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System Analysis of Biogeocenoses of the Yamal Peninsula: Simulation of the Impact of Large-Herd Reindeer Breeding on Vegetation

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Abstract—The systemic approach based mainly on computer simulation has been used to assess the dynamics of ecosystems of the Yamal Peninsula, which have been exposed to the impact of numerous reindeer herds because of extensive development of reindeer breeding during the past decades. This type of development has been demonstrated to result in degradation of vegetation, whose profound changes preclude further development of reindeer breeding in the same way. The current situation requires major amendments to the ethnic–cultural and economic policy in the region.

Keywords: simulation, vegetation, reindeer breeding, pasture load, green and lichen forage, vegetation degradation.
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The Yamal Peninsula is a unique region of the Russian Transpolar region. In contrast to most other regions with well-developed reindeer breeding, the numbers of reindeer have considerably increased rather than decreased there. This was accompanied by a rapid increase in the population of Nenets, who are the main reindeer-breeders in the region, compared to other indigenous ethnic groups of the North (Klokov and Khrushchev, 2004).

Under present-day conditions, the domestic reindeer is the main first-order consumer in Yamal; its population in the peninsula is currently as large as about 300000 head. At first glance, the food demand of reindeer is small, compared to the total forage reserve. However, rapid degradation of vegetation on the peninsula has become evident (Magomedova and Morozova, 1997; Morozova and Magomedova, 2004, 2006; etc.). To assess the current situation and predict further development of the vegetation–domestic reindeer system, we used the method of computer simulation, which is the main tool of system analysis.

The purpose of this study was a system analysis of the dynamics of the tundra ecosystem in the Yamal Peninsula, which is exposed to the heavy pressure of reindeer grazing. The objectives of the study were the following:

(1) To map the distributions of green and lichen forage reserves in the peninsula in the early and late 20th century that could be analyzed using information technology methods.

(2) To develop a simulation model of changes in the green and lichen forage reserves with time, taking into account the effects of reindeer grazing and trampling on vegetation and the roles of other key components of tundra ecosystems.

(3) To verify the model, i.e., to compare the simulated dynamics of the green and lichen forage reserves with the estimates of their actual changes in the period from the 1930s to the end of the 20th century and to assess the contributions of the main factors related to reindeer pasturing (grazing and trampling) to vegetation degradation.

(4) To use simulation experiments for analyzing various scenarios of changes in the green and lichen forage reserves with time as dependent on the numbers of domestic reindeer.

MATERIALS, METHODS, AND TERMINOLOGY

When mapping the spatial distribution of the green and lichen forage reserves in the peninsula in different periods of time, we divided the peninsula surface into squares 10 × 10 km (10000 ha) in size.

Andreev (1933) described the distribution of forage reserves over Yamal pastures in the early 20th century and presented the geobotanical characteristic of the main formations and groups of formations constituting the vegetation of Yamal, described their abundance in different parts of the peninsula on a geobotanical map, and estimated the green and lichen forage reserves inherent in them. So, the 1930s became the first time point in our analysis of the time course of forage reserves in Yamal.

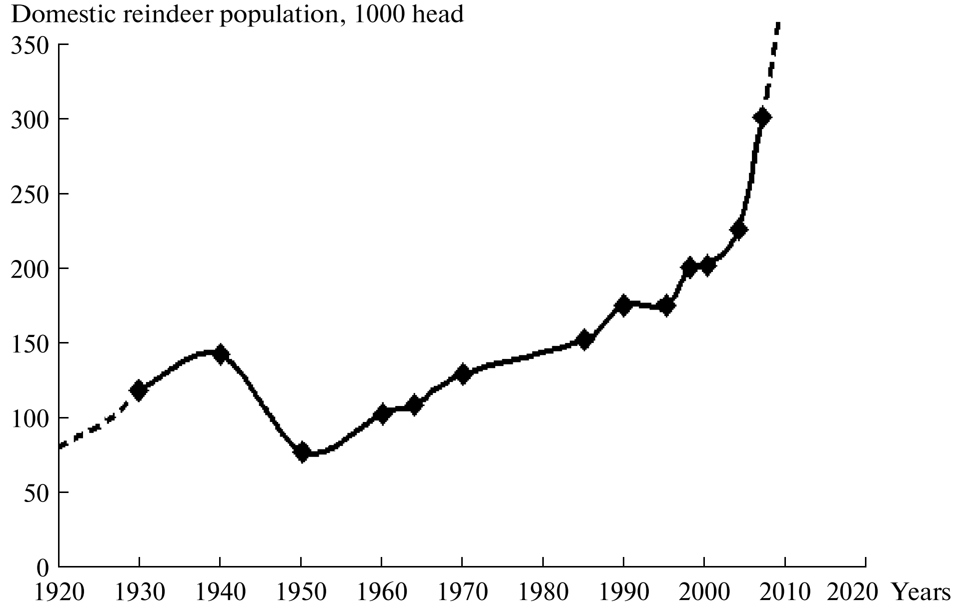

Fig. 1. Population dynamics of domestic reindeer in Yamal in the 20th century according to data from the Department of Agricultural and Industrial Development of the Yamalo-Nenets Autonomous Area.

The forage reserves of the same pastures in the late 20th century were estimated from the geobotanical map of reindeer rangelands of the Yamal Region of the Yamalo-Nenets Autonomous Area (YaNAA), scale 1 : 100000 (*Khozyaistvenno-geobotanicheskaya karta*..., 1995) provided by the Department of Agricultural and Industrial Development of YaNAA. This map was used to estimate the mean daily carrying capacity of pastures and the recommended numbers of reindeer allowed for grazing. The results were used to calculate the forage reserves determining the grazing potential as recommended by Andreev (1933).

The model was developed and operated in the AnyLogic University 6.0 certified simulation environment (Karpov, 2006).

In the early 20th century, the green forage reserves of Yamal allowed the reindeer numbers to be increased by a factor of four; however, the population growth was limited by the amount of available lichen forage. Andreev (1933) believed that, in the period of his study, their reserves in Yamal were sufficient for increasing the reindeer population from 100000–120000 to 160000 head.

Below, we use some terms that require special explanation:

Daily reindeer carrying capacity is a conventional unit indicating the number of reindeer that 1 ha of the rangeland can feed for one day (reindeer–day/ha), with the forage removal due to grazing and trampling taken into account.

Total carrying capacity of rangelands is the number of reindeer adequate to the resource potential. It is calculated from the specific reindeer carrying capacity (the available forage reserve), total rangeland area, and daily food demand per animal with allowance for unproductive loss (trampling) and rangeland accessibility. It is assumed that pastures should be used for a long time without reducing their forage value, i.e., so as to allow the vegetation to consistently restore its foraging potential.

Winter forage refers to lichens, the main food for reindeer during the show period (from late autumn to and early spring), which in Yamal lasts for an average of 250 days. The lichen forage reserve is taken to be equal to the annual production of lichens, which averages 5% of their total biomass (Andreev, 1933).

Lichen biomass is the proportion of live biomass relative to the total amount of lichens expressed as air-dry weight.

Winter pastures are areas with a high coverage of lichens in the plant cover, such as the lichen tundra, bogs, and dwarf birch thickets.

Green forage consists of edible herbage, dwarf shrubs, and shrubs that comprise the main “summer” forage during the 115-day snow-free grazing period (Andreev, 1954). According to Andreev’s calculations, the reserve of green forage is 50% of the total aboveground phytomass of edible plants.

Summer pastures are areas where the vegetation either lacks lichens altogether or their coverage is low (therefore, the division of Yamal pastures into summer and winter ones is somewhat conventional).

REINDEER NUMBERS AND THE STATE OF PASTURE VEGETATION

The total reindeer population in Yamal constantly grew in the second half of the 20th century (Fig. 1),

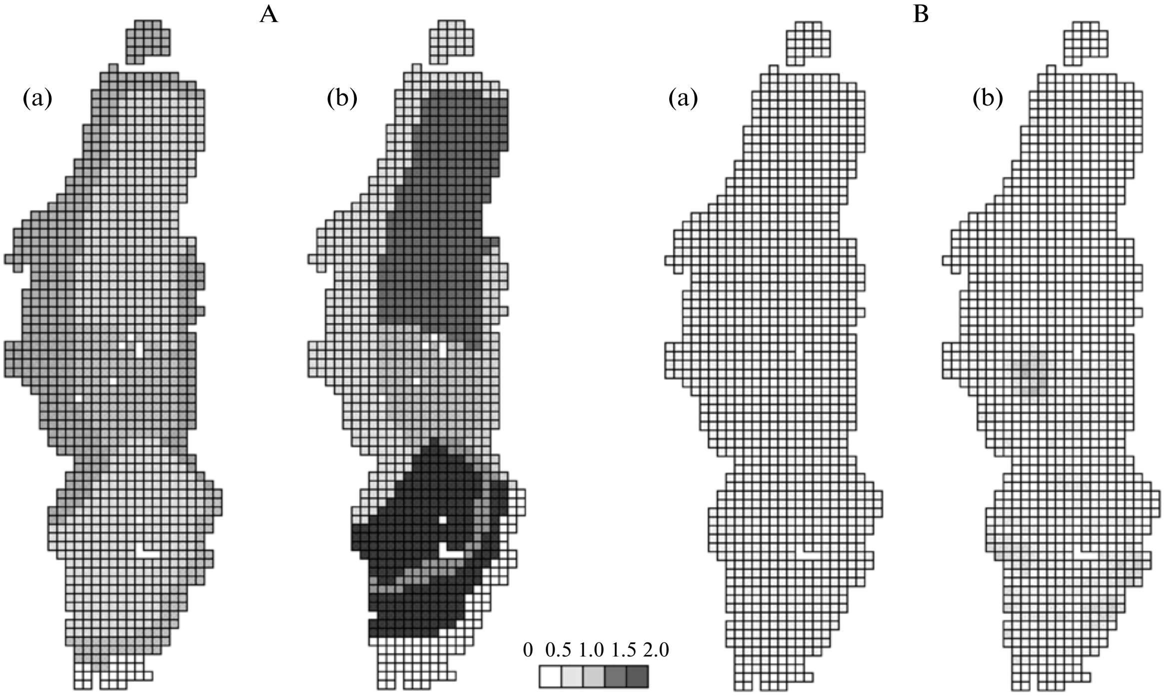

Fig. 2. Plant forage reserves (t/ha) in Yamal in (A) the 1930s and (B) the late 20th century: (a) green forage; (b), lichen forage; the area of each square is 100 km^2.

which was due mainly to an increase in the number of privately owned herds. Therefore, the pasture load on vegetation also increased, which affected the state of forage reserves.

The forage reserve is an integrated value characterizing mainly the first trophic level of Yamal tundra ecosystems. Changes in the forage reserve are determined by the changes in a number of interrelated key parameters: a decrease in the mean coverage, height, and biomass of different groups of producers differing in forage value, as well as the changes in their contributions to the vegetation (occurrence frequency, coverage, and area of distribution), which, in the tundra zone, is primarily pertinent to the lichen vegetation. The changes in these parameters of green fodder plants are slower but also inevitable.

The following factors are obviously responsible for the loss of lichen forage reserves and decrease in green forage reserves:

(1) A decrease in the height of the lichen cover from 3–4 cm in the 1930s to 0.5–2.0 cm by the late 20th century over vast rangeland areas.

(2) Change of edificator dominants of lichen synusiae: reindeer lichens of the genus *Cladina* have been everywhere replaced by low-productive but grazing-tolerant lichens of the genera *Cladonia, Sphaerophorus, Thamnolia, Bryocaulon*, etc. Foliose and crustose lichens of the genera *Ochrolechia, Pertusaria, Mycobilimbia*, etc. have become widespread (Magomedova and Morozova, 2000).

(3) Disappearance of lichen tundras from the plant cover of the peninsula. The area of lichen tundras has decreased by a factor of 3.5–4 since the 1930s (Morozova and Magomedova, 2004). The lichen tundras with the total lichen reserve of 6 t/ha that were described by Andreev (1933) have been transformed into moss and dwarf-shrub tundras with lichens as nondominant components.

(4) Herbs, shrubs, and, to a lesser extent, dwarf shrubs experience a high degree of suppression. Their abundance, height, and primary production decrease, and they cannot compensate for the loss of lichen forage. The reserves of herbage in tundras and bogs in the late 20th century were 1.5–2 times smaller than in the 1930s. The weight proportion of forbs (a nutritionally valuable group) in the aboveground phytomass has decreased by an order of magnitude. In willow scrubs, the total aboveground phytomass has mainly decreased because many branches have died off and the live ones bear less foliage (Morozova and Magomedova, 2004, 2006).

(5) Enhanced deflation is an important cause of the decrease in both lichen and green forage reserves in the peninsula. The thin vegetation on convex sandy watersheds covered by lichen tundras is not resistant to mechanical factors. Large reindeer herds passing through them every year rapidly destroy it, exposing the sandy substrate. At present, the total area of sand blow-ups is almost 600 000 ha, or about 6% of the total area of reindeer pastures (Golovatin et al., 2010).

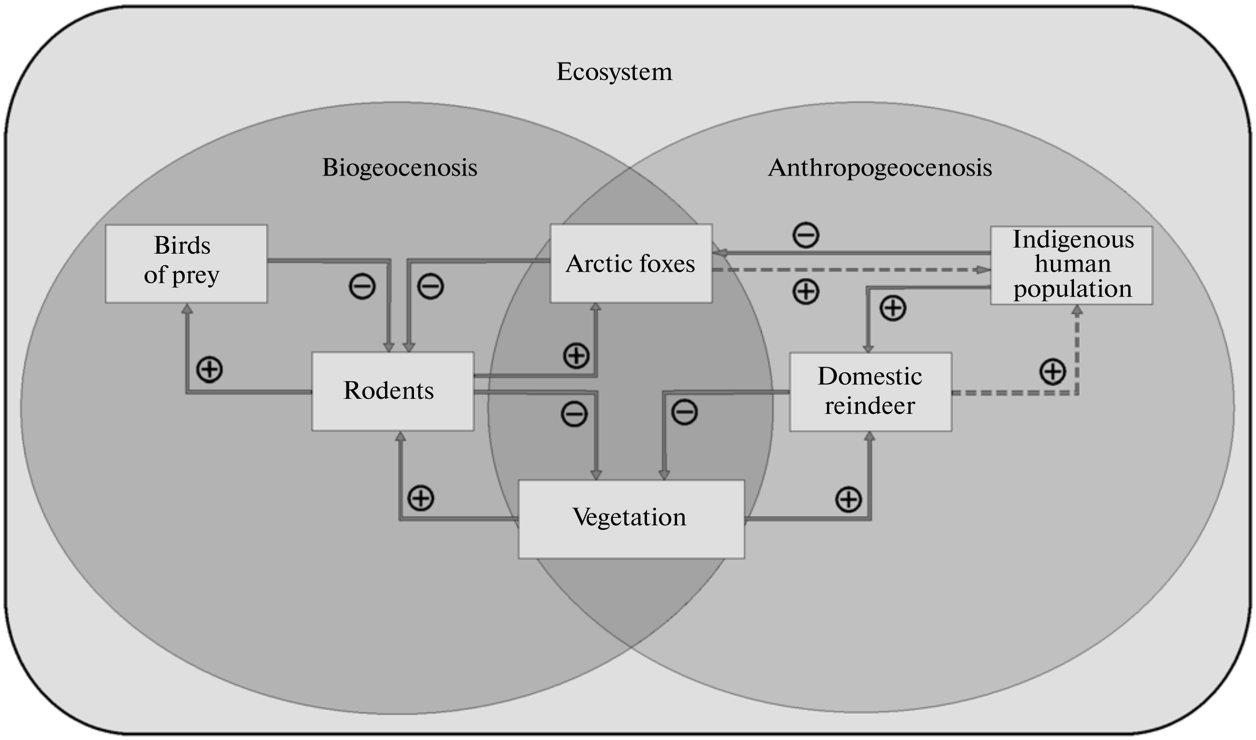

Fig. 3. Schematic diagram of the Yamal tundra ecosystem as a basis of computer simulation. *Dashed lines* show the connections determining economic benefit; *solid lines* show direct (trophic) connections; the “plus” and “minus” symbols indicate positive and negative connections, respectively.

(6) Industrial development of the peninsula related to the withdrawal and deterioration of rangelands leads to an increase in grazing loads on the remaining pastures. Lands temporarily withdrawn from the agricultural cycle are technically returned, but they are practically unsuitable for use as pastures. The area of irreversibly destroyed (foodless) lands has been permanently increasing during the past decades (Yuzhakov and Mukhachev, 2001). However, the damage related to the development of raw hydrocarbon deposits may be still regarded as local. Analysis of a map of reindeer pastures shows that the area of the lands undergoing technogenic deterioration in 1995 was less than 2% of the total land area (Khozyaistvenno-botanicheskaya…, 1995), whereas reindeer are annually grazing in an area of about 10.6×10^6 ha (Yuzhakov and Mukhachev, 2001), and there are no spare pastures left on the peninsula.

Comparison of the estimated reserves of both green and lichen forage in Yamal pastures in the 1930s and the late 20th century indicates a rapid decrease in forage reserves (Fig. 2). Below, we analyze complex interrelations between herds of grazing reindeer and available forage reserves with the use of computer experiments with a simulation model.

SUBSTANTIATION AND DESCRIPTION OF THE MODEL

Simulation models of biogeocenoses can only be based on factual data on the structure and dynamics of the main components, which, as Shvarts (1971) put it, constitute their “core.” In the case of Yamal tundras, these are the vegetation, small mammals, domestic reindeer, predatory mammals (mainly Arctic foxes), and birds of prey. The functional connections between these components are nonlinear, which complicates the prediction of ecosystem dynamics (Kryazhimskii and Danilov, 2000). The ecosystems are constellations of two overlapping subsystems: the natural one (the biogeocenosis) and the subsystem surrounding humans and “working” for them, or anthropogeocenosis according to Alekseev (1993). A schematic representation of such a system, which served as a basis for the model presented here, is shown in Fig. 3.

The simulation model of the interaction between domestic reindeer and tundra vegetation was a discrete-event system (Karpov, 2006). The following dependent variables were calculated at each step of simulation (one year): the lichen and green forage reserves, the food mass consumed by the reindeer, and the effect of mechanical damage of vegetation (trampling). These values varied in correspondence with the behavior of the number of reindeer, which was the

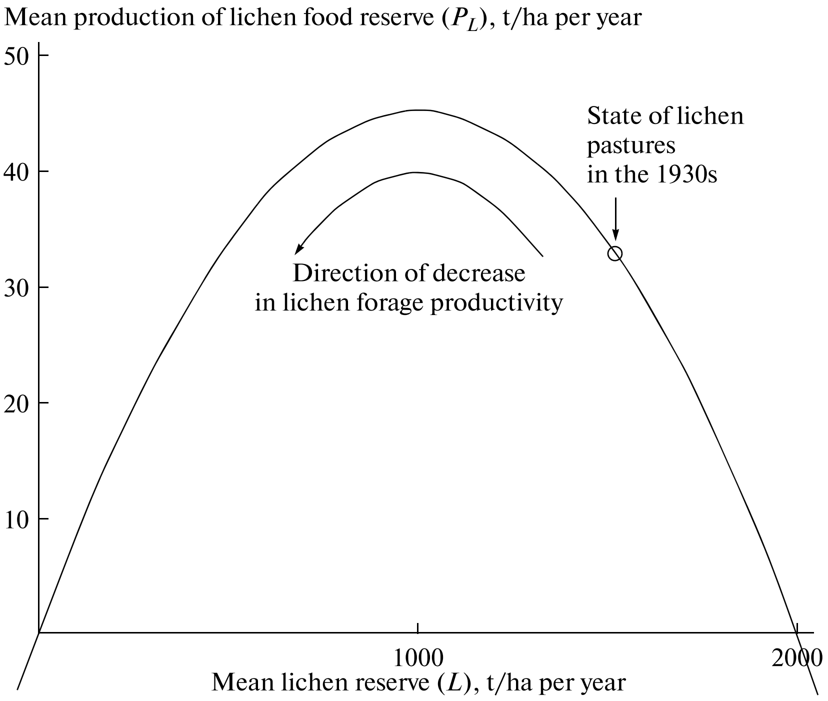

Fig. 4. Dependence of the lichen production on the absolute lichen pasture reserve assumed in the model. Canonical Verhulst's curve taking into account self-regulation: $P_L = 0.09L\left(1 - \frac{L}{2000}\right)$.

manipulated variable and was arbitrarily set in the simulation experiments. As a result, we obtained a computer simulation of the time course of lichen and green forage reserves, i.e., changes in the resource potential of the peninsula depending on the reindeer population dynamics.

Andreev (1933) estimated the mean annual food demand of a reindeer as 1.25 and 2.5 t of lichen and green forage, respectively. We took these estimates as basic assumptions when developing the model:

$$F_L = 1.25 \cdot N_y, \quad (1)$$

$$F_G = 2.5 \cdot N_y, \quad (2)$$

where F_L and F_G are food loads (t/year) on the lichen (L) and green (G) forage reserves, respectively, and N_y is the number of reindeer in the year y.

Andreev's (1933) calculations took into account unproductive loss of food. For example, Andreev wrote, "A reindeer's daily demand for lichens in winter (which includes the early spring and late autumn periods, when reindeer mainly feed on lichens) is limited by a value of 5 kg of air-dry lichen mass. However, since a considerable proportion of lichens, especially in snowless periods, is lost unproductively (mainly trampled), then the reference daily expenditure of lichens under the current conditions of reindeer grazing should be assumed to be twice as much as the daily demand; i.e., it should be taken to be 10 kg, which corresponds to 2.5 t of air-dry lichen mass throughout this period (250 days). Assuming a reindeer's daily expenditure of green food to be 20 kg, which considerably exceeds its daily demand, we obtain 2300 kg, or approximately 2.5 t of air-dry green mass throughout the summer period (115 days)... Our observations performed in tundras of Yamal and Northern Land and certain calculations made on their basis show that reindeer consumes about one-sixth of the annual production of the total grazed green mass, selecting, in this case, the best green forage and eating almost no lichens. To calculate the reindeer carrying capacity of summer pastures, we assume this value, (2.5 × 6) = 15 t of air-dry green mass" (Andreev, 1933, pp. 147–148).

Therefore, our model assumes that reindeer trample down as many lichens as they eat; hence, the mass of lichens removed is two times larger than required for food, specifically, 2.5 t/(reindeer year). The loss of green food in the same way was estimated to be five times higher: given that one reindeer needs 2.5 t/year, the correction for trampling was assumed to be 12.5 t/year, and the total removal of green food was taken to be 15 t/year.

These estimates agree with the observation that, the less food there is in pastures, the more rapidly the animals move; therefore, the loss of pasture resources due to trampling increases more rapidly than that due to grazing. Note that unproductive loss rapidly increases with decreasing amount of pasture food (Gambaryan,

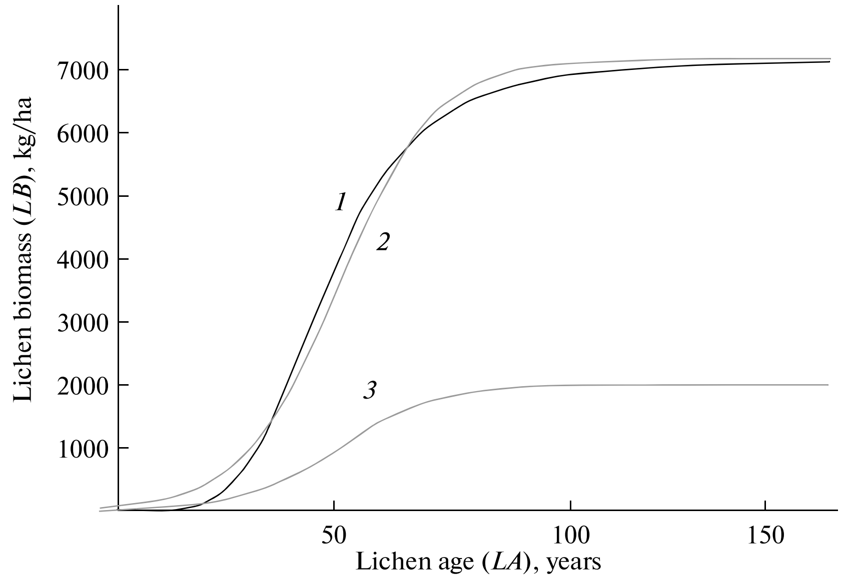

Fig. 5. The *S*-shaped curve describing the time course of the restoration of the lichen forage reserve: (*1*) the curve suggested by Kumpula et al. (2000), who analyzed the restoration of vegetation after forest fires that occurred at different times in the past in the taiga zone of Finland $LB = 4812.7364\Big/\left(\frac{1}{(LA/45)^{4.374}} + 1\right) + 2343.8862\Big/\left(\frac{1}{(LA/45)^{4.374}} + 1\right)^2$; (*2*) the canonical logistic curve calculated by us from the same data $LB = \frac{7156.6226}{e^{-0.09LA}(100-1)+1}$; it can be seen that complex parametrization of data on the restoration of the lichen cover describes the process only slightly better than canonical Verhulst's curve does; (*3*) the curve of the lichen forage reserve in Yamal calculated by Eq. (5) $LB = \frac{2000}{e^{-0.09LA}(100-1)+1}$.

1972; Abaturov, 1979; Polezhaev, 1980). Therefore, we assumed that the loss of resources due to trampling was directly proportional to the numbers of reindeer and inversely proportional to the food reserves:

$$T_L = t_L \cdot N_y/L_y, \qquad (3)$$

$$T_G = t_G \cdot N_y/G_y, \qquad (4)$$

where T_L and T_G are the losses due to trampling of lichen (L_y) and green (G_y) food, respectively; t_L and t_G are the coefficients of the effect of this factor on lichen and green food; N_y is the number of reindeer in the year *y*.

When calculating the proportionality coefficients ($t_L = 1375 \times 10^4$ and $t_G = 1625 \times 10^5$), we proceeded from the ratios between trampled and grazed food reserves assumed by Andreev (1933) and his estimate of the lichen and green food reserves.

The model described the lichen biomass production using classical Verhulst's (1845) *S*-shaped growth equation:

$$P_L = g_L \cdot L_y \cdot (1 - L_y/L_{\max}), \qquad (5)$$

where P_L is the annual production, L_y is the lichen reserve in the current year (*y*), $L_{\max}$ is the maximum possible amount of the reserve in the given geographic zone (the so-called "environment capacity"); g_L is a coefficient reflecting the specific annual production observed at small values of the reserve in the absence of limiting factors (the "starting production").

According to this dependence, the absolute annual production (P_L) is the highest when the reserve reaches about half the maximum possible value. If the lichen cover is close to the mature (stationary) state (L_y approaches $L_{\max}$) and the production compensates for the loss, then P_L approaches zero (Fig. 4). Under the conditions of grazing load, the stationary state is not reached (the reserve amount is permanently "thrown back" to the zone where the production rate is positive). The canonical logistical (*S*-shaped) curve of the dependence of renewal on the time is confirmed by data on restoration processes in lichens, e.g., in Fennoscandia (Fig. 5). Analysis of published data on lichen biomass production in different regions of the tundra zone (Andreev, 1954; Kumpula et al., 2000; Gaio-Oliveira et al., 2006), as well as our own observations on the natural restoration of lichens in Yamal (Morozova and Ektova, 2010) showed that the maximum specific production of lichens (g_L/L) was approximately the same in all cases (4.5–5.0% of the biomass reserve). On the other hand, the $L_{\max}$ varied under different climatic conditions (it was about 3.5 times higher in the taiga zone of Finland compared

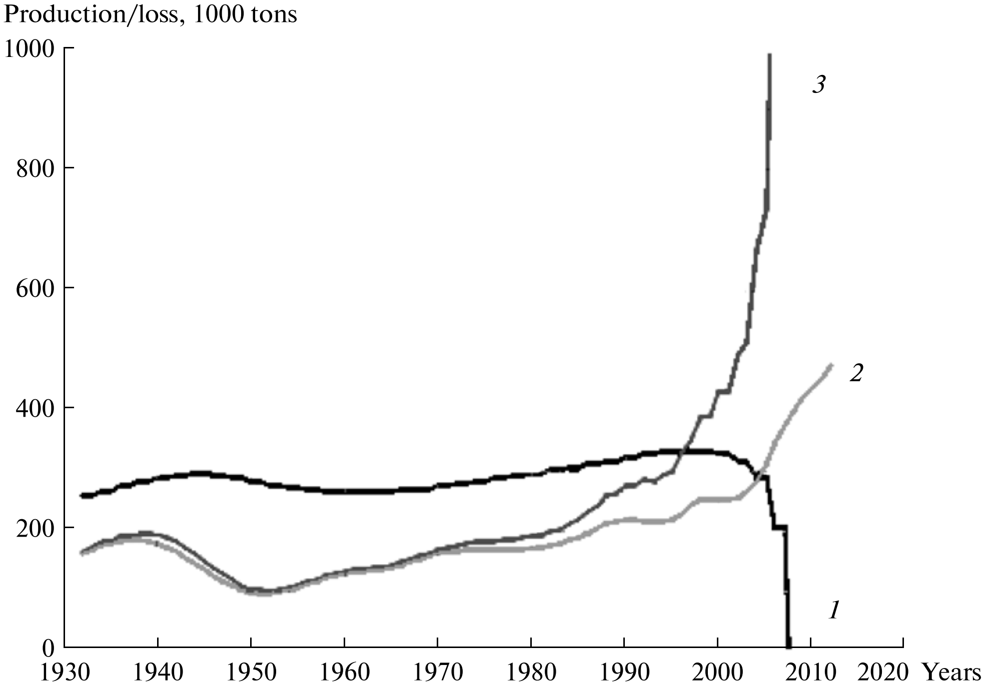

Fig. 6. Simulated time course of the loss and natural production of lichen forage reserves at the actual reindeer population growth rate in Yamal: (*1*) annual production of lichens, (*2*) annual loss due to grazing, and (*3*) annual loss due to trampling.

to Yamal). Therefore, our model assumed that, in Yamal, $g_L = 0.09$ and $L_{\max} = 14.8 \times 10^6$ t (Fig. 5).

Thus, the changes in the lichen reserve may be expressed by the balance equation

$$L_{y+1} = L_y - F_L - T_L + P_L, \qquad (6)$$

where L_y and L_{y+1} are the lichen reserves in the current (y) and next ($y + 1$) years, respectively; F_L and T_L are the same as in Eqs. (1) and (3), respectively; and P_L is the annual production of the lichen reserve, which is close to zero in the mature state in the absence of pasture load.

In the model, the annual production of green forage plants was assumed to be proportional to the reserve of their underground organs (roots and rhizomes). On the basis of general considerations, we assumed the production of the reserve of underground components in our model to depend on the mass of photosynthesizing organs (the live aboveground phytomass), as described by Eq. (7). In accordance with the published data (Titlyanova, 1977), the specific rate of loss of live green plants was taken to be constant (Eq. (8)).

The model employed the following algorithm of the calculation of green forage reserve:

$$P_R = g_R(G_y - F_G - T_G)(1 - R_y/R_{\max}), \qquad (7)$$

$$R_{y+1} = R_y + P_R - d_R \cdot R_y, \qquad (8)$$

$$G_{y+1} = d_K \cdot R_{y+1}, \qquad (9)$$

where P_R is the annual growth of reserve organs (which are underground in herbaceous plants and aboveground in small shrubs and shrubs); G_y and G_{y+1} are the productions of the photosynthesizing organs in the current and next years; F_G is the trophic load; T_G is the loss due to trampling; R_y and R_{y+1} are the masses of perennial organs of the plants (mainly the underground organs of herbaceous plants) in the current and next years, respectively, and $R_{\max}$ is the maximum possible value of this mass (environment carrying capacity); and $g_R = 10$ and $d_R = 0.2$ are the coefficients of relative production and loss, respectively, taken from published sources (Wielgolaski, 1973; Wielgolaski, 1974; Titlyanova, 1977; Kulikov, 1989; Nikonov, 1985).

The model also took into account the effect of the periodically increasing foraging pressure of rodents on the vegetation. The results of long-term observations have shown that rodent population outbreaks occur with a period of 3–4 years, corresponding to the trend first demonstrated by Elton (1942) and repeatedly confirmed since then. It is known that lemmings may remove as much as 70% of the aboveground mass of herbs in such periods (Thompson, 1955; Pitelka, 1964; Batzly, 1974). Therefore, taking into consideration that rodents forage on herbs but not shrubs, we calculated the maximum removal of green food in population peak years as

$$P_R = g_R(G_y - F_G - T_G - 0.5G_y)(1 - R_y/R_{\max}). \qquad (10)$$

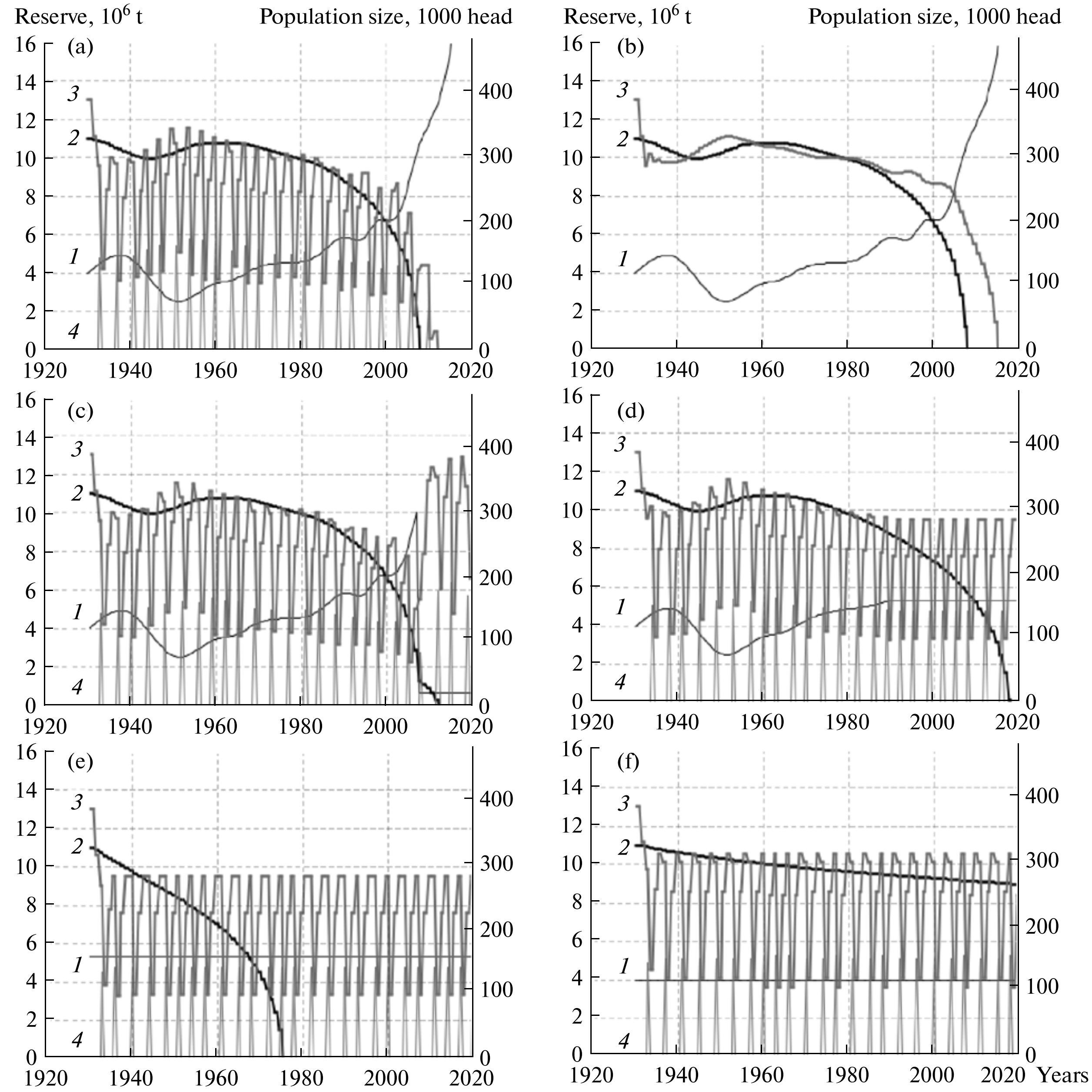

Fig. 7. Simulated dynamics of plant forage reserves in Yamal: (a) the scenario of the actual extensive growth of the domestic reindeer population (verification of the model); (b) the same scenario with the assumption on the absence of rodent impact; (c) the scenario of a decrease in the reindeer population to 20000 animals in the year 2007, which would be the "rational" population size if calculated by Andreev's (1933) method for the actual forage reserve in that year; (d) the scenario with the reindeer population maintained constant after the year 1990, when it reached 160 000 head, or the "rational" population size according to Andreev's (1933) calculations for the 1930s; (e) the scenario assuming that the reindeer population size remained at the level of 160000 head (the "rational" population size for the 1930s, according to Andreev); (f) the scenario where the initial reindeer population size (120000 head) remained constant throughout the period studied; (*1*) reindeer population size, 1000 head; (*2*) lichen forage reserve, 10^6 t; (*3*), green forage reserve, 10^6 t; (*4*) forage loss to rodents, 10^6 t.

RESULTS OF SIMULATION

The reindeer population size served as a manipulated variable in the model. As noted above, the initial conditions were set on the basis of Andreev's (1933) factual data and calculations, and the simulation algorithm was constructed according to considerations based on our own and literature data on the time course of, and the pattern of relationships between, different components of the Yamal ecosystem.

The relative roles of the trophic load and trampling for lichen forage directly indicate that the latter factor made the major contribution to the overall grazing load, which was taken into account in the model (Fig. 6). The annual production of lichens has become negative in the first decade of the 21st century. When the model was run, the trajectories of the changes in food reserves during the period from the 1930s to the end of the 20th century determined by the actual numbers of reindeer led to the present state, which was not prespecified (Fig. 7a). This confirms the acceptability of the functional relationships used and may be regarded as verification of the model: we succeeded in correctly reproducing the dynamics of pasture resources with increasing grazing load.

The first question to be answered in the course of simulation experiments was as to what the situation would have been if the lemming population bursts had not occurred. The results of this experiment showed that the simulated dynamics of green forage changed only slightly; specifically, the "moment of complete degradation of vegetation" shifted along the time axis (Fig. 7b). This indicates that the possible synergistic effects of superimposition of rodent population outbreaks onto reindeer grazing loads are unlikely to have played a key role in the overall pattern of the decrease in the green forage reserves during the period studied.

The scenario of the next experiment was that the reindeer population would not exceed 160000 head, the size that Andreev (1933) regarded as allowable for grazing in the peninsula (in fact, the population reached this size in 1990). According to the predictions of our model, the lichen food reserves under such conditions would have decreased anyway. By the year 1990, the food reserves had already decreased considerably, compared to those in the early 1930s, and the rehabilitation capacity of ecosystems would have been insufficient for counterbalancing the grazing load (Fig. 7d).

Thus, the results of simulation indicate that the reindeer population size of 160000 head in Yamal in 1990 already exceeded the maximum allowable level. This is explained by the fact that Andreev's (1933) calculations did not take into account the dependence of lichen cover damage by trampling on the total food reserve. The results of computer simulation experiments where intrasystem regulation was taken into consideration showed that, even if (as Andreev recommended) the reindeer population had increased to 160000 head in the 1930s and remained constant thereafter, the lichen food reserves would have nevertheless been depleted. Restoration could not compensate for the loss because of a decrease in the annual production and the total lichen food reserve (Fig. 7e).

We also considered another scenario, which assumed that the total number of reindeer grazing in Yamal in the early 1930s (about 100000 head) remained unchanged. The results of simulation showed that this is the only case where the lichen food reserve would have not decreased (Fig. 7f). This number is presumably comparable to the wild reindeer population size in Yamal before the extensive development of domestic reindeer breeding, when natural mechanisms of population control had been effective.

Following Andreev's (1933) recommendations, we simulated the allowable reindeer population size on the basis of forage reserves in the modern pastures. The following situation was considered: If the reindeer population had decreased to 20000 head in 2007, when the lichen forage reserve was about 10^6 t, then this reserve would have been restored, but extremely slowly, whereas the restoration of the green forage reserve could have been rapid (Fig. 7c). This indicates that the total carrying capacity of reindeer pastures in Yamal at present is no more than 20000 head.

CONCLUSIONS

Although any model is a simplification and gives only a rough picture of the actual situation, which partly accounts for the heuristic role of simulation (*Ekologicheskie sistemy*, 1981), verification of the model has generally confirmed its validity, as we have shown above.

The results of analysis of the Yamal ecosystem do not provide grounds to assume that any factors other than extensively developing large-herd (nomadic) reindeer breeding (climate changes, development of raw hydrocarbon deposits, etc.) account for the degradation of vegetation in the peninsula. The results of simulation indicate that the rapid growth of the reindeer population is the main factor responsible for deleterious changes in the natural territorial systems of Yamal. To date, the situation has already become catastrophic.

The technogenic impact is considerably exacerbating the situation, because grazing loads are transferred from the lands allotted for industrial development to neighboring areas. However, as compared to grazing, the current industrial development of Yamal may be only considered as a minor, local-scale negative factor as yet. Yamal lacks reserve pastures, and grazing loads are high almost everywhere. Furthermore, lichen tundras will not be restored naturally on sandy grounds.

Despite the established stereotype, the traditional natural resource use is not a model of harmonious coexistence of humans and plant resources. Conversely, the extensive growth of reindeer population is a more serious threat to Yamal natural systems than, e.g., the development of the oil and gas industry.

The results of simulation have shown that the method for calculating the total carrying capacity of pastures should take into account the nonlinear dependence of the annual lichen production on the amount of their reserve. Ignoring this fact would result in overestimation of the calculated capacity of pastures, which, in turn, would promote their degradation even if the recommendations on reducing the reindeer population to the presumably allowable (in fact, overestimated) level are complied with. The results of system analysis of the plant resources—domestic reindeer system have shown that, back in the 1930s, the maximum allowable number of reindeer were already grazing in Yamal, and there were no reserves for increasing their stock. Further growth of the reindeer population has undermined the resource basis of reindeer breeding.

To preserve reindeer breeding in Yamal, it is necessary to implement a system for monitoring grazing loads, with both the state of forage reserves and the characteristics of rehabilitation processes taken into account. The forage reserves are considerably smaller today than they were in the early 1930s; therefore, the maximum allowable stock of reindeer should be considerably smaller than 100 000 head. According to preliminary assessment, no more than 20 000 reindeer can be pastured (in the traditional way) in the Yamal Peninsula at present.

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