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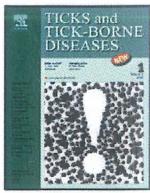
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### Original article

## The range of *Ixodes ricinus* and the risk of contracting Lyme borreliosis will increase northwards when the vegetation period becomes longer

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### ABSTRACT

In Sweden, the geographical distribution of Lyme borreliosis corresponds to that of its vector *Ixodes ricinus*. Both tick activity and the length of the vegetation period are determined by daily mean temperatures  $\geq 5^{\circ}\text{C}$ . We analysed the correspondence between the distribution of *I. ricinus* in Sweden, the start date, end date, and length of the vegetation period, and the distributions of tick habitat-associated plant species. The geographical distribution of *I. ricinus* in Sweden corresponds to a vegetation period averaging  $\sim 170$  days, an early start (before May 1st) of spring, and to the distribution of black alder (*Alnus glutinosa*). Based on scenario models for these parameters, changes in the range and abundance of *I. ricinus* were projected for the periods 2011–2040, 2041–2070, and 2071–2100. We conclude that climate change during this century will probably increase the geographic range of *I. ricinus* as vegetation communities and mammals associated with high tick densities will increase their geographic ranges due to a markedly prolonged vegetation period. By the end of this century, the ranges of *I. ricinus* and *Borrelia burgdorferi* sensu lato may, in suitable habitats, encompass most of Sweden, Norway, and Finland as far as  $70^{\circ}\text{N}$ , except the mountainous regions. This will lead to an increased Lyme borreliosis risk in northern Scandinavia.

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### Introduction

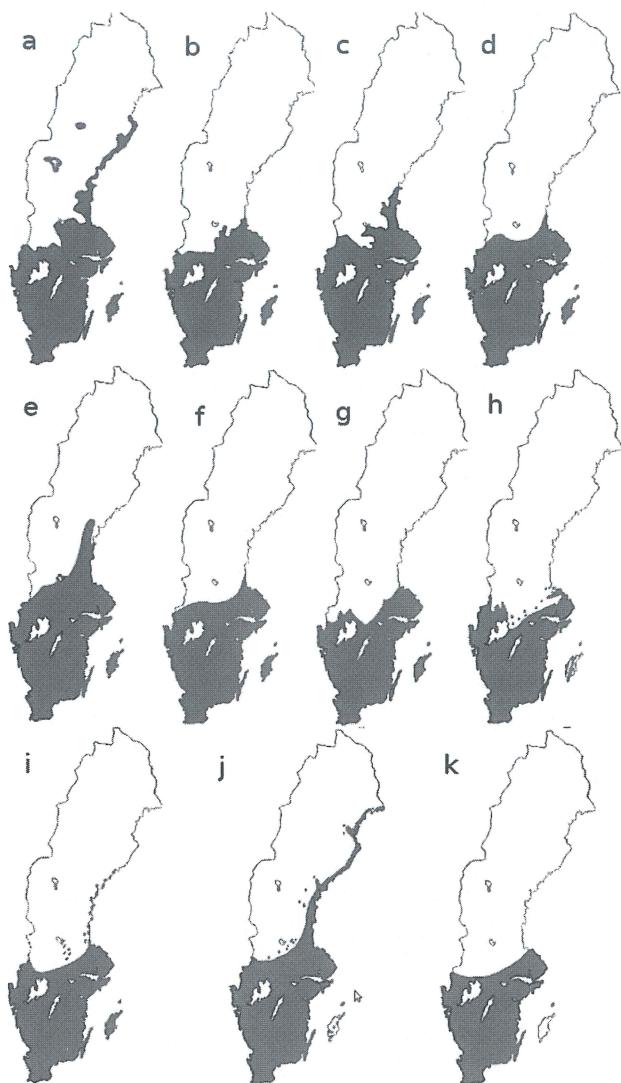
Ticks and other arthropod vectors of pathogens are directly and indirectly affected by temperature and humidity in their environment. Changes in weather and climate will, thus, influence seasonality, geographical distribution, and the incidence rates of vector-borne diseases (Gubler et al., 2001; Takken and Knols, 2007; Gray et al., 2009). Lyme borreliosis (LB, Lyme disease) is the most common vector-borne disease in Europe. The transmission intensity of LB spirochaetes (*Borrelia burgdorferi* s.l. Johnson et al.; Spirochaetaceae) depends on several factors, such as the vector's density and activity, abundance of pathogen reservoir animals, and other blood hosts, land cover, and human behaviour; factors which may also to a certain extent be affected by variations in weather and climate.

The northern distribution range of *Ixodes ricinus* L. (Ixodidae) in Europe has been shown to be associated with several climate parameters (Jaenson et al., 2009), in particular the length of the vegetation period, which is determined by daily mean temperatures of  $\geq 5^{\circ}\text{C}$ . Unpublished field data (T.G.T. Jaenson) from November 1992 and November 2009 show that nymphs of *I. ricinus*, collected

by the 'cloth dragging method', are active at  $5^{\circ}\text{C}$  at high humidity at ground level (>90% relative humidity, R.H.). Walker (2001) collected nymphs of this tick in the range 3.5–29.3 °C. We consider that this species is active at temperatures  $\geq 5^{\circ}\text{C}$  (to approximately 30 °C) and high relative humidity. ('Tick' or 'ticks' will henceforth denote '*I. ricinus*'.)

In Europe, changes in climate during the last decades appear to have caused an expanding range of the tick to higher latitudes and altitudes as well as affecting tick population densities (Tälleklint and Jaenson, 1998; Lindgren et al., 2000; Materna et al., 2005; Lindgren and Jaenson, 2006). The reasons are presumably that the changing climate, which shortens the winters and increases the length of the vegetation period, is beneficial to ticks both directly, and indirectly, by increasing tick development rate, and by increasing the abundance and geographical range of important hosts of the adult ticks, e.g., deer and hares (Tälleklint and Jaenson, 1994; Jaenson and Tälleklint, 1996; Jansson and Pehrsson, 2007; Piesman and Gern, 2008). Changes in seasonal climate and in the length of the vegetation season also affect the vegetation of tick habitats. The highest tick densities in Sweden are in the broad-leaf vegetation types dominated by hazel, beech, and oaks and in alder and mixed deciduous woodlands (Lindström and Jaenson, 2003). In Sweden, the geographical distribution of human-pathogenic LB spirochaetes is very similar or the same as that of their main vector, *I. ricinus* (Gustafson et al., 1995). In this study, we analysed the correspondence between key climate parameters and the northern

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**Fig. 1.** (a) Geographic area of Sweden where *I. ricinus* was recorded before early 1990s. (b) Area where the tick was recorded as abundant. (c) Area with a vegetation period  $\geq 170$  days (1961–1990). (d) Area with a vegetation period  $\geq 180$  days (1961–1990). (e) Area where the vegetation period starts before or on May 1st (1961–1990). (f) Area where the vegetation period's last day is on or later than October 25th (1961–1990). (g) The boreonemoral and nemoral zones combined. (h) Distribution of oak (*Quercus robur*). (i) Distribution of hazel (*Corylus avellana*). (j) Total distribution of black alder (*Alnus glutinosa*). (k) Area where black alder is abundant.

distribution limits of *I. ricinus* in Sweden, areas with recorded high tick abundance, and the distribution of plant communities with observed high densities of ticks. Scenario models for these parameters were used to project changes in the tick's distribution area and in the risk of Lyme borreliosis during this century in Scandinavia.

## Materials and methods

We used the latest updated maps for Sweden showing the geographical distribution of *I. ricinus*. The geographic area of Sweden where *I. ricinus* was recorded during the 1980s to the early 1990s, based on Fig. 2 in Jaenson et al. (1994) is marked in dark grey in Fig. 1a. The area of Sweden where the tick was recorded as abundant based on sampling data during 1992–1994 and questionnaire answers about ticks found on pets and humans by people living in Svealand (south-central Sweden) and Norrland (central and

northern Sweden) in 1992–1993 (Tälleklint and Jaenson, 1998), and records of ticks during the 1980s and the early 1990s (Jaenson et al., 2009), is marked in dark grey in Fig. 1b.

The 'winter climate parameters' that in other studies (e.g., Jaenson et al., 2009) have been found to be correlated with tick distribution are approximately inverted measures for the vegetation period, with the first day of frost corresponding roughly to the end date of the vegetation period, and the length of the vegetation period corresponding roughly to the length of the snow cover period. Thus, only vegetation period parameters were included in the analyses. From the Swedish Meteorological and Hydrological Institute (SMHI, 2009), we obtained maps for the start and end date and the length of the vegetation period for the generally used reference period 1961–1990. The vegetation period is here defined as the number of days per year with mean temperatures  $\geq 5^{\circ}\text{C}$  starting on the 5th day in a continuous period with temperatures above the threshold temperature and ending on the 4th day in the last continuous 4-day period.

We obtained from several sources distribution maps of vegetation types that are associated with high tick densities (Lindström and Jaenson, 2003): hazel, *Corylus avellana* L. (Corylaceae; SMNH, 2009), oak *Quercus robur* L. and *Q. petraea* (Matt.) Liebl. (Fagaceae; SMNH, 2009; Gustafsson and Ahlén, 1996), black alder, *Alnus glutinosa* (L.) Gaertn. (Betulaceae; SMNH, 2009), and the area denoted as the boreonemoral and nemoral zones combined (Gustafsson and Ahlén, 1996). Beech (*Fagus sylvatica* L.; Fagaceae) is only present in a minor part of the 'high-tick-density area' and was therefore not included in the analyses.

We analysed the correspondence, expressed as a percentage, between the 'total distributional area' (Fig. 1a) and the 'high-density area' (Fig. 1b) of *I. ricinus*; and the areas of the following parameters: vegetation period  $\geq 170$  days (Fig. 1c); vegetation period  $\geq 180$  days (Fig. 1d); start date of the vegetation period before or on day 120, i.e., May 1st (Fig. 1e); end date of the vegetation period before or on day 300, i.e., October 25th (Fig. 1f); the boreonemoral and nemoral zones combined (Fig. 1g); the distribution of oak (Fig. 1h), the distribution of hazel (Fig. 1i), and the distribution of black alder (Fig. 1j and k). A computer program, which analyses the number of pixels in an area marked dark grey in a map, was written in PHP (Hypertext PreProcessor, <http://www.php.net>). The program was used to measure the number of pixels of the dark grey-marked area for each of the maps shown in Fig. 1a–k.

The Rossby Centre at SMHI, Sweden, has developed a regional climate model for Sweden, Norway, Finland, and Denmark, the RCA3 model (Jones et al., 2004). From climate variables such as temperatures and precipitation, specific climate parameters, like the length of the vegetation period, may be derived (Persson et al., 2007). Based on the results of our distribution analyses, we obtained from the Rossby Centre scenario maps for the length, start, and end date of the vegetation season by using 2 different IPCC emission scenarios for each of the parameters, the B2 (medium-low emissions by 2100) and the A2 (high) emission scenario (IPCC, 2000) for the time periods 2011–2040, 2041–2070, and 2071–2100. From Smith et al. (2007), we obtained vegetation index scenario maps for similar time periods for changes in oak, alder, and hazel distribution in Sweden. Based on the climate and vegetation scenario maps, theoretical projections were made for possible changes in the tick's distribution range in Sweden for the 3 time periods.

## Results

The highest correspondence was found between the area with high abundance of *I. ricinus* and an early start of the vegetation period (before May 1st) and a late end date of the vegetation period

**Table 1**

Results of the analysis of correspondence between *Ixodes ricinus* distribution (total and with high abundance) and vegetation period parameters (means for 1961–1990), and distributions of tick habitat-associated plant species.

	Fig. no.	Total Swedish tick range (Fig. 1a), % correspondence (% not corresponding to tick range and % not corresponding to climate or plant parameters)	Area with high tick abundance recorded (Fig. 1b), % correspondence with climate and plant distributional parameters (% not corresponding to tick range and % not corresponding to climate or plant parameters)
Total range of <i>I. ricinus</i>	1a	'100'	83 (17)
Area with recorded high <i>I. ricinus</i> abundance	1b	17,991 pixels/21,614 pixels = 83 (17)	'100'
Duration of vegetation period ≥170 days	1c	85 (15 and 6 = 21)	93 (7 and 12 = 19)
Duration of vegetation period ≥180 days	1d	81 (19 and 7)	92 (8 and 8 = 16)
Start date of vegetation period before or on May 1st	1e	90 (10 and 12)	96 (4 and 19 = 23)
Last day of vegetation period on or later than October 25th	1f	83 (17 and 9)	95 (5 and 10 = 15)
The boreonemoral zone	1g	75 (25 and 5)	86 (14 and 5 = 19)
<i>Quercus robur</i> including <i>Q. petraea</i> (oak) total distribution	1h	70 (30 and 4)	80 (20 and 4)
<i>Corylus avellana</i> (hazel) total distribution	1i	79 (21 and 5)	90 (10 and 6 = 16)
<i>Alnus glutinosa</i> (black alder) total distribution including rare or local occurrence	1j	87 (13 and 11)	93 (7 and 16.5 = 23.5)
<i>Alnus glutinosa</i> abundant distribution; i.e., where common – very common	1k	69 (31 and 2)	80 (20 and 20)

that is after October 25th (Table 1). The total tick distribution area corresponded most closely to the areas representing an early start of the vegetation season (before May 1st) and a vegetation period length of about 170 days. Among the distributions of different plant species, that of black alder showed the closest fit with tick distribution.

During the period 1961–1990, the length of the vegetation period lasted 7–9 months in regions with observed high tick densities (8–9 months in the south and 7 months in central Sweden), whereas in areas with observed low tick densities (along the northern Baltic Sea coastline), the length of the vegetation period was ≤6 months. In regions where no ticks had been recorded, that is the northern inland and the mountainous areas, the length of the vegetation period was 3–5 months.

To project potential changes in tick distribution and abundance for the periods 2011–2040, 2041–2070, and 2071–2100, we used scenario models for the climate parameters that were found to be most closely correlated with *I. ricinus* occurrence in the analysis, that is the start date and the length of the vegetation period. The projections, based on the A2 and B2 emission scenarios, are presented in Fig. 2. Both climate parameters showed similar projection patterns (Fig. 2).

The winter season is predicted to become considerably shorter and milder during this century (SMHI, 2009). Accordingly, the vegetation period and the corresponding tick activity period are foreseen to increase in duration to become year-round in the southernmost regions by 2071–2100 (A2 scenario). In central Sweden, the vegetation period will be extended to 10–11 months, and along the northern Baltic Sea coastline to 6–8 months. The northern inland regions are expected to have a vegetation period of 3–6 months, with the shortest duration at high altitudes in the mountainous areas.

In the south and central regions, the vegetation period and the corresponding tick activity period will start 75–30 days earlier (moving in a south–north direction) by 2071–2100. In the Stockholm area, spring will arrive around mid-February (A2) or in early March (B2) instead of mid-April as observed in 1961–1990. In the northern parts, spring will start about 15–45 days earlier. In the A2 scenario, the last day of autumn in the north-eastern coastal

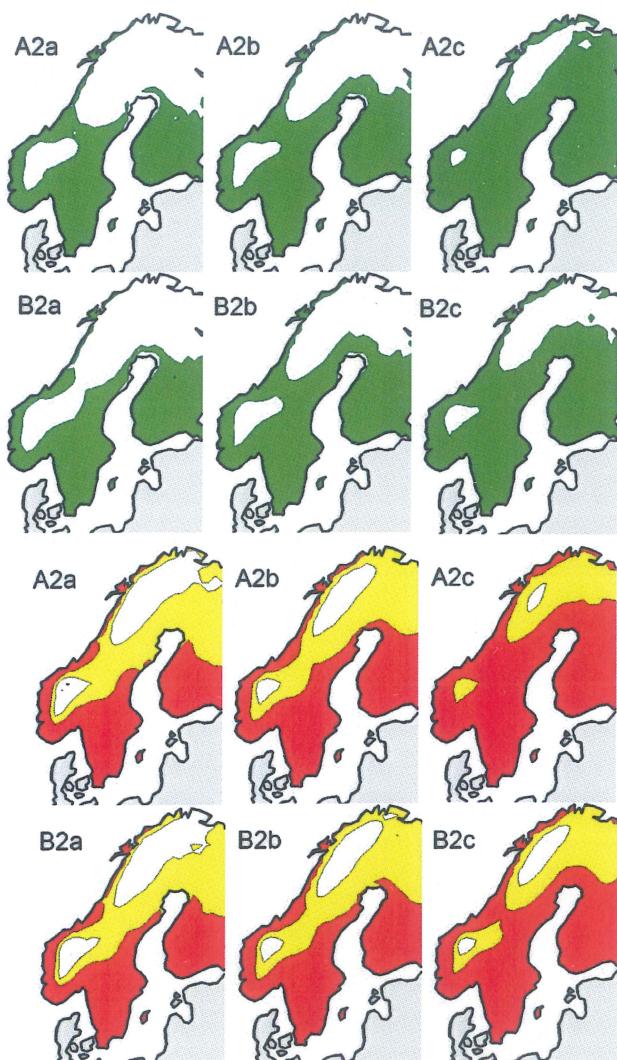
regions, except for the very northern coastline of the Gulf of Bothnia, will in 2071–2100 occur on the same dates (on or before November 15th–30th) as it occurred in the very south-western parts of Sweden during 1961–1990.

The projections, as shown in Fig. 2, suggest that by the end of this century *I. ricinus* distribution will encompass the whole of Norway, Sweden, and Finland except the mountainous regions. Ticks are projected to become more abundant in most of the region by 2071–2100 and will only be absent in the mountains at high altitudes and the inland regions above the Arctic Circle. The A2 scenario indicates a possibility of permanent tick establishment along the whole Norwegian coastline including areas bordering the Barents' Sea above 70°N.

## Discussion

Previous studies in Sweden have shown that the range of the pathogen causing Lyme borreliosis, *B. burgdorferi* s.l., coincides with that of *I. ricinus* (Gustafson et al., 1995). Our results, thus, suggest an emerging risk of contracting LB throughout Sweden except the mountain range in areas with suitable vegetation and hosts. These predictions are based on the a priori assumption that host availability and composition, vegetation characteristics, and other factors of the ecosystem will be permissive to permanent, reproducing *I. ricinus* populations.

During the last 3 decades, the climate has become significantly warmer in Sweden. For example, 8 of the warmest Novembers ever recorded (mean temperatures for the whole of Sweden) were observed between 2000 and 2009 (SMHI, 2010). Analysis of vegetation period data using 10-year mean values of daily temperatures observed at nearly 40 meteorological stations during 1961–2008 show that the length of the vegetation period has increased markedly from 1985 in the northern regions, including the Baltic Sea coastline (SMHI, 2010). The vegetation period was 30 days longer in 1985–1994, when most of the northern *I. ricinus* data were collected, compared to 1975–1984. This may have given less fit in our analysis of the total *I. ricinus* distribution area in relation to the length of the vegetation period. In southern Sweden, there has been a tendency towards an earlier start of spring.



**Fig. 2.** Projections of possible future changes in distribution and abundance of *I. ricinus* in Sweden, Norway, and Finland. In the top sequence, the green areas indicate regions that are or potentially may become favourable for tick populations during this century. In the lower sequence, the red areas indicate regions that may harbour permanent relatively high-density tick populations. Yellow areas indicate regions where sparse, low-density populations of ticks may occasionally be encountered. White areas indicate areas where ticks cannot or are unlikely to become established and reproduce. Grey areas are not included in the study. The projections are based on predicted changes in the start date (green-white) and the length (red-yellow-white) of the vegetation period using regional climate models (Jones et al., 2004) under the A2 and B2 scenarios (IPCC, 2000) for 2011–2040 (a), 2041–2070 (b), and 2071–2100 (c) (SMHI, 2009).

A microclimate with high humidity is essential for the survival of *I. ricinus*; conditions that may become more favourable in northern Sweden where precipitation is projected to increase year-round. However, the snow cover period will be shorter due to milder winters, in particular along the Baltic Sea coastline. Heavy rainfall events are expected to become more common than today. The risk of flooding may thus increase in flood-prone areas; conditions that locally may be detrimental to the ticks. In the south, summers will become drier, and depending on the capacity of soil and vegetation to maintain humidity, may locally lead to reduced tick activity and abundance. However, intense droughts will not become more common compared to 1961–1990 (SMHI, 2009).

Predictive risk mapping by Randolph and Rogers (2000) suggest that foci with tick-borne encephalitis virus-infected ticks will extend to the northwest in Sweden and may disappear from areas

where hot and dry summers become more prevalent due to climate change. Our data on LB conform to their data since also LB is predicted to extend northwards and may possibly become less prevalent in some locations in southern Sweden due to less summer rainfall. In North America, climate change is predicted to cause the main LB vector, *I. scapularis* Say, to retract from the southern U.S. and move into the central U.S. with a significant expansion of this tick species north into Canada during this century (Brownstein et al., 2005).

In southern Scandinavia, particularly during the summers in south-eastern Sweden, ground water levels often decrease so that water becomes a limiting factor to many deciduous tree species with a high leaf mass. Oak is considered to be more drought-resistant than other deciduous species (Swedish Forest Agency, 2007). Summers in the south are expected to get 5–50% less precipitation by the end of the century. Here, high-density tick populations will presumably persist in oak woodlands. Climate-vegetation index scenario models indicate that the distributions of hazel, alder, and oak will follow the changes in the length of the vegetation period in the northern parts (Smith et al., 2007). This will create additional favourable conditions for new tick population establishments and for augmenting tick abundance.

Of interest was the close correspondence between the distribution of *I. ricinus* and those of hazel and black alder, species that are known to harbour high densities of ticks (Lindström and Jaenson, 2003). The latter is associated with marshlands, lake-sides, and river banks. Oak has a more restricted, southern range than black alder, but oak woodland often harbours high tick densities. Deciduous broad-leaf tree species are expected to maintain their distributions in southern Sweden while increasing their ranges to the north during this century (Smith et al., 2007; Swedish Forest Agency, 2007). Such vegetation changes would be expected to benefit the persistence of *I. ricinus* in southern Sweden and permit a significant northward extension of its range. Similar northward expansions of the deciduous woodland vegetation are likely in Norway and Finland followed by extensions of the ranges of *I. ricinus* in these countries. Certainly, the final, overall composition of tree species and plant communities will depend on forestry and agricultural practices and legislation in the 3 countries.

Our projected changes in LB risk are based on subregional climate models for the parameters found to be correlated with *I. ricinus* distribution in our analysis and on the known ecology of the pathogen, its vector, its hosts, and their habitats, and how they are influenced by weather and climate. A changing climate will lead to increased soil temperatures and a prolonged vegetation period. This will increase the period during the year when ticks are active for host seeking and reproduction, and will shorten the length of the tick's life cycle. In agreement with this scenario, Gray (2008) concluded that in a future warmer climate, more of the activity of the tick population in northern Europe will be in late autumn, winter, and early spring. As a consequence, more cases of LB and TBE (tick-borne encephalitis) will probably manifest in late autumn, early winter, and early spring. Climate change will also influence tick abundance and disease risk indirectly through impacts on host and reservoir animals, on the habitat's vegetation, and on human behaviour, as discussed below.

Even though climate change will permit a northward extension of the range of *I. ricinus* in Sweden, Norway, and Finland, there are several other factors that could alter or even prevent such an increase of its range. Blood hosts of importance for the different tick stages need to be present. In northern Europe, large (roe deer, moose) and medium-sized (mainly cervids and hares) mammals are the main hosts for the female ticks, whereas insectivores, rodents, hares, and cervids are main hosts for the larvae and nymphs (Jaenson et al., 1994; Tälleklint and Jaenson, 1994, 1997; Jaenson and Tälleklint, 1996). The habitat vegetation and soil

conditions need to be able to provide food for the tick hosts, provide appropriate climatic conditions for the ticks and their hosts, permit hibernation of the ticks during frosts, and provide optimal aestivation conditions during dry spells.

Cervids (Cervidae), especially roe deer, *Capreolus capreolus* (L.), white-tailed deer, *Odocoileus virginianus* (Zimmermann) in Finland, red deer, *Cervus elaphus* L., and moose, *Alces alces* (L.), and the hares (Leporidae) *Lepus timidus* L. and *L. europaeus* Pallas are most important blood hosts for the maintenance of *I. ricinus* populations in northern Europe. A warmer climate will increase the production of plant biomass and proportion of young deciduous trees in Fennoscandia, particularly in the north, thereby presumably supporting denser deer (Swedish Forest Agency, 2007) and hare populations. In large parts of northern Fennoscandia, roe deer and brown hare (*L. europaeus*) are at present generally unable to survive the relatively harsh winters. In the near future, however, the much shorter and milder winters to be expected here will presumably increase roe deer and hare adult winter survival directly due to milder weather and indirectly through increased food supply. The earlier and wetter springs may cause earlier birth dates and increase the growth and survival of both juvenile deer and juvenile hares. The brown hare is more competitive in open or agricultural land, especially in milder climates (Thulin, 2003), but has expanded its Swedish distribution since the 1980s northwards and into forest habitats (Jansson and Pehrsson, 2007). At the same time, the range of the mountain hare (*L. timidus*) has decreased and is likely to shrink further. This species is better adapted to a forested and colder climate than the European hare and is likely to suffer more from the forthcoming warmer climate (Jansson and Pehrsson, 2007). Similarly, a warmer climate may during the summers increase the direct stress that high temperatures have on larger cervids. Moose, in particular, appears to be negatively affected by both warm winters and warm summers (Karns, 1997). The smaller cervids seem less affected by high temperatures. The distribution and density of moose in southern Sweden may thus be reduced in the future. Hunting pressure, game animal preservation, and nature conservation legislation will certainly have a strong impact on deer and hare abundances and thus indirectly influence the density and distribution of ticks in a future warmer northern Europe.

The bank vole, *Apodemus* mice, and other small mammals are important reservoirs for human-pathogenic viruses and LB bacteria. Climate changes in northern Europe may greatly affect the size and behaviour of these rodent populations, thereby altering the risk for transmission of several human pathogens (Evander and Ahlm, 2009). At least 4 human-pathogenic *B. burgdorferi* s.l. species, i.e., *B. afzelii* Canica et al., *B. burgdorferi* s.s. Johnson et al., *B. garinii* Baranton et al., and *B. valaisiana* Wang et al. are present in northern Europe (Fraenkel et al., 2002). Shrews (Soricidae: *Sorex* spp.), rodents (Muridae: *Apodemus* spp. and *Myodes glareolus* Schreber), and hares (*Lepus* spp.) are important vertebrate hosts for *B. burgdorferi* s.l. in Sweden (Tälleklint and Jaenson, 1994; Jaenson and Tälleklint, 1996; Piesman and Gern, 2008). These mammals are also important hosts for larvae and nymphs of *I. ricinus* (Jaenson and Tälleklint, 1996; Tälleklint and Jaenson, 1997; Piesman and Gern, 2008), and some of these mammals will, most likely, expand their ranges northwards in response to the warmer climate. Thus, in addition to the roe deer and brown hare mentioned previously, it is likely that the yellow-necked mouse *Apodemus flavicollis* (Melchior) and the wood mouse *A. sylvaticus* (L.) will expand their ranges in response to higher summer temperatures, provided that their other habitat requirement are met (Marsh et al., 2001). Other factors may, however, be unfavourable to certain small mammal populations: Thus, during the northern winters, many rodents, such as the bank vole (*M. glareolus*), are protected under the snow cover from predation. In a warmer climate, the bank vole

will be at greater risk from predation during the snow-free winters.

Birds, in particular ground-feeding species, are important hosts for immature *I. ricinus* and can be carried over long distances while attached to birds (Olsén et al., 1995). Some avian species, e.g., black-birds (*Turdus merula* L., Turdidae) and pheasants (*Phasianus colchicus* L., Phasianidae) are reservoirs for Lyme borreliosis spirochaetes, in particular *B. garinii* (except OspA serotype 4) and *B. valaisiana* (Humair et al., 1993, 1998; Kurtenbach et al., 1998; Olsén et al., 1995; Piesman and Gern, 2008). Ecological and evolutionary responses in the phenology and distribution of plants and animals to recent climate change have been documented in all well-studied terrestrial, fresh-water, and marine groups (Parmesan, 2006). Thus, there is evidence that birds are responding to recent global climate change by altering their geographic ranges to higher latitudes and altitudes and by changing their migration strategies (La Sorte and Jetz, 2010). A northward and altitudinal shift of many bird species' ranges in northern Europe, as a response to the warmer climate, is likely to facilitate the spread of *I. ricinus*, *B. garinii*, and *B. valaisiana* to higher latitudes and altitudes in the interior of northern Scandinavia, where so far these organisms do not occur.

LB is not a notifiable disease in Sweden, but about 10,000 cases are estimated to occur annually (Berglund, 2004), which gives an estimated annual incidence of 1.25 LB cases/1000 inhabitants in endemic areas. Changes in climate will increase the length of the year when people may come into contact with infected ticks. High-density tick habitats are often close to human dwellings and *Borrelia*-infected *I. ricinus* are present in central and suburban parks and gardens, in areas favoured for summer cottages and recreational purposes, e.g., the Baltic archipelago and around the major inland lakes (T.G.T. Jaenson, unpubl. data). Densities of *I. ricinus* nymphs and densities of *B. burgdorferi* s.l.-infected nymphs are significantly correlated, so nymphal density can thus serve as a general indicator of risk for exposure to LB spirochaetes (Jaenson et al., 2009). The higher tick densities that can be expected, particularly in the presently tick-free areas in most of central and northern Norway, Sweden, and Finland, will most likely increase the risk of people contracting LB. Our findings are in line with North American projections, based on annual degree-days >0 °C, which suggest a marked northward expansion of *I. scapularis* and of the range of Lyme disease during this century (Ogden et al., 2006).

In conclusion, our results suggest that climate change during this century will most likely increase the geographic range of *I. ricinus* populations infected with LB spirochaetes because vegetation communities, with important tick host mammals and LB reservoir mammals, associated with high tick densities will increase their geographic ranges due to a markedly prolonged vegetation period. This will lead to a gradually increasing Lyme borreliosis risk in northern Scandinavia.

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