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The Influence of Meteorological Factors on the Activity of Adult Taiga Ticks (*Ixodes persulcatus* Sch., Ixodinae) in St. Petersburg and Its Environs

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Abstract—The article deals with the influence of meteorological factors on the activity of the taiga tick *Ixodes persulcatus* Sch. in the city of St. Petersburg and its environs. The results of correlation analysis of meteorological data (21 parameters) and tick collection data for 1980–2012 demonstrated a linear dependence between 11 meteorological parameters and the mean abundance of ticks. Factor analysis reduced dimensionality down to 3 parameters: the accumulated temperatures higher than +5.0°C, the annual sum of daily precipitation amounts greater than 5 mm, and Selyaninov's hydrothermal coefficient. It was shown that, while the mean abundance of active ticks in the studied territories tended to decrease, correlation between the abundance of ticks and meteorological parameters varied significantly in both intensity and direction depending on the microclimatic features of the collection sites. At low annual variation of the mean tick abundance, the methods of collection can significantly affect the results of statistical analysis. This fact should be taken into account when predicting both the timing and the intensity of the epidemiological season.

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In the territory of St. Petersburg (over 1300 km^2), numerous forested areas of mixed natural and anthropogenic origin occupy over 330 km^2. These are residual woodland patches, recreational forests, cemeteries, and forest-shrub thickets near gardening plots and cottage settlements; a considerable part of these areas is inhabited by ixodid ticks with the absolute prevalence of *Ixodes persulcatus* (Zolotov et al., 1974; Vansulin et al., 1981; *Infections…*, 2008). The mean annual abundance of ticks is not high but relatively stable: 3.4 ind./flag-hour, varying from 1.3 ind./flag-hour in 2012 (data of St. Petersburg Center for Hygiene and Epidemiology) to 9.2 ind./flag-hour in 1995 and 2000 (*Infections…*, 2008). The taiga tick plays the leading role in preservation and transmission of natural focal infections, such as tick-borne encephalitis and ixodid tick borrelioses; the territory in question is no exception (Korenberg et al., 2002a; Korenberg, 2003; Tokarevich et al., 2008; Tretyakov et al., 2012). The distribution of ticks over the city is non-uniform, and so is the degree of potential danger of infections transmitted by them (Antykova and Kurchanov, 2002; Medvedev et al., 2013a, 2013b).

The taiga tick is a temporary ectoparasite with a pasture type of attack and a highly complex population structure. One generation includes four phases of development: egg, larva, nymph, and adult (females and males). In turn, the larval, nymphal, and adult phases include the stages of unfed, feeding, and engorged individuals. Each phase forms a separate hemipopulation that occupies its own microhabitat and responds in a specific manner to the whole set of biotic and abiotic factors (Daniel and Dusbábek, 1994; Balashov, 1998, 2012). The parasitic existence of the taiga tick is limited to the periods of feeding of all the three postembryonic development phases, which together take not more than 12–20 days (2–4 days in larvae and nymphs, 7–12 days in females) (Balashov, 1998; Grigoryeva, 2015). The non-parasitic period of all the phases of the taiga tick under the conditions of St. Petersburg and Leningrad Province lasts 3 years, with the exception of 2–3 weeks of feeding (Grigoryeva, 2015; Grigoryeva and Stanyukovich, 2016).

The abundance of questing unfed ticks in the ecosystem is determined by the balance between replenishment of their population with new individuals, removal of individuals which have found their hosts, death of starvation, and elimination by predators. The abundance of unfed adults can be assessed by flagging, but a one-time survey using this method can reveal not more than 10% of individuals (Balashov, 2012). The season of activity of adult taiga tick in St. Petersburg and its environs continues from mid-April to June and lasts 2.5–3 months on average; only the unfed females are potentially dangerous to man (Grigoryeva et al., 2014).

The geographic range of the taiga tick matches the distribution of the environmental conditions suitable to its existence. The species is widespread in the temperate climate of the Palaearctic, and the specific traits of its distribution are known to be determined by the sum of effective temperatures above +5°C (the values of 1600–1900° represent poor, 2000–2300°, average, and above 2300°, good heating conditions for ticks) combined with the humidity index, i.e., the annual precipitation related to the annual sum of mean daily values of moisture deficit (Korenberg, 1979, 2004).

The influence of abiotic factors on the activity and survival of ticks was considered in a fairly great amount of research which sometimes yielded contradictory results. Special attention was paid to the study of the effects of extreme temperature and humidity values on the survival of ticks (Kheisin, 1953; Kheisin et al., 1955; Belyaeva, 1977; Gigon, 1985) and the role of diapause in adaptation to the seasonal climatic rhythms (Belozerov, 1981). To-date, researchers have not reached common ground on the role of meteorological and climatic factors in the dynamics of population processes. The climatic parameters commonly used in meteorology do not correspond to the actual microclimate of the tick habitats. The latter are characterized by considerable vertical gradients of temperature and humidity which reflect the specific traits of their microclimate and are determined by thermal capacity and reflective property of the soil, the nature of the vegetation, and many other factors (Balashov, 1989). The complexity of the problem is not only in assessment of the influence of different-scale meteorological processes and climate on the abundance and activity of ticks but also in determining their role as abiotic factors regulating the rate of biological processes in such poikilothermic organisms as ixodid ticks. The solution is further impeded by the great number of meteorological parameters and their combinations. It should be noted that the set of meteorological features considered by different authors often varies depending on the region. For example, under the conditions of the northwestern periphery of *I. persulcatus* range, of utmost importance for reproduction and survival of the ticks are fluctuations of hydrothermal conditions during the whole spring-autumn season; especially important is the temperature at the beginning of the season and precipitation at the end of it (Bespyatova et al., 2009). In Irkutsk and Primorskii Territory, the main factors were considered to be the mean temperature of January, the absolute temperature minimum, the duration of the season with temperatures above 10°C, the mean temperature of May, the mean snow height, etc. (Bolotin et al., 2002; Nikitin and Antonova, 2005). Using the annual temperature fluctuations, Korotkov (1998) analyzed the dynamics of abundance of unfed adults in different parts of the taiga tick range (Udmurtia, Karelia, and the Baikal region) and noted that winter temperatures were the key factor determining the thermal limits of the tick distribution.

Since the contribution of the meteorological component may be difficult to distinguish in the multiple-factor processes of tick ecology, of great importance is the quality of the raw data. The tick sampling technique, the duration of periods of meteorological data collection, and the methods of data processing may all influence the results. In the opinion of some authors (Estrada-Peña et al., 2013; Randolph, 2013), the data analysis limited to the available current information, misinterpreted results of short-term field studies, and accumulating methodological errors may often result in wrong conclusions, especially when predicting the tick abundance, the timing of the epidemiological season, and its intensity. This aspect of the problem acquires still greater urgency against the background of global climate changes.

It is evident that information on the abundance of all the development phases of the ticks and also on the populations of their possible hosts would be essential for studying the dynamics of the tick population and the influence of abiotic factors on it. Using the data of long-term collections of adult taiga ticks, we have attempted to describe the dynamics of population processes based of the adult phase. The goal of this work is to study the meteorological factors influencing the activity of ticks (hereafter, adult females and males of the taiga tick) in St. Petersburg, for the purpose of predicting the timing and intensity of the epidemiological season.

Fig. 1. Location of sites where ticks *Ixodes persulcatus* were collected in 1980–2012.

The following problems were considered in this work: (1) revealing the meteorological factors influencing the activity of ticks; (2) determining the nature of interrelations between the meteorological factors and the activity of ticks.

MATERIALS AND METHODS

Research was carried out within the Baltic and Valdai regional population complexes of the taiga tick, existing under the conditions of moderate heat supply and elevated humidity (humidity coefficient > 0.60) (Korenberg et al., 1985).

We used the material of tick collections carried out by the St. Petersburg Center for Hygiene and Epidemiology in two localities positioned quite far apart (Fig. 1): (1) the research station located in Lisiy Nos, for the period of 20 years from 1992 to 2011; (2) the southern part of St. Petersburg, for the period of 32 years from 1980 to 2012. The Lisiy Nos research station is situated in Primorsky District in the north of St. Petersburg and includes a biotope typically inhabited by the taiga tick, namely mixed forest with weedy shrubs and trees and a well-developed deciduous litter layer, well drained due to the presence of old soil-reclamation trenches. The territory was rarely visited by people and provided a stable composition of hosts for all the taiga tick phases during the observation period. The second collection locality is not a single biotope but a complex of separate parks and public gardens with mixed woody vegetation; most of these areas are regularly visited by people but some represent harsh terrain and are not publicly accessible. All the separate areas are connected by forest belts to the forested territory south of St. Petersburg; this connection facilitates migrations of large and medium-sized mammals and is thus conducive to maintaining the tick population. Not all the stations by far are suitable for development of ticks and their preservation during the non-parasitic periods, since they do not have sufficient litter. In some stations, the numbers of ticks may be supported due to their intermediate spatial position and visits of tick-carrying birds. Within the second locality, ticks were collected in 10–12 stations with 10-day intervals. The activity of ticks was estimated by the density of the adults captured by the standard flagging technique (using 60 × 100-cm flags made of honeycomb cloth) in the first half of the day, every 10 days during the whole season of activity, from the end of March to June. The tick density was expressed as the number of captured individuals per 1 flag-hour (Zhmaeva and Piontkovskaya, 1964). The meteorological parameters for St. Petersburg were obtained from the daily data set of the World Data Center of All-Russian Research Institute of Hydrometeorological Information (http://meteo.ru). The data were processed using analytical and statistical methods, such as correlation and factor analyses.

RESULTS AND DISCUSSION

In the studies of tick ecology, the air temperature and humidity parameters are considered to be the leading abiotic factors (Belyaeva, 1977; Korenberg, 1979; Balashov, 1989; Gigon, 1985). Not only the absolute values of certain parameters but also their sums over different periods and the duration of such periods are important. Therefore all the meteorological factors were conditionally divided into three groups:

1. The limiting factors which determine the survival of ticks to a greater degree:

number of days with air temperatures below −2.0°C,

number of days with air temperatures below −10.0°C,

accumulated air temperatures below −2.0°C,

accumulated air temperatures below −10.0°C,

number of days with air temperatures below −2.0°C without snow cover,

accumulated air temperatures below −2.0°C without snow cover,

number of days with air temperatures below −2.0°C without snow cover in spring,

accumulated air temperatures below −2.0°C without snow cover in spring,

number of days with air temperature below 0.0°C,

accumulated air temperatures below 0.0°C,

drought index (number of consecutive days with positive temperatures and without precipitation; more than 20 such days are regarded as drought),

maximum of five-day precipitation totals (calculated as a maximum of five-day moving totals).

2. The factors which influence the seasonal activity of ticks in the spring-summer period:

number of days with air temperatures above +5.0°C per season,

accumulated air temperatures above +5.0°C per season,

number of days with air temperatures above +10.0°C per season,

accumulated air temperatures above +10.0°C per season,

number of days with precipitation greater than 10 mm per season,

sum of daily precipitation amounts greater than 10 mm per season,

number of days with precipitation greater than 5 mm per season,

sum of daily precipitation amounts greater than 5 mm per season.

3. The factors which both limit and influence the seasonal activity of ticks:

number of days with air temperatures above +5.0°C per year,

accumulated air temperatures above +5.0°C per year,

number of days with air temperatures above +10.0°C per year,

accumulated air temperatures above +10.0°C per year,

number of days with precipitation greater than 10 mm per year,

sum of daily precipitation amounts greater than 10 mm per year,

number of days with precipitation greater than 5 mm per year,

sum of daily precipitation amounts greater than 5 mm per year,

Selyaninov's hydrothermal coefficient (HTC).

Thus, a total of 21 meteorological parameters were determined. The relative tick abundance was determined as the mean number of ticks per 1 flag-hour and calculated separately for Lisiy Nos research station and the southern part of St. Petersburg. The study season comprised the period from the end of March to June.

Since the meteorological factors may differently affect the ticks depending on the stage of their development, we used both correlation and cross-correlation analyses with a one-year or two-year shift to reveal relations between the tick abundance and meteorological parameters.

Our analysis revealed 11 meteorological factors which were significantly correlated ($p \leq 0.05$) with the mean number of ticks per 1 flag-hour (Table 1). The results of correlation analysis demonstrated negative linear correlations between the number of ticks and the air temperature and humidity parameters, with the exception of the hydrothermal coefficient for which a positive correlation with a two-year shift was observed. In our opinion, such negative correlations may

Table 1. Coefficients of correlation between meteorological factors and abundance of adult ticks

Meteorological parameters	Number of ticks per 1 flag/hour					
	no shift		one-year shift		two-year shift	
	St. Petersburg	Lisiy Nos station	St. Petersburg	Lisiy Nos station	St. Petersburg	Lisiy Nos station
Accumulated air temperatures above +5.0°C per year	**–0.37**	0.03	–0.30	–0.03	**–0.37**	**–0.58**
Number of days with air temperatures above +10.0°C per year	**–0.43**	0.12	–0.34	–0.01	–0.30	**–0.54**
Accumulated air temperatures above +10.0°C per year	**–0.44**	0.01	–0.26	0.12	–0.32	**–0.58**
Number of days with precipitations above 5 mm per season	–0.08	0.31	**–0.56**	–0.43	–0.10	0.30
Precipitation total above 5 mm per year	0.03	0.01	**–0.40**	–0.19	–0.26	0.18
Precipitation total above 5 mm per season	–0.04	0.31	**–0.58**	**–0.47**	–0.10	0.31
Number of days with precipitations above 10 mm per year	–0.03	0.04	**–0.43**	–0.21	**–0.36**	0.16
Number of days with precipitations above 10 mm per season	–0.06	0.26	**–0.55**	–0.43	–0.25	–0.01
Precipitation total above 10 mm per year	–0.02	0.03	**–0.41**	–0.21	**–0.35**	0.30
Precipitation total above 10 mm per season	–0.01	0.31	**–0.49**	**–0.46**	–0.13	0.14
Hydrothermal coefficient (HTC)	0.07	0.11	–0.30	–0.29	–0.08	**0.56**

The values statistically significant at $p \leq 0.05$ are shown in bold.

be explained by the fact that the seasonal ranges of air temperature and humidity may include critical combinations of factors that considerably restrict the activity of ticks, such as periods longer than 7–10 days without precipitation and with maximal daily temperatures above 25°C, or showers flooding the places with low soil saturation capacity. These narrow limiting values hinder the understanding of the effect of fluctuations of hydrothermal conditions during the spring-autumn season upon the activity and survival of ticks. On the long-term scale, the selected meteorological parameters showed either a weak tendency for growth (annual accumulated air temperatures above +5.0°C; annual number of days with air temperatures above +10.0°C; annual accumulated air temperatures above +10.0°C; annual sum of daily precipitation amounts greater than 5 mm; seasonal sum of daily precipitation amounts greater than 10 mm) (Fig. 2*a*), or no distinct tendency (annual number of days with precipitation greater than 10 mm; annual sum of daily precipitation amounts greater than 10 mm; HTC) (Fig. 2*b*). At the same time, the long-term mean number of ticks showed a tendency for reduction over the last 20 years (Fig. 3). Considering these data, the observed increase in the number of St. Petersburg residents who suffered from ixodid tick bites within the suburbs in 2006–2015 and in various territories including those beyond the city limits in 2006–2015 (Fig. 4) cannot be attributed to an increasing abundance of ticks in the natural biotopes. Instead, this phenomenon may be explained by the social factors, namely the increased recreational use of the nearest environs and suburbs.

It should be noted that both the direction and strength of correlations varied depending on the biotope where the ticks were collected. In particular, the mean number of ticks collected in different areas of the southern part of St. Petersburg was correlated with the temperature parameters of the given year, reflecting the increase in the number of questing individuals. In Lisiy Nos research station, these correlations were observed only with a two-year shift. Correlations between the precipitation parameters and the tick abundance were revealed with a one-year shift regardless of the collection locality. The long-term mean number of ticks collected per 1 flag-hour in St. Petersburg only insignificantly differed from that for Lisiy Nos station (Table 2). It should be noted that under the conditions

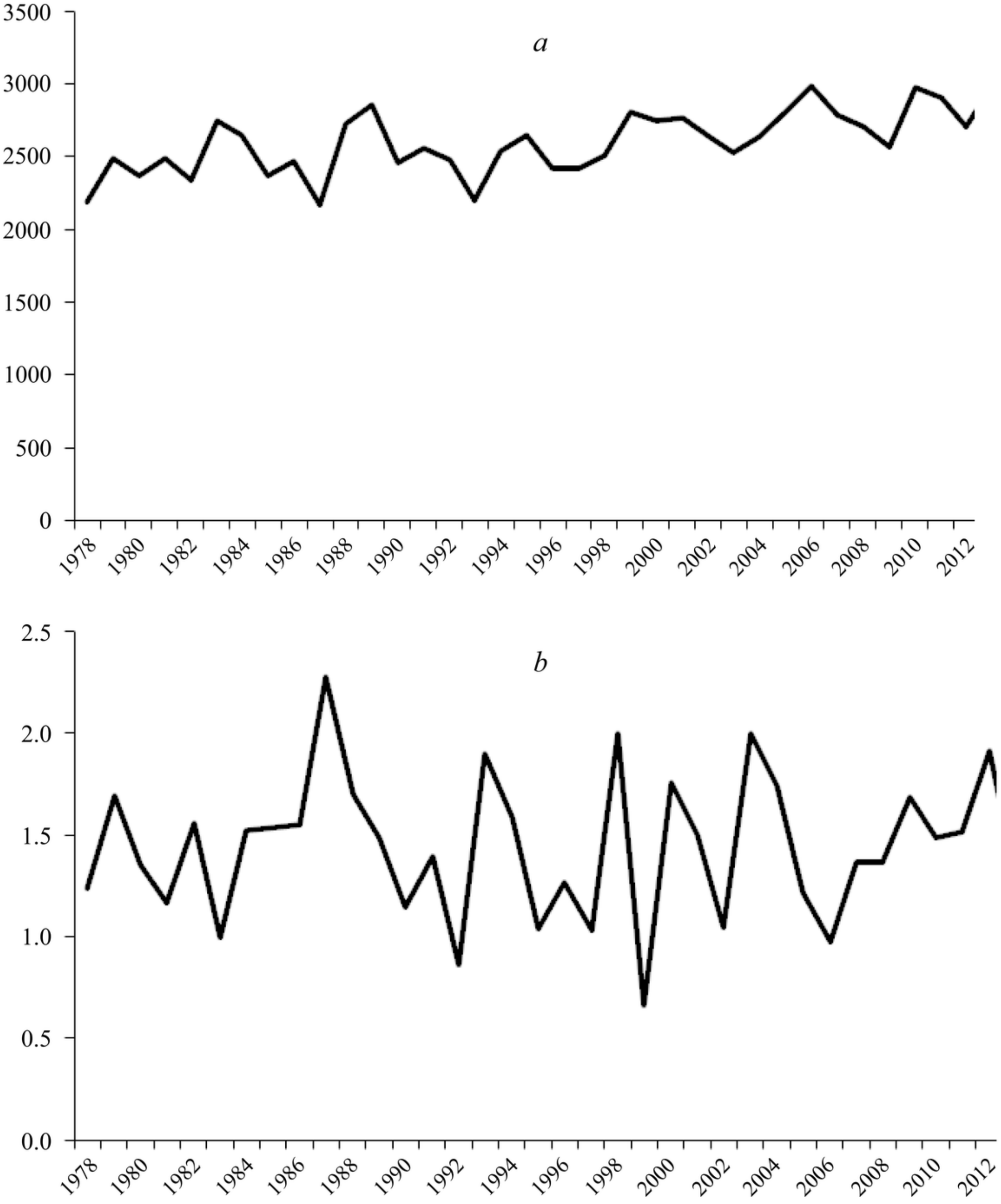

Fig. 2. Long-term dynamics of climatic parameters in St. Petersburg: (*a*) annual accumulated air temperatures above +5.0°C; (*b*) hydrothermal coefficient.

of St. Petersburg and Leningrad Province, the spatial structure of the tick population in each spring-summer season is established as the result of complex interaction between the ticks, their hosts, and abiotic environmental factors during the preceding 1–2 years. The territory of Lisiy Nos station is a typical biotope supporting the long-term stable population of the taiga tick. The preimaginal fraction of the population during each spring-summer period is formed by cohorts of larvae and nymphs of the same age. Unfed larvae and nymphs hatch in August–September (Grigoryeva, 2015); those of them which fail to engorge in autumn overwinter and have a chance to feed during the spring-summer season of the following year. The unfed larvae and nymphs spend their fat reserves during the active season and become dependent on the humid-

Fig. 3. Long-term dynamics of the mean tick abundance (ind. per 1 flag-hour): solid line, southern districts of St. Petersburg; dotted line, Lisiy Nos research station.

ity regime of their microstations. Therefore, drought during the active season may considerably reduce the number of individuals of the next development phase.

We used factor analysis to reduce the number of initial meteorological factors, exclude the correlated factors, and determine the possible predictors. The principal components method revealed the following meteorological parameters which may be considered as predictors of the tick abundance and the epidemiological intensity of the season: the annual accumulated air temperatures above +5.0°C, the annual sum of daily precipitation amounts greater than 5 mm, and Selyaninov's hydrothermal coefficient.

These parameters were not correlated to each other; they had high factor loads (−0.91, 0.95, and −0.84, respectively) and showed significant correlations with the tick abundance. The choice of these parameters is quite understandable from the viewpoint of the taiga tick ecology: activation of all the development phases of the tick starts at temperatures above +5.0°C, while the annual sum of daily precipitation amounts greater than 5 mm and Selyaninov's hydrothermal coefficient most adequately reflect the moisture reserve of the soil, which underlies the microstational conditions for all the phases.

The limiting meteorological factors that mainly characterize the winter period and determine the survival of ticks were not included in analysis since they did not reveal significant correlations with the tick abundance. This was also true of the extreme climatic parameters which had low recurrence during the study period.

Attempts at analysis of the influence of meteorological factors on the taiga tick abundance and its prediction have been made before us. It should be noted that in our opinion, the most accurate and objective

Table 2. Descriptive statistics of the tick abundance

	Number of observations (years)	Mean	Median	Minimum	Maximum	Variance	Standard deviation	Standard error
St. Petersburg	32	3.75	3.26	1.55	9.74	3.65	1.91	0.33
Lisiy Nos station	20	4.64	4.34	2.16	9.18	3.25	1.80	0.40

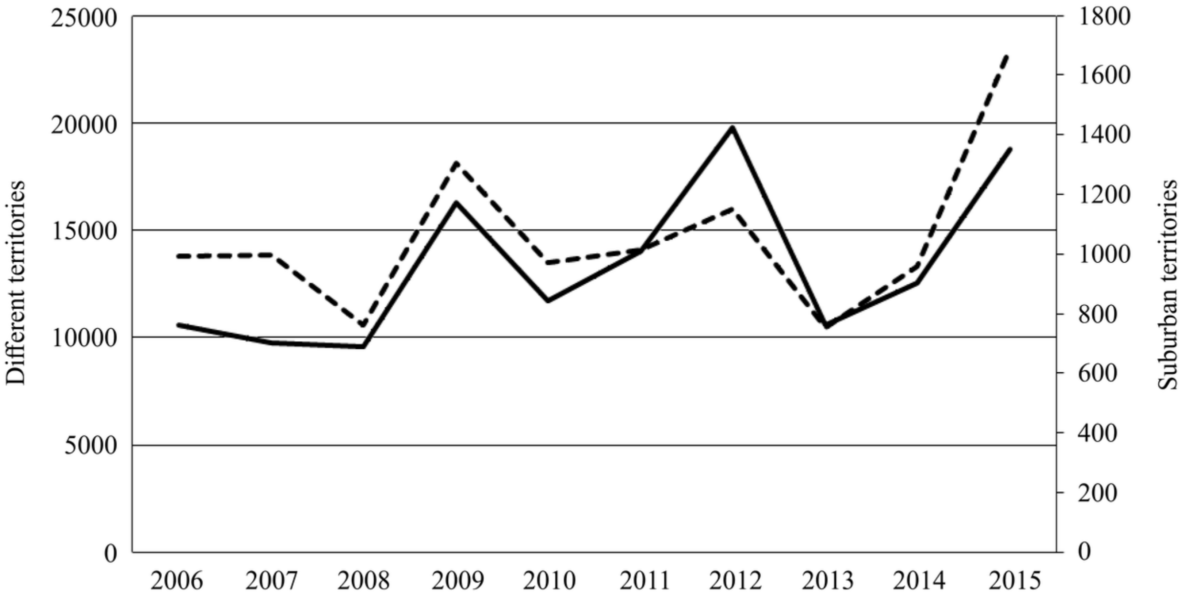

Fig. 4. Dynamics of the number of tick bite victims in St. Petersburg in 2006–2015: solid line, in different territories; dashed line, in suburban territories.

assessment of the abundance dynamics of active ticks is provided by the standard flagging surveys with ten-day intervals, whose data can be used in long-term comparative analysis. We also agree with the view of Korenberg (1979, 2004) and Korotkov (1989, 2008) that the hydrothermal conditions of the spring-autumn season are the main factors limiting successful development and reproduction of the taiga tick and influencing the manifestation of its seasonal activity in different parts of its range. However, in our opinion, these conditions should be studied in greater detail, and the factors most strongly affecting the tick micro-environment both during their seasonal activity and during overwintering should be revealed; the mean annual temperature fluctuations (Korotkov, 2009) are not at all sufficient since they do not reflect the real effect of hydrometeorological factors on the abundance of active ticks in natural populations in the study region.

Prediction of the incidence of tick-borne encephalitis based on the number of recorded cases (Bolotin et al., 2002a, 2002b) are extremely subjective since tick bite victims do not always seek specialized help, so that the number of victims would be initially underestimated. Besides, these records may include data on people visiting forest biotopes unsuitable for ticks, into which some ticks had been brought by their hosts. Such data are often used in predictions of the taiga tick range expansion (Popov, 2014), which do not reflect the real picture of population abundance and especially the species range. Such studies should be directed at revealing the biotopes in which the tick development follows the typical life cycle scenario.

Another important aspect is the choice of biotopes for surveys. Such biotopes should support development of ticks throughout their entire life cycle and contain suitable hosts of all the phases, especially the adults; this is the main feature that determines the stable existence of tick populations in biotopes suitable by the complex of abiotic factors. Data on the tick abundance in most recreational forests that are being collected by researchers of St. Petersburg Center for Hygiene and Epidemiology are not representative, since such collections are initiated by medical aid appealability in the territories often unsuitable for ticks. Such territories lie in the periphery of the principal biotopes sustaining tick populations, and the abundance of ticks in them is determined by individuals carried on their hosts, often on birds.

It should be noted that the abundance of ticks in St. Petersburg is currently declining (Fig. 3) due to considerable anthropogenic transformation of the city environs, mass development of multi-storey housing, and the completion of the encircling highway. Those recreational forests which quite recently were connected with the vast forested areas of Leningrad Province have now lost this connection either partially or completely. Consequently, migration of large and medium-sized mammals, which are hosts of adult ticks, has been either blocked or considerably reduced, so that the parasite populations are now in the pessimal phase in the terminology of Korenberg (1979). The popular notion of the increasing number of ticks, imposed by the mass media, has no objective basis but merely reflects the medical aid appealability statistics. The number of tick bite victims is increasing annually due to increasing recreation activity, particularly in May when adult taiga ticks are the most abundant. This increase corresponds to changes in the tourist market geography due to economic reasons, especially in recent years (Fig. 4). Elevated awareness and concern of the people combined with epidemiological ignorance result in more frequent requests for medical help. Instead of promoting public hysteria about "dreadful ticks," the mass media should explain the rules of safe behavior in forested areas and the need for self-examination (which is the principal way to prevent tick bites, apart from the use of repellents and insecticides) after visiting them.

CONCLUSIONS

The natural foci of tick-borne infections are complex objects whose function depends on the combination of abiotic and biotic factors. The meteorological factors are only a small part of the complex which influences both survival and activity of the ticks.

The following conclusions can be drawn as the result of our research.

1. Of the whole multitude of meteorological factors, the greatest influence on the tick activity is exerted by the precipitation parameters in combination with thermal regime. Besides the general tendency for decreasing abundance of active ticks in the studied territories, its correlations with meteorological parameters may vary considerably both in direction and in strength. This may be explained not only by the quality of the initial data but also by the specific microclimatic features of collection sites which affect the living conditions of the ticks not less than meso-scale processes.

2. Given insignificant interannual variation of the mean tick abundance, the collection methods may considerably affect the results of statistical analysis.

3. Such meteorological parameters as annual accumulated air temperatures above +5.0°C, the annual sum of daily precipitation amounts greater than 5 mm, and Selyaninov's hydrothermal coefficient may be regarded as predictors of the tick abundance in St. Petersburg.

4. In some years, the tick abundance is strongly affected by such extreme meteorological parameters as the number of days with air temperatures below 10°C without a snow cover. Although such phenomena are rare in St. Petersburg, they should also be taken into account in working out the prediction methods.

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