ABOUT COMPLETENESS OF CLASSIFICATION OF INSECTS ON THEIR TYPES OF DYNAMICS: PROBLEMS OF APPLICATION OF CLUSTER ANALYSIS

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In current publication problem of completeness of insects classification on their types of dynamics (Isaev et al., 1984, 2001) is analyzed with the help of cluster analysis methods. For a certain set of empirical trajectories (36 or 35 trajectories for 13 species) special transformation on non-negative integer net with various dimensions (10, 11, and 12) had been provided. Every empirical trajectory was transformed into set of points of non-negative integer net, and cluster process had been provided for these sets. For intersecting and non-intersecting sets two different measures of closeness were used. Analyses of processes of clustering showed that 12 or less number of points cannot give sufficient description of population dynamics type: first six steps only of cluster process can be interpreted in correct manner. Analysis of existing database allowed finding of species with dynamics which is far from all other types of dynamics.

Keywords: cluster process, population dynamics type, insect classification

Introduction

Analysis of predator-prey system dynamics (Isaev, Khlebopros, Nedorezov, 1978) of non-parametric type (model of Kolmogorov' type):

$$\frac{dx}{dt} = x(F(x) - f(x,z)), \quad \frac{dz}{dt} = z(-G(z) + g(x,z)), \qquad (1)$$

allowed obtaining of certain set of phase spaces which characterize dynamics of considering system for different conditions of species interaction. In model (1) $x(t)$ is prey population size (or density) at time t, $z(t)$ is predator population size. Function $F(x)$ describes a process of interaction between preys without influence of predators, and it was assumed that this function satisfies the following conditions:

$$F(0) > 0\,,\ \frac{dF}{dx} < 0\,,\ \exists K:\ F(K) = 0\,. \tag{2}$$

Function $G(z)$ in (1) describes dynamics of predators at absence of preys, and it is assumed that number of predators decreases monotonously in such a situation:

$$G(0) > 0\,,\ \frac{dG}{dz} > 0\,. \tag{3}$$

Function $f(x,z)$ in (1) describes a process of population interaction, and respective decreasing of prey population size:

$$\forall (x,z) \in R_+^2\ \ f(x,z) \ge 0\,,\ f(x,0) = 0\,,$$

$$\frac{\partial f}{\partial x} < 0\,,\ \frac{\partial f}{\partial z} > 0\,. \tag{4}$$

In (4) the effect of escape of preys under the control of predators was taken into account (Isaev et al., 1984, 2001). In a result of it system (1) became a non-balanced model (like, for example, well-known Leslie model of predator-prey system dynamics; Leslie, 1945, 1948). Later this problem was eliminated within the framework of continuous-discrete models (Nedorezov, Utyupin, 2003, 2011; Nedorezov, 2012).

Function $g(x,z)$ in (1) describes also a process of population interaction, and respective increasing of predator population size:

$$\forall (x,z) \in R_+^2\ \ g(x,z) \ge 0\,,\ g(0,z) = 0\,,$$

$$\frac{\partial g}{\partial x} > 0\,,\ \frac{\partial g}{\partial z} < 0\,. \tag{5}$$

Conditions (2)-(5) are rather common, and can be observed for various mathematical models of predator-prey system dynamics (see, for example, Bailey, 1970; Bazykin, 1985; Kolmogoroff, 1936; Kostitzin, 1937; Maynard Smith, 1974; Nedorezov, 1986, 1997 a, and many others). Analysis of this model (1)-(5) allowed obtaining a group of phase portraits which can characterize different types of population outbreaks: fixed, permanent, reverse, and an outbreak proper. For every type of outbreak real species of forest insects were pointed out (Isaev, Nedorezov, Khlebopros, 1978, 1979, 1980). Some interesting examples of real species were pointed out by V.V. Rubtsov (1992) and A. Berryman (1981, 1990, 1991).

Three basic phase portraits corresponding to various types of population outbreak on a plane “population density – birth rate” are presented on figure 1. Birth rate y is determined as relation of two nearest numbers of population densities:

$$y_n = \frac{x_{n+1}}{x_n}.$$

Pointed out phase portraits were obtained under qualitative transformation of non-negative part of phase space of the system (1). On presented pictures $\bar{y}$ is upper boundary of phase portrait; it corresponds to the situation when $z(0) = 0$ (outbreaks trajectory cannot intersect this curve: it will correspond to the situation when population size becomes negative). Stationary state $(x_r, 1)$ is a saddle point: y_r is incoming separatrix of this saddle, and y_q is outcoming separatrix. Point $(x_1, 1)$ (fig. 1 a, c) is stable knot or focus: it is equal to stable level of population in stable ecosystem. Under normal conditions and stable ecosystem population fluctuates near this stable level. Point $(x_2, 1)$ is stable level which can be realized for system when regulative mechanisms cannot return the system back (to zone of stability; fig. 1). Points $(x_i, 1)$ and $(x_e, 1)$ are unstable knots or focuses; $(x_T, 1)$ is maximum population size which can be observed in system when number of predators is equal to zero.

Fixed outbreak (fig. 1 a) is realized for *Monochamus urussovi* F. and for Xylotrechus altaicus Gebl. (Isaev et al., 1984, 2001). Permanent outbreak is observed for larch bud moth (*Zeiraphera diniana* Gn.) in Swiss Alps (fig. 1b; Baltensweiler, 1964, 1970); V.V. Rubtsov (1992) assumes that this dynamic regime can be observed for green oak tortrix in European forests. An outbreak proper is observed for biggest part of outbreak species and, in particular, for Dendrolimus superans sibiricus Tschetv. (Isaev et al., 1984, 2001), for pine looper caterpillar (*Bupalus piniarius* L.) (Klomp, 1966; Schwerdtfeger, 1941, 1944, 1968) and so on.

Later it was proved that dynamics of outbreak types (fig. 1) can be observed within the limits of some other models describing the process of interaction of population with other components of ecosystem (Nedorezov, 1979 a, b, 1985, 1986, 1997 b; Isaev, Nedorezov, Khlebopros, 1982, 1984, 2001). Obtained results of the analyses of mathematical models were put into the base of monofactor theory of population dynamics (Nedorezov, 1986, 1989, 1997, 2012; Nedorezov, Utyupin, 2011).

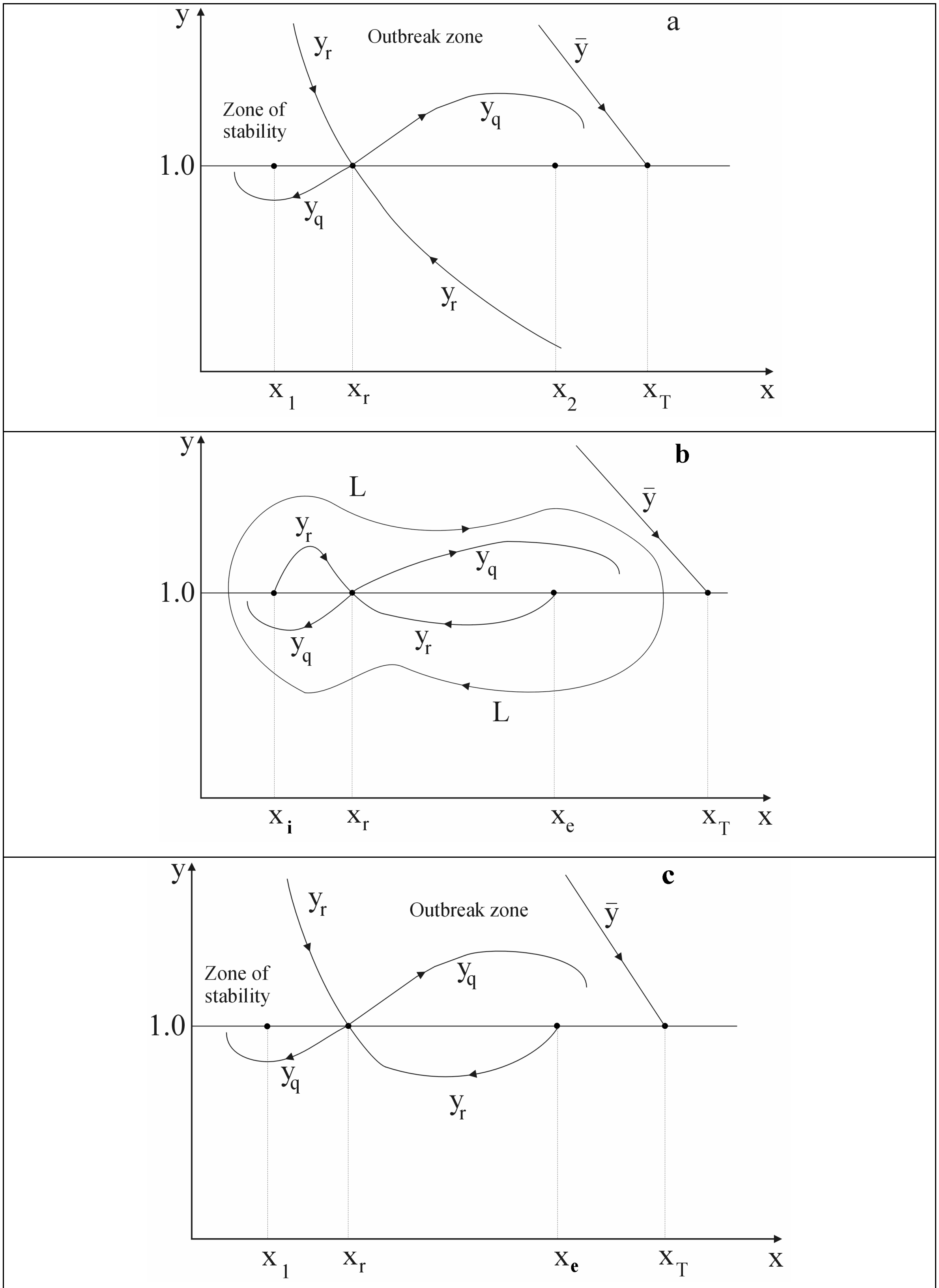

Fig. 1 Phase portraits for basic types of population outbreaks: a – fixed outbreak; b – permanent outbreak; c – an outbreak proper. Notifications are in the text.

Finally, analyses of a set of mathematical models describing processes of interaction of insects with various components of ecosystems allowed creating a classification of insects with respect to their types of dynamics. This classification contains the following basic groups (Isaev et al., 1984, 2001). First group contains indifferent species: their dynamics characterizes by rather small fluctuations near stable level. Second group contains prodromal open-living and close-living species. Dynamics of these species can be characterized by the phase portraits with one stationary state but their fluctuations can be rather big (under the influence of favorable weather or food conditions). Third group contains eruptive species: their dynamics corresponds to one of outbreak regimes pointed out above.

Within the limits of classification it is assumed that final characteristics of species must correspond to their maximum of possibilities: if it is possible to point out locations where species demonstrate periodic or non-periodic eruptive changing of sizes this species belong to the respective group of eruptive species. At the same time in other locations considering species can demonstrate prodromal characteristics of population size changing.

After presentation of theoretical results the following very important question arises: is it possible to say that presented classification is full and contains all types of population dynamics which can be observed in nature? Solution of this question requires constructing of the respective database which allows comparison of various trajectories; this comparison will be useful as for identification of dynamics types for new analyzing species as for finding of artifacts which are out of classification. The last can be interesting for further development of modeling and modification of classification.

Non-linear transformation of empirical trajectories

Let's assume that $u_1, u_2, \dots, u_n$ is empirical trajectory: changing of population size or density in time, n is the number of observations (number of years). It is well-known that u_j can be presented in various units: it can be number of individuals per squared meter, number of individuals per some kilograms of leafs, it can be presented in logarithmic scale with unknown base etc. This is the first problem in comparison of various trajectories. The second problem is in precision of provided estimations of population size. Provided modeling analysis showed (Nedorezov, 2012) that, for example, when population size is rather small number of cases when real (known) population density is out of confidence interval can be about 50%. Taking into account that in nature we have more complicated relations between individuals and more difficult behavior, we can conclude that we have no reasons to believe in small values of population size. But we can believe in relations “bigger” and “smaller”.

Thus, we can transform initial trajectory into set of any points which will characterize population dynamics and correspond to initial trajectory. Let’s fix integer number m, $m < n$. Every considering trajectory we can present as sequence of small parts: u_1, u_2,…, u_m; u_2, u_3,…, u_{m+1}; u_3, u_4,…, u_{m+2} and so on. Every sub-trajectory we transform into point of m-dimensional space with integer coordinates: minimum value of every sub-trajectory has rank 1, maximum value has rank m.

Note, that provided transformation of trajectories can be applied for datasets of different natures. It can also be applied to datasets in logarithmic scale because logarithm transformation saves the order between numbers. After this transformation we have a possibility to compare various sub-trajectories with each other. But at this step we get new problem: what is the optimal value of m?

Taking into account that, for example, dynamics of larch bud moth (*Zeiraphera diniana* Gn.) can be characterized as cyclic regime with cycle in 8-9 years (Baltensweiler, 1964, 1970, 1978; Baltensweiler et al., 1977; Baltensweiler, Fischlin, 1988) we cannot choose $m \le 9$. If we have $m \le 9$ we have a guarantee that species with an outbreak proper and permanent outbreak can be divided. On the other hand, if we choose $m \ge 10$ it doesn’t give a guarantee that species with different outbreak types can be divided. In current publication three different variants were considered: $m = 10$, $m = 11$, and $m = 12$.

Cluster process

For considering dataset we used two measures together. If two sets of points A and B intersect, $A \cap B \ne \varnothing$, we used the following measure:

$$\upsilon(A,B) = \frac{2\mu(A \cap B)}{\mu(A) + \mu(B)}, \qquad (6)$$

where $\mu(A)$ is a number of points in a set A. Respectively, $\mu(A \cap B)$ is a number of points in intersection of sets. Measure (6) has several important properties and was used for clustering (Andreev, 1979; Nedorezov, 1986): $\forall A, B \quad 0 \le \upsilon(A,B) \le 1$; $\upsilon(A,B) = 0 \Leftrightarrow A \cap B = \varnothing$; $\upsilon(A,B) = 1 \Leftrightarrow A = B$; $\upsilon(A,B) = \upsilon(B,A)$. These properties correspond to obvious imagination about the proximity of two sets.

For the situations when measure υ (6) is equal to zero we have to have a possibility to estimate the proximity between sets. For the estimation of the proximity between sets we used the following formula:

$$d(A,B) = \min_{a \in A, b \in B} \sum_{i=1}^{m} |a_i - b_i|, \qquad (7)$$

where $a = \{a_1, a_2, ..., a_m\}$ and $b = \{b_1, b_2, ..., b_m\}$.

Empirical trajectories

In table 1 there is general information about analyzing datasets. It is obvious that increase of the amount of m (the length of sub-trajectory) leads to decrease of number of species (in situation when empirical trajectory is rather small), number of time series, and to decrease number of points in m-dimensional space which correspond to every empirical trajectory.

Table 1
General information about analyzing samples

	10	11	12
Number of species	13	13	13
Number of points	744	697	652
Number of time series	43	42	42

The following time series were used in calculations:

- Larch bud moth (*Zeiraphera diniana* Gn.), GPDD 1407, GPDD 1531, GPDD 6195;
- Pine looper caterpillar (*Bupalus piniarius* L.), GPDD 6145, GPDD 6086, GPDD 3759, GPDD 2727, GPDD 2728, GPDD 2729, GPDD 2730, GPDD 6513, GPDD 9232, GPDD 9381, GPDD 9382;
- Siberian silkworm (*Dendrolimus superance sibiricus* Tschetv.) (Kondakov, 1974; Isaev et al., 1984, 2001);
- Green oak tortrix (*Tortrix viridana* L.) (Rubtsov, 1992; Hunter, Varley, Gradwell, 1997; Hassell, 1998; Korzukhin, Semevsky, 1992);

- Pine beauty (*Panolis flammea* L.), GPDD 6089, GPDD 6090, GPDD 3756;
- Gypsy moth (*Lymantria dispar* L.), GPDD 9308, GPDD 9309, GPDD 9646, GPDD 10165;
- Pine sawfly (*Diprion pini* L.), GPDD 6087, GPDD 6088;
- Black arches (*Lymantria monacha* L.), GPDD 6000;
- Winter moth (*Operaphtera brumata* L.), GPDD 4011, GPDD 4012, GPDD 4013, GPDD 4014, GPDD 4015;
- Pine hawkmoth (*Hyloicus pinastri* L.), GPDD 3757;
- Autumnal moth (*Epirrita autumnata* Bkh.), GPDD 6002;
- Pine-tree lappet (*Dendrolimus pini* L.), GPDD 3758;
- Gall-forming sawfly (*Euura lasiolepis* L.), (Hunter, Price, 1998, 2000).

Clustering

Variant 1. Let's consider a situation when empirical trajectories are transformed into points of 10-dimensional space. On the first step of clustering process two clouds of points which correspond to larch bud moth fluctuations (GPDD 6195 and 1407) combine in one set (measure (6) $\upsilon = 0.33$; in intersection of sets there are 16 points). On the next step of process two sets of points which correspond to gypsy moth fluctuations (GPDD 10165 and 9646) combine in one set (measure $\upsilon = 0.122$; in intersection of sets there are 5 points).

On the third step of process cloud of points which correspond to gypsy moth fluctuations increases in one set of points (GPDD 9308) which is also correspond to gypsy moth time series. At the same time two clouds which correspond to green oak tortrix time series (Rubtsov, 1992) are combined in one cluster. For both these cases $\upsilon = 0.0833$. After that process of clustering was provided with the measure d (7).

Taking into account that measure d (7) has integer values only on the next step of cluster process several new clusters were organized. First cluster was organized after combining of clouds of points which correspond to time series of winter moth (*Operophtera brumata*) (GPDD 4015 and 4011). One more cluster was also organized with clouds corresponding winter moth time series (GPDD 4014 and 4013). The biggest cluster including 15 clouds of points is organized too.

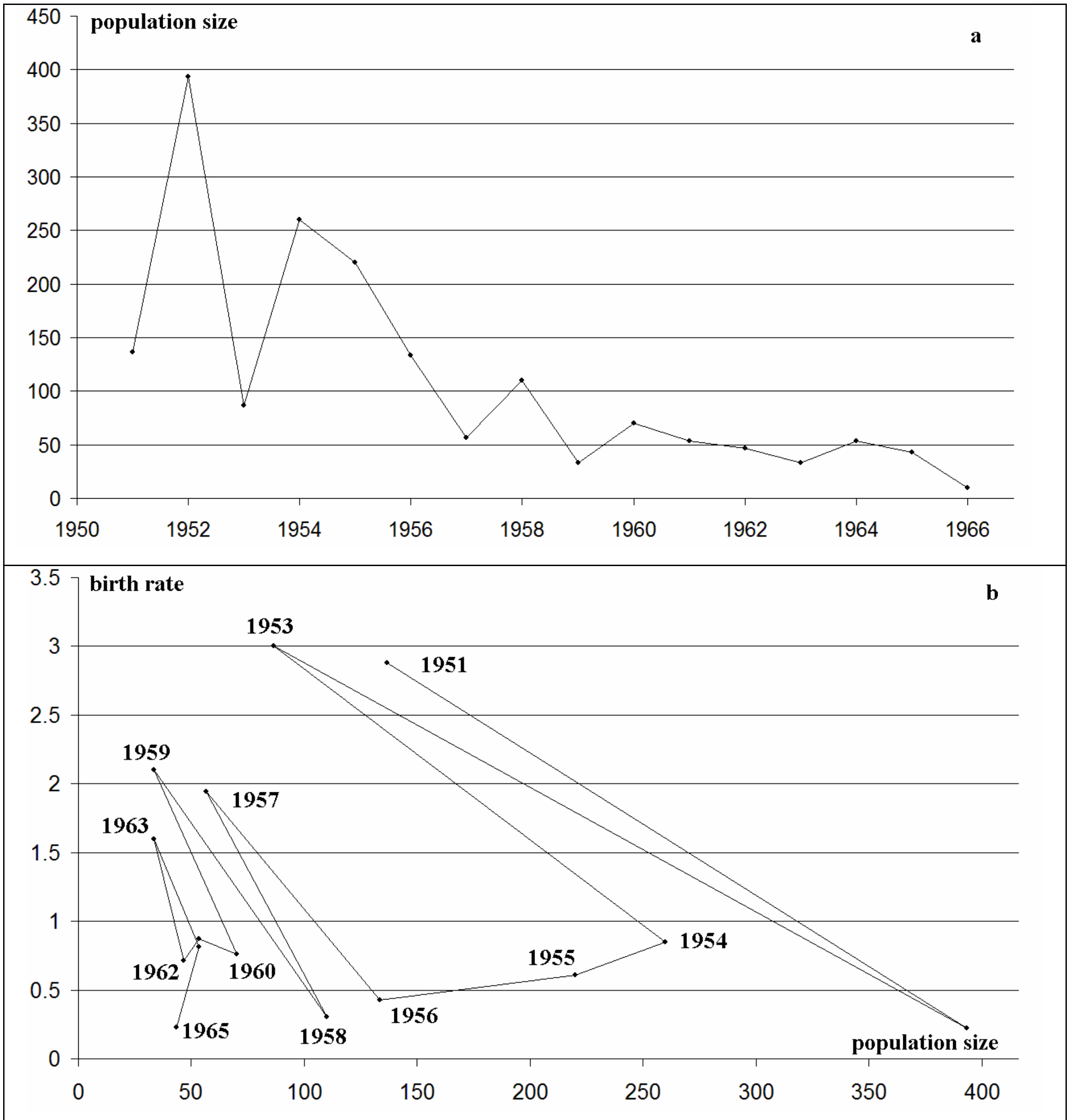

Fig. 2 Dynamics of green oak tortrix on plain "time – population size" (a) and on plain "population size – birth rate" (b).

Following opinions of experts (Isaev et al., 1984, 2001) we can say that this biggest cluster contains trajectories which correspond to various types of dynamics. In particular, cluster contains clouds corresponding to time series of larch bud moth (with permanent outbreak; fig. 1b), and time series of Siberian silkworm (*Dendrolimus sibiricus superans* Tschetv.) with an outbreak proper (fig. 1c). Finally, we can conclude that initial stages of cluster process were correct and it led to organizing of clusters with close types of dynamics;

but further steps of clustering led to situation when species with different types of dynamics were combined together. It means that there are no possibilities in analysis of considering cluster process.

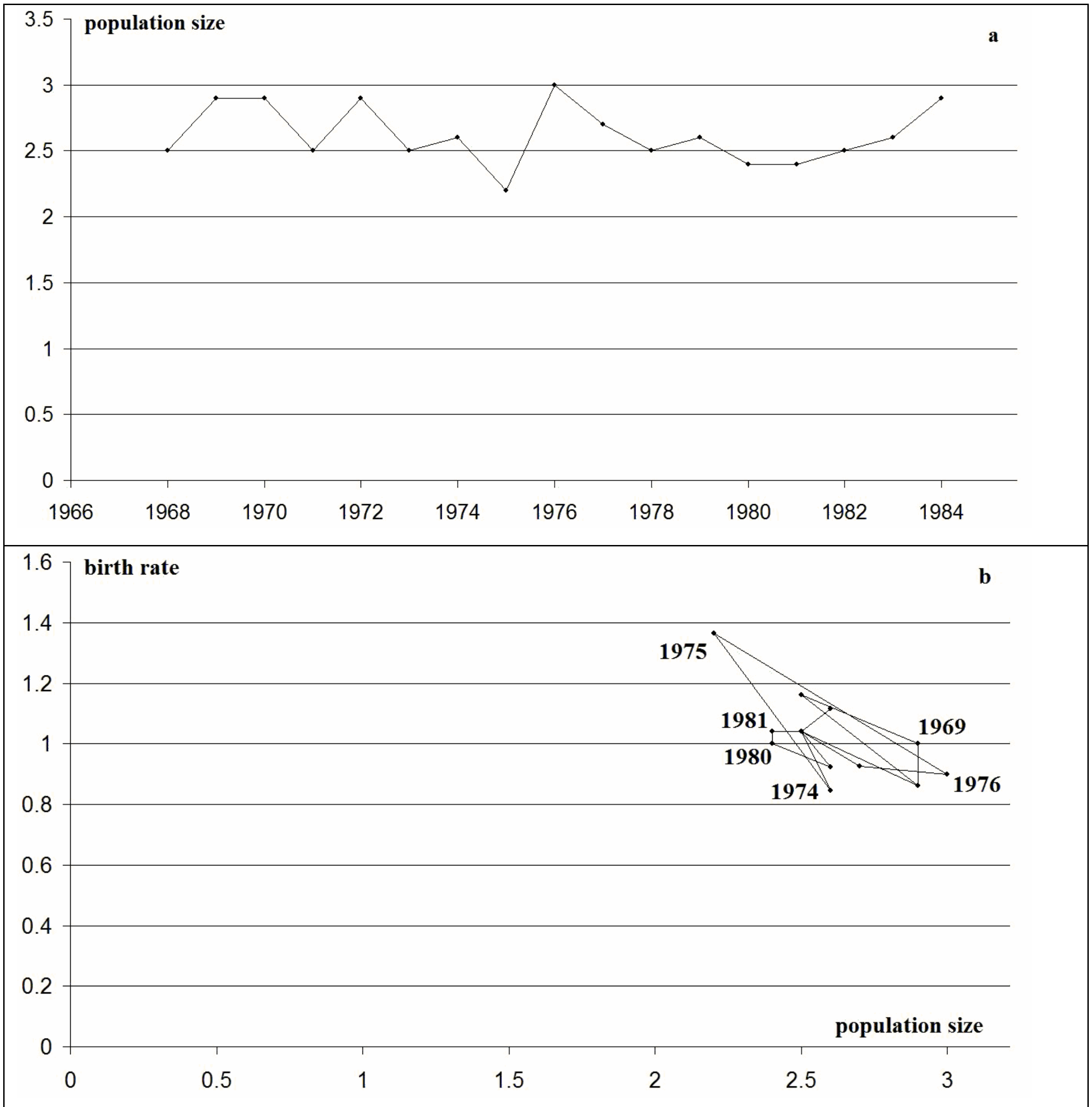

Fig. 3 Dynamics of pine looper caterpillar on plain "time – population size" (a) and on plain "population size – birth rate" (b).

For considering situation two clouds of points – one of clouds corresponds to green oak tortrix (*Tortrix viridana* L.) dynamics (Hunter, Varley, Gradwell, 1997; Hassell, Crawley, Godfray, Lawton, 1998), and another one corresponds to pine looper caterpillar

(GPDD 6513) dynamics – are far from all other clouds. In first case we have obvious tendency to population decreasing (fig. 2) but asymptotic behavior of this decreasing isn't clear. In the second case (fig. 3) dynamics of pine looper looks like fluctuations near stable level. Like in previous case it is impossible now to identify a population dynamics type.

Variant 2. Let's consider a situation when empirical trajectories are transformed into points of 11-dimensional space. Like in Variant 1, on the first step of clustering process two clouds of points which correspond to larch bud moth fluctuations (GPDD 6195 and 1407) combine in one set (measure $\upsilon = 0.283$; in intersection of sets there are 13 points). It is obvious increasing of dimension of space can lead to decreasing of number of points in intersection of any sets.

On the next step of process two sets of points which correspond to gypsy moth fluctuations (GPDD 10165 and 9308) combine in one set (measure $\upsilon = 0.103$; in intersection of sets there are 4 points). At the third step of clustering two clouds which correspond to green oak tortrix time series (Rubtsov, 1992) are combined in one cluster. Measure $\upsilon = 0.029$ and in intersection of sets there is one point only. On the last step of using measure (6) cluster with gypsy moth trajectories increases with points corresponding also to time series of gypsy moth fluctuations (GPDD 9646). Measure (6) $\upsilon = 0.026$ and in intersection of sets there is point only. Thus, in both situations (for 10- and 11-dimensional spaces) we can observe forming of one and the same clusters at initial steps of process.

On the 5th step of process cloud of points (corresponding to time series of pine looper caterpillar dynamics, GPDD 9381) was added to first cluster formed by trajectories of larch bud moth fluctuations (GPDD 6195 and 1407). Experts assume that fluctuations of larch bud moth correspond to permanent outbreak (fig. 1 b; Baltensweiler, 1964, 1970; Isaev et al., 1984, 2001; Berryman, 1990). At the same time dynamics of pine looper caterpillar was identified as an outbreak proper. But our last investigations of pine looper empirical time series showed that its trajectories can be very close to regime of permanent outbreak (Nedorezov, 2012, 2013).

On the 6th step of process two new clusters were organized. First cluster corresponds to time series of *Operophtera brumata* (GPDD 4014 and 4013). The second new cluster corresponds also to time series of *Operophtera brumata* (GPDD 4011 and 4015). At this step of clustering the biggest cluster was organized too: clusters corresponding to fluctuations of gypsy moth and larch bud moth were combined together and several clouds were added to this biggest cluster too (*Hyloicus pinastri*, GPDD 3757; *Bupalus piniarius*, GPDD 3759; *Dendrolimus superance sibiricus*, Isaev et al., 1984, 2001). Taking into account that *Dendrolimus superance sibiricus* Tschetv. is the classic example of observing in nature of the regime of an outbreak proper, and fluctuations of *Zeiraphera diniana* Gn. is the best example of observing in nature of the regime of permanent outbreak, further consideration of cluster process is out of interest.

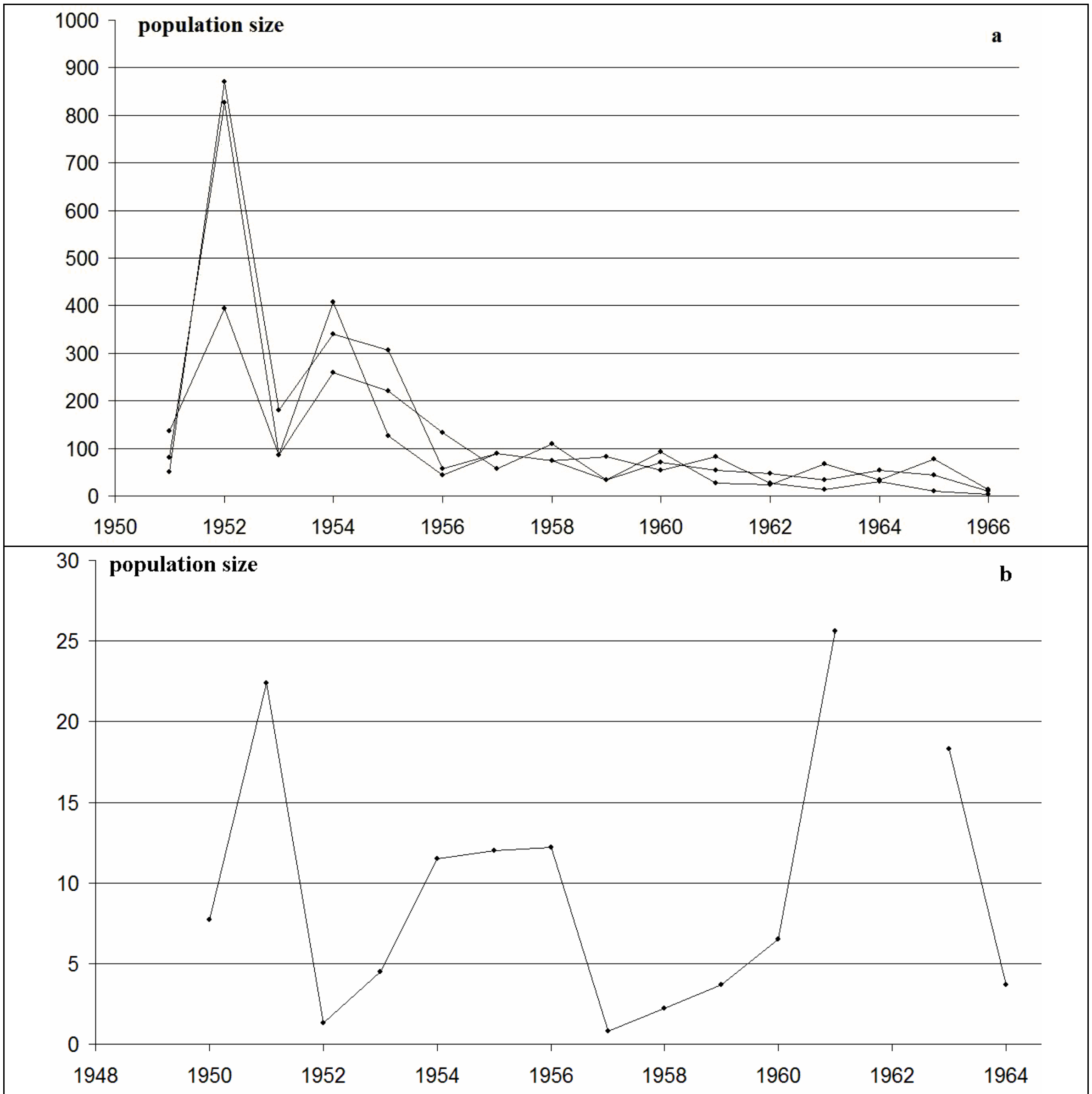

Fig. 4 Dynamics of green oak leaf roller (a) and pine looper moth (b) on a plane "time-population size"

For considering situation one cloud of points is far from all other points – this cloud corresponds to pine looper caterpillar (GPDD 6513) dynamics (like in previous case; fig. 3). Some other species are far from other points too: it was observed for three trajectories of *Tortrix viridana* (Hunter, Varley, Gradwell, 1997; Hassell, Crawley, Godfray, Lawton, 1998; fig. 4a), and for points corresponding to one of trajectories of *Bupalus piniarius* (fig. 4b; GPDD 2728; Klomp, 1966). Initially interpretations of observed fluctuations of pine looper (Klomp, 1966) met with serious problems (Isaev et al., 1984, 2001); later it was showed (Nedorezova, Nedorezov, 2012) that these fluctuations can be effectively described with generalized discrete logistic model. It gives a background for conclusion that fluctuations of pine looper in the respective location corresponds to prodromal type of dynamics.

Variant 3. Let's consider a situation when empirical trajectories are transformed into points of 12-dimensional space. Like in both previous variants on the first step of clustering process two clouds of points which correspond to larch bud moth fluctuations (GPDD 6195 and 1407) combine in one set (measure $\upsilon = 0.25$; in intersection of sets there are 11 points).

On the next step of process two sets of points which correspond to gypsy moth fluctuations (GPDD 9646 and 9308) combine in one set (measure $\upsilon = 0.0455$; in intersection of sets there is 1 point). At the third step of clustering this cluster increases and combines with cloud corresponding to gypsy moth fluctuations (GPDD 10165) too. Step number 4: points corresponding to pine looper dynamics (GPDD 3759) combined with cluster formed by points corresponding to larch bud moth fluctuations (GPDD 6195 and 1407). In previous variant this combination was appeared at fifth step.

Step number 5: two clouds which correspond to green oak tortrix time series (Rubtsov, 1992) are combined in one cluster. At previous variant it was observed at third step. Step number 6: to first cluster (initially formed by points corresponding to GPDD 6195 and 1407) some points corresponding to *Dendrolimus superans sibiricus* Tschetv. (Isaev et al., 1984, 2001) were added. Step number 7: new cluster was formed (*Operophtera brumata*, GPDD 4011 and 4015); at this step of clustering the biggest cluster was organized: clusters corresponding to fluctuations of gypsy moth and larch bud moth were combined and several clouds were added to this biggest cluster too (*Hyloicus pinastri*, GPDD 3757; *Operophtera brumata*, GPDD 4013 and 4014; *Dendrolimus pini*, GPDD 3758; *Bupalus piniarius*, GPDD 9381). Taking into account opinions of experts (Isaev et al., 1984, 2001; Berryman, 1981, 1990, 1991) that pointed our species have qualitatively different types of dynamics, we can conclude that further consideration of cluster process is out of interest.

For considering situation one cloud of points is far from all other points – this cloud corresponds to pine looper caterpillar (GPDD 6513) dynamics (like in both previous cases; fig. 3). It is interesting to note that distance between this cloud of points and all other points became bigger than in previous variants.

Discussion

Provided analysis of databases which were obtained with transformation of empirical time series into sets of ranked values (into points of 10-, 11-, and 12-dimensional spaces with integer positive coordinates) showed that 10, 11 or 12 points cannot characterize observed population dynamics. In particular, for 12-dimensional space on the sixth step of cluster process two sets of points which correspond to two qualitatively different types of dynamics – *Dendrolimus superans sibiricus* Tschetv. can be characterized by an outbreak proper (fig. 1c; Isaev et al., 1984, 2001) and *Zeiraphera diniana* Gn. can be characterized by permanent outbreak (fig. 1b; Baltensweiler, 1964, 1970), – were combined in one cluster. At this step of clustering there is a lot of separated sets of points which don't belong to any clusters. It means that further development of cluster process and its analysis is out of interest. At the same time, it is interesting to note, that number of steps of cluster process which corresponds to classification and can be interpreted in the respective manner increases with increasing of dimension of space.

Thus, we have to conclude that further consideration of analyzing problem requires increasing of the dimension of space. Taking into account that it will lead to decreasing of numbers of points in intersections of sets which correspond to dynamics of species in respective locations, we have to increase the size of database. There exists one more problem which requires further increasing of database: this is a problem of necessity to use two different measures (6) and (7). Using of these measures looks like absence of homogeneity in cluster process.

Analysis of ends of cluster processes for different dimensions of space allowed obtaining artifact – it is fluctuations of pine looper in one of locations (fig. 3). On one side, presented fluctuations looks like obvious changing of population size within the boundaries of stable zone (fig. 1). The similar behavior of trajectories we can observe for other species. And it looks rather strange that these fluctuations of *Bupalus piniarius* are far from all other empirical trajectories. Analysis of this trajectory must be provided separately.

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