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Oak acorn crop and Google search volume predict Lyme disease risk in temperate Europe

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Abstract

Lyme disease is a major zoonosis in the northern hemisphere. It is caused by the spirochete *Borrelia burgdorferi*, transmitted by ticks (genus *Ixodes*), and the abundance of infected tick nymphs determines the risk of the disease in humans. In eastern USA, fluctuations in oak (*Quercus* spp.) acorn production (including mast seeding) determine rodent abundance, which has been linked with Lyme borreliosis risk in humans. However, the predictive power of masting on Lyme disease risk in other systems has never been tested. We used a combination of field and Internet data to trace the ecological chain reaction that links acorn production by oaks and Lyme borreliosis risk in European forests. We found a positive relationship between oak acorn production (*Q. robur* and *Q. petraea*) in year T and the number of Lyme borreliosis incidences in year $T+2$. Acorn production was also positively correlated with Google search volume for the terms “tick” and “Lyme disease” two years later. Our results suggest that acorn production influences tick population, leading to fluctuations in the intensity of interactions between humans and ticks that can be seen in Google search dynamics. Thus, mast seeding together with the volume of specific Internet web searches appears to be a promising tool that could be used to alert public.

Zusammenfassung

Die Lyme-Borreliose ist eine bedeutende Zoonose der nördlichen Hemisphäre. Sie wird von dem Spirochäten *Borrelia burgdorferi* verursacht und von Zecken (Gattung *Ixodes*) übertragen. Mit der Abundanz infizierter Zeckennymphen steigt das Krankheitsrisiko für den Menschen. In den östlichen USA bestimmen die Schwankungen der Eichelproduktion (*Quercus* spp.) mit dem Auftreten von Mastjahren die Abundanz der Kleinsäuger, die mit dem Lyme-Borreliose-Risiko für den Menschen in Zusammenhang gebracht wurde. In anderen Gegenden wurde die Vorhersagekraft der Mastjahre noch nicht getestet. Wir nutzten eine Kombination aus Freiland- und Internetdaten, um die ökologische Wirkungskette aufzuspüren, die Eichelproduktion und das Lyme-Borreliose-Risiko in europäischen Wäldern verbindet. Wir fanden eine positive Korrelation zwischen Eichelproduktion (*Q. robur* and *Q. petraea*) im Jahr T und der Anzahl von Lyme-Borreliose-Fällen im Jahr $T+2$. Die Eichelproduktion war

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auch positiv mit dem Google-Suchvolumen für “Zecke” und “Lyme-Borreliose” im Jahr $T+2$ korreliert. Unsere Ergebnisse legen nahe, dass die Eichelproduktion die Zeckenpopulation beeinflusst, was zu Schwankungen der Intensität der Interaktionen zwischen Mensch und Zecke führt, wie wir sie bei der Google-Suche beobachten können. Damit scheinen Eichelmast und Internet-Recherchen ein vielversprechendes Mittel zu sein, das für Warnungen an die Bevölkerung genutzt werden kann.

Keywords: Google Trends; *Ixodes scapularis*; *Ixodes ricinus*; Mast seeding; Rodent outbreak; Zoonotic disease

Introduction

Lyme borreliosis is the most common zoonosis and a major health concern in the northern hemisphere (Barbour & Fish 1993; Pfäffle, Littwin, Muders, & Petney 2013). It is caused by *Borrelia burgdorferi* sensu lato transmitted by hard–bodied ticks (genus *Ixodes*), and the abundance of infected tick nymphs is a good predictor of the disease risk in humans (Barbour & Fish 1993; Ostfeld 2010; Stafford, Cartter, Magnarelli, Ertel, & Mshar 1998). In the eastern United States temporal fluctuations in oak (*Quercus* spp.) acorn production (mast seeding: Crone & Rapp 2014; Kelly 1994) cause temporal variation in food provision for granivorous rodents, which shapes their population dynamics (McShea 2000; Wolff 1996). This in turn influences the abundance of infected tick nymphs and the risk of Lyme disease in humans (Jones, Ostfeld, Richard, Schauber& Wolff 1998a; Ostfeld 2010; Ostfeld, Canham, Oggenfuss, Winchcombe, & Keesing 2006; Ostfeld, Jones, & Wolff 1996; Schauber, Ostfeld, & Evans 2005). However, the connection between masting and Lyme disease in the eastern United States has been disputed, given the variety of factors that may contribute to the disease risk (Estrada-Pena 2009; Randolph 1998).

The ecological link between mast seeding and Lyme disease in eastern United States is as follows. In summer after a good acorn year, host-seeking larvae of the blacklegged tick (*Ixodes scapularis*) co-occur with high abundance of rodents caused by previous year surplus food supply (Jones et al. 1998a; Ostfeld et al. 2006; Ostfeld et al. 2001). High rodent numbers increase larval feeding chances and survival, which leads to high nymph densities next season (Keesing et al. 2009; Ostfeld 2010; Ostfeld et al. 2006). Moreover, high reservoir-competence of rodent hosts increases *B. burgdorferi* prevalence among tick nymphs (Ostfeld et al. 2001, 2006). Next spring, numerous infected nymphs search for vertebrate hosts, including humans (Schauber et al. 2005). Nymphs are mostly responsible for transmitting Lyme disease to humans because their small size makes them difficult to detect. Moreover, their summer peak in activity coincides with the peak of human outdoor activity (Barbour & Fish 1993; Ostfeld 2010). Thus, oak acorn production in year T influences rodent abundance next year ($T+1$), which subsequently affects infected nymph abundance and Lyme disease risk in year $T+2$ (Barbour & Fish 1993; Ostfeld et al. 2001, 2006; Schauber et al. 2005).

Fluctuations in oak acorn production have similar effects on wildlife in Europe (Bogdziewicz, Zwolak, & Crone 2016; Jędrzejewska, & Jędrzejewski 1998; Pucek, Jędrzejewski, Jędrzejewska, & Pucek 1993), but the effects of oak masting on the incidence of Lyme disease have not been studied. Seed fall in autumn determines rodent abundance next summer (Jensen 1982; Pucek et al. 1993; Zwolak, Bogdziewicz, & Rychlik 2016), and small mammals are a good reservoir for the *Borrelia* spirochete (Franke, Hildebrandt, & Dorn 2013; Gern 2008; Michalik, Hofman, Buczek, Skoracki, & Sikora 2003; Siński, Pawelczyk, Bajer, & Behnke 2006). Moreover, the sheep tick (*Ixodes ricinus*), ecological equivalent of *I. scapularis* in the European host–tick–pathogen system, has similar ecology to the blacklegged tick (Barbour & Fish 1993; Beytout et al. 2007; Hubálek, Halouzka, & Juřicová 2003; Korenberg, Kovalevskii, & Gorelova 2002; Siński et al. 2006). Thus, we hypothesize that a similar chain of ecological events linking acorn production and Lyme borreliosis risk might occur in Europe.

Traditional methods of gathering ecological data can be supplemented with new technologies. Temporal fluctuations in Google search volume and Wikipedia logs have been used to forecast influenza, dengue or tuberculosis outbreaks (Generous, Fairchild, Deshpande, Del Valle, & Priedhorsky 2014; Ginsberg et al. 2008; McIver & Brownstein 2014). In a recent study, Google Trends were successfully used to collect national–scale data on fluctuations in rodent numbers, to study the role of rodent predation pressure in wood warbler (*Phylloscopus sibilatrix*) habitat selection (Szymkowiak & Kuczyński 2015). Indices of rodent abundance obtained using Google search engine were positively validated with field data (see details in Szymkowiak & Kuczyński 2015). Here, we used temporal changes in Google search volume to trace ecological chain reactions linking acorn production with Lyme disease risk. We assumed that people use the Internet as a source of information about ticks and Lyme disease. Hence, an increase in number of interactions between humans and ticks should lead to increase in the search volume of focal keywords. We selected two unambiguous keywords i.e., “*kleszcz*” (which stands for *tick* in Polish) and “*borelioza*” (*Lyme disease*), and calculated search volumes for each year of the study period. Moreover, we calculated search volumes for the term “*na myszy*” (in Polish: *something for/against mice*, hereafter “*mice*”) for each year as this appears to provide a reliable index of annual fluctuations in rodent numbers (cf. Szymkowiak & Kuczyński 2015).

We used our dataset to test the predictions derived from Ostfeld et al.'s works (referenced above). First, acorn production should positively influence rodent numbers (e.g. Pucek et al. 1993). Thus, we tested whether acorn production in year T positively correlates with Google index of mice abundance in year $T+1$. Second, the positive effect of acorn production (year T) on rodent numbers (year $T+1$) should translate into increase in intensity of tick-human interactions and, consequently, Lyme disease cases (in year $T+2$). Thus, we tested whether Google index of rodent abundance in year $T+1$ correlates positively with Google search volume for "*tick*" in year $T+2$. Next, we tested whether acorn production (year T) correlates positively with Lyme disease-related key words ("*tick*" and "*Lyme disease*"), and Lyme disease casesin year $T+2$. To our knowledge, this is the first study linking temporal fluctuations in acorn production with Lyme disease risk in Europe. Our research answers the call of Jones et al. (1998b), "Nevertheless, we hope that epidemiologists will test the power of acorn production as a predictor of Lyme disease risk in European oak forests", which stayed ignored for almost 20 years.

Materials and methods

Data collection

We extracted the epidemiological data on the number of reported cases of Lyme disease in Poland from annual (2006–2013) reports on infectious diseases (Fig. 1B). These data were collected by the Provincial Sanitary–Epidemiological Stations and provided by the National Institute of Public Health–National Institute of Hygiene in Poland (http://www.pzh.gov.pl/).

Data on annual acorn production of pedunculate (*Quercus robur*) and sessile oak (*Q. petraea*) were collected in years 2005–2011 for the purpose of the Polish Forest Gene Bank, and provided by the State Forests in Poland. Each year, oak seed crop was assessed in September and October on permanent forest plots which were evenly distributed across all 17 Regional Directorates of the State Forests (RDSF) in Poland. The median area surveyed in each year was 25,988.77 ha ($Q25$–$Q75\% = 25{,}441.09$–$26{,}059.23$). Acorns were collected from the forest floor and by using standard seed traps. Considering that the area surveyed during the study period was unequal among years, we calculated the mean amount of acorns (kg/ha) collected in each year by all RDSFs and used it as a measure of annual acorn production across the country (Fig. 1A). We used oak masting as a predictor of Lyme disease risk because the geographical range of these two species (*Q. robur* and *Q. petraea*) covers the whole country (which corresponds to the spatial scale of other variables, see below), it dominates deciduous stands across the country, and oak acorn production is highly synchronized across Poland (Kantorowicz 2000).

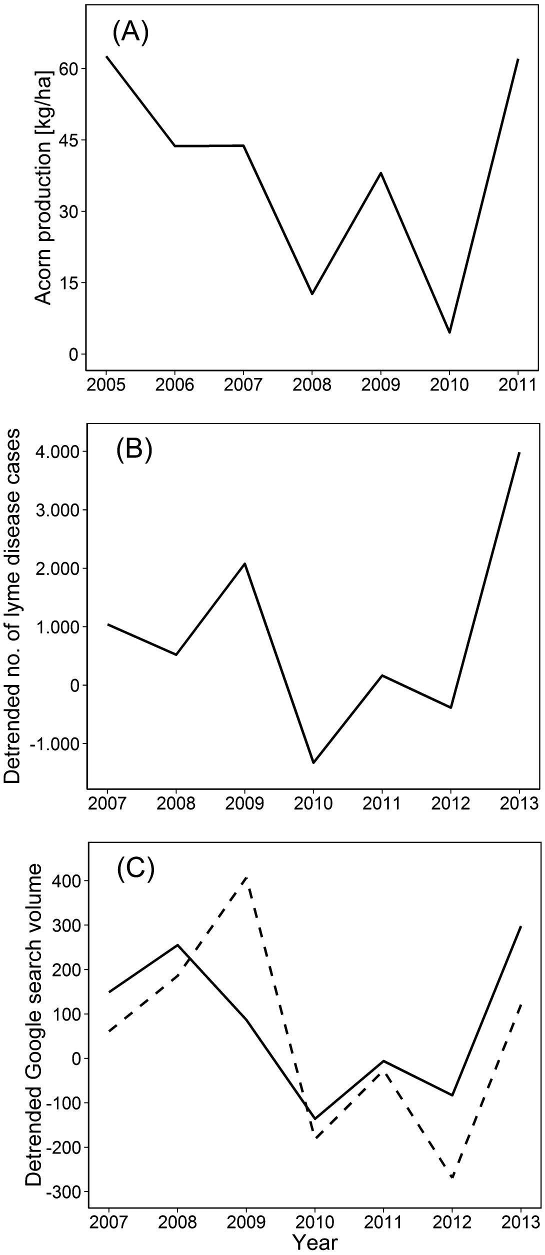

Fig. 1. Time series showing (A) acorn production, (B) detrended number of reported Lyme disease cases, and (C) detrended Google search volume for term "tick" (solid line), and "Lyme disease" (dashed line), in Poland.

We used the search query series from the Google Trends website to calculate the yearly (2006 to 2013) search volumes of specific Lyme – and tick – related keywords in Google search engine, and tracked how these volumes changed over time (Fig. 1C). We used 2006 as the first data point because it was the first year when Google search engine market share exceeded the share of all other web search engines in Poland (Megapanel PBI/Gemius). Google

Table 1. Models testing predictions on acorn production – Lyme disease risk association derived from Ostfeld et al.'s works (referenced in the main text). "Google" indicates Google search volume obtained from Google Trends (see the Materials and methods section for details). Data was detrended before analysis. Each row represents a separate model.

Predictor	Response	Model estimate	SE	*t* Value	*p* Value	R^2
Acorn production in year *T*	Google for "mice" in year $T+1$	9.49	7.493	1.27	0.274	0.11
	Google for "tick" in year $T+2$	6.28	1.727	3.64	0.015	0.67
	Lyme disease cases in year $T+2$	60.4	21.94	2.75	0.04	0.52
	Google for "Lyme disease" in year $T+2$	7.1	3.26	2.18	0.082	0.38
Google for "mice"in year *T*	Google for "tick" in year $T+1$	0.34	0.138	2.48	0.056	0.46
Google for "tick" in year *T*	Lyme disease cases in year *T*	8.43	2.843	2.96	0.031	0.56
Google for "Lyme desease" in *T*	Lyme disease cases in year *T*	5.03	2.571	1.96	0.108	0.32

keywords ("*tick*", "mice", "*Lyme disease*") were chosen *a priori*, before we started working with the internet data. Because Google Trends data are reported by country and language, the spatial scale of collected internet metrics corresponds to spatial scale of acorn production data and Lyme disease cases (all national).

Internet popularity and awareness for tick-borne diseases are increasing, leading to an overall increasing trend of Google search volume and reported numbers of Lyme disease cases over recent years. Thus, we detrended these variables using the first–order differencing method (Box, Jenkins, & Reinsel 2013; Cowpertwait & Metcalfe 2009), which allowed

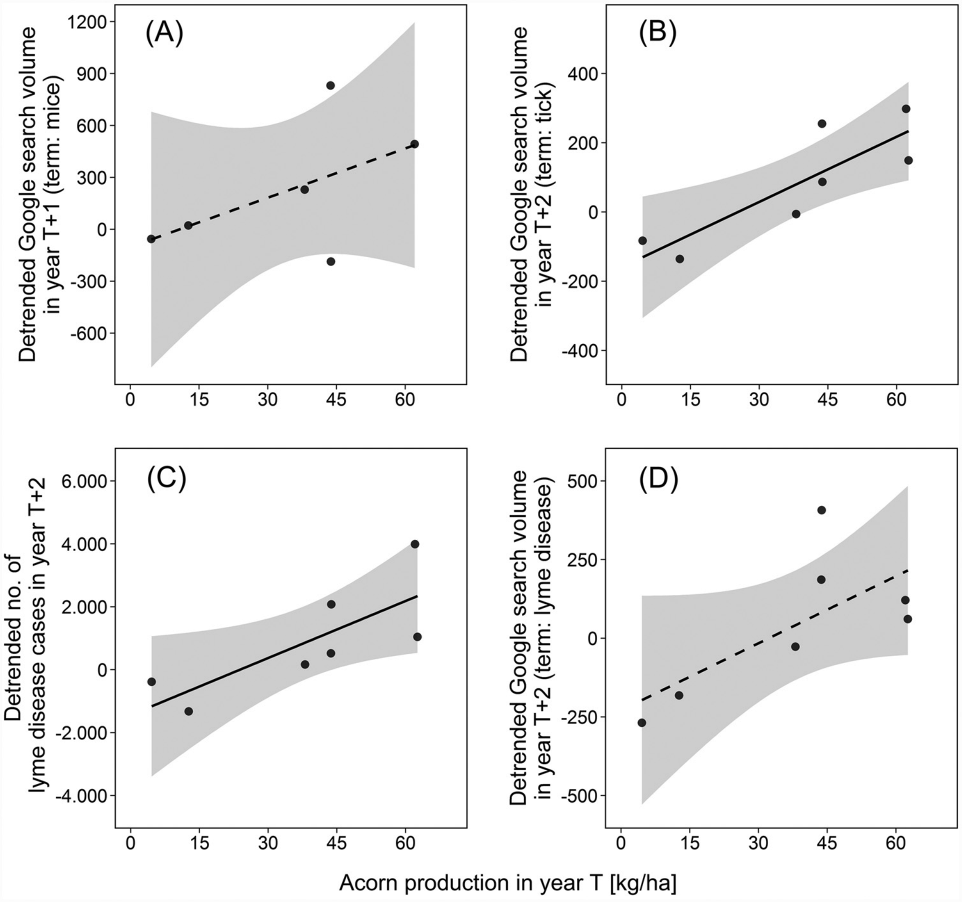

Fig. 2. Generalized linear models representing the modeled effect of oaks acorn production in year *T* on (A) Google search volume for the term "mice" in year $T+1$, (b) Google search volume for the term "tick" in year $T+1$, (C) number of Lyme disease cases in year $T+2$, and (D) Google search volume for the term "Lyme disease" in year $T+2$. Shaded regions represent 95% confidence intervals, and dots represent data points. Dashed lines represent non-significant relationships. Negative values on axes are the result of data detrending (see the Materials and methods section).

us to analyze their fluctuations not explained by increasing temporal trend itself.

Analysis

We used Generalized Linear Models (GLMs) to test for the relationships between oak acorn production, number of Lyme disease cases, and Google search volume of borreliosis–related keywords (summarized in Table 1). We tested whether acorn production in year T is a good predictor of Google search volume for “*mice*” (year $T+1$), “*tick*” (year $T+2$), “*Lyme disease*” (year $T+2$), and Lyme disease cases (year $T+2$). Next, we tested whether Google search volume for “*mice*” (year $T+1$) is positively correlated with Google search volume for “*tick*” (year $T+2$). Moreover, we tested whether the number of reported Lyme disease cases correlates positively with Google search volume of Lyme disease-related key words (“*tick*” and “*Lyme disease*”) in the same year.

To provide stronger inference, we fitted the same models but the time lags between response and predictor variables were rearranged (we subtracted one year from all lags). In this set of models the relationships not matched the mechanistic link between acorns, rodents, ticks, and Lyme disease described in the Introduction section; thus, no correlation should be expected. This approach allowed, at least partially, to address the possibility of obtaining spurious correlations between analyzed time-series. We used R version 3.1.2 for performing statistical analysis (R Development Core Team 2013). The normality of residuals was assessed by graphical inspection of residual patterns and Shapiro–Wilk test.

Results

As hypothesized, acorn production in year T was a good predictor of the number of Lyme disease cases in year $T+2$ (Table 1 and Fig. 2C). We also found a postivie correlation between acorn production in year T and Google search volume for “*tick”* in year $T+2$ (Table 1 and Fig. 2B). Moreover, there was a positive correlation between acorn production in year T and Google search volume for “*mice*” ($T+1$) and “*Lyme disease*” ($T+2$) (Fig. 2A and D), but both relationships were not significant at $\alpha = 0.05$ level (Table 1).

Google search volume for “*mice*” (year $T+1$) tended to be positively related with the search volume for “*tick*” (year $T+2$) (Table 1 and Fig. 3A). Finally, the number of Lyme

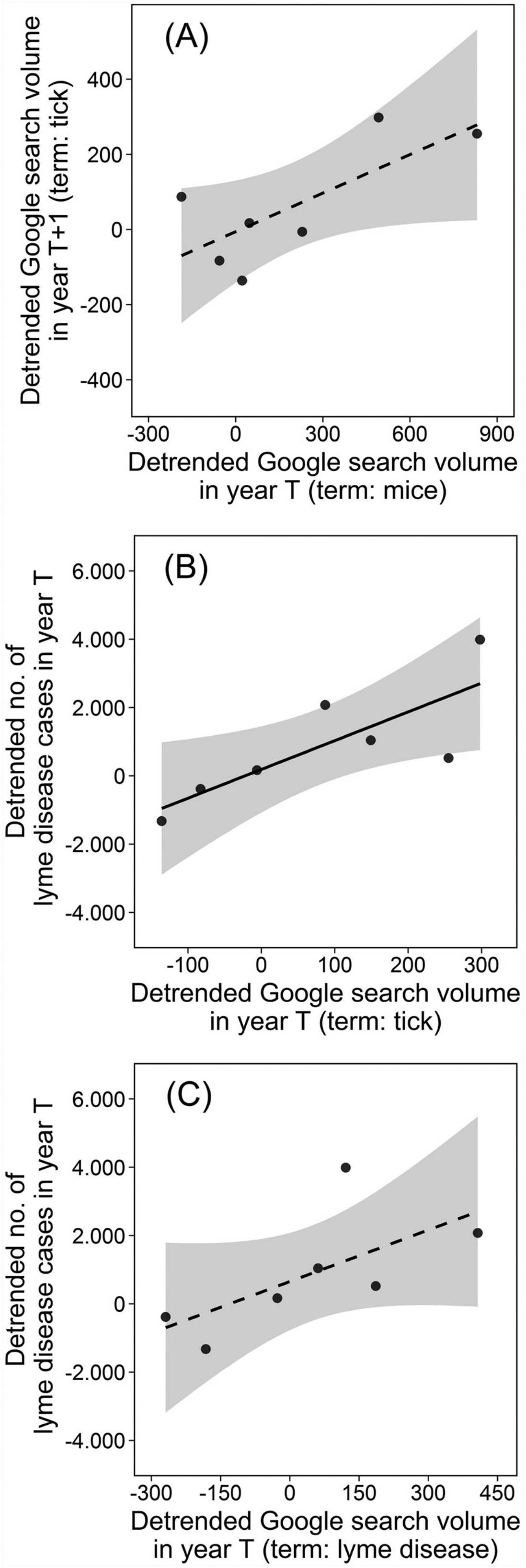

Fig. 3. Generalized linear models representing the modeled effect of (A) Google search volume for the term “mice” in year T on Google search volume for the term “tick” in year $T+1$, and effects of (B) Google search volume for the term “tick” in year T, and (C) Google search volume for the term “Lyme disease” in year T, on the number of Lyme disease cases in year T. Shaded regions represent 95% confidence intervals, and dots represent data points. Dashed lines represent non-significant relationships. Negative values on axes are the result of data detrending (see the Materials and methods section).

disease cases in year T was positively correlated with Google seach volumes for Lyme disease-related key-words ("*tick*" and "*Lyme disease*") (Fig. 3B and C), but only the first relationship was significant (Table 1).

None of the relationships with rearranged time lags between resposne and predictor variables was significant. Acorn production was not correlated with Lyme disease cases, nor with Google search volume for "*mice*", and "*Lyme disease*" in the same year (all $p \geq 0.30$). The relationship between Google search volumes for "*mice*"and "*tick*" in year T was negative and not significant ($p = 0.58$). Finally, no relationships were found between Lyme disease cases in year T and Lyme-disease related key words in year $T - 1$ (all $p \geq 0.23$).

Discussion

Risk of acquiring Lyme disease by humans is directly linked with the abundance and distribution of questing ticks. Thus, it is essential to understand factors shaping tick population dynamics. We used a combination of three sources of the data: National Institute of Hygiene in Poland on Lyme disease incidence, Polish State Forests on oak acorn crop, and Google Trends, and demonstrated that oak acorn production is associated with the Lyme disease risk in humans. The increase in Google searches for "tick" two years after a good acorn year most likely reflects the increase in the number of humans bitten by ticks. Increase in this internet search coincided with the number of diagnosed cases of Lyme disease which supports the contention that focal search terms indicate fluctuating disease risk.

Host importance for the total tick infection prevalence depends on the proportion of parasite population fed by the host (Brunner & Ostfeld 2008; Ostfeld 2010). Rodent hosts have a great impact on tick infection prevalence in the eastern US because they are abundant and heavily infested with ticks (Keesing et al. 2009; Ostfeld 2010). Moreover, they are highly competent vectors (Mather, Wilson, Moore, Ribeiro, & Spielman 1989) that are inefficient in killing ticks while grooming (Keesing et al. 2009). Hence, larvae that feed on rodents have a high probability of getting infected and to survive until molting into a nymph (Keesing et al. 2009). All these characteristics also hold for European rodents. They reach extreme densities after mast years (Jensen 1982; Pucek et al. 1993; Zwolak et al. 2016), may harbor numerous tick individuals (Harrison, Scantlebury, & Montgomery 2010; Kiffner, Vor, Hagedorn, Niedrig, & Rühe 2011; Perkins, Cattadori, Tagliapietra, Rizzoli, & Hudson 2003), and are a highly competent reservoir of *Borrelia* spirochete (Gern et al. 1998; Hanincova et al. 2003). Moreover, survival of ticks feeding on rodents might be exceptionally high. For example, the percentage of larvae that reaches full engorgement while feeding on wood mouse (*Apodemus sylvaticus*) ranges from 72 to 100% (Randolph 1979). Importantly, the positive effect of rodent numbers on abundance of infected nymphs in Europe has been already established (Beytout et al. 2007; Paziewska, Zwolińska, Harris, Bajer, & Siński 2010; Siński et al. 2006), such as the impact of infected nymph number on Lyme disease risk (Beytout et al. 2007; Hubálek et al. 2003; Jaenson et al. 2009). Here, we added oak mast seeding to the picture, likely providing a more comprehensive view on ecological phenomena shaping temporal variation in risk of acquiring Lyme disease by humans in Europe.

New data sources resulting from human use of the internet offer new perspectives on cheap and fast data collection. Recently, ecologists start to utilize it to gather data that would otherwise be logistically or economically infeasible to collect. For example, Google Street View was used to remotely extract data on nesting habitat of vultures and saved 49.5% of funds (Olea & Mateo-Tomás 2013). Google score was also used to measure popularity of bird and butterfly species among public to facilitate the choice of flagship species (Żmihorski, Dziarska-Pałac, Sparks, & Tryjanowski 2013), or to assess public interest in wetland conservation (Do, Kim, Lineman, Kim, & Joo 2015). Here, we combined field and internet data to trace the chain of ecological reactions that was documented previously in the USA with extensive field sampling.

Given the complicated ecology of Lyme disease (Randolph 2001; Ostfeld 2010), such a clear signal found in our study provides reliable support for the notion that Lyme disease risk can be predicted using mast seeding data (Jones et al. 1998a; Randolph 1998; Schauber et al. 2005). Nevertheless, inclusion of longer time series and data from other European countries would be a valuable direction of future research. In western Europe, fluctuations in rodent numbers caused by mast seeding were shown to correlate with other zoonoses, especially with nephropathia epidemica caused by rodent–borne hantaviruses (Clement, Vercauteren, Verstraeten, Ducoffre, Barrios et al. 2009; Tersago et al. 2009). Thus, a good seed year may serve as a first indicator of imminent increase in rodent-borne disease risk. Moreover, effect of masting on Google search volumes (tick, mice) may be further used as cues.

Acorn production cannot be experimentally manipulated at a scale large enough to affect Lyme disease incidence in humans. Thus, causality must be cautiously inferred from correlative studies at large scales (Schauber et al. 2005). Ideally, such studies should be followed up by small scale experiments that test proposed mechanisms (Jones et al. 1998a; Schauber et al. 2005). Here, we showed the link for temperate forest of Eastern Europe and outlined a promising area of future experimental research.

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