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Climate change, biodiversity, ticks and tick-borne diseases: The butterfly effect

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A B S T R A C T

We have killed wild animals for obtaining food and decimated forests for many reasons. Nowadays, we are burning fossil fuels as never before and even exploring petroleum in deep waters. The impact of these activities on our planet is now visible to the naked eye and the debate on climate change is warming up in scientific meetings and becoming a priority on the agenda of both scientists and policy decision makers. On the occasion of the Impact of Environmental Changes on Infectious Diseases (IECID) meeting, held in the 2015 in Sitges, Spain, I was invited to give a keynote talk on climate change, biodiversity, ticks and tick-borne diseases. The aim of the present article is to logically extend my rationale presented on the occasion of the IECID meeting. This article is not intended to be an exhaustive review, but an essay on climate change, biodiversity, ticks and tick-borne diseases. It may be anticipated that warmer winters and extended autumn and spring seasons will continue to drive the expansion of the distribution of some tick species (e.g., *Ixodes ricinus*) to northern latitudes and to higher altitudes. Nonetheless, further studies are advocated to improve our understanding of the complex interactions between landscape, climate, host communities (biodiversity), tick demography, pathogen diversity, human demography, human behaviour, economics, and politics, also considering all ecological processes (e.g., trophic cascades) and other possible interacting effects (e.g., mutual effects of increased greenhouse gas emissions and increased deforestation rates). The multitude of variables and interacting factors involved, and their complexity and dynamism, make tick-borne transmission systems beyond (current) human comprehension. That is, perhaps, the main reason for our inability to precisely predict new epidemics of vector-borne diseases in general.

1. Introduction

The scientific evidence for rapid climate change is compelling and most experts in the field have now reached a consensus: the Earth's climate is changing. Evidence for this includes increasing global temperature, sea level rise (Fig. 1), warming oceans, shrinking ice sheets, declining Arctic sea ice, glacial retreat, increasing extreme events, ocean acidification, and decreased snow cover (http://climate.nasa.gov/evidence/).

Climate change is modifying the environment where we live and our way of living. For instance, global warming is booming the market for air conditioning, which is expected to grow in the coming decades. The explosive growth of the air conditioning market and the increased fossil fuel burning in response to increased temperatures may contribute to greenhouse gas emissions and, again, to global warming. Indeed, the discovery that chlorofluorocarbons are major contributors to ozone layer breakdown, resulted in their replacement by hydrochlorofluorocarbons and, more recently, by hydrofluorocarbons (Dahl, 2013). Hydrofluorocarbons are better coolants and have no impact on ozone depletion, but they are super-greenhouse gases with high potential to contribute to global warming (Dahl, 2013). Hence, the solution for the ozone layer breakdown is contributing to the greenhouse gas effect. It is like a dog chasing its tail.

Climate change may impact human health and wellbeing in many ways, including by facilitating the spread of many infectious agents. For instance, the changing scenarios of major vector-borne diseases (e.g., malaria, leishmaniasis, Chagas disease) have been linked to several factors, including urbanization and deforestation,

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Fig. 1. Climate change is contributing to sea level rise. The Boa Viagem beach is a tourist destination in Recife, north-eastern Brazil. If current trends in sea level rise persist, cities like Recife may be literally swallowed the sea in the coming decades.

changing demographics in both developing and developed countries, economic crisis, increased global movement of people and animals, and climate change (Colwell et al., 2011). For quite some time, scientists have endeavoured to predict large-scale responses of infectious diseases to climate change (reviewed in Altizer et al., 2013), as many components of the transmission cycles of vector-borne diseases are inextricably tied to climate (Harvell et al., 2002; Altizer et al., 2013). For instance, many blood-feeding arthropods such as ticks spend the bulk of their life cycle in the environment and their development, survival and population dynamics depend on many factors, including host availability, vegetation coverage, and climate (Randolph, 2009; Dantas-Torres, 2010). Climate change may influence tick distribution and density, as well as the risk of tick-borne pathogen transmission to humans (reviewed in Léger et al., 2013).

The climate change debate is warming up in the scientific meetings and becoming a priority on the agenda of both scientists and policy decision makers. On the occasion of the Impact of Environmental Changes on Infectious Diseases (IECID) meeting, held in the 2015 in Sitges, Spain, I was challenged to give a 20-min keynote talk on climate change, biodiversity, ticks and tick-borne diseases. Because 20 min is not enough to deal with such a complex subject, the objective of this article is to logically extend my rationale presented on the occasion of the IECID meeting. This article is not intended to be an exhaustive review, but an essay on climate change, biodiversity, ticks and tick-borne diseases.

2. Our planet, our future

Over the past 4.5 billion years, our planet has passed through ice ages, warmer interglacial periods, such as the present Holocene epoch that began about 10,000 years ago (Thompson, 2010). The planet has also witnessed at least five big mass extinctions (Jablonski, 2002) and, throughout these years, it has shaped its surface, pretty much helped by the world's most dominant species: *Homo sapiens*. Indeed, when our ancestors took the decision to move out from Africa (Shriner et al., 2014), humankind embarked on a journey of no return (Diamond, 1997). In fact, many of the global changes we are witnessing in the present days may be partly attributed to anthropogenic factors.

Since ancient times, humans have killed wild animals for obtaining food and decimated forests for many reasons, including for building villages (...towns, cities, metropolis and megalopolis), crop plantation, cattle grazing, and road construction (Diamond, 1997). And the impact is impressive. Amazingly, it is estimate that over 475 million wild animals (Fig. 2) are killed on Brazilian roads each year (http://cbee.ufla.br/portal/atropelometro/). Furthermore, modern humans are also currently obtaining natural gas and oil by utilizing hydraulic fracturing (Ellsworth, 2013), burning fossil fuels as never before and even exploring petroleum in deep waters (Fisher et al., 2014). The impact of these human activities is unpredictable in the long term, but will certainly influence the course of our existence on Earth.

Tropical deforestation, mainly for grazing cattle and cropland expansion (Morton et al., 2006; Armenteras et al., 2013), creates a drier, hotter climate in the tropics. For instance, land surface acts as a strong global carbon sink and a recent study reported a long-term decreasing trend of the Amazon carbon sink (Brienen et al., 2015), underscoring the importance of preserving tropical forests, not only to protect our global biodiversity but also to mitigate eminent deleterious effects on Earth's climate.

Human development may benefit our way of living today, but also affect our future. All these changes, including our changing behaviour in response to these changes, may affect all kinds of

Fig. 2. Sloth found on a road that crosses a region of Atlantic rainforest in Aldeia, north-eastern Brazil. Crab-eating foxes (*Cerdocyon thous*) and other wild animals are commonly seen crossing this road and are frequently victims of car crashes.

living creatures, including wild animals (potential hosts for deadly pathogens) and arthropods such as ticks and mosquitoes, the most important groups of vectors of pathogens from a medico-veterinary perspective (Dantas-Torres et al., 2012; Caraballo and King, 2014).

3. Human development and climate change: threats to biodiversity

Human development is a major threat to global biodiversity. Transformation of natural environments (e.g., tropical forests) into farming lands and urban settlements, introduction of invasive alien species, pollution of land, air and water, sustained over-exploration of natural resources, and unsustainable harvesting of wild plants and animals are among the main drivers of biodiversity loss (http://www.iucn.org/what/biodiversity/). For example, across the tropics, between 1980 and 2000, more than 55% of new agricultural land (Fig. 3) became available at the expense of intact forests (Gibbs et al., 2010). Furthermore, using a global Earth-system model coupled with fine-scale habitat suitability models and parameterized according to four global scenarios of human development, Visconti et al. (2011) identified future hotspots of terrestrial mammal loss worldwide, particularly in Africa and the Americas. It may be anticipated that the growing world human population and the consequently increasing demand for food will cause profound changes in terms of hydric resources, land cover, and global biodiversity in the coming years.

The increased amount of greenhouse gases in the atmosphere, which is also intimately linked to human development (Fig. 4), is among the man-made causes of climate change (Shepherd, 2012; Müller et al., 2013). Since the Industrial Revolution, increased greenhouse gas emissions (e.g., combustion of fossil fuels for electricity and heat generation, transportation, and manufacturing, land use changes) have greatly contributed to the natural greenhouse gas effect (Malhi et al., 2002).

Many studies have recently investigated the effects of climate change on the Earth's biodiversity. The predicted impact of climate change on biodiversity may vary widely, depending on several variables (e.g., method of analysis, taxonomic group, biodiversity loss metrics, spatial scales and time periods considered). In their review, Bellard et al. (2012) came to the conclusion that “the majority of models indicate alarming consequences for biodiversity, with the worst-case scenarios leading to extinction rates that would qualify as the sixth mass extinction in the history of the Earth”. This has been just been confirmed (Ceballos et al., 2015) and the scenario is expected to be worse in the fore coming decades, not only due to climate changes and but also other factors such as

Fig. 3. Deforestation of Atlantic rainforest for the establishment of banana tree plantations in Amaraji, north-eastern Brazil.

Fig. 4. Shanghai, China: the largest city proper by population in the world. China is the world's largest carbon emitter; it accounted for 29% of global total emissions in 2012 (Olivier et al., 2013).

deforestation (Struebig et al., 2015).

One may prognosticate that human development and climate change will negatively affect biodiversity at local to global scales. Accordingly, there is now weighty evidence that decreases in biodiversity increase risk of transmission of different infectious diseases (Keesing et al., 2010; Cardinale et al., 2012; Civitello et al., 2015). Zargar et al. (2015) highlighted that the biodiversity-disease relationship is a multifactorial process and suggested the use of a multidimensional approach, whereby the same disease system could be studied in different ecological zones. New databases (e.g., PREDICTS and BIOFRAG databases) are being made available and will be useful for future assessments on terrestrial biodiversity responses to human impacts (Hudson et al., 2014; Pfeifer et al., 2014). These biodiversity databases will also be critical for future investigations on the relationship between biodiversity and tick-borne pathogen transmission risk.

4. Climate change *versus* tick distribution and abundance

Tick questing activity, reproduction, and survival, depend on several factors that, in turn, have a direct impact on tick distribution and abundance (Estrada-Peña et al., 2013; Lauterbach et al., 2013; Léger et al., 2013; Medlock et al., 2013; Jore et al., 2014). These include vegetation coverage, host availability, moisture and temperature conditions, photoperiod, and human activities. A very good account on the ecological physiology of ticks may found elsewhere (Randolph, 2009).

Recent, long-term studies have demonstrated changes in the distribution of the castor bean tick *Ixodes ricinus* in different parts of its range. For instance, data from a 30-year study conducted in Sweden indicated a clear expansion of the distribution range of this tick towards northern latitudes (Jaenson et al., 2012). Indeed, the range of *I. ricinus* in Sweden increased by 9.9% during the observation period and most of expansion occurred in the north (north of 60°N) where the tick's coverage area doubled from 12.5% in the early 1990s to 26.8% in 2008. Another long-term study carried out from 1977 to 2011 in Russia reported an increase in the abundance of *I. ricinus* in the eastern part of its range (Korotkov et al., 2015). These studies have shown that the northward spreading of *I. ricinus* in Sweden and Russia appear to be associated to climate change, particularly to the occurrence of milder winters and extended growing seasons. Host population dynamics, in response to climate change or due to human activities, may also have played a role in this process.

On the occasion of the IECID meeting in Sitges, someone asked me about the threshold temperature for *I. ricinus*, considering that winter temperatures in Sweden and Russia may be very cold for any living creature (a Brazilian would be inclined to agree). I probably did not elaborate a proper answer for that question, because the relationship between tick development rates and temperature is nonlinear (Randolph, 2009; Estrada-Peña et al., 2012). Categorically, Tomkins et al. (2014) stated "while the idea of fixed temperature thresholds applying across populations may be a convenient assumption from the point of view of predicting the distribution of ticks, it may lack realism". For instance, it has been demonstrated that geographically separated populations of *I. ricinus* show clinal variation in the response of questing to temperature, suggesting that physiological thresholds are not fixed in this species (Gilbert et al., 2014).

In the United Kingdom, the onset of larval activity coincides with a threshold of 10 °C (Randolph et al., 2002), whereas the threshold temperature for activity by questing nymphs and adults of *I. ricinus* has been estimated as a weekly mean daily maximum temperature of approximately 7 °C (Randolph, 2009; and

Fig. 5. A male of the winter tick *Haemaphysalis inermis* collected in a cold winter day in January 2010 in Basilicata, southern Italy.

references cited therein). Interestingly, questing nymphs and adults of *I. ricinus* may be found during winter in southern Italy, the southernmost part of its distribution range, often in sympatry with the winter tick *Haemaphysalis inermis* (Fig. 5). Both species can be collected with mean daily temperature below 5 °C in southern Italy (Dantas-Torres and Otranto, 2013a,b).

The limiting temperature for winter survival depends on a range of factors, including tick species, developmental stage, number of days of tick exposure to a given temperature, and snow cover. For instance, *I. ricinus* can survive 24-h exposure to temperatures ranging from −14.4 °C to −18.9 °C, but exposure for 30 days to only −10 °C can be lethal for a high proportion of unfed nymphs and diapausing engorged larvae and nymphs (Knülle and Dautel, 1997). Northern temperate tick species (e.g., *I. ricinus* and ornate cow tick *Dermacentor reticulatus*) are well adapted to survive in sub-zero temperatures (Medlock et al., 2013), but the capacity to supercool to temperatures of ≤ −17 °C appears to be an inherent ability of many tick species, regardless geographic origin (Dautel and Knülle, 1996). Paradoxically, enhanced snow cover may promote overwintering tick survival by preventing repeated freeze–thaw cycles, which may be more detrimental (Medlock et al., 2013). On the Antarctic Peninsula, the seabird tick *Ixodes uriae* is exposed to extreme environmental conditions during the off-host phase of its life cycle (Benoit et al., 2007). An interesting study has demonstrated that winter temperature affects the prevalence of *I. uriae* in the Brünnich's guillemot *Uria lomvia*; an increase of 1 °C in the average winter temperature at the nesting colony site was associated with a 5% increase in the number of infested birds in the subsequent breeding season (Descamps, 2013).

Climate change will likely increase the climatic niche of *I. ricinus* in Europe, including in northern Eurasian regions (e.g., Sweden and Russia) that were previously unsuitable for this species (Porretta et al., 2013). However, the response of ticks to climate change will vary widely from region to region and according to tick species. A recent ecological niche model for *I. ricinus* in Europe under a changing climate scenario predicted a potential habitat expansion of 3.8% in all of Europe. Interestingly, this model indicated habitat expansion in some areas (e.g., Scandinavia, the Baltics, and Belarus) and habitat contraction in others (e.g., Alps, Pyrenees, interior Italy, and north-western Poland) (Boeckmann and Joyner, 2014). Projected temperature changes also increased the basic reproductive number (R_0) of the blacklegged tick *Ixodes scapularis* in Canada and in the United States (Ogden et al., 2014). Levi et al. (2015) recently reported that projected warming by the 2050s is expected to advance the timing of average nymph and larva activity by 8–11 and 10–14 days, respectively.

The effect of climate change (particularly of increased temperatures) in tropical zones may be deleterious to some species, adversely affecting habitat suitability and forcing certain tick species to colonize new areas. In South Africa, for example, it has been predicted that increasing the temperature by 2 °C will decrease habitat suitability for four tick species (i.e., the African blue tick *Rhipicephalus decoloratus*, the South African bont tick *Amblyomma hebraeum*, the brown ear tick *Rhipicephalus appendiculatus* and the small smooth bont-legged tick *Hyalomma truncatum*) (Estrada-Peña, 2003). Another study suggested that the progressive increase in temperatures seems to be forcing the dispersion of tropical bont tick *Amblyomma variegatum* towards areas outside of zones that have a prolonged dry period in Zimbabwe (Estrada-Peña et al., 2008). Indeed, high temperatures adversely affect tick questing activity, especially at dry conditions (Randolph, 2009). In southern Italy, we observed a decline in the questing activity by nymphs and adults of *I. ricinus* during summer (Dantas-Torres and Otranto, 2013a). Interestingly enough, questing activity by larvae was apparently not affected in the same area. We have also observed a seasonal variation in the effect of climate on the biology of brown dog tick (*Rhipicephalus sanguineus* sensu lato) in southern Italy (Dantas-Torres et al., 2011). Indeed, high temperatures may be deleterious under low humidity conditions, even for ticks that are physiologically adapted to drier environments, such as the brown dog tick (Yoder et al., 2006).

5. Climate change, biodiversity and tick-borne diseases

The issues of global changes, climate change and tick-borne diseases are becoming the order of the day (LoGiudice et al., 2008; Gray et al., 2009; Keesing et al., 2010; Estrada-Peña et al., 2012, 2014b; Ogden et al., 2013; Estrada-Peña and de la Fuente, 2014; Granter et al., 2014; Parham et al., 2015; Medlock and Leach, 2015). There is convincing evidence indicating the direct or indirect effects of global changes on tick-borne diseases. Importantly, it is impossible to disconnect the mutual influences of global changes such as deforestation, land use change, and climate change on tick-borne pathogen transmission systems, as several of these factors may act synergistically on hosts, vectors, pathogens and humans themselves.

Many recent studies have investigated the influence of climate change on tick-borne disease upturn in different parts of the world. For instance, Parola et al. (2008) correlated a cluster of Mediterranean spotted fever cases to a warming-mediated increase in the aggressiveness of brown dog ticks. Climate change has been implicated as an important driving force for the expansion of the taiga tick *Ixodes persulcatus* habitat and the incidence of tick-borne encephalitis in the north of European Russia (Tokarevich et al., 2011). It is also recognized that *I. ricinus* and *Borrelia burgdorferi* sensu lato are spreading to northern latitudes and to higher altitudes as a result of the effects of climate change on host populations and on tick development, survival and seasonal activity (Mannelli et al., 2012; Léger et al., 2013; Medlock et al., 2013). Nonetheless, the relationship between climate change and tick-borne diseases is not uniform across all regions and tick species. For instance, Feria-Arroyo et al. (2014) used a maximum entropy approach to forecast the present and future distribution of *B. burgdorferi*-infected *I. scapularis* in the Texas–Mexico transboundary region by correlating geographic data with climatic variables. According to this modelling approach, habitat suitable for the distribution of *I. scapularis* in the

Texas–Mexico transboundary region will remain relatively stable until 2050. In the same way, the increased incidence of tick-borne encephalitis in Sweden during 2011–2012 is apparently more correlated to host population dynamics than to climate factors (Palo, 2014).

The impact of climate change on tick-borne diseases has long been a subject of debate (Gilbert, 2010; Randolph, 2010) and is still a controversial issue. While some models suggest dramatic range expansions of *Ixodes* ticks and tick-borne diseases as a result of climate warming, predicted distributions may also vary widely with the models' assumptions (Ostfeld and Brunner, 2015). It has been stated that the impact of global warming on tick-borne diseases will be more evident at the geographical limits of current distributions, where suboptimal temperatures are currently limiting the spread of infected vectors (Randolph, 2013). Ostfeld and Brunner (2015) argued that more data on key tick-demographic and climatic processes, as well as the incorporation of non-climatic processes are required to develop better models.

Habitat disturbances may alter terrestrial mammal communities and tick-borne pathogen transmission systems. For instance, Lou et al. (2014) developed a model to investigate the joint effects of seasonal temperature variation and host community composition on *B. burgdorferi* transmission by *I. scapularis*. They proposed a stage-structured periodic model by integrating seasonal tick development and activity, multiple host species and complex pathogen transmission routes between ticks and reservoirs. In such model, climate warming can amplify and slightly change the seasonality of disease risk. Both the dilution and amplification effects could be detected by feeding the model with different animal hosts.

Although there has been considerable debate on the biodiversity-buffers-disease paradigm (Randolph and Dobson, 2012, 2013; Ostfeld, 2013; Salkeld et al., 2013; Wood et al., 2014), recent studies assessing the effects of host diversity on Lyme disease risk or incidence at both small and large scales have found very strong support for dilution effect (Turney et al., 2014; Werden et al., 2014). Indeed, a new meta-analysis of 202 effect sizes on 61 parasite species provided widespread support for dilution effects across different ecological contexts, indication that biodiversity declines could increase human and wildlife diseases and decrease crop and forest production (Civitello et al., 2015).

6. The butterfly effect: the importance of trophic cascades

In common sense, *chaos* denotes extreme confusion, disorder, a state in which behaviour and events are not controlled by anything, in sum, a pandemonium. For instance, I say very often these days to my wife: “The car traffic in Recife is becoming chaotic”. In Greek mythology, chaos (Greek χάος, *khaos*) is the most ancient of gods, formless or void state preceding the creation of the universe. But only recently, I also came to understanding that, in mathematics, chaos theory is a field that studies the behaviour of dynamical systems (Rickles et al., 2007). The principle is that small changes in the initial conditions will result in different outcomes for such dynamical systems; this sensitive dependence on initial conditions is the so-called “butterfly effect”. The chaos theory has many potential applications, including in medicine (Philippe, 1993), ecology (Hastings et al., 1993) and evolution (Ferrière and Fox, 1995).

The response of ticks to changes in climate and in densities of their hosts can be variable. For instance, manipulations of models (even deterministic ones) can produce different outcomes, including tick populations that either rise or fall under increasing host densities, depending on initial conditions (Dobson, 2014a). Tick-borne pathogen transmission systems are also difficult to predict (perhaps, unpredictable) in the long term, because of the possibility of chaotic behaviour (sensitive dependence on initial conditions). The existence of complex ecological processes (e.g., trophic cascades) and their possible influences on the tick-host-pathogen triad increase the complexity of models of multi-host transmission systems. For instance, a trophic cascade is ecological process that starts at the top of the food chain and fall down to the bottom (Paine, 1980). Food-webs may be influenced by top-down effects from carnivores to plants and by bottom-up effects that link plants to herbivores and higher trophic levels, and the importance of each in a given ecosystem is a subject of debate (Muhly et al., 2013). A classical example of a trophic cascade is what happened in the Yellowstone National Park in the United States, when grey wolves (*Canis lupus*) were reintroduced in 1995 (Beyer et al., 2007; Kauffman et al., 2010; Ripple and Beschta, 2012; Dobson, 2014b; Ripple et al., 2014). In his talk “For more wonder, rewild the world” filmed July 2013 at TEDGlobal 2013, George Monbiot presented a very exciting description of what happened in this park, explaining how wolves transformed not just the local ecosystem, but also its physical geography (see video at: http://www.ted.com/talks/george_monbiot_for_more_wonder_rewild_the_world).

Even if the relationship between grey wolf reintroduction and increased fruit availability and consumption by grizzly bears (*Ursus arctos*) in the Yellowstone National Park is an on-going debate (Barber-Meyer, 2015; Ripple et al., 2015), the occurrence of a wolf-inducted trophic cascade in this area is evident. The reintroduction of wolves triggered important changes in the local ecosystem, when they started preying on ungulates, particularly elk (*Cervus elaphus*) (Metz et al., 2012). The interactions between wolves, ungulates, coyotes (*Canis latrans*), red foxes (*Vulpes vulpes*), and so on, resulted in important changes in terrestrial mammal and bird communities in the Yellowstone National Park.

Trophic cascades may potentially affect the transmission dynamics of pathogens such as *B. burgdorferi*, through dilution and/or amplification effects. For example, Levi et al. (2012) elaborated a theoretical model suggesting that changes in predator communities may have cascading impacts that facilitate the emergence of Lyme disease. They showed that increases in Lyme disease in the north-eastern and mid-western United States over the past three decades coincide with a range-wide decline of a key small-mammal predator, the red fox, likely due to expansion of coyote populations, being uncorrelated with deer abundance as usually thought.

7. Final thoughts and perspectives

Life is an unpredictable, but finite process. Our dead-end journey on this planet begins from the moment we are born. In the famous 1955 play *Auto da Compadecida*, by the late Ariano Suassuna, the character Chicó says about his friend's death: “Cumpriu sua sentença e encontrou-se com o único mal irremediável, aquilo que é a marca de nosso estranho destino sobre a terra, aquele fato sem explicação que iguala tudo o que é vivo num só rebanho de condenados, porque tudo o que é vivo morre”; translated from the Portuguese this means: “He fulfilled his sentence and met with the only irredeemable evil, which is the mark of our strange destiny on Earth, that unexplainable fact that equates all living beings into a flock of convicts, because all that is alive dies”. When Chicó (the most cowardly of men and an insatiable liar) said “all that is alive dies” he was fatally telling the truth. Although we may be living shorter lifespans than we could (Werfel et al., 2015), nobody lives forever. But even if life is finite, our existence is still an intriguing, unpredictable process. Indeed, improvements in healthcare practices, nutrition, housing, sanitation, working conditions, and efforts towards a more universal access to healthcare have greatly increased our lifespan in the past centuries, even in developing countries (Atun et al., 2015). We are living more, but we want to live better.

The life of any living creature on Earth is influenced by the climate. Plants, terrestrial mammals, birds, reptiles, fishes, insects and other invertebrates are all influenced and, to some extent, dependent on climate. Earth's climate used to be cooler than today. Since the end of the last ice age (10,000 years ago), we have lived in a relatively warm period with stable carbon dioxide concentration. Over the last 200 years, the rate of carbon dioxide accumulation due to our emissions has increased to unprecedented levels (http://www.theccc.org.uk/). This is amplifying the natural greenhouse effect and contributing to changes in the Earth's climate, including atmospheric and oceanic warming (Shevenell et al., 2011).

The future of the Earth's climate is uncertain in the long term. Hence, the impact of climate change on biodiversity and on tick-borne diseases at local to global scales is unpredictable. Some causes and consequences of climate may vary in space and time, sometimes being reversible. Can we slow down our unsustainable population growth through family planning? Can we reduce our greenhouse gas emissions by exploring alternative, renewable energy sources? Can we reforest and re-wild the world? Will this positively influence our existence on this planet?

Box 1
The big data of tick-borne diseases

> The amount of knowledge of different aspects related to pathogens, hosts and vectors accumulated over the half past century is incalculable. Several molecular aspects involved in the vector-pathogen-host triad have been deciphered. But the more we know, the more we need to know. Let me make a point here. The relationship between climate and vectors, such as ticks and mosquitoes is relatively well known, right? The relationship between biodiversity loss and increased transmission risk of several infectious diseases is recognized, as well. However, all of this is just part of a much bigger picture that involves complex micro and macro-processes, starting from intimate interactions between pathogen, vectors and host molecules, and finishing in the whole Earth ecosystem. Imagine a single Lyme disease spirochete *Borrelia burgdorferi* (with its genome, transcriptome and proteome). Then, imagine a blacklegged tick *Ixodes scapularis* (with its genome, transcriptome and proteome) that is infected by millions of *B. burgdorferi* spirochetes and other bacterial organisms. Now, consider a population of blacklegged ticks (different developmental stages, different feeding status, infection rates by different pathogens) in a forested area and its host communities (e.g., mice, birds, deer, foxes, wolves, lizards) with varying susceptibility to *B. burgdorferi*. Imagine the whole forest ecosystem and relevant ecological processes going on (e.g., trophic cascades). Add human pressure (e.g., deforestation, fruit harvesting, hunting, road construction, land use). Imagine that this forest belong to a municipality. Consider the whole infrastructure (e.g., roads, cars, power stations, transmission networks, houses, schools, hospitals) and features of the human population (e.g., culture, education, work activities, socioeconomic conditions, public health policy). Considering all this together (and perhaps other aspects that we may be less aware at present) and their possible dynamical interactions, a complete understanding of all aspects involved in the transmission dynamics of tick-borne pathogens is possibly beyond current human capabilities. Additional knowledge on ticks, animals, pathogens and their interactions with the whole ecosystem will be needed and, perhaps, new developments in the field of bioinformatics to analyse simultaneously such a big amount data in a comprehensive way.

The relationship between tick development rates and temperature is nonlinear, as the relationship between entomological measures of infection and human risk of vector-borne diseases (Hollingsworth et al., 2015). Moreover, there are also several methodological caveats (e.g., use of inadequate environmental variables, differences between real and visible tick populations) that should be taken into account while developing models to investigate tick responses to changes in climate and host densities (Dobson, 2014a; Estrada-Peña et al., 2014a, 2015). Further studies are needed to investigate the complex relationships between landscape, climate, host communities (biodiversity), tick demography (see Balashov, 2012), pathogen diversity, human demography, human behaviour, economics, politics, and human exposure to pathogens, also considering all ecological processes (e.g., trophic cascades) and other possible interactions (mutual effects of increased greenhouse gas emissions and increased deforestation rates). The elevated number of variables and of interacting factors involved and their complexity make tick-borne pathogen transmission systems beyond (current) human comprehension (Box 1).

Strong commitment of scientists and professionals from different disciplines (e.g., medicine, veterinary, parasitology, biology, ecology, epidemiology, statistics, geography, physics, mathematics, and anthropology) will be needed to address tick-borne diseases from a broad perspective. It may be anticipated that warmer winters and extended autumn and spring seasons will continue to drive the expansion of the distribution of some tick species (e.g., *I. ricinus*) to northern latitudes and to higher altitudes. Livestock movements will also play a role in the latitudinal dispersion of ticks in some areas (Fig. 6). Nonetheless, it remains unclear whether and to what extent climate change will influence the upsurge of tick-borne diseases in new areas and/or their re-emergence in core endemic areas. Certainly, other factors such as urbanization, population growth, economic downturn, and political crisis (Sumilo et al., 2008; Godfrey and Randolph, 2011) should also

Fig. 6. Podolica cattle in the Gallipoli Cognato Regional Park, Basilicata, southern Italy. These cattle move freely within the park's territory, helping in disseminating *Ixodes ricinus* to different altitudes (from 200 m to over 1000 m).

be considered while assessing this multifaceted problem. Furthermore, it is now more evident than ever that biodiversity loss may increase disease risk (see Civitello et al., 2015). Therefore, humans have now another relevant reason for conserving wildlife.

Human development is transforming most of Earth's natural systems, but the health impacts of ecosystem alteration are still poorly understood (reviewed in Myers et al., 2013). Human behaviour is also a strong determinant of environmental health, animal health and human health. With regard to tick-borne diseases, changes in human behaviour may result in diverging outcomes in terms of transmission risk. Even if general conditions are favourable to transmission in a given region, the avoidance of tick-infested habitats by people could change the outcome of the transmission risk model. Likewise, even if a person bitten by a tick, the rapid removal of this tick may reduce the transmission risk to near zero.

Conflicts of interest

The author declares that there are no conflicts of interest.

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