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I. V. ZENKOV *(Doctor of Engineering Sciences, Professor, Reshetnev Siberian State Aerospace University, Krasnoyarsk)*
Yu. P. YURONEN *(Candidate of Engineering Sciences, Associate Professor, Reshetnev Siberian State Aerospace University, Krasnoyarsk)*
B. N. NEFEDOV *(Candidate of Engineering Sciences, Director, Berdsk Division of the Institute of Computational Technologies, Siberian Branch, Russian Academy of Sciences, Berdsk)*
I. M. BARADULIN *(Post-Graduate Student, Siberian Federal University, Krasnoyarsk)*

REMOTE SENSING IN ESTIMATION OF FOREST ECOSYSTEM GENERATION AT CRUSHED STONE QUARRIES IN SIBERIA*

In the territory of industrially advanced regions in Central Siberia, large-scale industrial and civil construction as well as building of motor roads and railways requires considerable amount of construction and road stone. The Krasnoyarsk Territory and Irkutsk Region, alone, have twenty six crushed stone quarries with an overall area of 580.1 ha at deposits of granite, limestone, porphyrite, keratophyre and marble. The monitoring using the tools and resources of remote sensing has revealed negative trends in recovery of natural vegetative ecosystems at mined-out and operating crushed stone quarries. Natural recovery processes have resulted in regeneration of young forest ecosystem over the overall area of 90.7 ha. The field researches have specified the structure of forest ecosystems and determined specific weight of species of mixed forest and taiga at the close vicinity of examined quarries. The area at all quarries is dominated by pine, birch is in the second place, and poplar and quaking asp share the third position. Larch, willow shrub formation, fir tree and cedar make 5.6 % of the population of all trees growing in the quarries. The factors influencing number of tree groups in the quarries are determined. The principal effect on the forest population is exerted by the geographical orientation of a quarry relative to cardinal points; the annual rate of forest yield is affected by the presence or absence of a fertile mixture composed of soil layers and overburden. All quarries are conventionally placed into two groups with respect to conditions of generation and growth of forest ecosystems: lateral geometry and number of spoil banks. The remote sensing has detected quarry sites where local forest ecosystems have generated. The article puts forward a package of measures aimed at enhancement of ecological efficiency of natural forest recreation in the areas of mined-out quarries.

Key words: *remote sensing, crushed stone quarries, mining landscapes, forest ecosystems, natural forest recovery, quarry revegetation.*
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Introduction

Nonmetal mining has more than 100 years long experience in Central and East Siberia. In the last 25–30 years, production and consumption of crushed stone has been increasingly growing as far as construction of new civil and industrial infrastructure and building of motor roads and railways are always related with the demand of large amounts of crushed stone. In the 21st century, in the same way as before, the national economy in the Russian Federation advances industrialized areas of Siberia (Kuzbass, Krasnoyarsk Territory, Irkutsk Region). As of today, in the territory of the latter two regions, crushed stone quarries exceed in number open pit mines of the mineral mining branch of the metallurgy industry (iron ore, aluminium) and of the coal mining branch of the fuel-and-energy industry. At the present time, the Krasnoyarsk Territory and Irkutsk Regions hold 26 mined-out and operating quarries of crushed stone at the deposits of granite, limestone, dolomite, keratophyre, porphyrite and marble.

The monitoring of mining-and-industrial landscape at crushed stone quarries using ground penetrating radar techniques has revealed a negative tendency — natural recovery of ecosystems (grassland, tree and shrub vegetation) has occurred on 15.6% of the entire quarrying area irrespective of the time of quarry closure. This problem is even more pronounced in quarries where spoil bank is represented by exposure of hard and medium-hard rocks unfavorable for higher vascular plants.

As a consequence of disregard of ecological impact induced by open pit mining, natural ecosystems have generated at none of mined-out crushed stone quarries in the Krasnoyarsk Territory and Irkutsk Region. Such quarries look like moonscape with no a ring of any vegetation. This is true despite numerous scientific publications on promotion of ecologization of mining both in Russia and abroad [1–5, 6–21]. The foreign researchers in the area of ecosystem rehabilitation widely use data of remote sensing [22–25]. A critical review of the listed and other studies allows drawing a conclusion that trends of recovery of natural ecosystems considering features of natural climate and soil geography of Siberia remain yet to be studied to handle ecological problems connected with crushed stone quarrying.

Research findings

Interpretation of data of remote sensing has enabled determining geometry of each quarry, i.e. its length and width on surface, and the depth, as well as the presence/absence and qualitative composition of vegetation cover. The analyzed quarries are divided into two groups according to geographical location (**Tables 1** and **2**).

Selective presentation of crushed granite quarries based on the remote sensing data is shown in **Fig. 1**.

The overall area of all examined quarries is 580.1 ha, the average area of a quarry is 22.3 ha. The area of the quarries

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Table 1. Characteristics of crushed stone quarries in the Krasnoyarsk Territory

Quarry no.	Quarry name	Areal size, m	Depth, m	Area, ha	
				Quarry	Vegetative ecosystem
1	Divnogorsky	80090	75–80	7.2	4.3
2	Gromadsky	550420	30–40	23.1	3.2
3	Zelenogorsky	300200	40–45	6.0	4.9
4	Kuraginsky	1270400	70–80	50.8	6.7
5	Kodinsky	1500280	30–35	42.0	1.4
8	Kuskunsky	260×215	20–25	5.6	0.8
9	Zykovsky 1	320×330	48–60	10.2	7.9
10	Zykovsky 2	300×300	40–42	9.0	6.5
11	Krutokachinsky	800×400	50–60	32.0	3.6
12	Boguchansky	790×130	20–25	10.3	0.8

Table 2. Characteristics of crushed stone quarries in the Irkutsk Region

Quarry no.	Quarry name	Areal size, m	Depth, m	Area, ha	
				Quarry	Vegetative ecosystem
13	Bratsky	870×270	30–35	23.5	2.4
14	Ust-Ilimsky	830×290	45–52	24.1	1.8
15	Nevonsky	160×380	15–20	6.1	0.8
16	Chernukhinsky	605×210	25–30	12.7	1.9
17	Novonukutsky	690×550	24–28	38.0	4.2
18	Angasolsky	1320×715	68–80	94.4	20.6
19	Burovshchina	410×680	55–65	27.9	2.1
20	Kimilteisky	330×160	15–20	5.3	0.6
21	Tulunsky	900×430	32–38	38.7	4.5
22	Morgudonsky	820×510	65–70	41.8	5.7
23	Petrovsky	400×250	30–40	10.0	1.6
24	Svirsky	400×420	20–40	16.8	1.7
25	Karstovy	круг Ø 700	45–60	38.5	1.8
26	Ust-Kutsky	210×290	12–16	6.1	0.9

in the Krasnoyarsk Territory and Irkutsk Region is 196.2 and 383.6 ha, respectively. As of August 2015, the total area of vegetative ecosystems makes 40.1 ha at quarries nos. 1–12 and 50.6 ha at quarries nos. 13–26. The rate of natural recovery, defined as a ratio of the overall area of vegetative ecosystems at quarries to the area of all quarries, equals 0.2 and 0.13 for quarrying in the Krasnoyarsk Territory and Irkutsk Region, respectively.

To the present authors' opinion, the situation in the both regions is ecologically unacceptable as the mining landscape at the quarries is unprepared for the efficient processes of natural forest recreation and no mined-land reclamation is in progress there. Spoil banks and bottoms of the quarries are unreclaimed: there is no soil layer or tree planting. At the same time, all quarries unexceptionally are supplied with natural seed stock and occur in the zone of influence of mixed forest or a taiga sub-zone that produce seeds with wings. Forest representatives of these geographical zones are effectively disseminated in the adjacent areas by wind that carries the seeds for great distances in various directions. In all cases analyzed, the quarries locate within the maximum distance of wind transfer of mature tree seeds. Nonetheless, to date, natural forest recovery has covered the site of 15.6% of the overall area of the quarries. This implies that engineering solutions are to be developed individually for each group of quarries in order to improve the ecological situation connected with the absence of vegetative ecosystems in the areas of mining landscapes at mined-out quarries.

Then, an emphasis was laid on factors favorable for rapid and appropriate development of vegetative ecosystems in quarries. It was required to study: the effect of the presence/absence of productive mixed soil on increment in forest cover; distribution of forest ecosystems depth-wise the quarry spoil banks; structure of settled trees; and to assess the influence of orientation of spoil banks relative to cardinal points on the population of species of the forest ecosystems settled on the quarry slopes.

The first stage was the study into the productivity of the surface soil on the upper benches of quarries. Demarcation was carried out relative to inactive sites between benches, accidently covered with mixture of fertile soil layer, potentially fertile soil and overburden (clay, loam, sand, sand clay, etc.) in the course of inwash or due to operation of quarry transport. Depending on the thickness of this layer, rates of stand growth were determined. Pine was chosen as an indicator as its specific mass dominated the structure of forest ecosystems. The yield of pines was studied on sites with the fertile layer thickness of 10 to 80 cm.

The analysis of the trends in the yield of pines shows that when the thickness of the fertile soil layer grows from 0.1 to 0.4 m, the rates of yield increase in direct proportion by 15 and 32 cm yearly for the lower and upper limits of the mentioned range, respectively. This is not incidental — on the sites with the thicker fertile layer, the fourth (lower) storey, which supplies root systems of pines with humic and fulvic acids, develops better. Then, with the fertile layer thickness of 0.41 to 0.6 m, the change in the pine yield exists but is less rapid than in the case of the fertile soil layer thickness range 0.1–0.4 m. Within the fertile layer thickness range from 0.6 to 0.8 m, the rate of the pine yield is considerable and makes 2–3% per 10 cm of the fertile layer thickness. The latter circumstance became the basis of the fertile layer thickness evaluation before coating benches in the course of reclamation. Concurrently, it was found that the change of humus

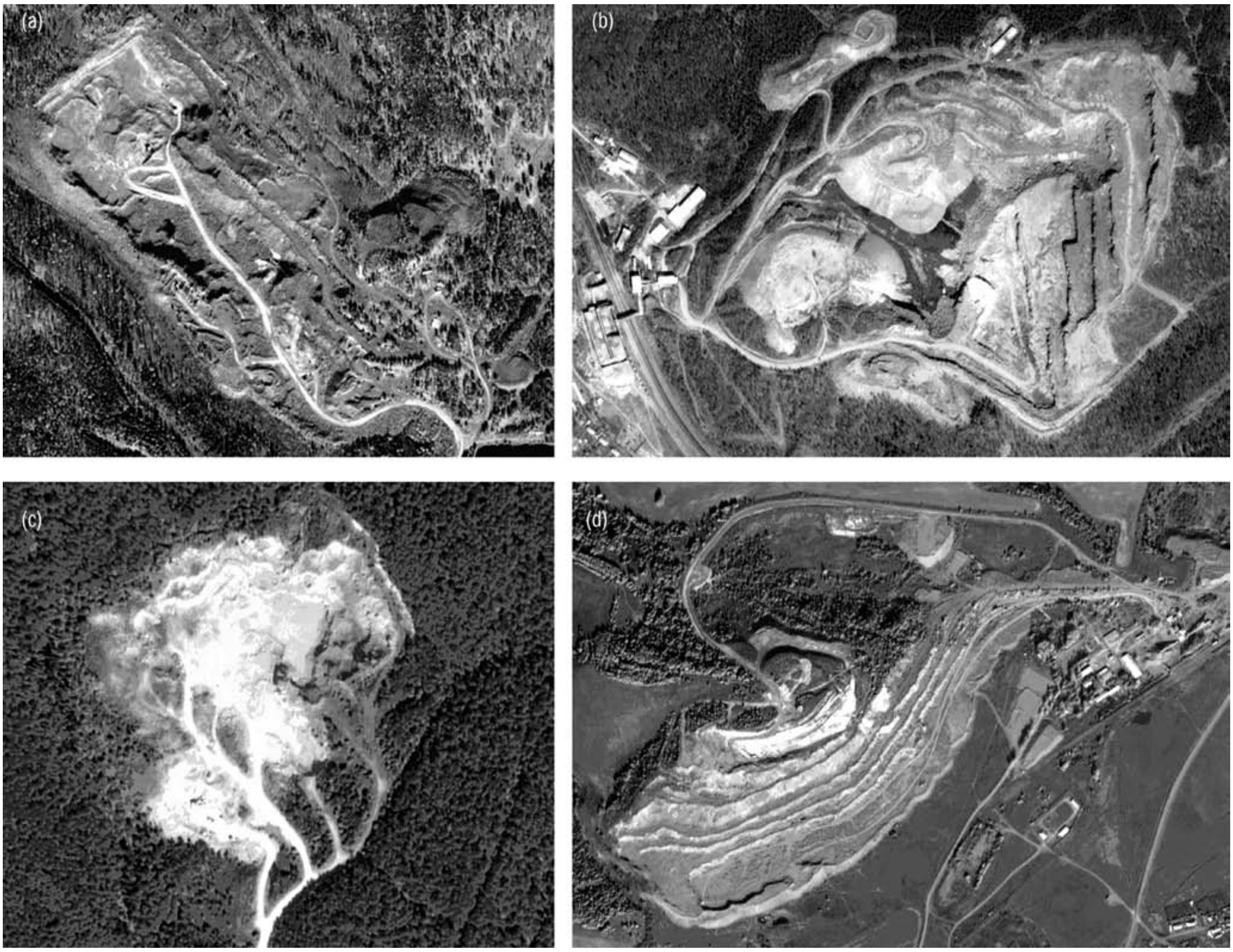

Fig. 1. Fragments of satellite images of crushed stone quarries: (a) Tulunsky; (b) Burovshchina; (c) Zelenogorsky; (d) Kuraginsky

content of the fertile layer from 5 to 5% had almost no influence on the forest yield, inasmuch as sites with different humus content of the fertile layer in the mentioned ranges of thickness were also analyzed.

Exposed rocks after quarrying termination are absolutely unsuitable for growth of higher vascular plants as the exposure surface lacks nutrition sources (humic soil). Generation of nutrition source for plants on such surfaces needs performing a package of measures aimed at application of fertile mixture of soil and overburden. Such mixture is obtainable, in the right and good quantity, from near-surface layer, namely, when stripping upper benches of quarries.

The second stage of the research involved estimation of concentration of growth on benches in the mined-out quarries (see **Fig. 2**). The studies used the remote sensing data and information of many-years field researches into conditions of initiation and maturation vegetation and forest ecosystems in crushed stone quarries. The geodetic surveys determined the depth of the quarries, the height and slope of benches. Furthermore, the area of the sites and the areals of growth of forest species were assessed.

Environmentally, the lower curve in **Fig. 2** illustrates the perfect uniform healing of spoil banks per depth. In vivo, the situation is far from ideal. For crushed stone nonmetal quarries, the curves of forest ecosystems against the depth of a quarry are plotted. The analysis of the ecosystem distributions yields that approximately 50–60% of trees grow at a depth of 20 m and only 20–25% of trees plant the sites with the elevations from –20 to –40 m. Spoil banks in the depth range of –40 to –80 m has poor growth at a level of 15–20%. The reason of this is, in the present authors' view, that sites located closer to the ground surface have the coat of higher fertility sufficient to spur development of the fourth storey and seeds with wings are capable to grow on these sites.

At the bottom of spoil banks, no sites with fertile mix coat were observed. However, natural forest recovery processes ran there. The efficiency of the processes was certainly lower than at the top of spoil banks though the same temperature conditions and moisture content of soil layers.

High resolution images of remote sensing highlighted a very positive fact for the formation of forest ecosystems in mined-out quarries — the presence of large sites of mixed and taiga forests composed of pine, birch, quaking asp, larch, etc nearby. These trees annually produce seeds with wings. This natural seed material is picked up from strobiles (pines, larch, etc.) and catkins (birch, quaking asp, etc.) by wind, and the seeds with wings are carried over large ranges. The structure of forest ecosystems in the areas of quarries producing construction and road stone at all nonmetal deposits mentioned above has been studied (**Fig. 3**).

At the fourth stage of the research using remote sensing method, in the quarries with differently oriented spoil banks, the sites of efficient forest recovery were determined. It has been found with probability of 98% that the southern and eastern spoil banks geographically oriented toward the north and west, respectively, have areas of forest ecosystem recovery 2.3–2.5 times larger than the forest ecosystem recovery areas on the northern and western spoil banks oriented, accordingly, toward the south and east, which is explained by the features of local climate [5]. Between the beginning of June up to the end of July, moisture and temperature were measured at a depth of 2 cm in soil on the sites of forest ecosystem generation. The soil moisture of the southern and eastern spoil banks was 11.5–13.1% as opposed to the northern and western spoil banks where the soil moisture ranged between 18.3 and 21.1%. The maximum short-term temperature of the soil on the northern and western spoil banks varied from 62 to 65°, while it was lower on the southern and eastern spoil banks and made 48–51°.

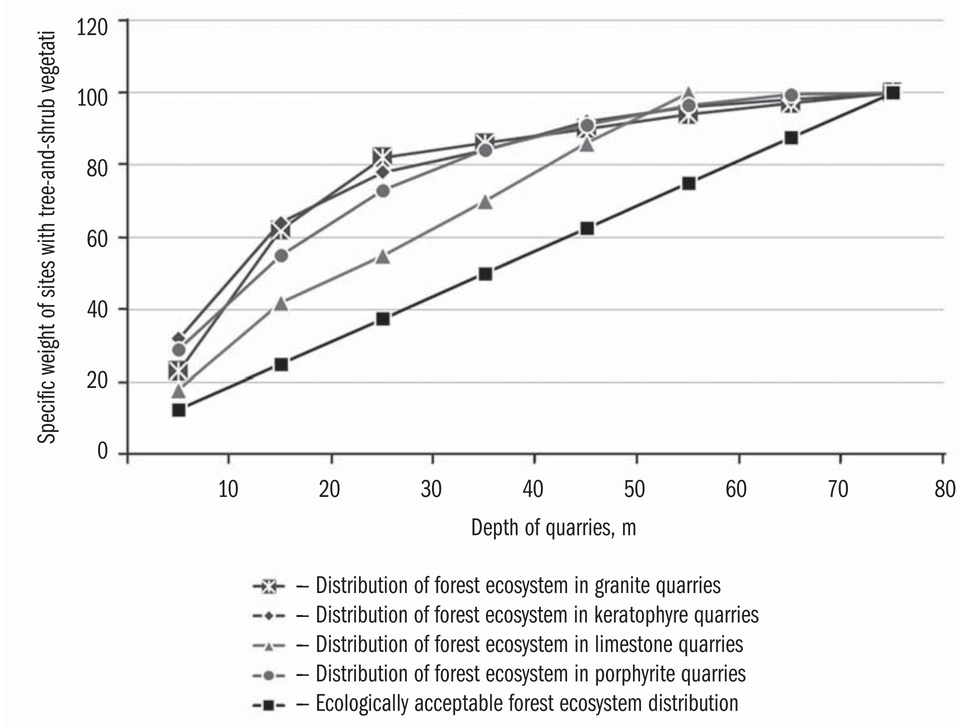

Fig. 2. Density of sites of young forest ecosystems per depth of spoil banks in crushed stone quarries

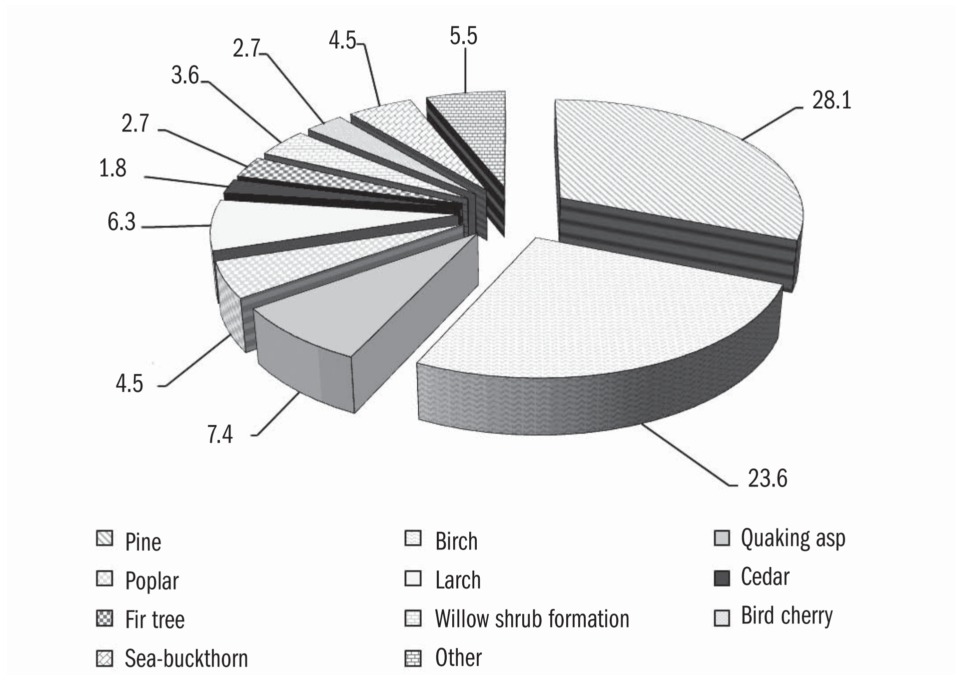

Fig. 3. Structure of forest ecosystems at crushed stone quarries (in hectares)

Conclusion

Based on the system analysis of influence exerted by all natural and mining-induced factors, the recommendations on crushed stone quarrying have been developed, including: ecologically validated orientation of a quarry relative to cardinal points; coating of horizontal benches and flattened slopes with a man-made mix of soil layer and overburden at a sufficient fertility thickness not less than 60 cm; sloping benches at 3 to 5˚ toward the spoil bank in order to maintain required moisture content of the topsoil. The implementation of these recommendations on open pit mining and land reclamation ensures the maximum coefficient of natural recovery of forest ecosystems at each quarry at a level of 96–98 %.

Finally, it is worth emphasizing that the new shaping trend in the theory and practice of mining ecologization at crushed stone quarries will allow sustainable and efficient development of nonmetal mineral reserves. Our recommendations are aimed at improvement of open pit mining ecologization, when the environmentally reasonable relief of a quarry landscape, the architecture of which will contribute to accelerated generation and rapid natural recovery of forest ecosystems at a level of efficiency of natural forestation, will be cultivated by the time of mining close-down.

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