Impact of the expropriation of the territories of natural reserves for mining purposes on protected populations

M D Vasilyev, NV Vasilyeva, OI Matveeva and Yu I Trofimtsev

1Institute of Mathematics and Informatics, M.K. Ammosov North-Eastern Federal University, 58, Belinsky str, Yakutsk, 677013, Russia

E-mail: trofimtsev@mail.ru

Abstract. The paper discusses the impact of allocation of resource reserves for the development of mineral deposits on protected populations. The main method of assessing this effect is mathematical modeling. The results of the study were obtained using a model based on two parabolic partial differential equations (diffusion equations). The equations describe the dynamics of a population in a bilocal habitat, when the boundary of the protected area divides the area into two parts—protected and unprotected. At the same time, the species are free to pass from one part of the habitat to another. The model also takes into account the diffusion movement of species across the habitat and cross-diffusion, which means both the competition of species for available resources and their possible coexistence. Numerical calculations demonstrate that with a proper assessment of the impact on the natural potential of the reserve, it is possible to maintain stable densities of protected populations in both parts of the habitat, but at a slightly lower level. The case of high man-made loads on protected populations leading to their degeneration is also considered. The work shows that the presence of a sufficient food resource has a beneficial effect on the density of the protected and unprotected parts of the population.

1. Introduction

Diamond mining is one of the main industries of the Republic of Sakha (Yakutia). After the accident at the Mir mine, which will begin to be restored only in 2024, production fell by 10–11 percent. Therefore, placer deposits are becoming increasingly attractive for industrial development. A significant increase in their production is associated with the activities of LLC Almazy Anabara. Among placer deposits, the alluvial type is most common, developed in small and medium rivers. The length of the placers varies from kilometers to several tens of kilometers, while width varies from several tens to hundreds of meters [1].

The territory of Yakutia is more than three million square kilometers, of which 28.5 percent belong to protected areas. This is also due to the low population density, about 0.3 people per square kilometer. In Yakutia, a harmonious system of specially protected natural areas (PAs) has been developed, including natural parks, sanctuaries, wildlife refuges, resource reserves, protected landscapes and natural monuments, as well as green areas of residential areas [2]. A fundamentally new form of protected areas has been introduced: a resource reserve containing elements of the fourth and seventh categories of protected areas of the International Union for Conservation of Nature. The introduction of reserves is dictated by the extensive network of protected areas, which affects the way of life of indigenous peoples. Resource reserves include zones of absolute peace, sacred sites, licensed resource extraction areas,
seasonal natural resource extraction areas, traditional nature management areas, protected landscapes and nature monuments.

2. Problem statement

Placer diamond mining in Yakutia is moving farther north to the Arctic Circle expropriating the territories of resource reserves. An example of such a progression is the Verkhne-Munskoye diamond deposit, which is located in the west of Yakutia, 170 km from the city of Udachny in the territory of the Muna resource reserve. At present, four kimberlite pipes have been explored: Zapolyarnaya, Deimos, Novinka, and Komsomolskaya Magnitnaya. Today it is the largest investment project of the ALROSA company. The Verkhne-Munskoye field will bring about 1.8 million carats of diamonds per year, and its reserves are sufficient to continue production for more than 20 years until 2042. The official discovery of the Verkhne-Munskoye diamond deposit was held on October 31, 2018. The reduction of the territory of the resource reserve affects the protected animal populations, which include moose, wild deer, sable and Siberian weasel. The aim of the work is to assess the impact of mining on the density of protected populations using mathematical modeling of their dynamics.

3. Methods for study

We consider the dynamics of the population in a bilocal area, which is specific in the presence of protected and unprotected parts and a generalized resource conducive to the existence and development of the population. The study uses a mathematical model, which is a system of parabolic partial differential equations and describes arbitrary (diffusion) distribution of the population in a two-dimensional area [3]. The model that takes into account migration flows caused by the uneven distribution of parts of the population in the range is as follows:

\[
\frac{\partial u}{\partial t} = \nabla \left( \varepsilon_1(u,v) \nabla u - p_1 \mu \nabla v - q_1 \mu \nabla r \right) + f_1(u,v),
\]

\[
\frac{\partial v}{\partial t} = \nabla \left( \varepsilon_2(u,v) \nabla v - p_2 \nu \nabla u - q_2 \nu \nabla r \right) + f_2(u,v).
\]

Here \( u(x,y,t) \) and \( v(x,y,t) \) are population density, divided into two parts—unguarded and protected—respectively. Migration flows are described by diffusion coefficients \( e_1(u,v) \), \( e_2(u,v) \) and directional migration parameters \( p_1, p_2 \). The resource function is set as \( r(x,y) \). The natural increase in the density of parts of a population is determined by functions \( f_1 \) and \( f_2 \):

\[
\begin{align*}
f_1(u,v) &= m_1 u + d_1 (v - u) - c_1 u^2 - b_1, \\
f_2(u,v) &= m_2 v + d_2 (u - v) - c_2 v^2.
\end{align*}
\]

In functions \( m_1 \) and \( m_2 \) are the coefficients of population growth outside the protected area and inside it; \( c_1 \) and \( c_2 \) are the coefficients of competition within the population in and outside the protected area; \( d_1 \) and \( d_2 \) are the coefficients of exchange of individuals between the protected area and the rest of the habitat. The term \( b_1 \) is interpreted as a quantity that describes external impact on the unprotected part of the population caused by mining operations.

The diffusion coefficients \( e_1(u,v) \) and \( e_2(u,v) \) are positive values depending on the density of populations:

\[
e_{i}(u,v) = \alpha_i + \beta_i u v, \quad i = 1,2.
\]

Here \( \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22} \) are taken as second-order matrices with non-negative elements; the case of linear diffusion is obtained at zero \( \alpha_{12}, \alpha_{22} \). The introduction of non-linearity into migration processes is explained by the existing competition between species of different parts of the population for resources, which increases the dispersion of species across the habitat. It is also associated with the Allee effect which states that the accumulation of species increases the competition between them for resources and...
living space, but increases survivability of the group as a whole. This implies that for the development of the population, the limiting factors are both “overpopulation” and “under-population” [4, 5].

The treatise considers habitat $\Omega = [0, l_1] [0, l_2]$, on the boundaries of which conditions were set that suggest that species of the population do not leave the habitat, and that their numbers on the borders are zero. The alienation of the protected area was described by changing parameter $l_2$. The system of equations was solved numerically [6–9].

![Figure 1](image.jpg)

**Figure 1.** Case of the same areas of the protected and unprotected parts of the habitat

4. **Discussion**

The calculations showed that a decrease in the area of the protected area causes a much smaller effect than expected. Moreover, if a technogenic impact is small, they stabilize at a certain, but lower initial level. This can be explained by the presence of the protected part of the reserve. Fig. 1 shows the initial and limiting values of the densities of both parts of the population with the same areas of the protected and unguarded parts of the habitat. The limiting values of densities are 0.5 for unprotected and 0.9 for protected parts. When the protected area decreases, the limiting values stabilize at a lower level—0.4 and 0.8, respectively (Fig. 2). A further decrease in the area of the protected part practically does not change the limiting densities of both parts of the population (Fig. 3).

In our model, there is a fold-type bifurcation [10], which leads to the degeneration of the entire population, which is shown in Fig. 4. It occurs at high man-made loads, i.e. with a large value of $b$ in the model. At moment of time $t = 3$, with equal areas of the habitat parts, non-zero densities of the protected and unprotected parts of the population preserve. If the area of the protected part of the habitat is reduced, then at the same time point, the unprotected part of the population no longer exists (Fig. 5). Let the main food resource of individuals is concentrated on the unguarded part of the habitat (Fig. 6). With a large anthropogenic impact and equal areas of the habitat parts, this leads to a small but non-zero density of the unprotected part of the population (Fig. 7). The expropriation of a part of the reserve for mining results in a very small but non-zero density of the unprotected part of the population (Fig. 8).
Figure 2. Case of the ratio of the areas of the protected and unguarded parts of the habitat of 5:3

Figure 3. Case of the ratio of the areas of the protected and unguarded parts of the habitat of 3:1
Figure 4. Case of the same areas of the protected and unguarded parts of the area in the presence of bifurcation in the system

Figure 5. Case of the ratio of the areas of protected and unprotected parts of the habitat of 1:3 in the presence of bifurcation in the system
Figure 6. Setting generalized resource, the most favorable zone is in the unguarded part of the habitat

Figure 7. Case of the same areas of protected and unprotected parts of the habitat with the introduction of a generalized resource

5. Conclusions
When solving problems of the economy, it is necessary to take into account the industrial impact on the environment and to solve environmental problems simultaneously with the economic ones. The transfer of a part of the lands of a natural reserve for the extraction of natural resources does not lead to a large negative impact on the protected populations only with a correct assessment of the natural potential.
Figure 8. Case of the ratio of the areas of protected and unprotected parts of the habitat of 1:3 with the introduction of a generalized resource

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