Original Study Article
https://doi.org/10.36233/0372-9311-647

Prediction of the incidence of lyme disease using mathematical modeling methods (using the example of the Kirov region)

Elena O. Utenkova✉**, Ilya S. Knyazhev, Nikolay S. Shchur**

Kirov State Medical University, Kirov, Russia

Annotation

Introduction. The Kirov region is an endemic region for Lyme disease (ixodic tick-borne borreliosis), which is caused by climatic conditions, an abundance of ticks and their feeders. The economic damage caused by Lyme disease includes the cost of treating patients and eliminating natural foci. Morbidity forecasting is necessary for planning preventive measures (acaricide treatments, awareness-raising activities with the population) and entomological monitoring. The effectiveness of such measures exceeds the above costs, which underlines the relevance of the study.

The **aim** of the study is to analyze the influence of various factors on the incidence of Lyme disease using mathematical modeling methods for further epidemiological forecasting using the example of the Kirov region.

Materials and methods. The data of the state reports «On the state of sanitary and epidemiological welfare of the population in the Kirov region» for 2006–2023 on the incidence of Lyme disease, the first and last reported cases of tick attachment to humans and the volume of acaricide treatments were studied. Hydrometeorological data: monthly and annual averages of air temperature, humidity, and precipitation. Spearman correlation analysis and multiple regression analysis were performed using the «Excel MS Office-2021» and «Statistica Advanced 12 for Windows RU» software. The level of $p < 0.05$ was chosen as a criterion of statistical significance.

Results. The interval forecast of incidence is up to 18.67 by 2024, 16.51 by 2025, and 14.36 per 100,000 population by 2026. Correlations between climatic factors and morbidity have been identified. A negative reliable correlation of moderate density was revealed between the incidence of Lyme disease in the Kirov region and the volume of acaricide treatments. Two forecasting models have been developed: based on the timing of the first and last reported cases of tick bites; based on hydrometeorological factors and the volume of acaricide treatment.

Conclusion. The incidence of Lyme disease in the Kirov region is characterized by a downward trend. Mathematical models for predicting morbidity in the Kirov region are proposed.

Keywords: *Lyme disease, morbidity, mathematical model, abiotic factors, biotic factors, anthropogenic factors*

Funding source. This study was not supported by any external sources of funding.

Conflict of interest. The authors declare no apparent or potential conflicts of interest related to the publication of this article.

For citation: Utenkova E.O., Knyazhev I.S., Shchur N.S. Prediction of the incidence of lyme disease using mathematical modeling methods (using the example of the Kirov region). *Journal of microbiology, epidemiology and immunobiology.* 2025;102(2):179–189.
DOI: https://doi.org/10.36233/0372-9311-647
EDN: https://www.elibrary.ru/NWVFFR

Оригинальное исследование
https://doi.org/10.36233/0372-9311-647

Прогнозирование заболеваемости иксодовым клещевым боррелиозом с использованием методов математического моделирования (на примере Кировской области)

Утенкова Е.О.✉**, Княжев И.С., Щур Н.С.**

Кировский государственный медицинский университет, Киров, Россия

Аннотация

Введение. Кировская область — эндемичный регион по иксодовому клещевому боррелиозу (ИКБ), что обусловлено климатическими условиями, обилием клещей и их прокормителей. Экономический ущерб от ИКБ включает затраты на лечение больных и ликвидацию природных очагов. Прогнозирование забо-

леваемости необходимо для планирования профилактических мероприятий (акарицидных обработок, информационно-разъяснительной работы с населением) и энтомологического мониторинга. Эффективность таких мер превышает вышеуказанные затраты, что подчёркивает актуальность исследования.
Цель исследования — изучение влияния различных факторов на заболеваемость ИКБ с использованием методов математического моделирования для дальнейшего эпидемиологического прогнозирования на примере Кировской области.
Материалы и методы. Изучены данные государственных докладов «О состоянии санитарно-эпидемиологического благополучия населения в Кировской области» за 2006–2023 гг. по заболеваемости ИКБ, первому и последнему зарегистрированным случаям присасывания клеща к человеку и объёму акарицидных работ. Гидрометеорологические данные: среднемесячные и среднегодовые значения температуры воздуха, влажности воздуха и объёма осадков. Проводили корреляционный анализ по Спирмену и множественный регрессионный анализ, в качестве критерия статистической значимости был выбран уровень $p < 0{,}05$.
Результаты. Интервальный прогноз заболеваемости: к 2024 г. — до 18,67 на 100 тыс. населения, к 2025 г. — 16,51, к 2026 г. — 14,36. Выявлены корреляции между климатическими факторами и заболеваемостью ИКБ, отрицательная достоверная корреляционная связь умеренной тесноты между заболеваемостью ИКБ в Кировской области и объёмом акарицидных работ. Разработаны две модели прогнозирования: на основе сроков первого и последнего зарегистрированных случаев присасывания клещей; на основе гидрометеорологических факторов и объёма акарицидных работ.
Заключение. Заболеваемость ИКБ в Кировской области характеризуется тенденцией к снижению. Предложены математические модели для прогнозирования заболеваемости ИКБ в Кировской области.

Ключевые слова: *иксодовый клещевой боррелиоз, заболеваемость, математическая модель, абиотические факторы, биотические факторы, антропогенные факторы*

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Для цитирования: Утенкова Е.О., Княжев И.С., Щур Н.С. Прогнозирование заболеваемости иксодовым клещевым боррелиозом с использованием методов математического моделирования (на примере Кировской области). *Журнал микробиологии, эпидемиологии и иммунобиологии.* 2025;102(2):179–189.
DOI: https://doi.org/10.36233/0372-9311-647
EDN: https://www.elibrary.ru/NWVFFR

Introduction

Lyme disease is a natural focal zoonotic disease with a vector-borne mechanism of transmission caused by bacteria of the genus *Borrelia* of the family *Spirochaetaceae*, transmitted by ticks of the genus *Ixodes*. In the epidemiologic aspect, the *I. persulcatus* and *I. ricinus* ticks are of significance, the role of other species is not excluded [1–3]. The Kirov region is located in the north of the Volga Federal District and is characterized by the highest level of Lyme disease incidence not only in the district, but also in Russia [4]. Most of the territory of the subject under study is located in the middle and southern taiga zone, which is characterized by favorable conditions for the activity of ticks – vectors of Borrelia and their feeders [5]. Natural focal infections, which include Lyme disease, are climate-dependent, as the variation of weather conditions not only affects the habitat of ticks, expanding their range, but also affects their vital activity. High average annual temperature, warm interseasons, abundant precipitation, increased air and soil humidity, increased intensity of solar radiation contribute to the survival, early activation, reproduction, and prolongation of the period of activity of mites [6–9]. Analysis of the influence of abiotic, biotic and anthropogenic factors on the tick population plays a key role in epidemiological surveillance, as it allows predicting the activity and distribution of ticks, optimizing preventive measures and reducing the risks of mass infection of the population [4, 10–16]. Taking into account the above facts, it becomes clear that tick-borne infections are a serious threat to both public health and the economy of the region. The high intensity of the epidemic process of Lyme disease can lead to significant financial losses due to the costs of medical care, increased temporary disability, long-term complications and reduced efficiency of the production sector [17–19].

All of this makes it important to forecast the level of Lyme disease incidence. Predicting the next rise in the incidence of Lyme disease will allow timely implementation of a set of preventive measures: acaricide treatment of territories and informing the population about protection measures. The economic benefit and efficiency of such measures significantly exceeds the costs of eliminating natural foci and treating patients [10, 14–16, 20].

The aim of the study is to investigate the influence of various factors on the incidence of Lyme disease using mathematical modeling methods for further prediction of Lyme disease incidence, using the example of the Kirov region.

Materials and methods

For retrospective analysis of Lyme disease incidence in the Kirov region we used the data of state reports of the Department of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Kirov region "On the state of sanitary-epidemiological well-being of the population in the Kirov region" for 2006–2023 by indicators: Lyme disease incidence rates (per 100 thousand population) in the Kirov region, the first registered case of tick bite (February, March and April) from 2006 to 2023, the last registered case of tick bite on a person (September, October and November) from 2006 to 2023, and the volume of acaricide treatment (ha).

As hydrometeorological data we used data from the weather archive of Pobedilovo airport by months (January-December) for 2006–2023: mean monthly and mean annual values of air temperature (°C), air humidity (%) and precipitation volume (mm) for 2006–2023. The results were processed using methods of mathematical statistics using Excel MS Office-2021 and Statistica Advanced 12 for Windows RU standard software packages. Spearman correlation analysis was used to establish relationships between the studied variables. Multiple regression analysis was used to assess the possibility of prediction. The level of $p < 0.05$ was chosen as the criterion of statistical significance, which corresponds to a 5% probability of error of the first kind.

Results

In 2006–2023, the epidemic process in Kirov region was characterized by a downward trend in Lyme disease morbidity (**Fig. 1**). Thus, there is a decrease in Lyme disease incidence in Kirov region – annually on average by 2.2 per 100 thousand population ($R^2 = 0.660$).

Indicators of the dynamic series of Lyme disease incidence (per 100 thousand population) in Kirov region are shown in **Table 1**.

Forecasting of Lyme disease incidence in the Kirov region till 2026 has been carried out. With an error probability of 5%, it can be stated that the Lyme disease incidence rate on average for 2024 will be up to 18.67 per 100 thousand population, for 2025 — up to 16.51, for 2026 — up to 14.36 (**Fig. 2**).

To study the influence of the beginning and end of the epidemic season (the period of high activity of ticks — vectors of *Borrelia*) on the Lyme disease incidence in the Kirov region, a multiple linear regression model was built, where the variable was: y_1 — incidence of Lyme disease in the Kirov region per 100 thousand population. Factors: x — time factor (the period from 2006 to 2023), the first registered case of tick bites to a person (February, March and April) from 2006 to 2023, the last reported case of tick to human (September, October and November) from 2006 to 2023. Since the model used qualitative attributes, dummy variables were introduced: z_1 (1 — for the factor value March, 0 — for the rest of the factor values); z_2 (1 — for the factor value April, 0 — for the rest of the factor values); h_1 (1 — for the factor value September, 0 — for the rest of the factor values); h_2 (1 — for the factor value October, 0 — for the rest of the factor values). The mathematical model is: $y_1 = 4433.314 - 2.190x + 9.614z_1 + 4.629z_2 - 19.565h_1 - 3.617h_2$ (**Table 2**). The coefficient of determination is $R^2 = 0.718$. This means that the Lyme disease incidence rate is 71.8% determined by factors x, z_1, z_2, h_1, h_2 and 28.2% by unaccounted factors. Fisher's coefficient < 0.05, at 5% level the model is recognized as significant. At the 5% level, the factor x is significant. It can be said that every year the Lyme disease incidence in the Kirov region decreases on average by 2.19 per 100 thousand population.

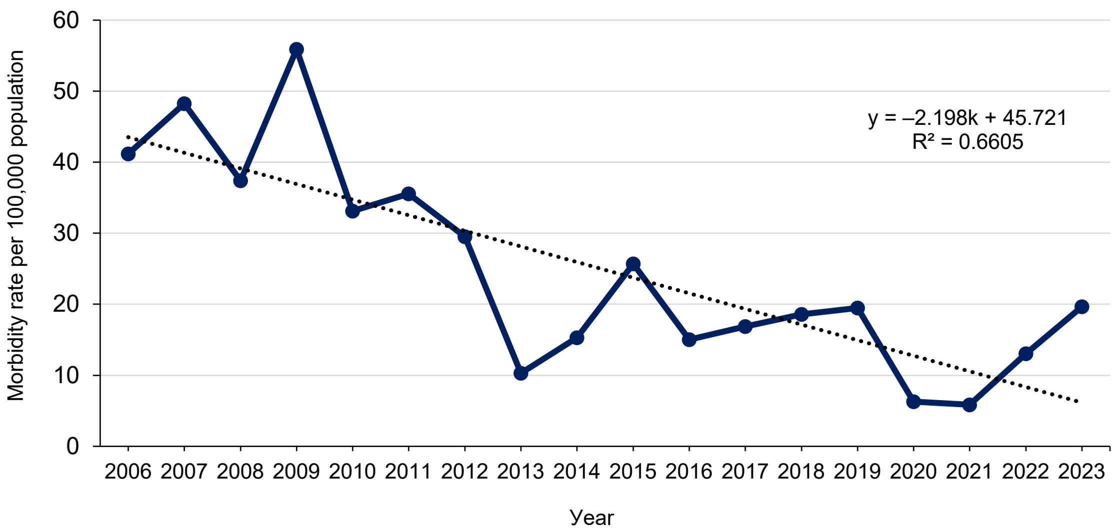

Fig. 1. The dynamics of the Lyme disease incidence in the Kirov region in 2006–2023.

JOURNAL OF MICROBIOLOGY, EPIDEMIOLOGY AND IMMUNOBIOLOGY. 2025; 102(2)
DOI: https://doi.org/10.36233/0372-9311-647

Table 1. Indicators of the dynamic range of Lyme disease incidence per 100,000 population of the Kirov region

Year	The registered Lyme disease incidence per 100,000 population of the Kirov region	Absolute increase	Growth rate, %	The value of a 1% increase	Growth rate, %
2006	41.19	–	–	–	–
2007	48.24	7.1	17.1	41.19	117.1
2008	37.42	–10.8	–22.4	48.24	77.6
2009	55.9	18.5	49.4	37.42	149.4
2010	33.11	–22.8	–40.8	55.90	59.2
2011	35.57	2.5	7.4	33.11	107.4
2012	29.52	–6.1	–17.0	35.57	83.0
2013	10.3	–19.2	–65.1	29.52	34.9
2014	15.31	5.0	48.6	10.30	148.6
2015	25.71	10.4	67.9	15.31	167.9
2016	15.03	–10.7	–41.5	25.71	58.5
2017	16.88	1.9	12.3	15.03	112.3
2018	18.58	1.7	10.1	16.88	110.1
2019	19.48	0.9	4.8	18.58	104.8
2020	6.29	–13.2	–67.7	19.48	32.3
2021	5.86	–0.4	–6.8	6.29	93.2
2022	13.04	7.2	122.5	5.86	222.5
2023	19.68	6.6	50.9	13.04	150.9
2023/2006	–	–21.5	–52.2	41.19	47.8

Since qualitative features were used in the model: the first registered case of tick-borne infections (February, March and April) from 2006 to 2023, the last registered case of tick-borne infections (September, October, November) from 2006 to 2023, correction factors were introduced before dummy variables (**Table 3**). The Lyme disease incidence in the Kirov region per 100 thousand population in the system varies: with the first registered

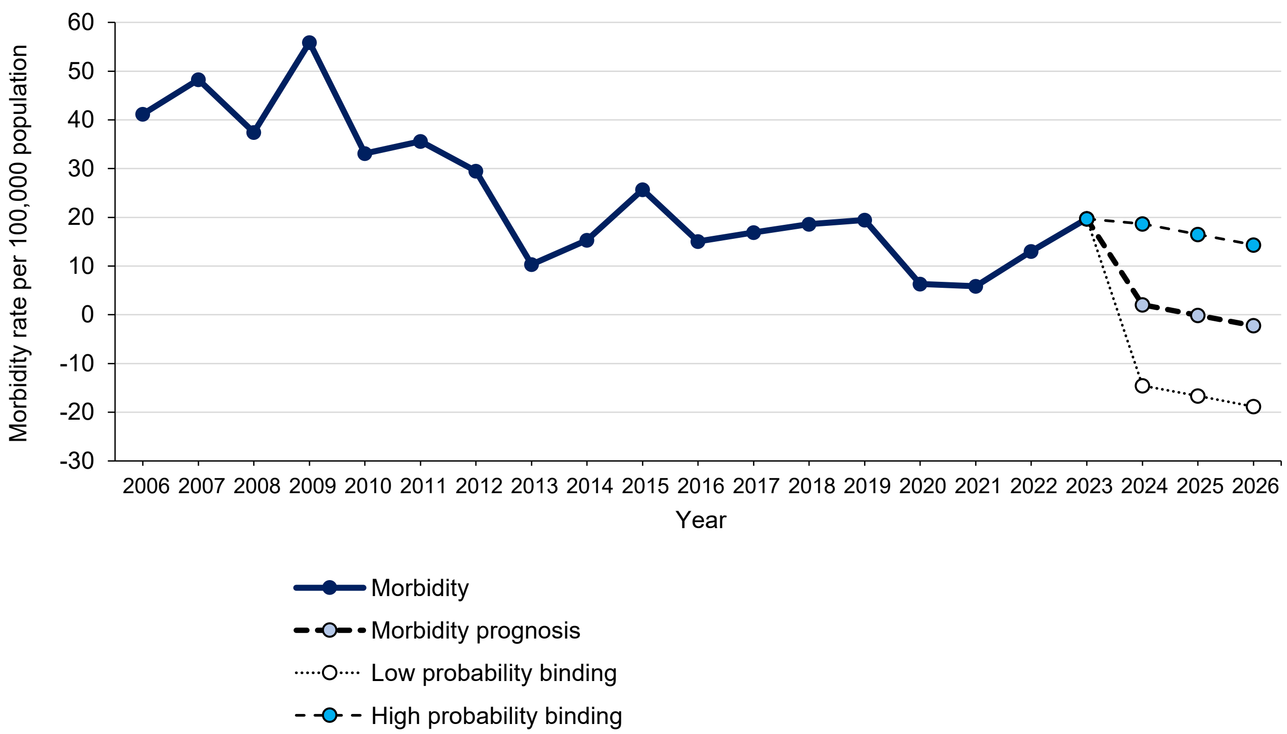

Fig. 2. Interval forecast chart for the Lyme disease incidence in the Kirov region until 2026.

Table 2. Standardized β-coefficients for the multiple regression model

Factor	β*	SE of β*	β	SE of β	t(69)	*p*-value
Intercept	–	–	4433,314	904,802	4,900	0,000
x	–0.810	0.165	–2.190	0.447	–4.905	0.000
z_1	0.340	0.316	9.614	8.925	1.077	0.303
z_2	0.165	0.314	4.629	8.804	0.526	0.609
h_1	–0.319	0.149	–19.565	9.155	–2.137	0.054
h_2	–0.115	0.174	–3.617	5.443	–0.664	0.519

Note. Intercept is a free term of the regression equation; β* — standardized regression coefficient; SE of β* — standard error of standardized regression coefficient; β — regression coefficient; SE of β — standard error of regression coefficient; t (69) — calculated value of T-criterion in assessing the significance of regression coefficient; p-value — the significance level.

Table 3. Correction coefficients of regression

The value of the factor	β	$β^{попр}$ = β–Δ	The value of the factor	β	$β^{попр}$ = β–Δ
The first recorded case of a tick bite of a human was in February	0.000	–4.750	The last recorded case of a bite of a human was in September	–19.565	–11.840
The first recorded case of a tick bite of a human in March	9.614	4.870	The last recorded case of a tick bite of a human was in October	–3.617	4.110
The first recorded case of a tick bite of a human in April	4.629	–0.120	The last recorded case of a tick bite of a human was in November	0.000	7.730
The amount	14.24	–	The amount	–23.18	–
Δ	4.75	–	Δ	–7.73	–

Note. β — standardized regression coefficient; $β^{попр}$ — standardized correction for regression coefficient.

case of tick bite in February the incidence of Lyme disease is below average, in March — above average, in April — below average; with the last registered case of tick bite in September the Lyme disease incidence is below average, in October and November — above average.

In the Kirov region there is a tendency to increase the areas subject to acaricide treatments (**Fig. 3**). Based on the regression coefficient value, it can be concluded that every year the volume of acaricide treatments in the Kirov region increases on average by 125.87 ha. Indicators of the dynamic series of acaricide treatment volume in the Kirov region are shown in **Table 4**.

The correlation matrix of dependence of Lyme disease incidence in the Kirov region per 100 thousand population from 2006 to 2023 on hydrometeorological factors (by months) and the volume of acaricide treatments was constructed (**Table 5**). A strong negative relationship between Lyme disease incidence and time factor, as well as negative relationships of medi-

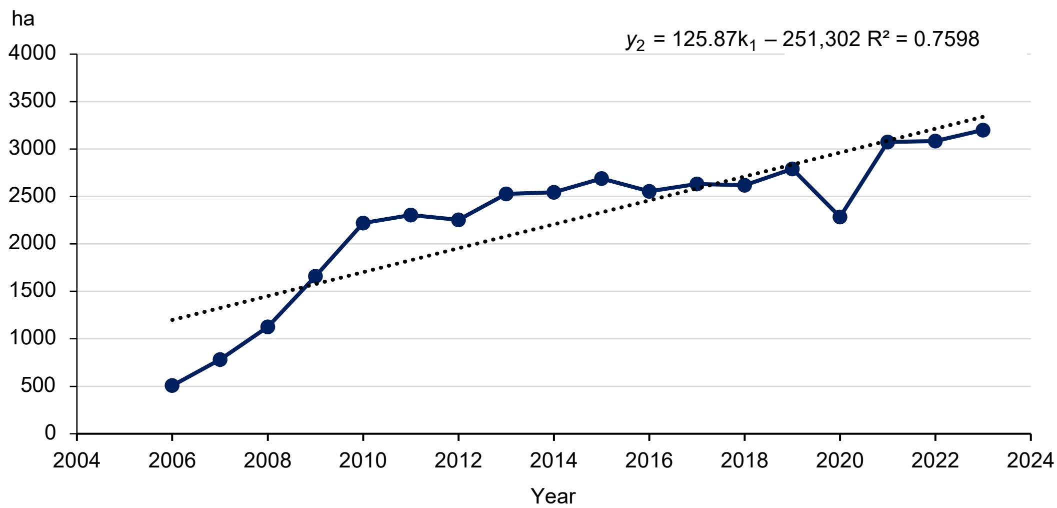

Fig. 3. The volume of acaricide treatments in the Kirov region in 2006–2023.

DOI: https://doi.org/10.36233/0372-9311-647

um strength between Lyme disease incidence and the volume of acaricide treatments were revealed. A medium positive correlation was found between the Lyme disease incidence and air temperature in September ($r = 0.51$; $p < 0.05$). Weak positive correlations were found between air humidity in June and August and Lyme disease incidence ($r = 0.47$; $p < 0.05$ and $r = 0.47$; $p < 0.05$, respectively). We found weak positive correlations between December precipitation volume and Lyme disease incidence ($r = 0.49$; $p < 0.05$), medium positive correlations between June, August and November precipitation volume and Lyme disease incidence ($r = 0.52$; $p < 0.05$; $r = 0.68$; $p < 0.05$ and $r = 0.66$; $p < 0.05$, respectively), and a strong positive association between October precipitation volume and Lyme disease incidence ($r = 0.75$; $p < 0.05$).

The correlation matrix of dependence of Lyme disease incidence (per 100 thousand population) in Kirov region on average annual values of hydrometeorological factors (air temperature and humidity, precipitation for 2006-2023) and the volume of acaricide treatment has been constructed (**Table 6**).

For multiple regression analysis of the resultant variable we used the indicator y_3 — incidence of Lyme disease (per 100 thousand population) in the Kirov region. Sample correlation coefficients are presented in Table 6. Factor signs and model: v_1 — volume of acaricide treatment (ha); v_2 — average annual air temperature (°C); v_3 — average annual air humidity (%); v_4 — average annual precipitation (mm); $y_3 = –70.117 – 0.003v_1 – 1.304v_2 + 0.993v_3 + 93.133v_4$. The regression equation is statistically valid at the significance level of $p < 0.05$. The 75.1% of the variation in the incidence of Lyme disease is explained by the variation in factor attributes ($R^2 = 0.751$).

Based on the standardized β-coefficients, the influence of factors on the dependent variable was assessed (**Table 7**). The incidence of Lyme disease in Kirov region per 100 thousand population in the system is changing:

- the average incidence of Lyme disease decreases when the volume of acaricide treatments is increased;
- an increase in average annual air temperature leads to a decrease in the incidence of Lyme disease on average;
- an increase in average annual air humidity leads to an increase in the incidence of Lyme disease on average;
- with an increase in average annual precipitation, the incidence of Lyme disease increases on average.

Discussion

The Lyme disease incidence in the Kirov region in 2006–2023 had an uneven tendency. When comparing the incidence in 2023 with 2006, there is a decrease in the intensity of the epidemic process manifestation

Table 4. Indicators of the dynamic range of acaricide treatments in the Kirov region

Year	The volume of acaricide treatments in the Kirov region, ha	Absolute increase, ha	Growth rate, %	The value of a 1% increase	Growth rate, %
2006	507.0	–	–	–	–
2007	782.7	275.7	54.4	507.00	154.4
2008	1125.0	342.3	43.7	782.70	143.7
2009	1660.5	535.5	47.6	1125.00	147.6
2010	2220.6	560.1	33.7	1660.50	133.7
2011	2303.4	82.8	3.7	2220.60	103.7
2012	2253.0	–50.4	–2.2	2303.40	97.8
2013	2526.3	273.3	12.1	2253.00	112.1
2014	2545.7	19.5	0.8	2526.27	100.8
2015	2688.4	142.7	5.6	2545.73	105.6
2016	2553.7	–134.7	–5.0	2688.44	95.0
2017	2633.2	79.5	3.1	2553.72	103.1
2018	2617.7	–15.5	–0.6	2633.20	99.4
2019	2790.8	173.1	6.6	2617.70	106.6
2020	2284.3	–506.5	–18.1	2790.80	81.9
2021	3075.3	791.0	34.6	2284.30	134.6
2022	3083.0	7.7	0.3	3075.26	100.3
2023	3200.7	117.7	3.8	3083.00	103.8
2023/2006	–	2693.7	531.3	507.00	631.3

Table 5. Correlation matrix of the dependence of the Lyme disease incidence in the Kirov region per 100000 population from 2006 to 2023 on the average monthly values of hydrometeorological factors and the volume of acaricide treatments

Indicator	Lyme disease incidence in the Kirov region per 100000 population	
	r	*p*
The time factor, years	–0.77	< 0.05
Volume of acaricide treatments, ha	–0.64	< 0.05
Air temperature, °C		
in January	–0.28	> 0.05
in February	–0.41	> 0.05
in March	0.18	> 0.05
in April	–0.29	> 0.05
in May	–0.10	> 0.05
in June	–0.15	> 0.05
in July	–0.16	> 0.05
in August	–0.19	> 0.05
in September	0.51	< 0.05
in October	0.15	> 0.05
in November	–0.11	> 0.05
in December	0.24	> 0.05
Air humidity, %		
in January	0.22	> 0.05
in February	–0.28	> 0.05
in March	0.36	> 0.05
in April	0.15	> 0.05
in May	–0.15	> 0.05
in June	0.47	< 0.05
in July	0.35	> 0.05
in August	0.47	< 0.05
in September	–0.04	> 0.05
in October	0.05	> 0.05
in November	0.45	> 0.05
in December	0.20	> 0.05
Precipitation, mm		
in January	0.50	< 0.05
in February	0.03	> 0.05
in March	0.43	> 0.05
in April	0.36	> 0.05
in May	0.47	> 0.05
in June	0.52	< 0.05
in July	0.24	> 0.05
in August	0.68	< 0.05
in September	0.40	> 0.05
in October	0.75	< 0.05
in November	0.66	< 0.05
in December	0.49	< 0.05

(per 100 thousand population) by 52.2%. The most significant changes are observed in 2009 (increase by 49.4%) and in 2013 (decrease by 65.1%). The growth of Lyme disease morbidity in 2009 (by 49.4%) can be explained by the lengthening of the ticks activity season: it amounted to 208 days in the region on average, which is 14 days more compared to 2008 (194 days), by the increase in the number of ticks in the region, by the increase in the number of ticks active in the region (194 days), increase in the number and activity of vectors, which is indirectly evidenced by the increase in the number of visits to medical and preventive institutions for tick bites by 1.6 times from 13,432 people in 2008 to 21,477 people in 2009, and insufficient volume of acaricide treatments (2 times lower than required)[1]. The decrease in the incidence of Lyme disease in 2013 (by 65.1%) can be explained by a 1.5-fold increase in the volume of acaricide treatments (2526.3 ha in 2013 compared to 1660.5 ha in 2009), a decrease in the number and activity of vectors, which is indirectly evidenced by the decrease in the cases of seeking health care after tick bites by almost 3 times from 21,477 people in 2009 to 7219 people in 2009, and rodent control measures[2]. Despite the overall downward trend, the incidence dynamics remain unstable. After a significant drop in 2013, there is a gradual increase in the following years, followed by a decrease in 2020, which may be related to the COVID-19 pandemic[3]. The dynamics of incidence in 2005–2009 is explained by the lengthening of the tick activity season due to the warm and long autumn period, in which people were more often engaged in collecting wild plants in natural biotopes, continued work on garden plots, which led to an increase in contact of the population with ticks [7–9, 21, 22].

The interval forecast of Lyme disease incidence in the Kirov region for the 2024–2026 period demonstrates a downward trend. The observed decrease in the intensity of manifestations of the epidemic process can be explained by an increase in the volume of acaricide treatments, changes in weather conditions (a tendency to decrease the average annual precipitation). It should be noted that the influence of other factors cannot be excluded.

Early or, on the contrary, late onset of ixodid tick activation can lead to changes in the timing of the epidemic season [10–13]. The lengthening of the tick ac-

1 The State report "On the sanitary and epidemiological situation in the Kirov region in 2009". URL: https://www.43.rospotrebnadzor.ru/documents/gosregdoklad/publications/svoddokl2009.pdf
2 The State report "On the sanitary and epidemiological situation in the Kirov region in 2013". URL: https://www.43.rospotrebnadzor.ru/documents/gosregdoklad/publications/svoddokl2013.pdf
3 The State report "On the sanitary and epidemiological situation in the Kirov region in 2020". URL: https://www.43.rospotrebnadzor.ru/documents/gosregdoklad/publications/gosudarstvennyy-doklad-2020.pdf

DOI: https://doi.org/10.36233/0372-9311-647

Table 6. Correlation matrix of the dependence of Lyme disease incidence in the Kirov region per 100000 population on the average annual values of hydrometeorological factors and the volume of acaricide treatment

Correlated indicators	Incidence of Lyme disease	Volume of acaricide treatment, ha	Air temperature, °C	Air humidity, %	Precipitation, mm
Incidence of ixodic tick-borne borreliosis	1.00	–0.64	–0.03	0.35	0.74
Volume of acaricide treatment, ha	–0.64	1.00	–0.20	–0.10	–0.69
Air temperature, °C	–0.03	–0.20	1.00	0.19	–0.06
Air humidity, %	0.35	–0.10	0.19	1.00	0.40
Precipitation, mm	0.74	–0.69	–0.06	0.40	1.00

Table 7. Standardized β coefficients of the regression model

Factor	β*	SE of β*	β	SE of β	t(69)	*p*-value
Intercept	–	–	–70,117	56,530	–1,240	0,237
v_1	–0.147	0.218	–0.003	0.004	–0.675	0.512
v_2	–0.083	0.125	–1.304	1.955	–0.667	0.517
v_3	0.167	0.128	0.993	0.758	1.310	0.213
v_4	0.715	0.224	93.133	29.210	3.188	0.007

Note. Intercept is a free term of the regression equation; β* — standardized regression coefficient; SE of β* — standard error of standardized regression coefficient; β — regression coefficient; SE of β — standard error of regression coefficient; t(69) — calculated value of T-criterion in assessing the significance of regression coefficient; *p*-value — the significance level.

tivity season is a consequence of the warm and long fall period [21]. Using the method of multiple linear regression, we proposed a mathematical model of Lyme disease incidence in Kirov region per 100 thousand population, for prediction of which we used such indicators as the first and the last registered cases of ticks biting a person for 2006–2023. With the first registered case in February, the incidence of Lyme disease is below average by 4.75 per 100 thousand population, in March — above average by 4.87, in April — below average by 0.12. With the last reported case of a tick biting a person in September, the incidence of Lyme disease is below average by 11.84 per 100,000 population, and above average by 4.11 and 7.73 in October and November, respectively. It should be noted that any forecast cannot be absolute, as the influence of other factors can never be completely excluded. An example can be 2020, when the first victim of tick bites was registered in February, but the incidence of Lyme disease in the Kirov region in this year was low. In this case, the influence of anti-epidemic measures related to the COVID-19 pandemic cannot be excluded.

The area of acaricide treatments in 2010 compared to 2006 increased 4.4 times — from 507 to 2220.5 ha [9]. Our statistical analysis for 2006–2023 showed that the volume of acaricide treatments in the Kirov region increased annually by an average of 125.87 ha. We found a negative reliable correlation of moderate closeness between Lyme disease incidence in 2006–2023 and the volume of acaricide treatments during this period.

Biotic factors play no less significant role in the life cycle of ticks. Many vertebrates: hares, ungulates, rodents, birds serve as feeders for ticks and reservoirs for tick-borne pathogens. The increase in the number of animals directly correlates with the growth rate of the population of ixodid ticks [4, 23–25]. Anthropogenic factors should be considered from the position of economic activity and human behavior in nature. Active logging of forest areas leads to dynamic changes in microclimatic conditions. The replacement of old forest by young growth causes an increase in exposure to sunlight, changes in temperature, air humidity and upper soil layers. The cleared areas are populated with small-leaved tree species, shrubs, and grasses, creating a favorable niche for the reproduction of tick feeders and vectors [24, 25]. Reduction of species biodiversity of a particular ecosystem, resulting in disruption of food chains, is associated with an increased probability of tick-borne infection. For example, the decline of a key predator of small mammals, the red fox, in the northeastern and western United States has led to an increase in the incidence of Lyme disease in this region. In turn, active recreation or labor activity in open spaces during the warm season increases the probability of human contact with infected arthropod vectors of Borrelia [26–29]. These factors directly influence the risk of human contact with ticks, which is necessary to build an accurate predictive model of the epidemiologic risk of population morbidity.

Tick activity can be influenced by weather conditions [10]. Abiotic factors have a significant impact on the survival and reproduction of ticks in a particular biogeocenosis. It has been proved that mean annual temperatures and seasonality of their fluctuations play a critical role in the life cycle of arthropods [23, 25]. Thus, mild winters contribute to higher survival rates of individuals, and warm interseasonal periods promote early activation and prolong the period of mite activity, which leads to habitat expansion [24, 25]. The abundance of precipitation, high relative air humidity and the degree of soil moisture are critical at all stages of the tick life cycle. The amount of solar radiation and daylight hours are positively related to mite activity [23]. From 1984 to 2010, a significant increase in the average annual air temperature and relative air humidity was recorded in the Kirov region. The main changes occurred in the autumn months, which had a favorable effect on the life activity of ixodid ticks [27, 30]. Russian scientists proposed a regression equation, where the dependent variable is the incidence of tick-borne encephalitis, and the factors are the temperature of May in season n in the medium-term cycle, the temperature of August in season n in the medium-term cycle, the temperature of October of the previous season ($n - 1$) and the temperature of November. According to the authors, the course of change in the incidence of tick-borne encephalitis in Irkutsk agrees quite well with the course of climate change in its macrocyclical and trend components. A study conducted in 2011 found that for three natural foci of tick-borne encephalitis (located in the territory of Novosibirsk, Irkutsk and Gorno-Altaisk), the common significant factors in predicting the incidence of this natural focal infection are: air humidity in November of the previous year, humidity in April and June, and temperature in June of the current year [31,32]. These factors were identified both in the construction of the logical solving function and in the regression equation. The positive influence of solar activity on the incidence of tick-borne encephalitis in Novosibirsk and Irkutsk was shown. Using the method of multiple linear regression, we proposed a mathematical model indicating the dependence of morbidity of tick-borne encephalitis on climatic indicators and the volume of acaricide treatments. Based on the values of regression coefficients the incidence of Lyme disease (per 100 thousand population) in the Kirov region in the system changes:

- increase in the volume of acaricide treatments per 1 hectare decreases the incidence of Lyme disease on average by 0.003 per 100 thousand population;
- an increase in the average annual air temperature by 1°C leads to an average decrease in Lyme disease morbidity by 1.304 per 100 thousand population;
- an increase in average annual air humidity by 1% leads to an average increase in the incidence of Lyme disease by 0.993 per 100 thousand population;
- an increase in the average annual precipitation by 1 mm leads to an average increase in the incidence of Lyme disease by 93.133 per 100 thousand population.

It should be noted that with an error probability of 5%, the average annual precipitation is significant, while the other factors are insignificant. Based on the values of β-coefficients, the greatest contribution to the change in the incidence of Lyme disease is made by the average annual precipitation volume.

Conclusion

Today, mathematical modeling methods are successfully used to predict the incidence of various nosological forms of infectious diseases. Lyme disease has long been an urgent problem for Russia as a whole and, especially, for regions with high morbidity, such as the Kirov region. The authors for the first time made an attempt to predict the level of morbidity of infectious diseases on the territory of this subject depending on some hydrometeorological and anthropogenic factors using mathematical modeling methods. A mathematical model for forecasting the incidence of Lyme disease in the Kirov region depending on the average annual values of climatic indicators and the volume of acaricide treatments was proposed. An interval forecast of Lyme disease incidence in the Kirov region for the 2024–2026 is made, which demonstrates a tendency to decrease the intensity of epidemic process manifestations. For a more accurate prediction of the level of Lyme disease incidence in the Kirov region, a set of factors is required, including the number and species diversity of tick feeders, changes in the structure of forest ecosystems due to anthropogenic impacts, human activity in natural areas during the season of increased tick activity, as well as geographical peculiarities of tick distribution in the administrative-territorial units of the region, taking into account hydrometeorological indicators. The study requires further development, including determination of the prospects for practical application of the proposed forecasting models. This will help to substantiate the necessity for further research and develop strategies to stabilize the epidemiological situation in the Kirov region.

СПИСОК ИСТОЧНИКОВ | REFERENCES

1. Mahajan V.K. Lyme disease: an overview. *Indian Dermatol. Online J.* 2023;14(5):594–604.
DOI: https://doi.org/10.4103/idoj.idoj_418_22
2. Рудакова С.А., Теслова О.Е., Муталинова Н.Е. и др. Эпидемиологическая ситуация по иксодовым клещевым боррелиозам в Российской Федерации в 2021 г. и прогноз на 2022 г. *Проблемы особо опасных инфекций.* 2022;(2):46–53. Rudakova S.A., Teslova O.E., Mutalinova N.E., et al. Epidemiological situation on tick-borne borreliosis in the Russian Federation in 2021 and forecast for 2022. *Problems of Particularly Dangerous Infections.* 2022;(2):46–53.
DOI: https://doi.org/10.21055/0370-1069-2022-2-46-53
EDN: https://elibrary.ru/xkxzol

3. Wang S.S., Liu J.Y., Wang B.Y., et al. Geographical distribution of *Ixodes persulcatus* and associated pathogens: analysis of integrated data from a China field survey and global published data. *One Health.* 2023;16:100508.
DOI: https://doi.org/10.1016/j.onehlt.2023.100508
4. Ястребов В.К., Утенкова Е.О. Актуальные направления эпидемиологического надзора за природно-очаговыми инфекциями (на примере Волго-Вятского региона). *Здоровье населения и среда обитания — ЗНиСО.* 2011;(12):25–7. Yastrebov V.K., Utenkova E.O. Actual trends of epidemiological inspection of natural foci infections (by the example of the Volga-Vyatsk region). *Public Health and Life Environment – PH&LE*. 2011;(12):25–7. EDN: https://elibrary.ru/ooqwlr
5. Любезнова О.Н., Бондаренко А.Л., Карань Л.С. Зараженность клещей *Ixodes persulcatus* возбудителями различных заболеваний в эндемичном регионе европейской части России. *Актуальная инфектология.* 2014;(2):49–52. Lyubeznova O.N., Bondarenko A.L.1, Karan L.S. Infectiousness of *Ixodes persulcatus* ticks with pathogens of various diseases in endemic regions of European Russia. *Journal Infectology.* 2014;2(3):49–52. EDN: https://elibrary.ru/thebot
6. Лопух П.С., Гладкая И.Н. Влияние природных факторов на возникновение и распространение природно-очаговых заболеваний (на примере клещевых инфекций). *Вести БГПУ. Серия 3. Физика. Математика. Информатика. Биология. География.* 2020;(3):33–6. Lopuch P.S., Gladkaya I.N. Influence of natural factors on appearance and spreading of natural-focal diseases (on the example of tick infections). *BSPU Bulletin. Series 3, Physics. Mathematics. Biology. Geography.* 2020;(3):33–6. EDN: https://elibrary.ru/xenxwa
7. Прислегина Д.А., Дубянский В.М., Платонов А.Е., Малецкая О.В. Влияние природно-климатических факторов на эпидемиологическую ситуацию по природно-очаговым инфекциям. *Инфекция и иммунитет*. 2021;11(5):820–36. Prislegina D.A., Dubyanskiy V.M., Platonov A.E., Maletskaya O.V. Effect of the natural and climatic factors on epidemiological situation related to natural focal infections. *Russian Journal of Infection and Immunity.* 2021;11(5):820–36.
DOI: https://doi.org/10.15789/2220-7619-EOT-1631
EDN: https://elibrary.ru/eqduvj
8. Eisen R.J., Eisen L. Evaluation of the association between climate warming and the spread and proliferation of *Ixodes scapularis* in northern states in the Eastern United States. *Ticks Tick Borne Dis.* 2024;15(1):102286.
DOI: https://doi.org/10.1016/j.ttbdis.2023.102286
9. Voyiatzaki C., Papailia S.I., Venetikou M.S., et al. Climate changes exacerbate the spread of *Ixodes ricinus* and the occurrence of Lyme borreliosis and tick-borne encephalitis in Europe — how climate models are used as a risk assessment approach for tick-borne diseases. *Int. J. Environ. Res. Public Health*. 2022;19(11):6516.
DOI: https://doi.org/10.3390/ijerph19116516
10. Дубянский В.М., Прислегина Д.А., Платонов А.Е. «Объясняющие» модели заболеваемости клещевыми инфекциями (на примере Астраханской риккетсиозной и Крымской-Конго геморрагической лихорадок). *Журнал микробиологии, эпидемиологии и иммунобиологии.* 2023;100(1):34–45. Dubyanskiy V.M., Prislegina D.A., Platonov A.E. Explanatory models for tick-borne disease incidence (Astrakhan rickettsial fever and Crimean-Congo hemorrhagic fever). *Journal of Microbiology, Epidemiology and Immunobiology*. 2023;100(1): 34–45. DOI: https://doi.org/10.36233/0372-9311-344
EDN: https://elibrary.ru/udgjnt
11. Gray J.S., Kahl O., Lane R.S., et al. Diapause in ticks of the medically important *Ixodes ricinus* species complex. *Ticks Tick Borne Dis.* 2016;7(5):992–1003.
DOI: https://doi.org/10.1016/j.ttbdis.2016.05.006
12. Voyiatzaki C., Papailia S.I., Venetikou M.S., et al. Climate changes exacerbate the spread of *Ixodes ricinus* and the occurrence of Lyme borreliosis and tick-borne encephalitis in Europe — how climate models are used as a risk assessment approach for tick-borne diseases. *Int. J. Environ. Res. Public Health.* 2022;19(11):6516.
DOI: https://doi.org/10.3390/ijerph19116516
13. McVicar M., Rivera I., Reyes J.B., Gulia-Nuss M. Ecology of *Ixodes pacificus* ticks and associated pathogens in the Western United States. *Pathogens.* 2022;11(1):89.
DOI: https://doi.org/10.3390/pathogens11010089
14. Deshpande G., Beetch J.E., Heller J.G., et al. Assessing the influence of climate change and environmental factors on the top tick-borne diseases in the United States: a systematic review. *Microorganisms*. 2023;12(1):50.
DOI: https://doi.org/10.3390/microorganisms12010050
15. Hromníková D., Furka D., Furka S., et al. Prevention of tick-borne diseases: challenge to recent medicine. *Biologia (Bratisl.).* 2022;77(6):1533–54.
DOI: https://doi.org/10.1007/s11756-021-00966-9
16. Eisen L. Control of ixodid ticks and prevention of tick-borne diseases in the United States: the prospect of a new Lyme disease vaccine and the continuing problem with tick exposure on residential properties. *Ticks Tick Borne Dis.* 2021;12(3):101649.
DOI: https://doi.org/10.1016/j.ttbdis.2021.101649
17. Mac S., da Silva S.R., Sander B. The economic burden of Lyme disease and the cost-effectiveness of Lyme disease interventions: A scoping review. *PLoS One.* 2019;14(1):e0210280.
DOI: https://doi.org/10.1371/journal.pone.0210280
18. Hook S.A., Jeon S., Niesobecki S.A., et al. Economic burden of reported Lyme disease in high-incidence areas, United States, 2014–2016. *Emerg. Infect. Dis.* 2022;28(6):1170–9.
DOI: https://doi.org/10.3201/eid2806.211335
19. van den Wijngaard C.C., Hofhuis A., Wong A., et al. The cost of Lyme borreliosis. *Eur. J. Public Health.* 2017;27(3):538–47.
DOI: https://doi.org/10.1093/eurpub/ckw269
20. Жигальский О.А. Анализ методов прогнозирования заболеваемости зоонозными инфекциями. *Эпидемиология и вакцинопрофилактика.* 2012;(3):26–31. Zhigalsky O.A. The analysis of forecasting methods of morbidity from zoonotic infections. *Epidemiology and Vaccinal Prevention.* 2012;(3):26–31. EDN: https://elibrary.ru/ozinjp
21. Любезнова О.Н., Бондаренко А.Л., Опарина Л.В., Ламбринаки Е.В. Эпидемиологические особенности боррелиозной инфекции на территории Кировской области. *Эпидемиология и инфекционные болезни.* 2012;(6):24–8. Lyubeznova O.N., Bondarenko A.L., Oparina L.V., Lambrinaki E.V. Epidemiological features of a borrelial infection in the territory of the Kirov region. *Epidemiology and Infectious Diseases.* 2012;(6):24–8. EDN: https://elibrary.ru/pvblfb
22. Ostfeld R.S., Brunner J.L. Climate change and Ixodes tick-borne diseases of humans. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 2015;370(1665):20140051.
DOI: https://doi.org/10.1098/rstb.2014.0051
23. Giesen C., Cifo D., Gomez-Barroso D., et al. The role of environmental factors in Lyme disease transmission in the European Union: a systematic review. *Trop. Med. Infect. Dis.* 2024;9(5):113.
DOI: https://doi.org/10.3390/tropicalmed9050113
24. Radolf J.D., Strle K., Lemieux J.E., Strle F. Lyme disease in humans. *Curr. Issues Mol. Biol.* 2021;42:333–84.
DOI: https://doi.org/10.21775/cimb.042.333
25. Гнатив Б.Р., Токаревич Н.К. Результаты многолетнего мониторинга клещевого вирусного энцефалита и клещевого боррелиоза в Республике Коми. *Инфекция и иммунитет.* 2021;11(4):707–22. Gnativ B.R., Tokarevich N.K. Long-term monitoring of tick-borne viral encephalitis and tick-borne borreliosis in the Komi Republic. *Russian Journal of Infection and Immunity*. 2021;11(4):707–22.
DOI: https://doi.org/10.15789/2220-7619-ROL-1299
EDN: https://elibrary.ru/nxhtts

26. Bouchard C., Dumas A., Baron G., et al. Integrated human behavior and tick risk maps to prioritize Lyme disease interventions using a 'One Health' approach. *Ticks Tick Borne Dis.* 2023;14(2):102083.
DOI: https://doi.org/10.1016/j.ttbdis.2022.102083
27. Steinbrink A., Brugger K., Margos G., et al. The evolving story of *Borrelia burgdorferi sensu lato* transmission in Europe. *Parasitol. Res.* 2022;121(3):781–803.
DOI: https://doi.org/10.1007/s00436-022-07445-3
28. Dantas-Torres F. Climate change, biodiversity, ticks and tick-borne diseases: the butterfly effect. *Int. J. Parasitol. Parasites Wildl.* 2015;4(3):452–61.
DOI: https://doi.org/10.1016/j.ijppaw.2015.07.001
29. Millien V., Leo S.S.T., Turney S., Gonzalez A. It's about time: small mammal communities and Lyme disease emergence. *Sci. Rep.* 2023;13(1):14513.
DOI: https://doi.org/10.1038/s41598-023-41901-z
30. Reynolds C., Kontschán J., Takács N., et al. Shift in the seasonality of ixodid ticks after a warm winter in an urban habitat with notes on morphotypes of *Ixodes ricinus* and data in support of cryptic species within *Ixodes frontali*s. *Exp. Appl. Acarol.* 2022;88(1):127–38.
DOI: https://doi.org/10.1007/s10493-022-00756-1
31. Коротков Ю.С., Никитин А.Я., Антонова А.М. Роль климатических факторов в многолетней динамике заболеваемости населения г. Иркутск клещевым энцефалитом. *Бюллетень Восточно-Сибирского научного центра Сибирского отделения Российской академии медицинских наук.* 2007;(3S):121–5. Korotkov Yu.S., Nikitin A.Ya., Antonova A.M. Role of the climatic factors in long-term dynamics of tickborn encephalitis disease of Irkutsk population. *Bulletin of the East Siberian Scientific Center SB RAMS.* 2007;(3S):121–5. EDN: https://elibrary.ru/kjaazp
32. Бериков В.Б., Лбов Г.С., Полякова Г.Л. и др. Анализ факторов, влияющих на заболеваемость клещевым энцефалитом, с использованием логико-вероятностных и корреляционно-регрессионных моделей. *Эпидемиология и вакцинопрофилактика.* 2011;(6):25–34. Berikov V.B., Lbov G.S., Polyakova G.L., et al. Analysis of factors influencing the incidence of tick-borne encephalitis, using logical-and-probabilistic and correlation-regression models. *Epidemiology and Vaccinal Prevention.* 2011;(6):25–34.
EDN: https://elibrary.ru/okmurl

Information about the authors

Elena O. Utenkova✉ — Dr. Sci. (Med.), Associate Professor, Professor, Department of infectious diseases, Kirov State Medical University, Kirov, Russia, utelol@mail.ru,
https://orcid.org/0000-0001-7587-3437

Ilya S. Knyazhev — student, Kirov State Medical University, Kirov, Russia, knyazhev-01@mail.ru,
https://orcid.org/0009-0005-3270-1738

Nikolay S. Shchur — student, Kirov State Medical University, Kirov, Russia, k-shchur@mail.ru, https://orcid.org/0009-0001-9747-4872

Authors' contribution: *Utenkova E.O.* — idea formation, development of the concept and design of the study, data collection and statistical processing, analysis and interpretation of the data obtained, text writing, editing, approval of the final version of the article; *Knyazhev I.S., Shchur N.S.* — data collection and statistical processing, analysis and interpretation of the data obtained, text writing, editing. All authors confirm that they meet the International Committee of Medical Journal Editors criteria for authorship, made a substantial contribution to the conception of the article, acquisition, analysis, interpretation of data for the article, drafting and revising the article, final approval of the version to be published.

The article was submitted 07.02.2025;
accepted for publication 10.04.2025;
published 28.04.2025

Информация об авторах

Утенкова Елена Олеговна✉ — д-р мед. наук, доцент, профессор каф. инфекционных болезней Кировского ГМУ, Киров, Россия, utelol@mail.ru, https://orcid.org/0000-0001-7587-3437

Княжев Илья Сергеевич — студент Кировского ГМУ, Киров, Россия, knyazhev-01@mail.ru, https://orcid.org/0009-0005-3270-1738

Щур Николай Степанович — студент Кировского ГМУ, Киров, Россия, k-shchur@mail.ru, https://orcid.org/0009-0001-9747-4872

Участие авторов: *Утенкова Е.О.* — формирование идеи, разработка концепции и дизайна исследования, сбор и статистическая обработка данных, анализ и интерпретация полученных данных, написание текста, редактирование, утверждение окончательного варианта статьи; *Княжев И.С., Щур Н.С.* — сбор и статистическая обработка данных, анализ и интерпретация полученных данных, написание текста, редактирование. Все авторы подтверждают соответствие своего авторства критериям Международного комитета редакторов медицинских журналов, внесли существенный вклад в проведение поисково-аналитической работы и подготовку статьи, прочли и одобрили финальную версию до публикации.

Статья поступила в редакцию 07.02.2025;
принята к публикации 10.04.2025;
опубликована 28.04.2025