Mathematical modeling of ixodid ticks depending on three climatic factors

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Abstract. The article deals with the regulation of the number of ixodid ticks in the Non-Chernozem zone using mathematical modeling of ixodid ticks that live in the Kaluga region of the Russian Federation. Statistical data is taken for the period of the decade of the research. In the Kaluga Region, two species of ixodid ticks are presented, which are Ixodes ricinus (European forest) and Dermacentor reticulatus (pasture), both demonstrating two regular peaks of their activity in spring and autumn. Analytical and calculated mathematical models of the population of ixodid ticks are obtained based on the composition of three or four factors, including: average monthly air temperature per year, average monthly relative humidity per year, average atmospheric pressure per year. The analysis of the results shows that it makes sense to take into account the composition of the first three factors, excluding cloud cover, as long as the cloud value is minimal is minimal in the Kaluga Region and thus cannot affect the results of the mathematical calculations. There are theories which are based on the hypothesis that both the temperature and humidity have an effect on the size of the ixodid ticks' population. The obtained models presented in the article prove strong influence of these parameters, but moreover accents the monthly average atmospheric pressure having the greatest influence on the parasites' population.

1. Introduction

Mathematical modeling in parasitology is currently at the peak of its development and has not yet been sufficiently implemented. Indeed mathematical models are one of the most effective means of studying the quantitative characteristics of the course of infestations and vector-borne infections [1].

Mathematical modeling of the dynamics of the number of parasitic arthropod populations is especially relevant due to the tense conditions for the incidence of humans and animals with encephalitis virus, Lyme disease, tularemia, leptospirosis, pyroplasmosides and others. Tick-borne encephalitis virus, like others, for example, is transmitted by Ixodes ricinus, Ixodes persulcatus and Dermacentor reticulatus [2].

In the Kaluga region of the Russian Federation, which traditionally refers to the Non-chernozem zone, two species of ixodid ticks are presented, Ixodes ricinus and Dermacentor reticulatus [3].

The role of weather forecasting for the development of preimaginal phases of ixodid ticks is proved. It is believed that air temperature is especially important. The indicators of daylight hours is one more key research factor. Thus, the study been conducted in the Czech Republic since 2001 to 2006 confirms...
the data that shows the complete restoration of the viability and numerical population of ixodid ticks under short-term extreme weather conditions [4].

Many factors influence the growth of the parasite population: climatic conditions, geographical ones, urbanistic influences. It has been proved that deforestation has a qualitative and quantitative effect on the number of ticks of the species Dermacentor reticulatus [5].

Therefore, when developing the scientific basis for the regulation and control of the number of parasites and outbreaks of natural focal diseases, take into account numerical statistical indicators and mathematical models obtained.

2. Materials and research methods
Objective: to obtain calculated and analytical mathematical models of the number of ixodid ticks, depending on the following factors:

1) average monthly air temperature for a year, average monthly relative humidity for a year, average atmospheric pressure for a year;
2) average monthly air temperature for a year, average monthly relative humidity for a year, average atmospheric pressure for a year, and average monthly cloudiness for a year.

For this, over the course of 10 years (from 2009 to 2019 inclusive), a 2k type multivariate experiment was conducted in the field according to the standard method described in the works of V.V. Kalmykov [6].

Mathematical modeling was carried out using the programs MsWord, Exel, Ptc Mathcad.

To obtain statistical data for 10 years (from 2009 to 2019), ixodid ticks were collected in natural biotopes in the region. The collection and registration of ixodid ticks was carried out in accordance with standard methods.

3. Research results and their discussion
Since the manifestations of the activity of ixodid ticks occur in the period from March to October, it is advisable to take this period of time into account when planning the experiment.

Due to the fact that the wind speed is associated with the dynamics of atmospheric pressure, it is advisable to use one of the dependent factors according to the rules of factor analysis.

To obtain mathematical models, a complete factorial experiment was conducted on the collected statistical data. The values of the levels of factors are presented in table 1.

Table 1. Factor variation ranges.

| Factors | -1 | 0 | +1 |
|---------|----|---|----|
| X1      | +1.85°C | +11.485°C | +21.12°C |
| X2      | 56.02 % | 68.62 % | 81.22 % |
| X3      | 741.0 mm. hg. art. | 745.5 mm. hg. art. | 750.0 mm. hg. art. |

X1 is average monthly temperature (t °C).
X2 is average monthly relative humidity (Q, %).
X3 refers average atmospheric pressure (P mm Hg)

The Y response was the number of ixodid ticks in stationary observation points

\[ Y = b_0 + b_1X1 + b_2X2 + b_3X3 + b_{12}X1X2 + b_{13}X1X3 + b_{23}X2X3 + b_{123}X1X2X3 \]

To obtain a mathematical model in the form of a regression equation on a normalized scale, the coefficients were determined:

\[ b_0 = +1150; b_1 = -65; b_2 = +204.5; b_3 = +415; b_{12} = -234.5; b_{13} = -90; b_{23} = +10.5; b_{123} = -150; \]
To exclude the influence of systematic errors that are caused by external conditions, it is recommended that experiments with a given experimental design be conducted randomly in time. When organizing the experiment, the need to evaluate the variance of the experiments was taken into account. For this, the experiments were duplicated, i.e. determination of the number of individuals of ixodid ticks was carried out at three experimental stations in different regions of the region.

By the standard methodology of full factor analysis, the coefficients of the regression equation are calculated and the mathematical model takes the following form:

\[ Y = 1150 - 65X_1 + 204.5X_2 + 415X_3 - 234.5X_1X_2 - 90X_1X_3 + 10.5X_2X_3 - 150.5X_1X_2X_3 \]

The table value of the student coefficient for the probability \( p = 0.95 \), \( f_1 = 8 - 1 \), \( t_{p,f_1} = 2.306 \)

\[ \Delta b_i = 2.306 \cdot 2.62 = 6.0 \]

All coefficients of the obtained mathematical model in the form of a regression equation have a value exceeding \( = 6.04 \). This means that all coefficients are statistically significant. Therefore, each selected factor: monthly average temperature (\( t \, ^\circ C \)); monthly average humidity (\( Q \, \text{mm} \)); mean atmospheric pressure (\( P \, \text{mm Hg} \)) and the paired effects of their interaction have a statistically significant effect on the population of ixodid ticks.

The most significant effect on the arthropod population is average atmospheric pressure. The degree of its influence is two times stronger than the average monthly humidity and 6.4 times stronger than the influence of the average monthly temperature. The “+” sign indicates that the higher the atmospheric pressure, the more active ticks are observed. The same sign with coefficient \( b_2 \) indicates that the average monthly humidity also fruitfully affects the population of ixodid ticks. The “-” sign at a monthly average temperature coefficient says that when it increases, the population of ixodid ticks decreases. The paired effect of the interaction of temperature and humidity is 1.14 times stronger than the influence of one humidity and 3.6 times stronger than the effect of one temperature. With a simultaneous increase in average temperature and humidity, the population of ixodid ticks decreases. This pair effect is 2.6 times stronger than the effect of the interaction of the average monthly temperature and the average monthly pressure and 22.3 times stronger than the effect of the interaction of the average monthly pressure and humidity.

With the simultaneous observation of an increase in temperature and pressure, the tick population decreases (the “-” sign), and with a simultaneous increase in the average monthly humidity and pressure, the tick population increases (the “+” sign). It is worth noting the significant effect of the interaction effect of all three factors, the strength of their simultaneous influence is only 1.55 times weaker than the effect of humidity and temperature. With a simultaneous increase in the monthly average values of temperature, humidity and atmospheric pressure, the number of active ixodid ticks will decrease.

Figure 1 shows a graphical representation of the adhesion coefficients characterizing the effect of factors on the response.
Figure 1. Bar diagram of adhesion coefficients.

The calculated mathematical model after transformations to calculate the number of ixodid ticks will take the form:

\[ N = 3.339PQ - 2450.546Q - 15467.752t - 160.716P + 20.917Pt + 202.762Qt - 0.2745PQt + 118405.128 \]

4. Conclusion

This model allows you to calculate the number of ixodid ticks without resorting to expensive field harvesting, which can be useful in predicting the population size in the Kaluga region of the Russian Federation and other regions with similar climatic conditions.

The hypothesis of the adequacy of the obtained mathematical model in the form of a linear equation is checked in the following way: since the value of the coefficient \( b_0 \) in the model on a normalized scale shows the number of ixodid tick populations when the considered factors of the orthogonal plan are set to zero, then calculating the value according to the model in natural scale for factors of zero level, the obtained value can be compared with the experimental value of \( b_0 \). By the discrepancy of these values, one can judge the magnitude of the error of the calculation model.

Substituting the value of the factor corresponding to the zero level into the calculated mathematical model, namely:

\[ t = 11.485^\circ C, \quad Q = 68.62\%, \quad P = 745.5 \text{ mmHg} \]

\( N = 1211 \) individuals of ixodid ticks. Moreover, according to experimental statistics, under such conditions, 1150 individuals of ixodid ticks were found, the discrepancy with the calculation model is 5%, which indicates the adequacy of the obtained calculation model.

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