out open pits is as follows. Mine process water bodies cover the area of 75 ha. The areas containing all kinds of vegetation cover, excluding the areas showing no revegetation, total 223.1 ha. The self-restoring coefficient of the plant ecosystem is 0.41.

The ecological monitoring data on five railroad car-piled dumps at Bakal GOK are presented in more details as the specific weight of the dumps in the structure of the industrial landscape is maximum (41%).

The trends of change in the areas of five classes of the industrial landscape in the territory of the dumps over the monitoring period from 1995 to 2016 are shown in **Fig. 3**. It is found that the dump-disturbed lands insignificantly grew in the area from 834.9 to 849.6 ha. Furthermore, concurrently with dumping, the surveyed territory experienced recovery and revegetation.

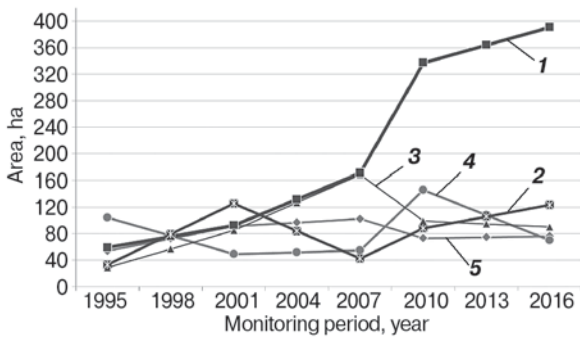

Fig. 3. Space monitoring data on change in the area with vegetation cover on the surface of railroad-car-piled dumps, ha:
***1* — mature mixed forest; *2* — grass and shrub vegetation;**
***3* — young mixed forest; *4* — revegetation showings;**
***5* — grass cover**

The change in the areas showing revegetation follows the alternating two downward trends and one upward trend. Between 1995 and 2001 the areas with the revegetation shrank from 104.5 to 49.1 ha. Later on, since 2002 the areas grew to 146 ha by 2010. Then, starting from 2011, these areas decreased by more than 2 times down to 70 ha.

The change in the area with grassland vegetation shows an alternation of two downward trends and one upward trend. According to the satellite survey data in 1995, these areas made 54.1 ha. Then, since 1996 the areas continuously expanded to 102.4 ha by 2007. Later on, starting from 2008, the areas decreased to 73.2 ha in 2010. In 2011 the areas began growing again and reached 76.3 ha in 2016.

The areas with the young mixed forest change with the alternation of one upward trend and one downward trend. This type vegetation covered the area of 28.9 ha in 1995. Since 1996 these areas grew more than 6 times up to 169.1 ha by 2007. After that, since 2008 it was found that the areas diminished to 90.4 ha in 2016.

The areas with the mature mixed forest changed with the single upward trend. By the satellite survey data in 1995, this type planting covered the area of 59.4 ha in the territory of the railroad car-piled dumps. In 1996 the areas began continuously expanding and reached 391.1 ha in 2016.

The change in the areas with the grass and shrub vegetation shows an alternation of two upward trends and one downward trend. From the space monitoring evidence in 1995 these areas made 33.1 ha. Starting from 1996 the areas grew to 125.7 ha in 2001. After that a decrease in the areas is observed down to 42.5 ha in 2007. In 2008 the areas began growing again up to 123.5 ha by 2016.

In 2018 the structure of the disturbed lands represented by the areas without plant formation as well as with vegetation and water ecosystem in the territory of the railroad car-piled dumps is as follows. The areas with all types of vegetation, excluding the areas showing revegetation total 710 ha. The self-restoring coefficient of the plant ecosystem is 0.83.

The trends in the change of the industrial landscape on the surface of four local dump truck-piled dumps over the monitoring period from 1995 to 2016 are determined by the data of long-term ERS. It is found that the area covered by the truck-piled dumps insignificantly grew from 420.8 to 425.4 ha within the mentioned period.

The change in the areas free from the vegetation cover shows a single downward trend. These areas reduced more than 4 times from 228.9 to 51.6 ha by 2016. Concurrently, the areas experienced recovery and formation of vegetation cover.

In the change in the areas showing revegetation, an alternation of one downward and one upward trend is detected. By the data of satellite survey in 1995 these areas were 25 ha and shrunk to 17.7 ha by 2001. Later on, since 2002 these areas continuously expanded up to 62.2 ha by 2016.

The areas with grassland vegetation change with the alternation of two upward trends and one downward trend. From the satellite survey evidence in 1995 such areas were 27.9 ha. Later on, starting from 1997 the areas continuously grew up to 50.2 ha in 2001. Then, since 2002 the areas first decreased to 34 ha in 2007, began growing again in 2008 and reached 62.9 ha in 2016.

The change in the areas with young mixed forest shows an alternation of two upward trends and one downward trend. These areas totaled 7.9 ha in 1995. Since 1996 the areas expanded almost 5 times up to 33.3 ha in 2007. After that, starting from 2008 the areas shrunk abruptly by 4 times down to 8.6 ha by 2010. In 2011 at the final stage of mining, the increase in these areas is observed up to 22.6 ha in 2016.

The areas with mature mixed forest exhibit a single upward trend of change. The satellite images show that the mature mixed forest covered the area of 121.2 ha on the surface of truck-piled dumps in 1995. Since 1996 these areas continuously expanded and reached 212.2 ha in 2016.

The change in the areas with grass and shrub vegetation shows an alternation of two downward and one upward trend. By the satellite survey data in 1995 such areas were 9.8 ha. In 1996 the areas began diminishing down to 6.6 ha in 2007. Then, a continuous growth in the areas was observed up to 13.7 ha in 2010. Since 2011 the areas were reducing again down to 11 h in 2016.

The structure of the disturbed lands free from vegetation cover and having plant and water ecosystems on the surface of truck-piled dumps in 2018 is as follows. The areas with all kinds of vegetation cover, excluding the areas showing revegetation, total 318.6 ha. The self-restoring coefficient of plant ecosystem on the surface of the truck-piled dumps is 0.75.

In the territory of the industrial landscape under analysis, there are two railroad car-piled dumps with a few new levels piled using dump trucks. It is found that these areas remained 247.4 ha over the period of monitoring. The areas without vegetation cover changed with a single downward trend. Between 1995 and 2016 these areas reduced from 148.2 to 66.9 ha.

The change in the areas showing revegetation has two downward trends alternating with one upward trend. From 1995 to 2011 these areas diminished from 19.8 to 16.6 ha. Later on since 2002, the areas started growing up to 19.1 ha by 2007. Then since 2008 these areas shrunk more than 10 times down to 1.7 ha in 2016.

In the change in the areas with grassland vegetation, there is an alternation of two downward trends and one upward trend. By the satellite images in 195 these areas made 15.1 ha. Then, since 1996 the areas reduced down to 6.6 ha in 2007. After that the areas grew up to 21 ha between 2008 and 2010, while in 2011 the areas decreased again down to 6.3 ha in 2016.

The change in the areas with young mixed forest shows an alternation of two downward and two upward trends. This type vegetation covered the area of 18.7 ha in 1995. Since 1996 these areas reduced to 10.7 ha in 2001, began growing in 2002 and reached 23.2 ha in 2007. In 2008 the areas decreased to 19.5 ha. Since 2011 the areas expanded again up to 31.6 by 2016.

The change in the areas with mature mixed forest shows a single upward trend. According to the satellite survey data in 1995 this type vegetation covered the area of 36 h on the surface of railroad car-piled dumps overlaid by the layers piled using dump trucks. Since 1996 the areas continuously expanded and reached 113.1 ha in 2016.

The areas with grass and shrub vegetation change as an alternation of two upward and two downward trends. The space images show that these areas were 8.6 ha in 1995. Since 1996 the areas grew up to 30 ha by 2001. Then, starting from 2002, the areas almost halved to 18.9 ha in 2007. Later on, a jump in the areas up to 41.9 ha by 2010 was observed. Then, the areas started decreasing in 2011 and reached 27.7 ha in 2016.

In 2018 the structure of lands without the vegetation cover and with plant ecosystem on the surface of railroad car-

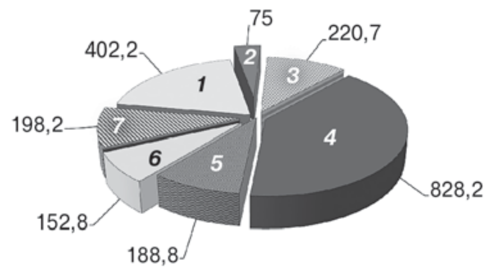

Fig. 4. Structure and disrobed lands and recovered ecosystem in the industrial landscape formed during Bakal iron ore development by 2018, ha:
***1* — no vegetation cover; *2* — mine process water body;**
***3* — young mixed forest; *4* — mature mixed forest;**
***5* — grass cover; *6* — revegetation showings; *7* — grass and shrub vegetation**

piled dumps overlaid with the layers piled using dump trucks is as follows. The areas containing all types of vegetation cover, excluding the areas showing revegetation total 179.3 ha. The self-restoring coefficient of plant ecosystem on the surface of the mixed dump is 0.72.

The structure of the mining-disturbed lands in the Bakal iron ore field is represented by the industrial landscape showing 8 open pits and many external overburden dumps piled using both railroad cars and dump trucks is illustrated in **Fig. 4**.

The total area of disturbed lands within the industrial landscape formed during mining of Bakal iron ore field by 2018 makes 2065.9 ha. The areas containing all types of vegetation cover, including the areas with revegetation showings, is 1588.7 ha. According to the graphical chart, in the territory of the disturbed lands, considerable reestablishment of vegetation cover at the level of 79.8% has taken place by the end of the monitoring period. Furthermore, by the results of the long-term monitoring using objective ecological control facilities, it is possible to draw a conclusion on admissible rate of restoration of the ecological balance in this territory.

Conclusion

Finally, according to the long-term monitoring data on ecological state of lands disturbed by opencast mining operations in the Bakal iron ore field, the rate of expansion of vegetation ecosystem is 7.9 ha per year. It is also found that after overburden dumping is terminated, showings of revegetation appear in 2–3 years and the mature grass cover is formed in 5–6 years. Then, in 10–12 years young mixed forest appears and becomes the mature forest in 16–18 years. All these facts speak in favor of the ecologically admissible rate of transformation of the vegetation ecosystem with self-planting of aboriginal types of wood and shrub vegetation from natural occurrence in the lands adjoining the open pits and overburden dumps.

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