Application of direct simulation Monte Carlo method to ecological objects modeling. Modeling a tundra animals population

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Abstract. Modeling based on properties and processes of individual persons (individual based modeling) began to use in the quantitative ecology.
In this paper such a model has been proposed for study of a lemming (tundra mammal of the field-vole subfamily) population. The model was oriented to using the direct simulation Monte Carlo method that has been developed and successfully applied to solving numerous rarefied gas dynamics problems [5]. The model takes into account the following processes: 1) displacement of person inside of natural living habitat, 2) guarding an individual region around a hole, 3) encounters with other persons, 4) pregnancy, 5) birth of posterity, 6)nutrition and hungry during different seasons and some others. Numerous calculations confirmed a model efficiency. For example, for some set of the model parameters an average period of a population cycling was equal to 3 years. The same value was fixed in field experiments at Taimir peninsula.
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1 Introduction

Population ecologists normally use two different approaches.
The first follows the ideas of Lotka-Volterra model [1],[2] describing a predator - prey interaction with the aid of systems of the ordinary differential equations coefficients of which are some average characteristics of a population. Thus age, sex, genetics and other characteristics of individuals, their distribution in space, migrations and social aspects of behavior, as a rule, are not taken into account. Accordingly, it is very difficult to compare the results obtained to experimental data. Essential updating of this approach are various models of trophy interactions in which the populations are structured on one or several parameters [3].
The second approach is based on modeling a behavior of population individuals and on obtaining the population dynamics on this basis ([4] and references therein). With such approach all features of separate individuals are taken into account by creating models of processes which they participate in. The amount of free model parameters for such an approach sharply grows allowing to take into account available experimental data practically in full. Statistical methods are the most natural numerical methods for such models.

In the present work a statistical model of tundra lemmings (Dirostonyx torquatus chionopyes) life and behavior has been constructed. For numerical modeling the direct simulation Monte Carlo (DSMC) method was used. This method was offered in the sixties by Australian professor G. A. Bird for numerical investigation of rarefied gas flows [5] and since then it became the conventional research tool not in this area only. The basic idea of the DSMC method consists in the assumption that during a small time step it is possible to share two interconnected processes - movement of molecules and their collisions with each other. Modeling process by the DSMC method can be described as follows. At the initial moment of time a computational region is populated by a large number of molecules for which the current coordinates and speed vectors are prescribed. During a small time step molecules move according to their speeds and collide with a surface of a flying body, fly in and fly out of the computational region according to the prescribed conditions. Then collisions among themselves are modeled. Laws describing all these collisions are considered as given. Summarizing the appropriate information on the molecules which are taking place in each cell of the computational grid a distribution of all parameters in the flow field can be obtained.
In our opinion this method can be successfully used for modeling a population dynamics of many animal communities.

2 The model description

The population of lemmings (Dirostonyx torquatus chionopyes) at Western Taimir peninsula was chosen as an object of modeling. Though the lemmings serve as food for polar foxes and some other tundra animals, both experimental data [6], [7] and results of trophy interactions modeling [3] point out that the role of the letters in lemming population dynamics is insignificant (but not vice versa). It allows to pick out a chain "vegetation - lemmings" from a more full system "vegetation - lemmings - polar foxes".
Several models of lemmings life and behavior have been constructed. In the present work we consider results of modeling based on the simplest of them. The model supposes that lemmings can be described by age, sex, life stage and life potential. The first two properties do not require any comments. There are three life stages for female individuals - junior, adult and pregnant adults and two of them for male individuals - junior and adult. The life potential is a variable characterizing the physical state of an individual. Its value changes from zero up to one in various life processes (see below).
During their life, lemmings participate in the following processes: movement, feeding, digestion of food, searching for a hole, collisions with other individuals, pregnancy, birth of posterity, growth and death. We shall consider these processes and their modeling in more detail.
Searching for forage, animals move with a fixed speed. The direction of movement in each time step is chosen equiprobably. If during a time step the

trajectory of movement crosses a border of the computational region, the individual "reflects" from the border to the direction which is chosen equiprobably. When feeding time expires, an individual moves back to the hole, if he or she has got one, using the shortest route for digestion and relaxation. During this digestion time the individual does not leave the hole.

When moving during feeding an individual collides with other individuals of the population. Such a meeting takes place each time when two or more individuals appear at the same single site (the whole computational region is divided into such sites). Two individuals are selected from the amount in collision, the rest run away. The life potentials of both participants decrease after collision at a value which depends on their life stages. In other words an interaction matrix of dimension 5x5 is set. After collision the life potential of the participants restores till the next collision. If such a collision occurs in the spring or in the summer (i.e. in a reproduction season) and the participants are of different sex, the female individual with some probability becomes pregnant. After the assigned time a posterity appears and the mother's life potential decreases at some given value. Sex of each offspring is chosen equiprobably. The offspring does not leave the hole for some time. The offspring acquire an initial value of the life potential which grows during the given time if collisions with other individuals do not occur.

From the first independent feeding, an individual searches for a free hole and he or she occupies it once found. The presence of the hole and reaching a certain age are two conditions of transition from junior stage to adult.

The death of an individual occurs in three cases: 1) if an individual has come of age limit; 2) if value of his or her life potential became zero or negative and 3) if a female has brought the third posterity. Besides during each time step there is a probability of destruction of an individual due to several other reasons. In all these cases the hole occupied by the lost individual, becomes free.

According to experimental data [6],[7] at the Taimyr peninsula, a year can be divided into two periods. The reproduction period extends from February, 1 till August, 31. During the other part of the year individuals colliding with each other during feeding gradually reduce their life potential.

Within the framework of the present research detailed modeling of a vegetation distribution, its consumption and reproduction was not made. Instead it was assumed that food resources were enough to feed the population until its size does not exceed the given maximal value which depends on a season. When this happens a starvation begins. During the starvation the life potential of each individual decreases at the end of each time step. Winter starvation stops when the population size decreases to a given minimum value.

Let's describe now a procedure of statistical experiment. Animals can move through the whole computational region but can get holes only in some strip part of it. At the initial moment the strip is filled by holes according to some random procedure. Another random procedure is used for prescribing at the initial moment both positions of individuals and other parameters describing their properties and conditions (As show results obtained, these initial data influence a population dynamics only till the first depression).

3 Results

It was proved possible to reproduce a three-year period oscillation of the population size which is typical for lemmings in western Taimir. Typical dependence of the population on time is shown on Fig. 1. The limiting values of the population size are shown by the horizontal straight lines. A growth of the population size between points 1 and 2, 3 and 4, 5 and 6 is a consequence of birth of new members of the population during the reproduction seasons, and decrease of the population size between points 2 and 3, 4 and 5 is a consequence of a reduction of the life potential during the winter seasons. Sharp decreasing of the population size before point 1 and after point 6 is a result of animal deaths during starvations. Certainly, for other sets of the

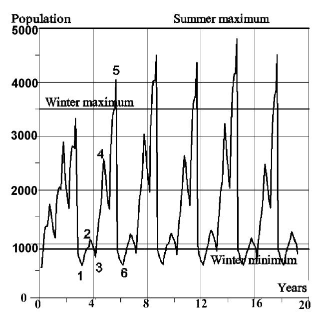

Fig. 1. Population size vs time

model parameter fluctuations of the population size are not so regular, and for some of them an extinction occurs.

One of the most attractive features of the individual-based approach is an opportunity to look at and to analyze various distributions. The most important among them are age, life potential, sex and space distribution. The first two of them at the time moments designated in Fig.1 by figures 1-3 and 4-6, are given in Figs. 2 and 3 respectively. At the 1, 3 and 5th time moments absence of individuals at the age of 0 up to 5 months corresponds to the previous non reproductive season. Similarly the second gaps in the age distributions at the 3 and 5th time moments correspond to next to last non reproductive seasons. One can expect that at least one of the life potential maxims has to be shifted to zero value at the time moments of minimum population size (1, 3 and 5th moments) and in the opposite direction at the time moments of maximum population size (2, 4 and 6th moments) due to a large number of offspring. These peculiarities can be seen in Fig. 2 and Fig. 3. A sex ratio is quite an

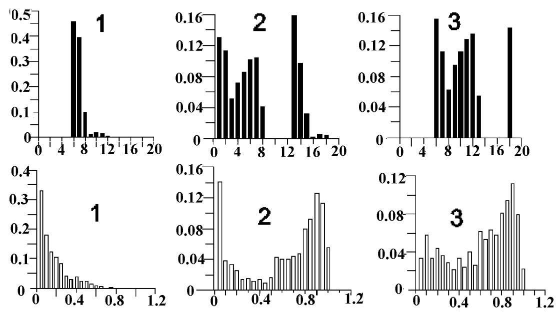

Fig. 2. Age and life potential distribution functions at 1st, 2nd and 3rd time moments

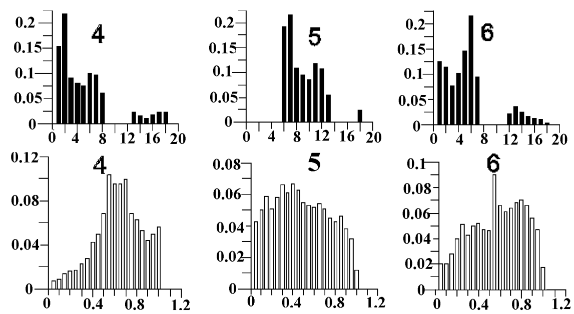

Fig. 3. Age and life potential distribution functions at 4th, 5th and 6th time moments

important characteristic of any population. Fig. 4 illustrates the dynamics of this ratio for the lemming population. Unfortunately a season of field experiments at the Taimir peninsula extends over 3-4 months in year only when a blanket of snow is absent. Following these summer experiments we supposed that the ratio can change from 0.5 to 1.5 and the model parameters were chosen in such a way to fulfill approximately this restriction. Space distributions of lemmings are presented in Figs 5 and 6 for the 1, 4 and 6th time moments. For all computational cases it was supposed that male individual site consists of four female adjacent individual sites, i.e. linear dimension of a male individual site was twice that of a female one. Fig. 5 illustrates a settling dynamics for a case when maximum numbers of male and female holes along x direction were the same. As the population increases (the 4 and 6th time moments) males and females scales up corresponding areas by their holes.

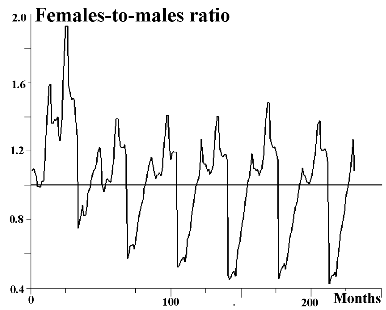

Fig. 4. Sex ratio vs time

Looking for free holes, the younger individuals with a high value of the life potential go to the boundaries of their habitat region. It is natural that after starvation these younger individuals survive there (the 1st time moment). The results obtained for another computational case are presented in Fig. 6. Here males and females can create holes in the same region only. So, the possible maximum number of male holes is one fourth of female ones. At some moment all possible male holes prove to be occupied and male juniors have to search for the holes outside the permissible region. Such individuals may not become adults and are condemned to death without reproduction.

4 Conclusions

DSMC method

- is well adapted to solving the population dynamics problems
- can be used to any mobile specie whose properties and behavior were well studied to construct the life process models
- can be generalized to several interactive species and to space and time distributed parameters (for example, food resources or/and weather)
- can be used for studying an influence of ?pathological? factors on the population dynamics (diseases and environmental catastrophes)
- can be used for proposing new field experiments
- can be easily adapted to massive-parallel computers

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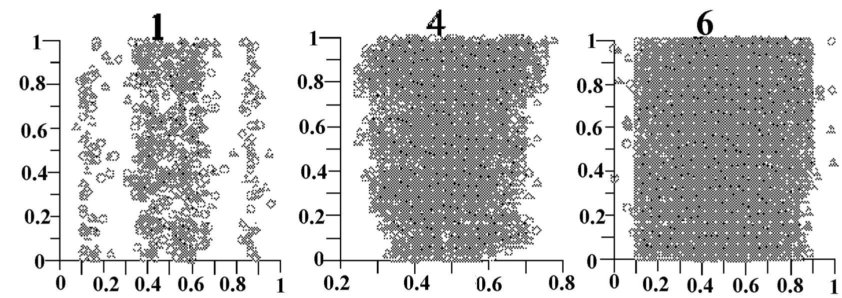

Fig. 5. Space distribution of lemmings at 1st, 4th and 6th moments (case 1)

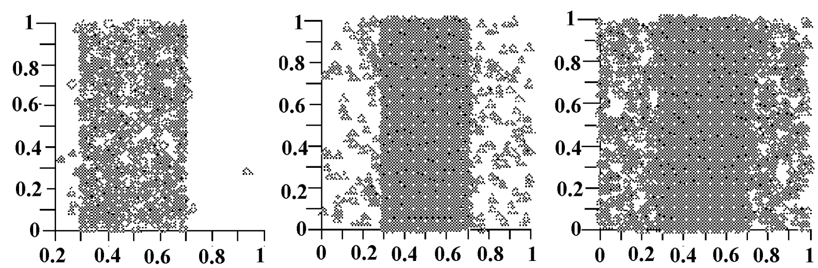

Fig. 6. Space distribution of lemmings at 1st, 4th and 6th moments (case 2)

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