Shifts in outdoor activity patterns in the time of COVID-19 and its implications for exposure to vector-borne diseases in the United States.

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ABSTRACT

Unintended consequences of human behavioral changes induced by governmental and individual responses to COVID-19 risk are yet to be fully realized. Herein, we evaluated changes in outdoor activity patterns during the spring and summer of 2020 vs. 2019 in the Northeast and Midwest United States. We used self-reported data from daily surveys available through a smartphone application, The Tick App. We simultaneously assessed changes in exposure to tick vectors in relation to changes in outdoor recreation. We observed a 30% increase in self-reported tick encounters during the spring and summer of 2020 compared to the same period in 2019, and a two-fold increase in outdoor activities. We observed a shift towards peridomestic activities in 2020; while peridomestic activities doubled after stay-at-home measures were first implemented, recreational activities in green spaces initially decreased and only increased towards when mobility restrictions were relaxed, leading to a 18% increase in 2020. The timing of the initial shift in outdoor activities coincides with COVID-19 stay-at-home orders in the United States, suggesting changes in tick exposure were influenced by 2020 COVID-19-driven behavioral changes. Our findings suggest that public health response should also address competing hazards from COVID-19 related outdoor exposure.

Introduction

The severity, complexity, and global reach of COVID-19 posed unprecedented challenges to public health practitioners. To combat the spread of SARS-CoV-2, starting in March 2020, millions of people in the United States were ordered to stay at home and voluntarily reduce in-person consumer traffic to avoid virus exposure. These actions were effective (Flaxman *et al* 2020, Kelso *et al* 2009, Haug *et al* 2020, Jacobsen and Jacobsen 2020), but also carried economic and social costs (Haug *et al* 2020, Maharaj and Kleczkowski 2012). Furthermore, stay-at-home orders only accounted for 7% of the observed reduction of consumer traffic (Goolsbee and Syverson 2020), as reductions were mainly driven by voluntary avoidance behaviors associated with fear of infection. The full consequences of the governmental and individual responses to the COVID-19 pandemic on societal well-being have yet to be fully understood.

The COVID-19 pandemic and associated governmental and individual responses have had a profound impact in the detection, diagnosis and treatment of non-communicable (World Health Organization 2020) and communicable diseases (Hogan *et al* 2020, Nikolayevskyy *et al* 2021) in 2020, including evidence of delayed diagnosis of tick-borne diseases in the United States (Wormser *et al* 2021). Moreover, significant disruptions to essential health services persist as of April 2021 (World Health Organization 2021b). At the same time, vector-borne diseases pose a growing threat to public health in the United States, with 650,000 cases reported between 2004 and 2016, 75% of which were tick-borne diseases (Rosenberg *et al* 2018). The epidemiology of vector-borne diseases is complex, with transmission to humans depending on human exposure and protective behaviors, as well as vector abundance, seasonality, infection status, distribution and behavior (Finch *et al* 2014, Fischhoff *et al* 2019b, Mead *et al* 2018, Diuk-Wasser *et al* 2021). The likelihood of vector-human contact also varies depending on the eco-social setting, ranging from natural areas, urban green spaces and peridomestic environments. Thus, we predicted that changes in human behavior in response to COVID-19 risk and policies could modify the frequency, duration, and type of outdoor activities that people engage in (recreational or peridomestic), altering the likelihood of vector-human contact.

In the United States, both green spaces and peridomestic environments are known risks areas for both tick- and mosquito-borne diseases (Fischhoff *et al* 2019a, Gujral *et al* 2007, Eisen and Eisen 2008). However, time spent in natural environments provide great benefits for human physical and emotional well-being (White *et al* 2019, 2016, Kardan *et al* 2015, Pearson and Craig 2014, Park *et al* 2010). Thus, during stay-at-home orders implemented to reduce SARS-Cov-2 transmission, many parks and natural areas remained open to provide safe spaces for physical activity and reduce stress and mental fatigue. Yet, the overall impact of COVID-19 responses on outdoor activity patterns remains unclear. At a national scale there was an initial reduction in park use (between -10 and -20%) at the beginning of the epidemic in the United States, but this varied by state (Google 2020b, 2020a, Ritchie 2020a). Park use then increased over the spring and summer, but this apparent trend did not account for seasonal effects, since baseline values were estimated during the winter (Ritchie 2020a). To our knowledge, no data are available regarding the impact of stay-at-home orders in 2020 on peridomestic outdoor activities, although an increasing trend in daily visits to nurseries, gardening and farm supply stores was registered from January 2020 through mid-April (Goolsbee and Syverson 2020). However, seasonal effects might be contributing to these observed changes as well.

In this study, we asked whether governmental mandates designed to promote physical distancing and individual responses to the COVID-19 pandemic led to changes in people's outdoor activities during 2020. We asked if activity differed between natural and peridomestic settings, and if these changes altered exposure to ticks in endemic areas of the United States. Although mobility datasets derived from cell phone data are useful to understand coarse activity patterns (Oliver *et al* 2020), individual-level data over time that incorporates adaptive behaviors (i.e., changes in the type of outdoor activities) can be more closely linked to potential changes in the exposure to vectors and corresponding risk of exposure to tick-borne (and other vector-borne) diseases (Fernandez *et al* 2019, Bron *et al* 2020). Herein, we focused on a spatially-explicit individual approach using a novel smartphone application, The Tick App, to characterize outdoor activity patterns that could lead to tick exposure (Fernandez *et al* 2019). The app collects self-reported data on the frequency and type of outdoor activities and tick encounters through daily surveys, allowing us to assess behavior change patterns over time and the impacts of COVID-19 in 2020 on Tick App users.

Methods

The Tick App is a smartphone application that was developed as a research tool to understand human behaviors affecting tick exposure and engage the general public in tick prevention across the United States(Fernandez *et al* 2019). The app uses epidemiological e-surveys and GPS capabilities on the smartphone to gather data about mobility and outdoor activity patterns. A one-time baseline survey collects data on the user's tick exposure risk factors, demographic information and primary residence. Participants are asked to complete daily 1-minute surveys for at least one week, in which they are asked about outdoor activities and tick encounters (Supplementary Text 1 and Supplementary Text 2). Enrollment strategies, user profiles of participants, and usage patterns have been previously described (Fernandez *et al* 2019, Bron *et al* 2020). In April 2020, we updated the daily survey to include questions related to COVID-19 transmission mitigation measures (Supplementary Text 2).

<u>*Data analyses*</u>

Analyses were conducted on user data from the Midwest and the Northeast, United States, which are Lyme disease endemic areas where most Tick App users are located (Fernandez *et al* 2019, Bron *et al* 2020). Users from these regions accounted for 95% (65.8%

from the Midwest and 29.2% from the Northeast) of all survey responses recorded during the spring and summer of 2019 and 2020. To compare outdoor activity patterns between 2019 and 2020, we estimated the daily proportion of users reporting any type of outdoor activity during the same time of year (April 1st to July 31st) and used generalized linear models (binomial GLM, link function: logit) at the group level (i.e., proportion of users who were active outdoors versus those who stayed indoors) to assess temporal variations (between years and months), adjusted for weather variables (daily mean temperature and occurrence of rainy days), county level urbanicity (i.e., rural, small/medium metro and large metro counties), and demographic characteristics of the users (gender and age). Detailed description of the models and variables used are described in Supplementary Methods, but briefly the response variable was coded for each day as a vector of (N, Total-N), where N corresponded to the number of people reporting outdoor activities and the Total corresponds to the total number of users completing a daily survey that day. Responses were analyzed at the group level (per day) because user engagement and reporting in the app was variable, limiting the analysis of individual responses over time. Given that the response variable was analyzed as a daily proportion of users (at the group level), independent variables were summarized from individual level responses into appropriate daily variables experienced by users reporting on a given day, namely: the daily proportion of reporting users that live in a rural county, that live in a small/medium metropolitan area, that live in a large metropolitan area, that are females, and the median age of users estimated for each day. Weather variables recorded for each user (county-level daily precipitation and mean daily temperature) were transformed into appropriate group-level variables per each day: the median of all mean daily temperatures experienced by reporting users and precipitation and the daily proportion of reporting users experiencing a rainy day (with more than 2.4 mm of rain coded as a ‘rainy day’ binary variable). Seasonality was adjusted by considering quadratic effects of temperature in the model (Supplementary Methods). Responses were also modeled separately for the daily proportion of users reporting outdoor activities in their yard (i.e., peridomestic activities) and in parks or natural areas (i.e., recreational activities in green spaces). To assess the robustness of our findings, we repeated analyses considering only returning users (those who completed surveys in both 2019 and 2020).

To explore the effects of COVID-19 mitigation measures on outdoor activity patterns, we assessed changes in the daily proportion of outdoor activities over time (for peridomestic, recreational and combined activities, both in green and grey spaces) from February 1st to July 31st, 2020, using a similar binomial GLM (link function: logit) than used in the interannual comparison. Instead of year and month, we included a dichotomous variable that accounted for the periods before and after stay-at-home orders (Supplementary Methods). We also considered the incidence of COVID-19 cases per 100.000 reported by county (i.e., locally) and nationwide per day and a daily, county-level Shelter-in-Place Index, which represents the change in the proportion of people staying home compared to baseline (February 6th to 12th, 2020) (SafeGraph 2020) (Supplementary Methods). Urbanicity, weather, and demographic variables were also included as explanatory variables for outdoor activity.

We explored self-reported impacts of COVID-19 on outdoor activities obtained from daily surveys in 2020. These responses were only available starting on April 28th, after an update in the Tick App. We created a binary variable ("yes/no") from responses about self-reported impact of COVID-19 on outdoor activities (Question 10 in Supplementary Text 2), and individual responses were analyzed using generalized linear mixed models (binomial GLMM, link function: logit) with user ID as a random variable. The independent variables considered included: Shelter-in-Place Index, the incidence of COVID-19 cases per 100,000 (locally and nationwide), urbanicity, gender, and age. We included month as an additional explanatory (ordinal) variable to analyze temporal changes between May and July 2020.

We used a binomial GLMM model to compare self-reported tick encounters ("yes/no") during the period when people are at greater risk for tick encounters (April–July) (Gatewood *et* *al* 2009) between 2019 and 2020, and assess its association with outdoor activities, adjusting for urbanicity, gender and age. We evaluated the model at the individual level rather than summarizing the daily responses across individuals to adjust for individual variation in tick exposure associated with reported preventative behaviors. We included an interaction between the month and year, as well as between month and outdoor activities to account for conditions that may have affected behavior at the population level. Data analyses were conducted in R statistical computing software (R Core Team 2020) and all models were checked for multicollinearity, misspecification, and performance (thoroughly described in Supplementary Methods). The code and data used in this manuscript are available at https://piliffq.github.io/outdooractivity_Covid/, except for individual level data to preserve users anonymity.

Results

Between April 1st and July 31st 2019, 992 users completed 7,511 daily surveys; during the same period in 2020, 1,328 users completed 9,295 surveys. Use of The Tick App was seasonal, mostly restricted to spring and summer (Figure 1). Of the surveys completed in 2020, 21.1% were completed by return users who had participated in 2019 (9.6% of 2020 users, n = 128). For the 2020 analysis of the effect COVID-19 mitigation measures, we extended the analysis period to February 1st to include data prior to the mandated stay-at-home order; 22 users and 355 additional surveys were included. When comparing the demographic characteristics of users from 2019 and 2020, we observed a 3-year difference in median age (Kruskal-Wallis, $P = 0.05$), 48 (IQR = 26) in 2019 and 51 years old (IQR = 26) in 2020; in both cases the age distribution was bimodal (Supplementary Figure 1). In both years, more women completed daily surveys than men (60.2% vs. 58.0%, $\chi^2(1) = 1.8$, $P = 0.31$). The distribution of users across a rural to urban gradient, however, was different between years ($\chi^2(2) = 46.6$, $P < 0.001$): in 2019, 19.9% of users lived in rural counties, 48.8% lived in small and medium metropolitan areas and 31.3% lived in large metropolitan areas; in 2020, the distribution of users was more even (30.9%, 36.6% and 32.4% respectively) with a significant increase in users from rural counties.

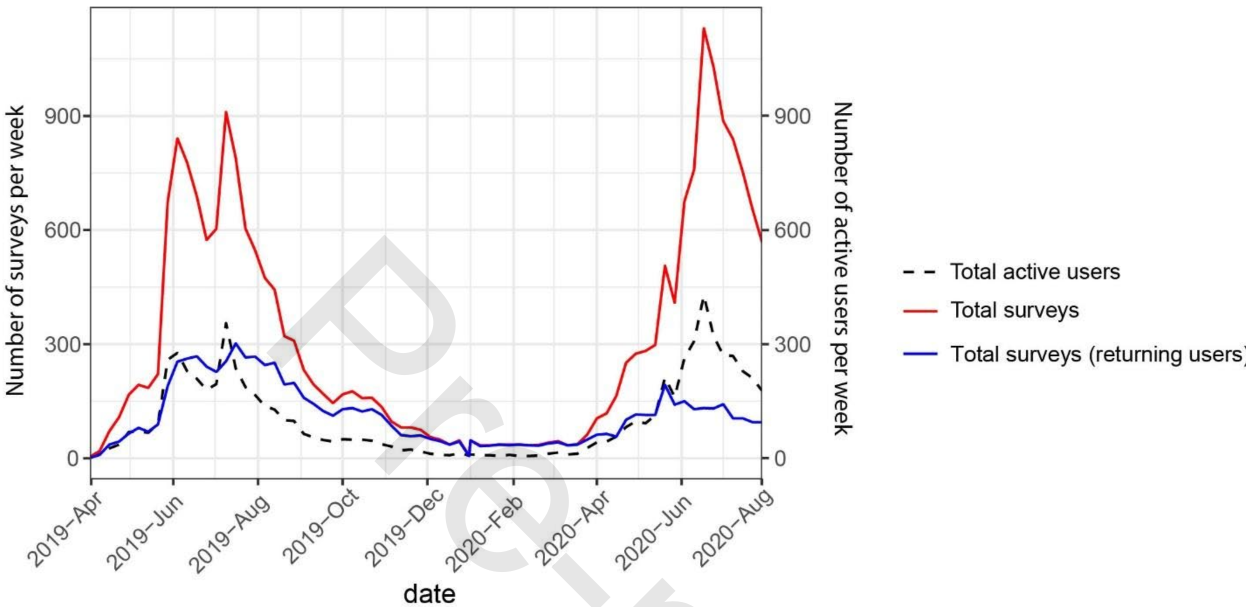

Figure 1. For a given week, the total number of surveys submitted and the total number of surveys submitted by returning users (those who participated in 2019 and 2020) (Left y-axis). For a given week, the number of total active users (those that submitted at least one survey) (Right y-axis).

Comparison of outdoor activity patterns between 2020 and 2019

The daily proportion of users reporting any type of outdoor activity increased by two-fold in 2020 (OR_{adj}=2.65, CI_{95}=2.33–3.01) compared to 2019, after adjusting for urbanicity, demographic and weather variables (Supplementary Table 1), even though outdoor activities during the spring and summer were commonly reported by users on a daily basis both years (daily proportion of outdoor activities: median = 71.1%, IQR= 12.3 for 2019 and median = 86.7%, IQR = 9.5 for 2020) (Figure 2). The two-fold increase was consistent during the period analyzed (the interaction term with month was non-significant).

Weather variables influenced outdoor activities, where engagement in outdoor activities increased with mean daily temperature and decreased on rainy days. Adding a quadratic term for temperature improved model fit by capturing the temperature-driven seasonality of outdoor activities. The relationship between temperature and overall outdoor activities was concave up, meaning that outdoor activities increased rapidly with temperatures at the beginning of the spring but the association decreased at high mean daily temperatures (e.g., in July) (Supplementary Table 1 and Supplementary Figure 3). Outdoor activities also decreased with an increasing proportion of users living in large metropolitan areas.

When distinguishing between the types of outdoor activities by location (peridomestic vs. in green spaces), we observed a similar increase in the daily proportion of users reporting peridomestic activities in 2020 (OR_{adj}=2.25, CI_{95}=2.04–2.50) as when considering all type of outdoor activities, after adjusting for the same covariates (Figure 2 and Supplementary Table 2). This increase in peridomestic activities in 2020 was most pronounced in April and May (Supplementary Table 3). Recreational activities in parks and natural areas also increased in 2020, but only between 7-30% compared to 2019 (OR_{adj}=1.18, CI_{95}=1.07–1.31) (Supplementary Table 4). We also observed an increase in recreational activities in grey spaces (e.g., walking in sidewalks) although this variable was only recorded for May–July 2020 (Supplementary Figure 2).

Both peridomestic and recreational activities in green spaces increased proportionally with daily temperature and decreased on rainy days. Peridomestic activities increased with the proportion of users in rural areas as opposed to urban users, while recreational activities were not associated to urbanicity levels. When only considering users who completed surveys both in 2019 and 2020, we observed similar shifts in the proportion of outdoor activities between years compared to the study population as a whole: an overall increase in outdoor activities, with an increase in peridomestic activities, but recreational activities in green spaces were not significantly different between 2019 and 2020 (Supplementary Tables 1, 2 and 4).

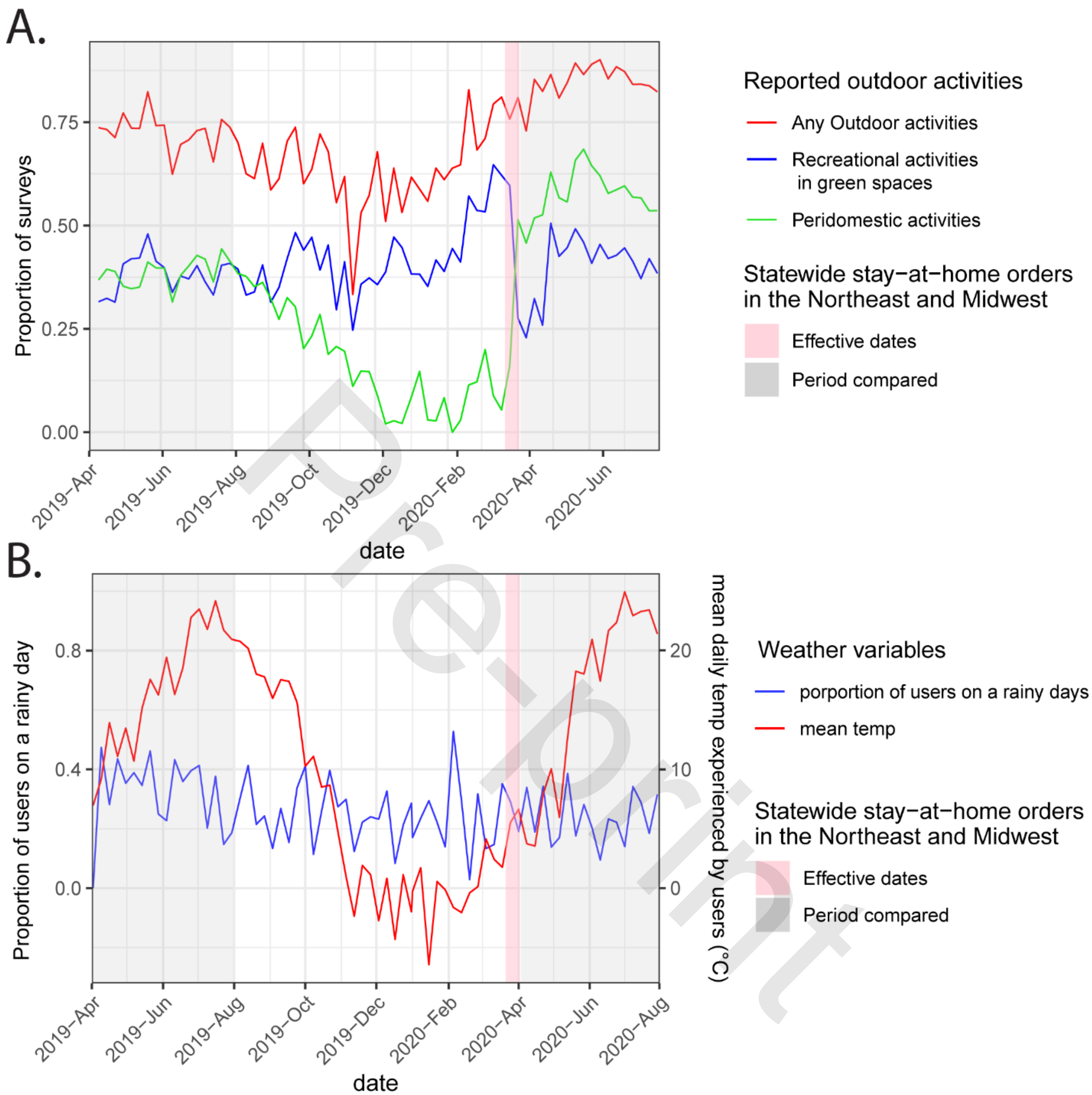

Figure 2. Unadjusted proportion of surveys reporting any type of outdoor activities, peridomestic activities or recreational activities in green spaces (parks and natural areas), per week (A). Weather variables experienced by users (weekly medians) (B). Weeks shaded in light grey indicate the time period that was compared between 2019 and 2020. Weeks shaded in light red indicate the effective dates for stay-at-home orders in Northeast and Midwest counties.

Impact of stay-at-home orders on outdoor activity patterns

For 2020, we observed a two-fold increase in the daily proportion of users reporting any type of outdoor activity after statewide stay-at-home orders went into effect (April to July versus February and March, 2020) after adjusting for covariates (OR_{adj}= 1.98, CI_{95}= 1.21–3.17) (Supplementary Table 5), and an even greater increase in peridomestic outdoor activities (OR_{adj}= 12.12, CI_{95}= 7.23–20.94) (Supplementary Table 6). In contrast, the proportion of users reporting recreational activities in green spaces decreased by 60% when stay-home orders went into effect (OR_{adj}= 0.40, CI_{95}= 0.27–0.60) (Supplementary Table 7), after adjusting for the effect of the county-level Shelter-in-Place Index as a measure of out-of-home mobility restrictions (i.e., higher SIP means lower out-of-home mobility, Supplementary Figure 5) and weather variables. The Shelter-in-Place index was negatively associated with the proportion of users reporting outdoor activities, and the same effect was observed when distinguishing between peridomestic and recreational activities in green spaces. In other words, as stay-at-home orders and human risk mitigation behaviors relaxed over time and out-of-home mobility increased (i.e., a decrease in the Shelter-in-Place Index, Supplementary Figure 5), the proportion of users engaging in outdoor activities increased (Supplementary Tables 5, 6 and 7). Moreover, we observed that the national incidence of COVID-19 cases was inversely associated to the proportion of users reporting any type of outdoor activities or peridomestic activities, but no association was observed with the proportion of users engaging on recreational activities (Supplementary Tables 5, 6 and 7). The local (county-level) incidence did not improve the fit of the models.

Regarding urbanicity levels, we observed that the proportion of peridomestic activities decreased significantly with the proportion of reporting users living in rural, possibly indicating that the increase in peridomestic activities was mostly driven by users living in small and medium metropolitan areas (Supplementary Table 6). No effect of urbanicity was observed for recreational activities in green spaces.

Self-reported impact of COVID-19

When asked about the impact of COVID-19 mitigation measures on outdoor activities on a daily basis (Question 10 in Supplementary Text 2), the majority of responses indicated no impact (Figure 3A; Supplementary Table 8). Among individuals who reported an impact, the most frequent response was that they spent more time in their yard, however the distribution of responses changed throughout the study period (χ2 test, $X^2(16)= 62.2$, $p <0.001$) (Figure 3A). The likelihood of reporting an impact on outdoor activities also varied by location and user demographics. The likelihood of reporting an impact increased with the Shelter-in-Place Index, if users lived in a metropolitan area as opposed to a rural county, and if they were female (Supplementary Table 9). For users who reported not recreating in parks or natural areas on a given day (Question 12 in Supplementary Text 2), most did not report reasons related to COVID-19 (Figure 3B; Supplementary Table 8). Nonetheless, the reasons reported varied by month (χ2 test, $X^2(18)= 113.7$, $p <0.001$), and avoiding crowds was more commonly reported in April and May compared to other months, as were reports that users did not have park access, parks were closed, or stay-at-home orders were in place (Figure 3B).

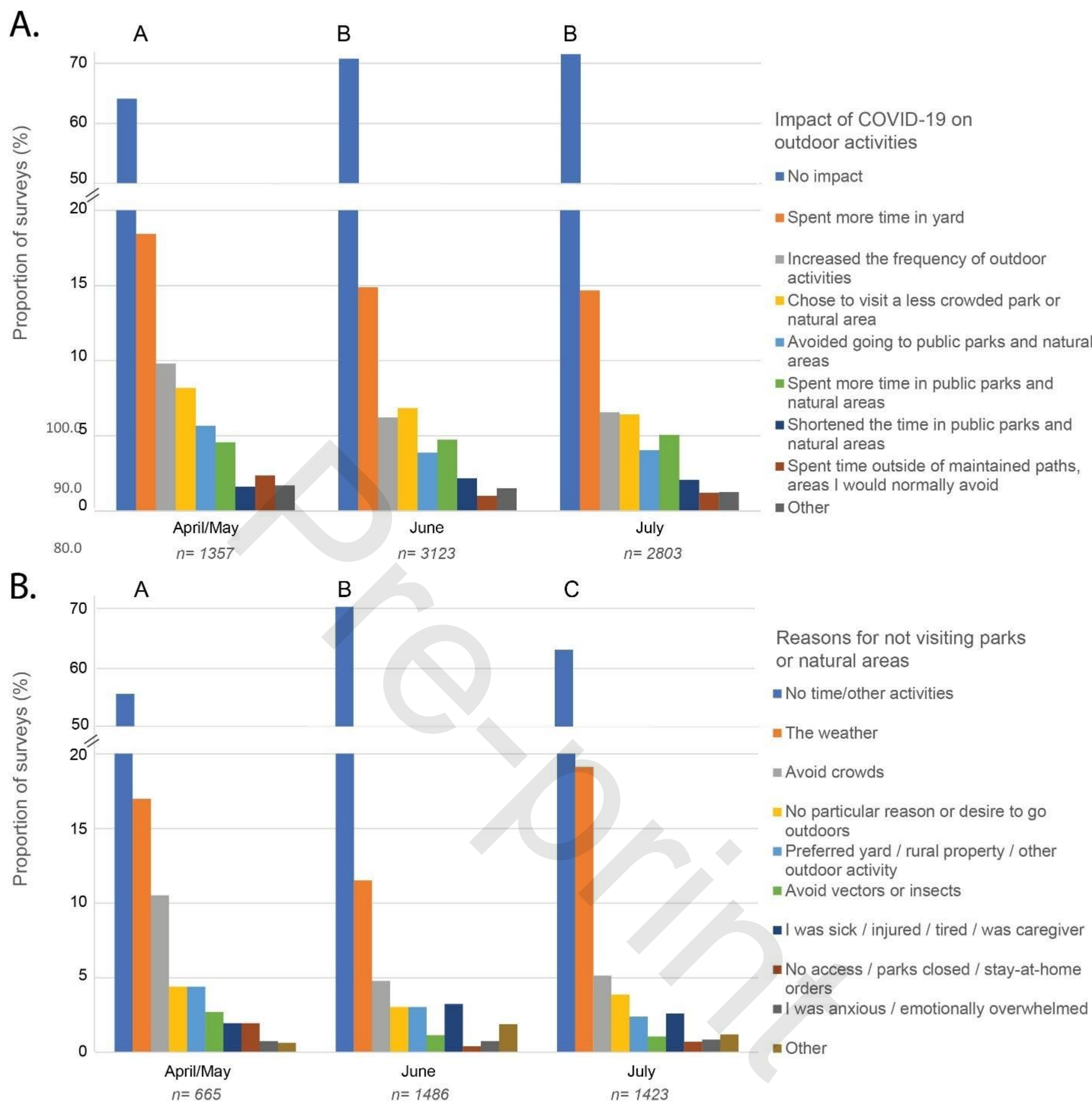

Figure 3. Self-reported impacts of COVID-19 on outdoor activities (A) and the reason for not having visited a park or recreational area that day (B). Different letters above the distributions (A-B-C) indicate significant differences (χ^2 test, $P < 0.001$) between pair-wise comparisons between months after applying a Bonferroni correction for multiple comparisons.

Self-reported tick encounters

Overall, self-reported tick encounters increased in 2020 (15.5%) compared to 2019

(11.6%) (OR_{adj}= 1.36, CI_{95}= 1.12–1.64) between April 1st and July 31st (Supplementary Table 10 and Figure 4). Self-reported tick encounters increased if the user reported doing an outdoor activity the same day and decreased if the user lived in a metropolitan area compared to a rural county (Supplementary Table 10). When peridomestic or recreational activities in green spaces were analyzed separately, we did not find a significant association with tick encounter for either variable. Although the overall probability of reporting a tick encounter was higher in 2020 compared to 2019, we observed monthly and yearly variation in the association between reporting an outdoor activity and a tick encounter (Supplementary Figure 8). The increase in self-reported tick encounters was verified with picture submissions. The proportion of users submitting at least one picture increased from 33.9% in 2019 to 57.3% in 2020. Although in both years the median number of ticks submitted per capita was one (median = 1, IQR = 1, range= 1-74 in 2020 and median =1, IQR = 0, range= 1-24 in 2019), the number of ticks per capita submitted was higher in 2020 vs 2019 (Mann-Whitney test, $P < 0.001$) as well as the proportion of users submitting more than one tick picture for identification (50.5% in 2020 vs. 37.1% in 2019). In 2020, between April and July, 1,560 pictures were submitted from the Midwest and Northeast regions, 94.1% were ticks (n=1,468), of which 69.1% were found on a person. During the same period in 2019, 434 were submitted from those regions, 92.0% were ticks (n= 400) of which 67.5% were found on a person.

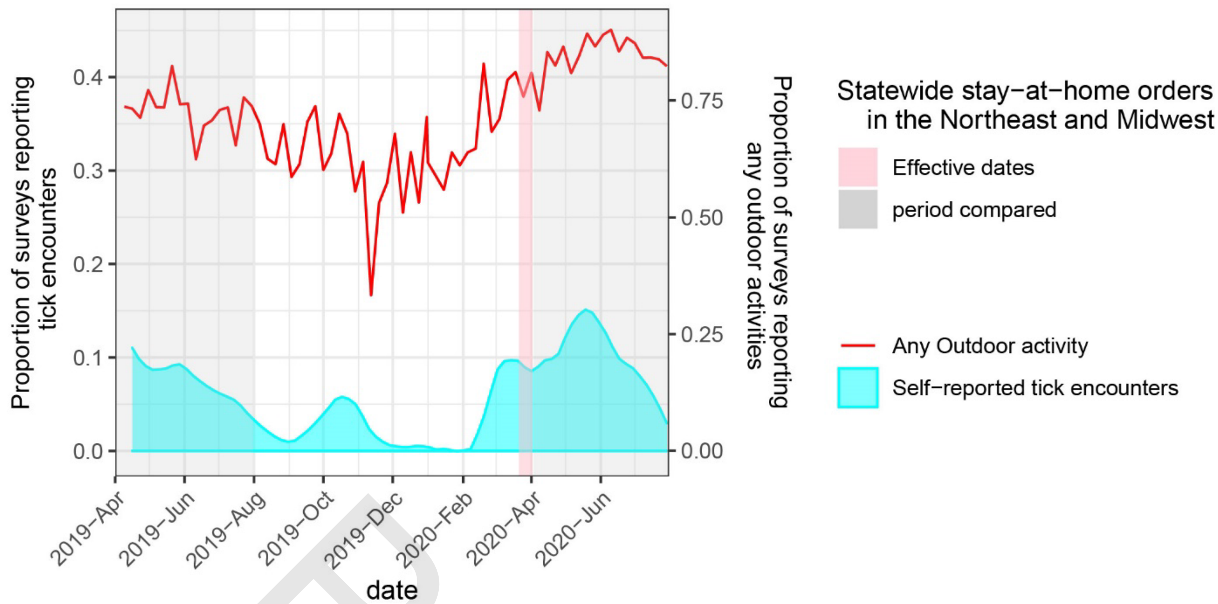

Figure 4. For a given week, we show the unadjusted proportion of surveys reporting at least one tick encounter (any tick species) (Left y-axis). For a given week, we show the unadjusted proportion of surveys reporting any outdoor activity (Right y-axis). Weeks shaded in light grey indicate the time period that was compared between 2019 and 2020. Weeks shaded in light red indicate the effective dates for stay-at-home orders in Northeast and Midwest counties.

Discussion

In this study, we observed an increase in self-reported tick encounters during the spring and summer of 2020 compared to the same period in 2019, and an increase in outdoor activities overall. The timing of the initial shift in outdoor activities coincides with COVID-19 stay-at-home orders in the United States, suggesting changes in tick exposure were influenced by 2020 COVID-19-driven behavioral changes. The comparison between pre- and amid-pandemic conditions (before and after March 2020) was enabled by the availability of a baseline dataset encompassing ~7000 responses from ~1000 users each year from the Tick App, a smartphone application designed to capture human behavioral risk factors associated with tick encounters. Although previous studies have shown an overall increase in outdoor activities in other countries in the Global North (Lesser and Nienhuis 2020, Venter *et al* 2020) and even locally in the United

States (Foley 2020), this is the first study to use individual-level data to show a two-fold increase in outdoor activities and a 30% increase in self-reported tick encounters in 2020 compared to 2019. Moreover, we showed a shift towards peridomestic activities relative to recreational activities in green spaces. While both type of activities increased in 2020, peridomestic activities doubled but recreational activities in green spaces initially decreased after stay-at-home measures were first implemented and later increased as mobility restrictions were relaxed, leading to an overall increase of 18% in the spring and summer of 2020 compared to 2019.

Throughout the COVID-19 pandemic, outdoor activities and gatherings have been encouraged over indoor activities in order to curb SARS-CoV-2 transmission (Center for Disease Control 2020). However, accessibility to public green spaces, differences in competing hazards (e.g. ticks, mosquitoes, rodents) between public green spaces and peridomestic settings, and risk perception (for COVID-19 transmission, and vector- or rodent-borne diseases), among other factors may have influenced not only the frequency of outdoor activities, but also where people decided to conduct their activities (peridomestic vs. green spaces). This study stands apart from previous assessments of outdoor activity during the COVID-19 pandemic by using individual-level information about shifts in outdoor activity patterns and self-protection efforts. Other studies have relied on aggregated mobility data to assess changes in park visitation as a proxy for outdoor recreation (Venter *et al* 2020, Abouk and Heydari 2021, Geng *et al* 2021, Hamidi and Zandiatashbar 2021). Individual-level data is essential to fully assess the risk of tick- and other vector-borne diseases, which depends on the background risk (e.g. vector density), exposure (e.g. the type, location and intensity of outdoor activities), and self-protection efforts (e.g. the use of repellents) (Diuk-Wasser *et al* 2021, Connally *et al* 2009, Fischhoff *et al* 2019a). Behavioral choices related to exposure and self-protection are made through decision-making processes where individuals make complex risk assessments in the face of tradeoffs between mitigating competing hazards. To identify how an individual adapts to changing risk, data collection must explicitly measure the behaviors at multiple time points and scenarios (i.e., changes in the type of outdoor activities). Another strength of the study is that we distinguished between activities undertaken in peridomestic environments vs. green spaces. Because unidentified mobility data cannot distinguish between yards and indoor locations, such datasets completely miss peridomestic activities.

The overall increase in any type of outdoor activity during the spring and summer of 2020 compared to 2019 (pre-pandemic) found in this study (after adjusting for weather and demographic covariates) may have resulted in increased exposure to vectors (ticks and mosquitoes) during the COVID-19 pandemic. This hypothesis is supported by the observed increase in self-reported tick encounters in 2020, verified by picture submissions through the smartphone app. At the individual level, we found that self-reported tick encounters were associated with engagement in outdoor activities, which provides further evidence for the link between increased outdoor activities and tick exposure. However, when evaluating the association of self-reported tick encounters and the type of activity (peridomestic activities or recreational activities in green spaces), no significant association was found with either type. The fact that the engagement in any type of outdoor activities was associated with a reported tick at the individual level but not for a specific type of activity could be explained by similar tick abundances in both settings, although no available data is available to assess this. Furthermore, ticks' prolonged attachment and increased likelihood of detection as ticks engorge creates uncertainty on the date when the tick was first attached and first spotted, making it difficult to match the tick to the specific activity that resulted in the exposure. Additionally, in the app, users can report several activities on the same day, further hindering the match with the tick report.

Nonetheless, the group-level shift towards peridomestic activities and increased tick exposure indicates either an increase in the overall tick population or increased exposure in those settings where participants are less inclined to use preventative measures against tick bites (Bron *et al* 2020). A similar pattern was observed for mosquito-borne disease in two studies on dengue infection: i) a simulation model found that COVID-19 stay-at-home measures (in which 70% of the population restricted their mobility to their house) led to an increase in overall infections and increased clustering of cases at the household level (Cavany *et al* 2020); and b) an empirical study using dengue case report data in Singapore found a 37.2% increase in the number of cases from expected baseline levels attributed to COVID-19 stay-at-home measures(Lim *et al* 2021).

Our study population was overrepresented by outdoor enthusiasts (Fernandez *et al* 2019), which is a group that tends to be at a higher risk of tick exposure than the population at-large. This makes The Tick App users a suitable population to explore how COVID-19 might have shifted overall exposure and the context of the exposure (in green spaces vs. peridomestic). Overall, statewide stay-at-home orders had a strong effect on reducing out-of-home mobility in the United States, reflected by a 15.2% increase in the time spent at home after the policies took effect (Abouk and Heydari 2021). In our study, this was also reflected in an increase in peridomestic activities in 2020 compared to 2019 and pre- and post-stay-at-home orders that were implemented in March 2020. This effect was more pronounced immediately after the orders went into effect, even after adjusting for weather variables to account for seasonality effects. This increase in peridomestic activities was reflected in the self-reported impacts of COVID-19 on the user's outdoor activities: among individuals who reported an impact, the most frequent response was that they spent more time in their yard, particularly in April and May.

Recreational activities in green spaces followed a different pattern compared to peridomestic activities in response to COVID-19 mitigation efforts: first decreasing by 60% in the period after stay-at-home measures were implemented towards the end of March 2020, but later increased to higher levels compared to the same period in 2019. Increased park visitations revealed by Google Mobility Reports were used by two studies (Geng *et al* 2021, Hamidi and Zandiatashbar 2021) as a proxy for changes in outdoor activities in these environments.

However, these trends were found to be primarily driven by seasonality at the county-level, providing little empirical support to an effect of COVID-19 risk mitigation responses on outdoor recreation activities (Rice and Pan 2020). By comparing the same period in 2019 and 2020 and adjusting for weather variables to account for seasonality, we found an overall increase in recreational activities, even after adjusting for urbanicity levels, but to a lesser extent compared to peridomestic activities. Consistent with our findings, another longitudinal study that used questionnaires to survey outdoor enthusiasts in the United States (Rice *et al* 2020b, 2020a) at different time points after stay-at-home measures took effect found a reduction in the frequency of outdoor activities and the distance traveled to partake in these activities between April and May 2020. Additionally, a nationwide online survey in the United States examining the effects of the COVID-19 pandemic on outdoor recreation trips, showed an estimated 26% reduction in trips per participant to public outdoor recreation sites post-COVID-19, as compared to pre-COVID-19 trips (Landry *et al* 2021). The shift to backyard activities detected in our study was also found in a survey administered to avid birdwatchers worldwide (mostly located in the Global North), 85% of respondents reported that COVID-19 changed their birding behavior, increasing their time focused on this activity but shifting mostly to yard birding (Randler *et al* 2020). It should be noted that crowded conditions forced park closures off and on to mitigate COVID-19 transmission risk or offered limited capacity -i.e., the crowds were too large for proper distancing, which could have affected people's engagement in these activities and the distance traveled, particularly in higher urbanicity locations. However, in our study few study participants reported not engaging in recreational activities due to 'no access' to parks (Figure 3B). As our study focused on two specific regions, these results cannot be generalized to the entire United States where activity patterns in recreational areas may have differed during the pandemic.

When taken together, our findings and those in the aforementioned studies, suggest a reduction in recreational activities in green spaces during the first couple of months of the COVID-19 pandemic after stay-at-home orders went into effect. However, we also found that the Shelter-in-Place Index (used as a proxy for reduced out-of-home mobility), which decreased over time after the first month following the stay-at-home others went into effect, was inversely associated with both the daily proportion of peridomestic activities and recreational activities in green spaces. In other words, as stay-at-home orders and COVID risk mitigation behaviors relaxed over time and out-of-home mobility increased (i.e., a decrease in the Shelter-in-Place Index, Supplementary Figure 5), outdoor activities increased. This temporal pattern was also observed in a national survey to outdoor enthusiasts; after the initial reduction in recreational activities in green spaces, there was a slight shift from neighborhood and city streets back to public lands in late May compared to early April, though still in lower proportions compared to pre-pandemic levels (Rice *et al* 2020b).

Although our study suggests that the overall increase in any type of outdoor activities during the COVID-19 pandemic were driven mostly by an increase in peridomestic activities, we cannot disregard an increase in recreational activities in grey spaces (e.g., walking around the neighborhood, Supplementary Figure 2); however, there is insufficient data to analyze the effects of COVID-19 on these types of recreational activities. Studies conducted in Canada and the United States showed that, in the first month of the pandemic, the majority of participants engaged in physical activity either in the home environment or in their neighborhood (Lesser and Nienhuis 2020, Rice *et al* 2020b).

Our study has several limitations, as with any observational and longitudinal study. Our conclusions are limited to a population that tends to engage in outdoor activities frequently and cannot be generalized to the general population. Given that The Tick App is marketed as an app to better understand human exposure to ticks, we expect that people at greater risk of tick encounters and previous tick exposure use it more frequently, introducing self-selection bias. Moreover, our population is biased towards older ages, thus limiting conclusions for younger age groups; children and teenagers were not included. Follow-up time and surveys completed by users were highly variable, thus data had to be pooled to study temporal (daily) variations. In addition, the survey was slightly modified in 2020 to capture outdoor activities more accurately. However, new changes were rolled out by late April 2020 and we validated our results by comparing reporting activities between and after roll out of the new version of the app. Lastly, although we accounted for urbanicity levels, pooling users from different geographical areas in the Northeast and the Midwest might mask other aspects affecting outdoor activity patterns and tick encounters occurring at the local level. Nonetheless, this study capitalized on a unique dataset collected that captures human behavioral risk factors for a consistent geographic area over time, allowing us to study the effects of COVID-19 mitigation efforts on outdoor activities and tick-borne disease risk, compared to a pre-pandemic baseline. Unlike other studies conducted after the pandemic started, this dataset is not subject to recall bias. Moreover, the data encompassed reports by a subset of users who completed surveys in both years, providing robust validation of findings. Finally, a limitation of the study is that the size of the dataset precludes assessments of local changes in vector exposure or geographic-specific risk of vector-borne diseases (Fernandez *et al* 2019, Bron *et al* 2020).

Conclusions

While the COVID-19 pandemic continues to represent a significant challenge to public health, we cannot neglect other health risks. In the United States, tick-borne disease cases have doubled during 2004-2016, and nine vector-borne human diseases have newly emerged during the last decade (Rosenberg *et al* 2018). The full impact of the pandemic on the transmission of tick-borne, and other vector-borne diseases is yet to be fully realized. This study could provide valuable insights into potential underreporting of tick-borne disease cases during the COVID-19 pandemic (Wormser *et al* 2021). During 2020, fewer tick bite–related emergency department visits were registered and fewer Lyme disease laboratory tests were performed by large commercial laboratories compared to 2018-2019 (McCormick *et al* 2021). By contrast, visits to the CDC website describing tick removal increased by 25% in 2020 compared to 2018-2019, suggesting that while tick exposure might have increased during 2020, changes in healthseeking behavior and provider services patterns might have artificially reduced Lyme disease case reporting (McCormick *et al* 2021). Our results show increased self-reported tick exposure (particularly among outdoor enthusiasts) in 2020, but its association to disease risk is unknown. We speculate that this increase is influenced by the shifts in outdoor activity patterns found in our study population. However, we cannot disregard effects of an increase in the population of ticks or in awareness of tick-borne disease risk resulting in a more diligent search for ticks after being outdoors. The links between outdoor recreation and wellbeing are well-established (Bell *et al* 2014) and particularly during the COVID-19 pandemic (Pouso *et al* 2021), outdoor activities have been (and should be) encouraged as a way to mitigate transmission risk while providing safe spaces for social interactions. Nonetheless, other hazards occurring in outdoor settings should be taken into account. Our results highlight the need to balance public health resources to avoid neglecting the disease burden caused by tick-borne and other vector-borne diseases.

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