Original article

Linking human tick bite risk with tick abundance in the environment: A novel approach to quantify tick bite risk using orienteers in Scotland

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ABSTRACT

The rate that people are bitten by ticks is critical in determining the risk of tick-borne infections but is rarely quantified accurately. Often tick abundance in the environment is used as a proxy for tick bite risk, but the relationship with risk is poorly understood. We used a novel citizen science approach to measure tick bite rate in orienteers, to assess the relationship between tick abundance and tick bite risk and to identify risk factors for tick bites. Eleven orienteering events were attended in Scotland between August 2018 and September 2019. The number of tick bites in orienteers, and the time and distance of activity were collected using an online questionnaire. Tick abundance in the same areas used for the orienteering events was estimated by surveying ticks on ground vegetation using blanket drags. Among orienteers, mean incidence was 409 tick bites per 1,000 person-hours. Tick abundance and tick bite rate were strongly correlated, indicating that data from questing tick surveys is a useful proxy for the risk of human tick bites. Tick bite rate was better explained by the activity duration than distance covered and was higher in orienteers that ran earlier in the day, exposed to higher temperatures and in woodland habitats. This study highlights the value of the citizen science approach used, which crucially included submission of activity reports both with and without ticks, to generate robust data on tick bite rate. Accurately measuring tick bite rate and understanding environmental factors that influence it are essential in mitigating the risk of tick-borne diseases.

1. Introduction

The rate that people are bitten by vectors is critical in determining the risk of infections with vector-borne pathogens, so this parameter is essential for informing policy to target preventive and control measures. In Europe, tick-borne diseases are the most common vector-borne diseases (ECDC, 2012). *Ixodes ricinus,* the most ubiquitous tick species (Gray, 1998), is the one most commonly found biting humans (Cull et al., 2019; Lernout et al., 2019; Robertson et al., 2000; Stjernberg and Berglund, 2002). *Ixodes ricinus* has public health importance as it is the dominant vector of *Borrelia burgdorferi* sensu lato, the causative agent of Lyme borreliosis (LB) and of other zoonotic microorganisms (Azagi et al., 2020; Gray, 1998; Perret et al., 2004).

Tick bite risk (the rate that people are bitten by ticks) depends on a combination of factors related to the environmental hazard (tick abundance in the environment) and human exposure (the likelihood of human contact with ticks) (Eisen and Eisen, 2016; Hall et al., 2017). It is challenging to measure and is rarely quantified accurately (Eisen and Eisen, 2016; Ginsberg, 1993). Studies that have reported tick bite rates are based on citizen science projects or volunteer submission of data (Faulde et al., 2014; Hall et al., 2017; Keukeleire et al., 2015). However, these studies have limitations in that they usually only consider when a tick bite has occurred, and do not include reports where people have not observed tick bites (Keukeleire et al., 2015 as exception), relying on the assumption that not reporting indicates not being bitten, whereas people may forget or choose not to report. Studies generally also do not account

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accurately for the time exposed or the distance travelled, usually estimating a daily tick bite rate. Human exposure is also difficult to quantify, because exposure encompasses multiple behavioural factors that influence the likelihood of an encounter with a tick, such as amount of time spent in tick-infested areas and degree of contact a person has with vegetation.

In the absence of data on tick bite rate or human exposure, many studies instead use the environmental hazard (Bouchard et al., 2018; Kjær et al., 2019; Schwarz et al., 2009; Swart et al., 2014) to indicate human tick bite risk. This is estimated by surveying questing ticks in the environment, usually by dragging or flagging to measure relative abundance. It is not clear how well the environmental hazard (i.e. questing tick abundance) reflects the actual rate of tick bites. Some studies have compared the abundance of questing ticks in the environment with the number of ticks found on clothing used by researchers after walking through vegetation in the same area and time period (Dobson et al., 2011; Faulde and Robbins, 2008; Walker et al., 2001). However, measuring ticks on clothing is not necessarily an accurate indicator of tick bite rate since it does not quantify the actual number of tick bites people receive; crawling ticks are often brushed off or removed before attachment.

Therefore, there is a need to generate accurate measures of the rate of tick bites as only this parameter provides direct information on public health risk. The relationship between tick bite rate and questing tick abundance needs to be identified to confirm the value of questing tick surveys in identifying high risk areas. In addition, generating accurate tick bite rate data means that risk factors for tick bites can be identified to inform risk reduction strategies. This study aims to address these objectives by collecting data from orienteers. Orienteering is a competitive outdoor running and navigation sport in which runners (orienteers) have to navigate as quickly as possible between checkpoints placed around the landscape, with the aid of a map and compass (Scottish Orienteering Association, 2020). Orienteering is an activity with high exposure to tick bites (Durand et al., 2021), because orienteers often run through rough vegetation, away from tracks, often in forests. Of particular value to this study, orienteers usually track and time their routes, providing accurate information on time and distance of exposure.

The aims of this study were therefore to (i) investigate whether tick abundance in the environment accurately reflects human tick bite rate; (ii) identify risk factors for tick bites in orienteers; and (iii) calculate the mean incidence of tick bites among orienteers. To estimate tick bite rates accurately, we present a novel approach which accounts for activities where tick bites did and did not occur, time of exposure and tracking of participants.

2. Materials and methods

To estimate tick bite rates, data from orienteers were collected using an online questionnaire, with participation promoted during orienteering events. Tick abundance in the same areas used for the orienteering events was estimated by surveying ticks on ground vegetation using blanket drags.

2.1. Data collection

A total of 11 orienteering events at world, national, regional, and local levels were attended in Scotland between August 2018 and September 2019. We attended only those events held during the months of main tick activity (March to October). At the events attended, competition courses opened between 10:00 h and 10:30 h and closed at 14:00 h. At each event, a 'tick tent' was provided with information about the project and with a private area to check for ticks. Orienteers who had finished competing were asked to participate. If they agreed, they were asked to check for ticks and to complete the questionnaire (Appendix 1 and 2) on a website, either at the time via a tablet, or later in their own

time. Participants could update the information later if further ticks were found when back home. The questionnaire collected information on the number of adult ticks and/or nymphs attached (bites) and crawling on orienteers' body or clothes (this question was accompanied by a picture identifying the three active stages of *I. ricinus* ticks, Appendix 1); the number of people running; duration of the activity; and the route taken (used to calculate the distance, Appendix 3). Orienteers submitted a report for each run, usually as individuals, although small groups running together could submit a single report. Orienteers added points manually indicating their route on a map or uploaded a GPX file with their route. Orienteers were strongly encouraged to report irrespective of whether ticks were found. Crawling ticks were included in the questionnaire to increase engagement since they are found more frequently; however, they were excluded from analysis since the parameter of interest was tick bite rate. The study protocol was approved by the Human (Research) Ethical Review Committee at the Royal (Dick) School of Veterinary Studies, University of Edinburgh (HERC_ 224_18). We did not ask for information on any tick preventive measures taken by orienteers, such as protective clothing (long sleeves or gaiters) or acaricide application. This was because we were interested in tick bite rates on people behaving in their usual way during orienteering events, and we did not aim to assess the efficacy of different anti-tick bite methods.

The temperature, the rain conditions on the day (classified as an ordinal variable: 0, no rain; 1, showers or light rain; 2, continuous rain), and the number of competitors, were recorded on the day. Tick bite rates were estimated as the number of tick bites divided by 1) the number of people per report; 2) the number of people per report multiplied by the number of hours of exposure; and 3) the number of people per report multiplied by the distance travelled.

Questing tick surveys were conducted in the same area as the orienteering events. These were areas predominantly covered by forest (deciduous, coniferous, and mixed woodland), or open habitats (grassland, moorland and pastures). Before each event, the organisers provided a map of the area, which distinguished the different types of vegetation and identified the location of each checkpoint that the orienteers had to visit. Questing tick surveys were conducted at three sites within each event area (total of 33 sites for 11 events). Each site was chosen to be representative of one habitat (definitions in European Environment Agency, 1995); the three habitats most commonly found in the area of the checkpoints for each event were selected. Questing tick surveys were conducted one or two days beforehand, with the day of sampling chosen to ensure that the weather conditions matched those of the event day. Questing ticks were sampled using the standard technique of dragging a white wool blanket of 1 m2 along the ground for 10 m (Gilbert, 2010; James et al., 2012). Questing ticks (adults and nymphs) attached to the blanket were counted. In each site, 25 drags were performed. We did not record larval ticks on blanket drags or orienteers because their small size makes them difficult to count accurately, they are very geographically clustered (Sormunen et al., 2016), and larvae are thought to present negligible risk of LB transmission (Hubálek and Halouzka, 1998; Strnad et al., 2017). Ticks collected by blanket dragging were not identified to species level. However, in Scotland, previous questing tick surveys found that 100% of the ticks found were *I. ricinus* (Gandy, 2020; Hall et al., 2017; James et al., 2012; Millins et al., 2015). The latitude and longitude of each site was recorded. Temperature and rain conditions of the day were recorded as for the event days. For analysis we used the mean number of questing ticks (nymphs and adults) per 10 m2 for each area.

2.2. Statistical analysis

2.2.1. Relationship between tick bite rate and questing tick abundance

We first checked that questing tick surveys were conducted in sites that were a good representation of the habitat where orienteers ran at each event, by testing the correlation between the proportion of habitats

covered by orienteers' runs and the proportion of habitats covered during questing tick surveys (Appendix 3). Descriptive analysis was performed at event level and the correlation was assessed using Spearman test. Conditions of temperature and rain between days of tick surveys and event were compared, to confirm similar conditions between sampling and event days.

Before assessing the relationship between tick bite rate and questing tick abundance, the best denominator for tick bite rate was identified. A first model assessed whether the number of tick bites reported per person per report was better explained by the duration of the activity (hours) or by the distance covered (km). A second model defined the relationship between tick bite rate and questing ticks in the environment. This model also tested the relationship with the alternative denominator options (per person, per person per hour and per person per distance). Both models were developed with a Bayesian approach using the integrated nested Laplace approximation R-INLA package (Rue et al., 2009). Statistical models were performed at report level and fitted using a negative binomial distribution to account for overdispersion in the tick bite data. To standardize the response variable as a rate, the logarithm of the denominator (i.e. per person, per person per hour, per person per distance) was used as an offset. Event was included as a random effect. Models were selected based on deviance information criteria (DIC) and the conditional predictive ordinate (CPO) for assessing model goodness of fit and predictive power. The model specification for the negative binomial regression is given as follows:

$LogTB_i \sim \alpha + \beta_1 Time + \varepsilon + fevent_i$

Where TB_i is the mean number of tick bites in each event i; α is the intercept; β_1 is the measure of time (or distance or tick abundance) effect and f denote the random effects due to event. When modeling the number of tick bites per person per report, or per person per hour, or per person per distance per report, the logarithm of the number of people per report, or per person per hour, or per person per distance per report, was added as an offset (ε).

2.2.2. Risk factors for tick bite rate

A third model was developed to assess the relationship between tick bite rates and environmental variables, using the same Bayesian approach, with the identified denominator as the tick bite response variable. The following explanatory variables were considered: a) variables that might affect tick activity: temperature and rain on the event day; season (spring (March to May), summer (June to August) and autumn (September to October)) or month; and six habitat types (proportion of land cover around the track run by orienteers per report that was deciduous, coniferous, mixed forest, moorland, grassland and pastures); and b) variables collected at report level which could potentially affect tick bite rate: start time in each report and type of paths used. First, a correlation matrix was used to identify highly correlated variables (correlation higher than 0.6). Then, univariable analyses were conducted to identify significant variables to include in the multivariable model. At the multivariable stage, a backward elimination procedure of variable selection was performed to identify the most parsimonious model. During the multivariable stage, if two variables were correlated, the variable with the strongest biological effect was retained while the weakest was excluded from the model.

2.2.3. Mean tick bite rate for orienteers

The mean incidence of tick bites (tick bite rate) per 1000 person-hours and the number of person-hours required for one tick bite were estimated for orienteers.

R software (R Core Team, 2019) was used for all analyses.

3. Results

The 11 orienteering events attended had a median of 137 competitors (range 37–2170) and in each event, a median of 20 competitors

participated in the study (range 8–98) (Appendix 4: distribution of event competitors and study participants). In total, 441 orienteers participated, submitting 340 reports. Whilst most (278/340, 81.8%) reports were from individual participants, some (62/340, 18.2%) orienteers participated as groups. Participants reported a mean duration of running of 1 hour and 30 min (median 1 hour, range 0.5–4.0 h), and the mean distance run was 4.2 km (median 3.3 km, range 1–20 km). Most (379/441, 85.9%) participants reported 'predominantly not running on paths' whilst a smaller number (49/441, 11.2%) reported 'predominantly running on small paths' or 'predominantly running on large paths' (13/441, 2.9%). From the 340 reports, 113 (33.2%) reported at least one tick bite and 162 (47.6%) reported at least one tick encounter (bites and/or crawling ticks). In total, 285 tick bites and 595 tick encounters were reported. More tick bites were reported in events carried out in the summer than in spring or autumn (Fig. 1).

From the questing tick surveys, 2379 ticks (nymphs and adults) were counted from 825 blanket drag transects; a mean of 2.9 (median 1, range 0–62) ticks were counted per blanket drag. The number of ticks per drag varied seasonally, with the highest mean of 7.4 ticks per drag counted in an event (E10) in July 2019 (Fig. 2). For the 11 events, the habitat with the highest count of ticks was always a woodland (55% [6/11] was deciduous, 27% [3/11] mixed and 18% [2/11] coniferous woodland).

3.1. Relationship between tick bite rate and questing tick abundance

The habitats where questing tick surveys were conducted were a good representation of the habitats where orienteers ran, with strong positive correlations between the proportion of land cover covered by orienteers and the land cover covered during questing tick surveys (mean correlation of 0.82, range 0.67–0.93, Appendix 5).

The number of tick bites per person per report is better explained by the duration of the activity than by the distance travelled, with models with the distance travelled presenting a worse fit (Table 1). Questing tick abundance correlated well with the rate of tick bites (Fig. 3). The model which used the denominator of tick bites per person per hour showed a better fit than those using the other two denominators (Table 2).

3.2. Risk factors for tick bite rate

Tick bite rates were higher in orienteers that started their run earlier in the day, and whose running route had less pasture. Tick bite rate was higher on warmer days (Table 3).

3.3. Mean tick bite rate for orienteers

The mean number of tick bites reported varied from 0 to 1.45 (mean 0.41) per person per hour per orienteering event. Across all events 1 bite was reported for every 4 person-hours (95% confidence interval 1–7). The mean bite rate was 409 tick bites per 1000 person-hours of activity (95% confidence interval 140–678).

4. Discussion

The aims of this study were to investigate the relationship between tick bite rate among orienteers and questing tick abundance in the environment, to identify risk factors for tick bite rate in orienteers and to determine the mean incidence of tick bites among orienteers.

We found a strong positive relationship between tick abundance and tick bite rate. This demonstrates, at least in this test case of orienteers, that data on questing tick abundance from blanket drag surveys accurately reflect tick bite rate in humans. Although blanket dragging (Ruiz-Fons and Gilbert, 2010) and volunteer submissions have high inherent variability, the approach used here allowed us to accurately measure tick bite rate, including measuring exposure, and to collect contemporaneous tick abundance data whilst minimizing other sources of variation. As far as the authors are aware, this is the first study that so
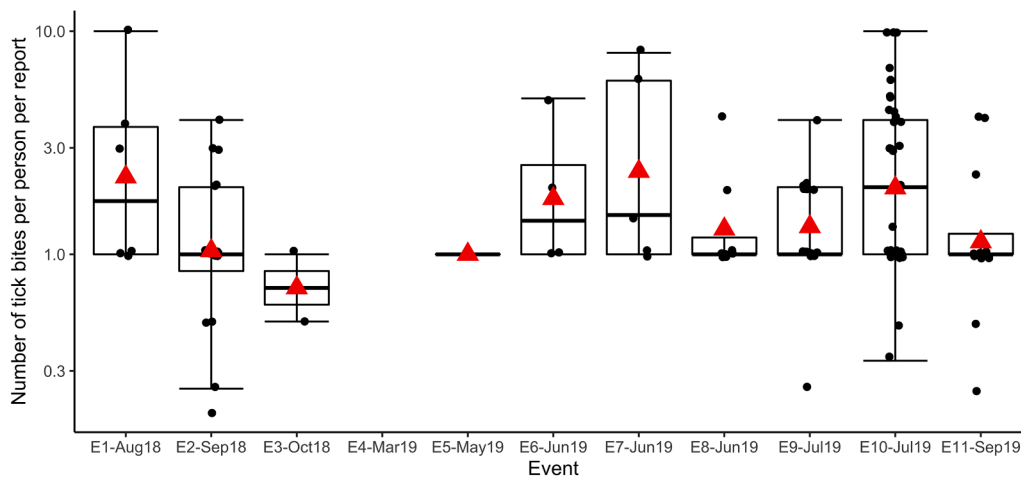
Fig. 1. Number of tick bites per person per report in each event (E1-E11). Month and year of each event are indicated (e.g. E1-Aug18 indicates the first event which took place in August 2018). Boxes indicate the interquartile range (25th to the 75th percentile); the horizontal line of the boxes indicate the median; the red triangle is the mean and the vertical line is the error bar. The reports (with respective value of tick bites per person) are the dots. Y-axis is log scaled. In the event in March (E4), no tick bites were reported.
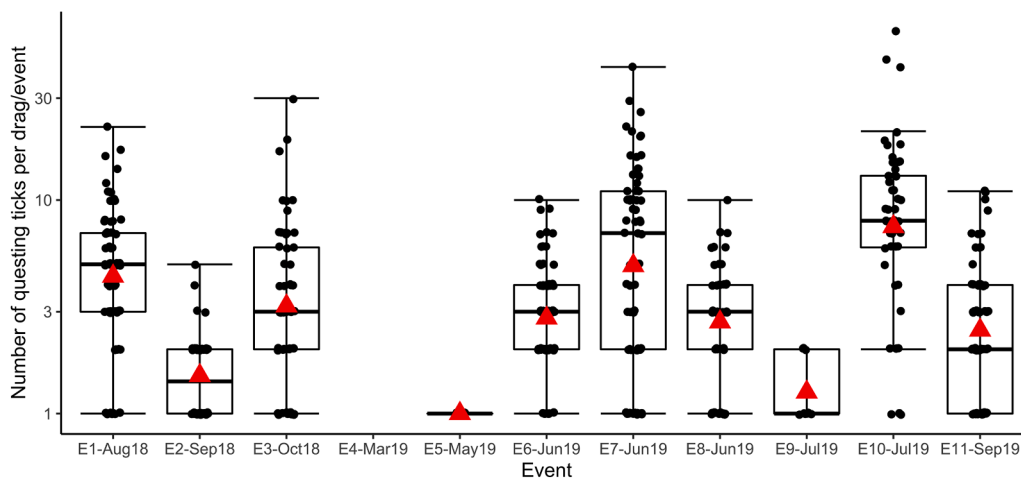
Fig. 2. Number of questing ticks per blanket drag (10 m2) in each event area (E1-E11). Month and year of each event are indicated (e.g. E1-Aug18 indicates the first event which took place in August 2018). Boxes indicate the interquartile range (25th to the 75th percentile); the horizontal line of the boxes indicate the median; the red triangle is the mean and the vertical line is the error bar. The blanket drags (with respective counts of questing ticks) are the dots. Y-axis is log scaled. In the event in March (E4), no questing ticks were counted.

Table 1

Assessment of whether the number of tick bites per person per report are better explained by the duration of the orienteering activity (hours) or by the distance covered (km)[a].

Response variable	Fixed effects	Mean	0.025 quantile	0.975 quantile	DIC[b]	CPO[c]
Number of tick bites per person report	Intercept	−1.21	−1.94	−0.53	790.7	396.5
	Time	0.41	0.07	0.78		
	Intercept	−0.90	−1.52	−0.34	792.9	397.5
	Distance	0.06	−0.007	0.12		

[a] The offset is the number of people reporting. The estimates of the fixed effects are presented in the logarithm form.
[b] CPO, conditional predictive ordinate.
[c] DIC, deviance information criteria.

directly relates tick abundance in the environment and tick bite rate in people. The findings highlight the value of blanket drag surveys as a proxy for human tick bite risk.

The number of tick bites reported per person was better explained by the duration of exposure than by distance covered, and tick bite rate per person per hour showed the strongest positive correlation with questing tick abundance. This indicates that, in the context of the times (0.5–4 h) and distances (1–20 km) in this study, the time of exposure has more influence on tick bite risk than the distance covered. The specific behaviours during a run that influence tick interactions and lead to the

patterns observed are not known (such as pace, time spent stopped) but could be valuable to explore in further research. Longer duration of activity may reflect longer periods of time spent stationary, such as at checkpoints or looking at the map, which may allow more ticks to crawl onto the orienteer. The relative importance of these factors has not been reported before, although research from Mead et al. (2018) in a study carried out in suburban settings in the North-eastern United States, found that one of the factors associated with increased odds of a tick encounter was the number of hours spent in the garden.

Our model output for our study with orienteers shows that for an increase of one degree Celsius, tick bite rate increases by a factor of 0.159 (Table 3). This positive influence of temperature on tick bite rate likely reflects the increase in the proportion of active ticks with temperature (Gilbert et al., 2014; Tomkins et al., 2014). The effect of temperature on tick bite rate may also have implications for LB risk, as the peak numbers of cases in Scotland are diagnosed in the summer months (Septfons et al., 2019; Tulloch et al., 2019). In countries with cool, wet climates such as Scotland, the implications for public health are that there is likely greater risk on warmer days. However, *I. ricinus* tick response to temperature also relies on humidity, and varies between countries with different climates (Gilbert et al., 2014; Tomkins et al., 2014), so the public health implications of temperature will vary between countries, regions and climates.

Lower tick bite rates were found on runs that passed through pasture, whilst higher questing tick abundance from blanket drag surveys were found in woodland. The relationship between tick bite rate and
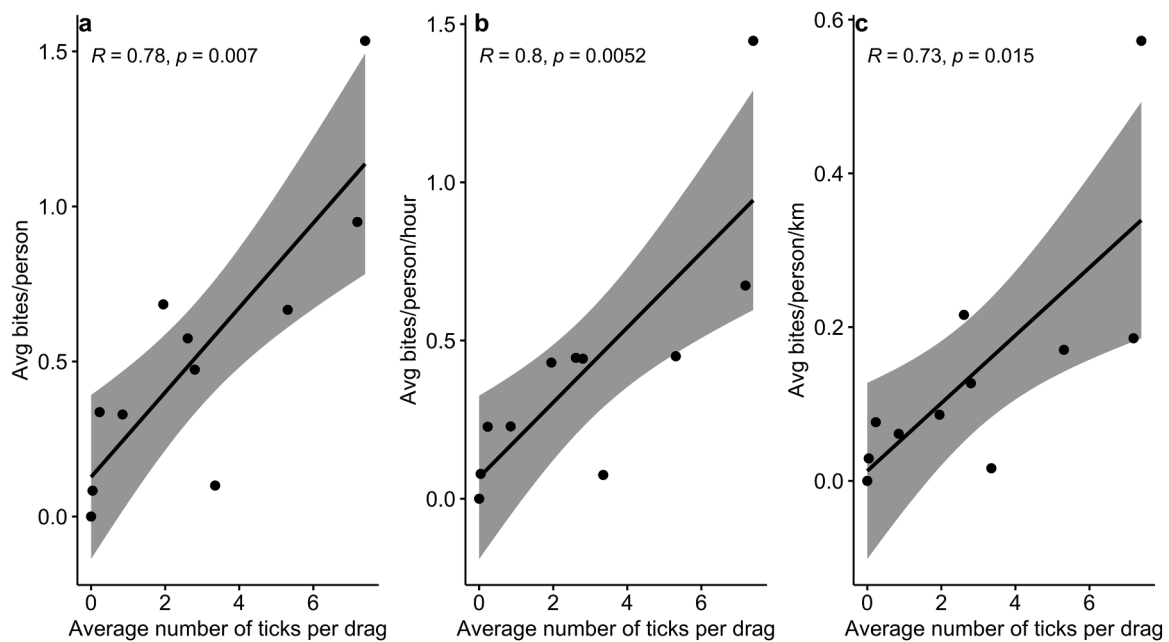
Fig. 3. Correlation between tick abundance and tick bite rate. Correlation coefficient (indicated as R) and respective P-value, between the mean number of ticks collected per drag (in 10 m2) per event area (mean of the three sites surveyed per event), and tick bite rate: (a) tick bites per person; (b) tick bites per person per hour; and (c) tick bites per person per distance (km). The black dots are each orienteering event, the dark line is the regression line and the gray shading represents the 95% confidence intervals of the regression line.

Table 2

Assessment of the relationship between tick bite rate (number of tick bites per person; per person per time (hour); and per person per distance (km)) and questing tick abundance[a].

Response variable	Fixed effects	Mean	0.025 quantile	0.975 quantile	DIC	CPO
Number of tick bites per person per report	Intercept	−1.27	−1.79	−0.79	790.6	395.9
	Questing tick abundance	0.22	0.10	0.33		
Number of tick bites per person per hour per report	Intercept	−1.60	−2.15	−1.08	785.3	393.4
	Questing tick abundance	0.24	0.11	0.36		
Number of tick bites per person per km per report	Intercept	−2.49	−3.32	−1.74	831.1	416.3
	Questing tick abundance	0.25	0.05	0.43		

[a] The offset is the number of people reporting, or the number of people reporting per time, or per distance. The estimates of the fixed effects are presented in the logarithm form.

Table 3

Results from the final multivariable negative binomial model for tick bite rate (per person per hour) and the studied environmental covariates[a].

Response variable.	Fixed effects	Mean	0.025 quantile	0.975 quantile	DIC	CPO
Tick bite rate	Intercept	−0.265	−2.906	2.336	780.7	391.6
	Start time	−0.226	−0.422	−0.031		
	Proportion of pastures covered by orienteers per report	−0.848	−1.579	−0.134		
	Temperature on the event day	0.159	0.073	0.253		

[a] The offset is the number of people reporting per time. The estimates of the fixed effects are presented in the logarithm form.

woodland was positive but not significant; although we were unable to identify where orienteers picked up most ticks, it is plausible that most tick encounters occurred when orienteers run through woodland. Habitat type determines communities and densities of tick hosts, such as deer, rodents, and birds, as well as influencing off-host tick survival, and many studies demonstrate higher tick densities in woodlands compared to open habitats (Lindström and Jaenson, 2003; Walker et al., 2001). Similarly, woodland habitats are often associated with higher tick bite risk (Garcia-Martí et al., 2017), in contrast to open habitats (Keukeleire et al., 2015). In a study conducted in Scotland, James (2010) found that the habitat most associated with acquiring LB is woodland, which emphasize the relevance of our findings to disease risk.

Orienteers that started their activity earlier in the day had higher tick bite rates, compared with later starts. Orienteers were running between

10:00 h and 14:00 h, so we might have expected the opposite pattern since temperature generally increases from morning to mid-afternoon, and the proportion of Scottish *I. ricinus* ticks that are active increases with temperature (6–15 °C) in the context of the high humidities encountered in the cool wet climate of Scotland (Gilbert et al., 2014). An untested hypothesis could be that by the time the last orienteers run through an area, there may be fewer questing ticks remaining on the vegetation if they have already attached to the previous runners. However, as there was a limited period (10:00 h and 14:00 h) over which orienteers started their events in this study, it would be important to test this finding over a wider range of times and activities, to study daily patterns of tick bite risk and it relation with questing tick activity. Another possible explanation for earlier runners having more ticks could be if earlier runners spent more time in the central registration/car park area than later runners, and if this central area also posed a risk of tick bites. While we did not survey the central registration area for ticks, the habitat was always open grassy habitat, usually short sward, which generally poses a vastly lower tick and LB hazard than woodland habitats (Gilbert, 2016). Nonetheless, the risk may not have been zero and future research should include surveys of the central area.

We found that, across all events, orienteers in Scotland experienced one tick bite every four hours and a mean incidence of 409 tick bites per 1000 person-hours. Previous studies have estimated the tick bite rate for other groups: 2.3 bites/1000 person-days among 568 soldiers in Germany (Faulde et al., 2014); 22.8 tick bites/1000 person-days among 931 scouts in Belgium (Keukeleire et al., 2015); 1.0 bite every 35 person-hours among 624 mountain marathon runners in the Highlands of Scotland (Hall et al., 2017); and 0.14 tick bites/10 h among 235 outdoor users in a tick-endemic area in Sweden (Stjernberg and Berglund, 2002). A direct comparison with these studies is difficult because the rates have been calculated in different ways, but the rate found in our study is clearly very high. Orienteers are known to be highly exposed to tick bites, since they normally run off tracks through rough vegetation, sometimes wearing short trousers and shirts (Durand et al., 2021; Fahrer et al., 1991). However there are also differences in the approach used that may explain the differences. Most studies using volunteer data on tick bites collect only positive reports (Cull et al., 2019, 2018; Garcia-Martí et al., 2018, 2017; Mulder et al., 2013), which limits the information available to a subset of the population that had tick bites, and therefore it cannot be used to assess tick bite rate and how this rate changes over time or space (Pearce and Boyce, 2006). In addition, it is common to assume that all people exposed are participating in the study (Faulde et al., 2014; Hall et al., 2017), and that people that do not report have not received tick bites; this assumption can lead to underestimates of the tick bite rate. Most previous studies also collect data on daily tick bite rates, even though participants are not always exposed to ticks all day, which can lead to underestimates if used to calculate an hourly tick bite rate. Our study addressed these limitations by collecting reports both with and, crucially, without ticks, and accounting for the real time of exposure to ticks. The high tick bite rate found here is therefore likely to be accurate. It is plausible that, despite specifically being asked to report zeros, people in our study may have been more likely to submit a report when they found a tick bite than when they did not, which would inflate our tick bite rate. However the importance of reporting all orienteering runs was heavily promoted during the study and we consider this not to be a significant issue.

One limitation of this study was that most of the tick reports were not confirmed by specialists. This is common in studies with data from volunteer reporting (such as Eisen and Eisen, 2021; Keukeleire et al., 2015; Mead et al., 2018; Mulder et al., 2013). Data on tick bites based on volunteer submissions are more reliable if a specialist is responsible for tick identification (Eisen and Eisen, 2016), since not everyone knows how to identify a tick. However, as LB is endemic in Scotland (Mavin et al., 2015) and orienteers are well informed about ticks (including through Scottish Orienteering Association (SOA) advice, through our publications in the SOA website and newsletter, and through the project website which contained photos of *I. ricinus* ticks in the three active stages), we have confidence in the results. We did not check the identification of the tick species found by orienteers; however, *I. ricinus* is the species responsible for the vast majority of tick bites in Europe (Faulde et al., 2014; Hugli et al., 2009; Stjernberg and Berglund, 2002) and the UK (Cull et al., 2019; Jameson and Medlock, 2011; Robertson et al., 2000) including Scotland (Hall et al., 2017). In addition, 100% of ticks found on blanket drag surveys in Scotland have been confirmed as *I. ricinus* (Gandy, 2020; Hall et al., 2017; James et al., 2012; Millins et al., 2015).

This study confirms that orienteering is an activity with high risk of tick bites. The risk is higher with warmer temperatures, in woodlands compared to pasture habitats, for earlier starters, and when exposed for a longer period of time. Knowledge of these risk factors can help inform orienteers and other outdoor users of when it is particularly important to adopt established mitigation measures such as applying acaricide, wearing long sleeves, gaiters, tucking trousers into socks, and checking clothing and body for ticks several times.

In summary, this is the first study to present an accurate measure of mean tick bite rate per 1000 person-hours for orienteers, a group with high exposure to tick bites. This study using orienteers in Scotland has demonstrated how data from volunteers engaged in recreational activities can be used to estimate tick bite rate, by including reports both with and without ticks and measuring the time of exposure. Importantly, we have demonstrated that data from blanket drag surveys of ticks questing in the environment is a useful predictor of the risk of human tick bites. We identified risk factors to be woodland habitats rather than pastures, warmer days, running earlier in the event and being exposed a longer period of time. While we used orienteers in this study, the risk factors identified are likely to apply to a range of other outdoor user groups and can inform when mitigation strategies are most needed.

CRediT authorship contribution statement

Rita Ribeiro: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft. **Jude I. Eze:** Methodology, Investigation, Supervision, Writing – review & editing. **Lucy Gilbert:** Data curation, Investigation, Supervision, Writing – review & editing. **Alastair Macrae:** Supervision, Writing – review & editing. **Andrew Duncan:** Software, Writing – review & editing. **Jo Baughan:** Data curation, Writing – review & editing. **George Gunn:** Supervision, Writing – review & editing, Funding acquisition. **Harriet Auty:** Conceptualization, Funding acquisition, Data curation, Investigation, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

I have shared the data as a supplement.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ttbdis.2022.102109.

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