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Associations between wildlife observations, human-tick encounters and landscape features in a peri-urban tick hotspot

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Abstract

Zoonotic disease vectors, their wildlife hosts, and the surrounding landscape interact in complex ways that vary spatially, temporally and with anthropogenic change. Ticks (Acari: Ixodidae) are one of the most important vectors of human disease globally but managing the risk of tick bites in urban areas requires a detailed understanding of these complex vector-host-environment relationships at multiple spatial scales. Extensive knowledge gaps of these interactions in Australia limits options for managing ticks and exacerbates human-wildlife conflict. To address this, we used an online survey to determine the potential drivers of human-tick encounters operating at the local, yard scale and at the broader, landscape scale in a peri-urban area of Australia. We explored the relationships between reported tick encounters in yards and yard traits, host sightings (yard-scale) and broader landscape traits (landscape-scale). We found that sightings of potential hosts such as long-nosed bandicoots (*Perameles nasuta*) and brush-turkeys (*Alectura lathami*), and broader landscape traits such as distance to wet sclerophyll forest, were important predictors of reported tick encounters. Yard traits such as garden mulching and leaf litter cover showed no relationships with tick encounters. However, garden mulching and the absence of pets were predictors of frequent bandicoot sightings in yards. Mulching over $20m^2$, moderate to dense leaf litter cover on lawns, and living adjacent to bush were predictors of frequent brush-turkey sightings in yards. Our results suggest that residents may be able to reduce tick encounter risk by making yards less attractive to potential hosts. The observed relationships provide a critical foundation for field studies that can determine underlying mechanisms and inform appropriate tick management in urban environments.

Keywords Urban ecology · Vectors · Wildlife hosts · Ticks · Landscape features

Introduction

Urban sprawl leads to habitat fragmentation, loss of biodiversity (McKinney 2002) and changes in human behaviour which in turn impacts the ecological dynamics of zoonotic pathogens and vectors (Allan et al. 2003; Mackenzie et al. 2004; Mackenstedt et al. 2015). Human-induced environmental changes have led to global concerns over the emergence and spread of various zoonotic diseases including those that are infectious such as SARS-CoV-2 (Zhang and Holmes 2020) and those transmitted to humans via arthropod vectors such as malaria, dengue and Lyme Borreliosis (Mayer et al. 2017; Swei et al. 2019; Klemola et al. 2019).

Ticks are one of the most important vectors of disease affecting humans and their companion animals in urban and peri-urban areas today (Rizzoli et al. 2014). The incidence of tick-borne diseases is increasing globally, with 20,000 – 30,000 cases reported annually in the US (Centers for Disease

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Control 2019a) and over 85,000 cases reported annually in Europe (Lindgren and Jaenson 2006; Vandekerckhove et al. 2019). Tick bites, once largely associated with outdoor leisure activities, are now known to occur in residential yards (E.g., Falco and Fish 1988; Mead et al. 2018). However, the complex interactions between ticks, their wildlife hosts, and the environment are poorly understood, which prevents reliable predictions of exposure risk and hampers effective tick management in urban ecosystems (Kilpatrick et al. 2017).

Urban wildlife host communities are often dominated by species that can adapt to anthropogenic disturbance (McKinney 2002; Bradley and Altizer 2007). These species can often reach high densities near humans and can support arthropod vectors such as mosquitoes and ticks (Pisanu et al. 2010; Goodman et al. 2018; Gibb et al. 2020). For example, urban Siberian chipmunks (*Eutamias sibiricus*), European hedgehogs (*Erinaceus europaeus*) and foxes (*Vulpes vulpes*) support high numbers of ticks and carry a range of tick-borne pathogens (Harris and Thompson 1978; Gern et al. 1997; Meyer-Kayser et al. 2012; Marsot et al. 2013). Understanding how urban wildlife influence tick dynamics is therefore becoming increasingly important (Medlock et al. 2013).

Urbanisation not only impacts host communities but can lead to changes in vegetation structure and microclimates important to tick persistence, making the ecology of ticks in urban areas likely to be different from that in more intact natural landscapes (Kilpatrick et al. 2017). Microclimate conditions including temperature, relative humidity, saturation deficit, and soil moisture are critical determinants of tick development, behaviour and ultimately survival (Heath 1981; Chilton and Bull 1994; Hubálek et al. 2004; Pfäffle et al. 2013). Characteristics of the surrounding vegetation directly influence these microclimate conditions affecting ticks and hosts (Fleetwood 1985) and are one of the many indicators of tick distributions across a landscape (Lindsay et al. 1999; Medlock et al. 2013; Ledger et al. 2019). Identifying which environmental variables influence urban tick occurrence at multiple spatial scales is considered important to determine how best to disrupt the tick life cycle to manage the risk of tick-borne illnesses (Fischhoff et al. 2019a).

Understanding the relative roles of the different wildlife hosts and vegetation properties in predicting tick abundance is essential to ensure correct management actions. For example, in the United States, tick abundance on residential properties is higher within woodlots (or woodland) and ecotonal areas (or edge habitat) compared to ornamental vegetation and lawns (Maupin et al. 1991; Stafford and Magnarelli 1993; Frank et al. 1998). These findings resulted in recommendations to remove leaf litter, reduce shade and moisture, and to mow lawns to make yards less suitable for ticks and hosts (Maupin et al. 1991; Centers for Disease Control 2019b). The presence of bird feeders (Smith et al. 2001; Mead et al. 2018), woodpiles (Smith et al. 2001; Connally et al. 2009), trash (Fischhoff et al. 2019b) and fencing (Perkins et al. 2006) have been associated with tick occurrence and tick-borne disease risk in some studies likely through impacts on hosts. The presence of hosts themselves has also been associated with tick-borne disease risk (Smith et al. 2001). Many of these studies have focused on the drivers of tick-borne disease *risk* rather than drivers of human-tick *encounters* (Fischhoff et al. 2019a). But in Australia, the most well-known threats from ticks include paralysis in pets and life-threatening allergies in people, with less known about the incidence of tick-borne diseases (Graves and Stenos 2017). Thus, understanding the drivers of tick *encounters* is critical. To date, this area of research in Australia has received no attention to our knowledge.

In the absence of an adequate understanding of tick ecology in urban areas, tick management is restricted to individual level protection (e.g., tick repellent) even though environmental tick management strategies that focus on reducing tick abundance might enhance protection in residential areas (Stafford et al. 2017) (Fig. 1). The problem is acute in Australia where little is known about which wildlife

Fig. 1 Graphic shows the two levels of protection against ticks. Individual level protection is currently the primary option in Australia. Landscape level protection is not feasible without a better understanding of tick ecology in urban areas

are important hosts of ticks (Lydecker et al. 2015), and what drives host and tick abundances in urban areas. Given Australia's unique flora and fauna and the ecosystems they inhabit, findings from the Northern Hemisphere may not translate to Australian urban systems.

Australian ticks are host of a range of unique bacteria, protozoa, and viruses (Egan et al. 2021a, b; Gofton et al. 2022). *Ixodes holocyclus* and *Amblyomma triguttatum* are common ticks on the east and west coast respectively and bites are known to cause systemic bacterial infections (Rickettsiosis and Q fever) (Graves and Stenos 2017). *Ixodes holocyclus* bites can also cause anaphylaxis, mammalian meat allergy (van Nunen 2018), and paralysis (Hall-Mendelin et al. 2011). In North Sydney, concerns over exposure to ticks has led to negative perceptions of native long-nosed bandicoots (*Perameles nasuta*) (Dowle and Deane 2008; Chen 2013; Stubbs 2016) due to widespread belief that bandicoots are the primary host (Lydecker et al. 2015). Although bandicoots are known hosts of ticks in Australia, other hosts such as wallabies (Roberts 1970), possums (Roberts 1970), and introduced rats (Lydecker et al. 2019) and rabbits (Taylor et al. 2020) likely play a role in urban tick dynamics. Brush-turkeys (*Alectura lathami*) are also common in our study area, though we only have anecdotal reports of brush-turkeys carrying ticks.

In this study we aim to identify potential drivers of human-tick encounters at multiple scales to inform tick management and generate testable hypotheses that can be examined with field sampling. We used an online survey of residents in peri-urban Northern Sydney, a tick-endemic area near Australia's largest city and hot spot for tick-borne health issues (van Nunen 2018), to assess potential drivers of tick and wildlife host encounters. We then examined how the characteristics of residential yards and nearby natural landscapes relate to self-reports of both tick encounters and wildlife hosts.

At the yard scale, we first explored the relationship between reported tick encounters and yard traits predicted to influence tick encounters including living adjacent to bushland, spending time in the yard, garden mulching and leaf litter cover on lawns. We predicted that traits such as mulching and leaf litter cover may modulate the ground-level microclimate available to ticks (e.g., soil moisture, soil temperature and ground level air temperature) impacting tick behaviour and survival (Vail and Smith 2002; Hubálek et al. 2004; see Pfäffle et al. 2013) and in turn the frequency of human-tick encounters. Second, we explored relationships between host sightings (e.g., bandicoots, possums, and rats) and tick encounters in yards as we predicted that hosts that spend more time in yards are likely to have ticks drop off them that can then bite residents. We also explored the relationships between host sightings and particular yard traits and activities that we predicted would influence host presence in yards and in turn sightings by residents. These include mulching, the presence of pets, and leaf litter cover (see Hughes and Banks 2010; Carthey and Banks 2012; Frank et al. 2016).

At the landscape scale, we then tested the relationship between reported tick encounters and coarse landscape traits including distance to wet and dry sclerophyll forest and urban vegetation (e.g., yard trees, gardens, and patches of exotic vegetation). We predicted that wet and dry sclerophyll forest likely differ in the microhabitat they provide to ticks and hosts influencing tick encounters in nearby residential yards. We also explored the relationship between population density (a proxy for urbanisation) and tick encounters predicting that urbanisation would have a negative effect on tick encounters, as tick persistence is likely to decline with increasing urbanisation due to the associated decline in suitable habitat for ticks and hosts (Kilpatrick et al. 2017).

Methods

Study area

Sydney's Northern Beaches region is approximately 254 km^2 comprised of 40 km of coastline, bushland remnants spanning 131 km^2, and urban development home to 252, 878 people living across 101, 475 households (Australian Bureau of Statistics 2016a, b). The bushland remnants contain a diverse range of vegetation types, including coastal heathland, dry sclerophyll forest, wet sclerophyll forest, rainforest, and freshwater, saline and forested wetlands (Office of Environment and Heritage Sydney 2016).

Common native mammals include brushtail (*Trichosurus vulpecula*) and ringtail possums (*Pseudocheirus peregrinus*), long-nosed bandicoots, brown antechinuses (*Antechinus stuartii*), swamp wallabies (*Wallabia bicolor*), grey-headed flying foxes (*Pteropus poliocephalus*), bush rats (*Rattus fuscipes*) and Eastern pygmy possums (*Cercartetus nanus*) (Northern Beaches Council 2010). Common introduced mammals include black rats (*Rattus rattus*), brown rats (*Rattus norvegicus*), European rabbits (*Oryctolagus cuniculus*), and European foxes (*Vulpes vulpes*) (Northern Beaches Council 2010). The Northern Beaches is home to a diverse range of birds and reptiles (Pittwater Council and EEC 2011); however, these groups are generally not considered major tick hosts in the region and are therefore not a focus of this study (with the exception of brush-turkeys).

Survey design and release

This study was conducted under the approval of The University of Sydney Human Research Ethics Committee (protocol number 2018/157). We created an online survey using REDCap (Research Electronic Data Capture) (Harris et al. 2009,

2019) to collect data on residents experiences with ticks and wildlife (see SI1 for copy of survey questions). To assess yard traits our survey included questions about residence type, yard size, yard type, garden watering frequency, tick control, pest control, the use of mulch in gardens, leaf litter cover on lawns, time in yards, and perceived accessibility of yards to animals that are ground-dwelling or able to climb or jump (See SI1 and Table 1). We asked residents to provide their street address or street name and nearest cross street for spatial analyses.

To quantify tick encounters we asked residents whether they find ticks on themselves (or other members of their household) after spending time in their yard and the frequency of encounters (from daily to never). In our survey we defined tick encounters as finding a tick on a person while in the yard or after being in the yard.

To determine host activity, we asked residents to select which wildlife they see in their yard and how frequently, out of the following animals common in the region and that are identifiable to the general public: possums (including brushtail and ringtail possums), bandicoots (long-nosed bandicoots), rats (black rats and brown rats), brush-turkeys, eastern blue-tongue lizards (*Tiliqua scincoides*), wallabies (swamp wallaby), rabbits, and foxes.

Given that pets can influence host activity in yards (Carthey and Banks 2012) residents were also asked to report whether they own a cat or dog, whether they keep their pets inside at night, and whether they find ticks on their pets and how frequently. Residents were asked to answer about their experiences with ticks and hosts at their current residence within the past two years only.

The survey was promoted by the Northern Beaches Council via an online media release on their website on November 20, 2018, and the release was shared via their Twitter and Facebook profiles. To target members of the public who might not engage in social media, the survey was shared in two traditional media types: the local newspaper Manly Daily (readership prior to becoming exclusively digital in 2020 was estimated to be 156,000) and local magazine Pittwater Life (readership 80, 000). Participation was voluntary and a completed survey indicated consent. The survey was active for 3 months over the summer, overlapping with the peak season for adult ticks on Australia's East Coast. Paralysis cases in pets peak in spring in Australia (Eppleston et al. 2013) when adult female ticks are active. Residents are also more likely to notice adult ticks on themselves and their pets than the smaller larvae and nymphs.

Given the reach of the platforms used to disseminate the survey and the local publicity about ticks spanning several decades (Webb 2014; Donegan 2015; Malik 2016; McMahon 2019; Salleh 2019), we consider that the survey would have been widely accessible to Northern Beaches residents. However, because the survey was self-selecting, there is a possibility that we have not obtained a representative sample of the target population. Further, our survey invited residents to provide information about their experiences with ticks and wildlife in their yard to inform future research, introducing a potential bias towards residents concerned about ticks. Nevertheless, 22.1% of respondents reported never having encountered ticks in their yard. Respondents that selected yes to encountering ticks in their yard were then prompted to report on the frequency of encounters in yards, and the most common response was 'a few times a year'. Daily, weekly, and monthly reports of ticks were less common, though align with anecdotal reports of tick problems in some residential yards (Northern Beaches Council pers comm).

Table 1 Response levels for each yard-scale variable including in the analyses

Residence type	Adjacent to bush	Garden watering	Pets
Freestanding house	Yes	Weekly	Cat
Semi-detached house/townhouse	No	Monthly	Dog
		Hardly ever/never	Both
			Neither
Yard size	**Time spent in yard**	**Leaf litter cover on lawn***	
Small ($<30m^2$)	Daily yard time	Moderate-dense leaf litter	
Medium ($30m^2$—$100m^2$)	Weekly yard time	Minimal litter	
Large ($>100m^2$)	Monthly or hardly ever	Lush lawn no litter	
Yard type	**Mulching**	**Mulch area**	
Mix grass/garden and hard surfaces	Yes	$<5\ m^2$	
Mostly grass or garden	No	$5-10\ m^2$	
Hard surfaces		$10-20\ m^2$	
		$>20\ m^2$	

*See SI1 page 5 for images provided with the question on leaf litter cover on lawns

Data analysis

Yard-scale

We removed individually identifiable information and assigned each response with a unique identifier. Due to the low number of observations in individual categories, we grouped daily, weekly, and monthly reports of tick encounters in yards into a new category called ‘frequent tick encounters’ to be compared with responses where residents selected ‘no’ to ticks in their yard (for pooling of responses in other categories see SI2). Occasional (a few times a year) reports of tick encounters in yards were not included due to the likelihood that these encounters would be due to other random factors. We also grouped daily and weekly sightings of hosts into a new category called “Frequent *insert animal* sightings”. We did not include monthly reports for wildlife sightings as the more frequent categories (daily, weekly) had adequate sample sizes.

We removed 39 responses with apartments as the house type due to the low sample size in this category and the absence of a yard, as well as responses where respondents did not specify the house type. For analyses on bandicoot or possum sightings, we removed responses where residents reported that both their front and back yard was inaccessible to that animal. Due to the low number of reports of frequent rabbit, wallaby, fox, and blue-tongue lizard sightings in yards, we excluded these variables from all analyses. Eight additional responses were removed because they were either duplicates or > 50% of questions were unanswered.

We used logistic regression models to predict the odds of frequent tick encounters in yards (frequent tick encounters vs. no tick encounters) based on 1) yard traits (n = 219): and 2) host sightings (n = 218). Fisher’s exact tests or Pearson’s Chi-Squared tests (χ^2) of independence were used to examine the association between categorical variables during model building to minimise the number of associated variables in each model. We used two additional logistic regression models to predict the odds of frequent bandicoot sightings (frequent sightings vs. no sightings; n = 220) and brush-turkey sightings (n = 292) in yards, the two species with a strong relationship with tick encounters according to our results. We excluded tick control and pest control from all models as respondents were not required to indicate the type of treatment and how often it was applied and both factors may influence tick encounters.

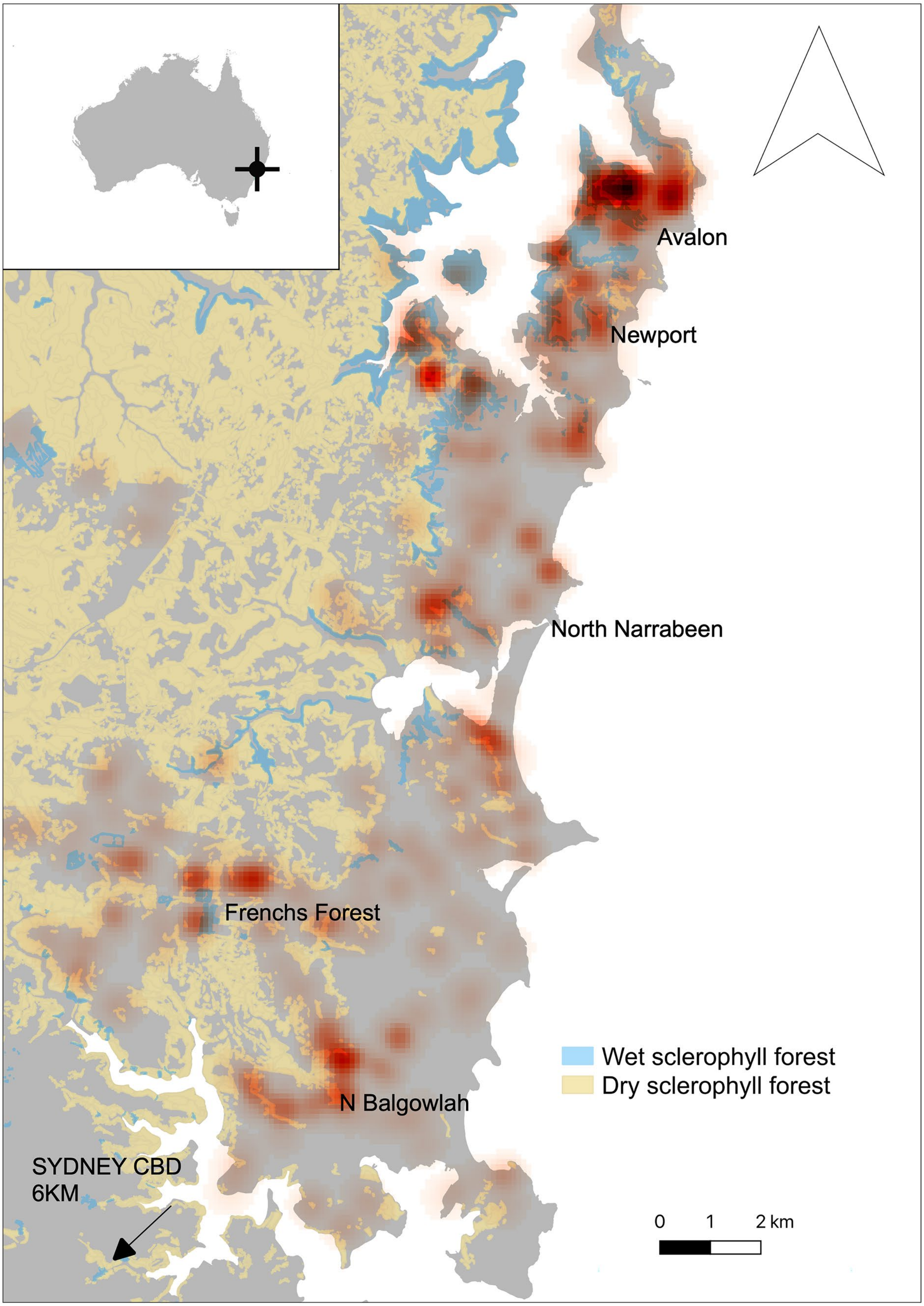
All models were built using the *glm* function (family = binomial) in packages MASS and pROC in R (R Core Team 2021). Confidence intervals (CI) for the coefficient estimates were obtained using the *confint* function (CI based on profiled log likelihood). Coefficient estimates and CI were then exponentiated to interpret the odds ratios. Sample sizes in the different regression models differ depending on the outcome variable.

In the yard traits model, we included the following yard traits predicted to influence frequent tick encounters in yards: yard type, living adjacent to bush, time spent in yard, garden mulching, and leaf litter cover on lawns. In the host sightings model, we included the following host sightings (frequent, occasional, never): bandicoot sightings, brush-turkey sightings, possum sightings, and rat sightings. Despite little recorded evidence of ticks feeding on brush-turkeys, *Ixodes holocyclus* is a generalist and has been found on a range of native and domestic birds (Roberts 1970). In the bandicoot sightings model, we included variables predicted to influence bandicoot sightings in yards, for example, variables that provide opportunities for sightings by residents or provide habitat or foraging opportunities for bandicoots. Bandicoots feed on invertebrates, fungi, and plant material by digging conical holes in the soil and prefer foraging in moist soil close to cover (Hughes and Banks 2010). Therefore, the final model included yard type, living adjacent to bush, time in yard, garden mulching, leaf litter cover on lawn, and pets. In the brush-turkey sightings model, we included variables predicted to influence brush-turkey sightings in yards, for example, variables that provide opportunities for sightings by residents or provide habitat or foraging opportunities for brush-turkeys. Male brush-turkeys construct a large mound each breeding season by raking up to over 2000 kg of leaf litter and moist soil (Jones 1988b) and thus, are likely to be attracted to yards with dense leaf litter or mulch cover. Thus, the final model included house type, living adjacent bush, time in yard, mulching, leaf litter cover on lawns, and pets.

Landscape-scale

We geocoded the street addresses (n = 516) in R Studio using the package *ggmap* before importing the points into QGIS (QGIS Development Team 2019). For the spatial analyses we: 1) removed 8 duplicate/incomplete responses, 2) removed responses where residents indicated that they lived in an apartment or where they did not specify the house type, 3) excluded responses where residents did not answer the question on tick encounters, 4) removed responses with an incomplete address or street name only, 5) calculated spatial information in QGIS and 6) performed logistic regression using the spatial data in R Studio as described above.

To explore whether distance to dry or wet vegetation types or urban vegetation influences tick encounters, we imported tick encounters (presence/absence or ticks/no ticks) into QGIS and calculated the distance to wet sclerophyll forest, dry sclerophyll forest, and urban vegetation using the Sydney Metro Area Vegetation layer (Office of Environment and Heritage Sydney 2016). Wet sclerophyll forest occurs in high rainfall zones and is comprised of tall


Avalon
Newport
North Narrabeen
Frenchs Forest
N Balgowlah
SYDNEY CBD
6KM
Wet sclerophyll forest
Dry sclerophyll forest
0 1 2 km

◂**Fig. 2** Heatmap using Kernel Density Estimation created in QGIS displays the density of reports of tick encounters (n = 420) across the study area. The density is calculated based on the number of tick encounter reports in a 500 m radius of each location and tick encounter reports were weighted based on frequency of tick encounters: daily, weekly, monthly and a few times a year

canopy with either a complex understory of soft-leaved shrubs or an understorey of ferns and grasses (Peeters and Butler 2014a). Moisture availability in wet sclerophyll forest is intermediate between rainforest and dry sclerophyll forest and woodlands (Dickinson and Kirkpatrick 1985). Dry sclerophyll forest is generally open with hard-leaved shrubs, grassy ground cover on low fertile soils and is prone to bushfires (Dickinson and Kirkpatrick 1985; Peeters and Butler 2014b). Therefore, we predicted that wet sclerophyll forest may provide more favourable microhabitat for ticks and their small mammal hosts, influencing their activity and in turn tick encounters in adjacent residential areas. Urban vegetation included areas dominated by exotic species and backyard trees, gardens, and median strips.

We performed logistic regression to determine whether distance to dry sclerophyll forest, wet sclerophyll forest, and urban vegetation were predictors (positive or negative) of tick encounters in yards (tick encounters vs. no tick encounters) (n = 474). We included bandicoot sightings and brush-turkey sightings in the model to determine whether there was an interaction between bandicoot sightings and wet sclerophyll forest i.e., were tick encounters near wet sclerophyll forest dependent on the presence of bandicoots (as reported by residents) or vice versa.

We used population density as a proxy for urbanisation to determine whether there was a relationship between tick encounters in yards and the level of urbanisation. We calculated population density by intersecting mesh blocks containing 2011 census data with 100 m and 500 m buffers around points (Australian Bureau of Statistics 2016a, b). We consider that a 100 m buffer represents the scale of habitat relevant to free-living tick life stages and a 500 m buffer represents the scale of habitat relevant to hosts. We then performed a logistic regression to determine whether population density at the 100 m and 500 m level was a predictor (positive or negative) of reported tick encounters in yards (tick encounters vs. no tick encounters) (n = 516).

Results

We found that reported tick encounters in yards were widespread across the study region with the largest clusters of reports in suburbs Avalon, Newport, Warriewood, Bayview, North Narrabeen, Narrabeen, Frenchs Forest, and North Balgowlah (Fig. 2).

Of the respondents with a yard (n = 578), 77.9% reported encountering ticks in their yard in the past two years and 31.8% of these tick encounters were reported as occurring frequently. Most respondents bitten by ticks indicated they suffered a mild local reaction or a large local reaction (90.1%, n = 519), with some suffering systemic illness (e.g., headache, nausea, fever) (13.3%, 69). Not owning a cat or dog was the most common response on pets (39.6%, n = 226), followed by dog ownership (34.6%, n = 197), cat ownership (14.9%, n = 85) then both cat and dog ownership (10.9%, n = 62). More than half of cat and dog owners (68% and 69% respectively) found a tick on their pet in the past two years despite 88.6% of pet owners reporting they use tick repellent on their pets. Possums were the most frequently observed animal in yards (n = 532), followed by brush-turkeys (n = 458), bandicoots (n = 436), rats (n = 372), blue-tongue lizards (n = 415), rabbits (n = 231), wallabies (n = 87) and foxes (n = 64).

Yard-scale drivers of tick encounters

The odds of reporting frequent tick encounters in the yard was 2.6 times greater for respondents with "Yard mostly grass or garden" compared to those with a yard comprised of hard surfaces or a mix of hard surfaces and grass or garden. For respondents "living adjacent to bush", the odds of reporting frequent tick encounters in the yard was 2.4 times greater compared to those that did not (Table 2). The odds of reporting frequent tick encounters in the yard was also 5.1 times greater for respondents that reported "Daily yard time" compared to those reporting never spending time in the yard, though the confidence intervals are large (low precision) (CI 95%: 1.14—28.98). "Garden mulching", "Moderate to dense leaf litter cover" and "Lush lawn no litter" were not associated with frequent tick encounters in the yard compared to no mulching and minimal litter (Table 2). Although leaf litter cover was associated with living adjacent to bush and garden mulching was associated with yard time ($p < 0.05$), there was still no association between tick encounters and leaf litter cover or mulching when controlling for living adjacent to bush or yard time respectively ($p > 0.05$). Yard size was associated with house type ($\chi^2 = 35.95$, df = 2, $p < 0.0001$) and yard type ($\chi^2 = 12.96$, df = 2, $p = 0.002$) and therefore was not included in the model. Similarly, garden watering was associated with mulching ($\chi^2 = 9.65$, df = 2, $p = 0.008$) and leaf litter cover ($\chi^2 = 20.65$, df = 4, $p = 0.0004$) and was not included in the model.

The odds of reporting frequent tick encounters in the yard was 9.5 times and 6.3 times greater for respondents that reported "frequent bandicoot sightings" and "frequent brush-turkey sightings" respectively, compared to those that did not report sightings of either animal (Table 2).

Table 2 Coefficient estimates (log odds), odds ratios (OR), and p-values of logistic regression models investigating the relationship between reported tick encounters (frequent encounters vs. no encounters) and a) yard traits (n = 219) and b) host sightings (n = 218)

a) Yard traits					
Predictors	Estimate	SE	Z	OR (CI 95%)	*p*
(Intercept)	-2.000	0.850	-2.354	0.14 (0.02 – 0.66)	0.019
Yard mostly grass or garden	0.955	0.302	3.168	**2.60 (1.45 – 4.75)**	**0.002**
Adjacent to bush	0.866	0.337	2.566	**2.38 (1.24 – 4.69)**	**0.010**
Daily yard time	1.642	0.805	2.039	**5.16 (1.14 – 28.98)**	**0.041**
Weekly yard time	0.857	0.843	1.017	2.36 (0.48 – 13.99)	0.309
Garden Mulching	0.106	0.308	0.345	1.11 (0.61 – 2.04)	0.730
Lush lawn no litter	-0.133	0.340	-0.389	0.88 (0.45 – 1.71)	0.697
Moderate to dense leaf litter	0.392	0.372	1.055	1.48 (0.72 – 3.09)	0.291
b) Host sightings					
(Intercept)	-1.959	0.644	-3.042	0.14 (0.04 – 0.47)	0.002
Frequent bandicoot sightings	2.247	0.445	5.051	**9.45 (4.06 – 23.39)**	**< 0.001**
Occasional bandicoot sightings	0.422	0.410	1.029	1.53 (0.69 – 3.45)	0.304
Frequent brush-turkey sightings	1.843	0.413	4.461	**6.31 (2.87 – 14.58)**	**< 0.001**
Occasional brush-turkey sightings	0.494	0.419	1.181	1.64 (0.72 – 3.77)	0.238
Frequent possum sightings	0.388	0.630	0.615	1.47 (0.44 – 5.34)	0.538
Occasional possum sightings	0.105	0.693	0.152	1.11 (0.29 – 4.53)	0.879
Frequent rat sightings	0.037	0.526	0.070	1.04 (0.37 – 2.95)	0.944
Occasional rat sightings	0.187	0.359	0.521	1.21 (0.60 – 2.45)	0.602

Traits in bold are statistically significant at the p<0.05 level

Importantly though, all the wildlife sightings were associated with another except for brush-turkey and rat sightings.

Drivers of host presence in yards

The odds of reporting frequent bandicoots sightings in the yard was 2.4 times greater for respondents that reported "Garden mulching" compared to those that reported no mulching. For respondents that reported owning a "cat and dog", there was a 70% decrease in the odds of reporting frequent bandicoot sightings in the yard (Table 3) compared to those that reported not owning a cat or dog. We excluded yard size and house type because they were associated with multiple variables in the model. We excluded watering because watering and mulching were associated with one another ($\chi^2 = 7.48$, df = 2, $p = 0.02$), and both activities may lead to increased moisture in gardens. Bandicoot sightings were not affected by whether cats (p = 0.36) or dogs (p = 0.24) were kept outside at night.

The odds of reporting frequent brush-turkey sightings in the yard was 8.8 times greater for respondents living "Adjacent to bush" compared with those that reported not living adjacent to bush. For respondents with "moderate to dense leaf litter" cover on lawns, the odds of reporting frequent brush-turkey sightings in the yard was 2.6 times greater compared to those that reported no litter on lawns (Table 3 and Fig. 3). A chi-square test showed that mulching area (10 -20 m^2 and > 20 m^2) was positively associated with frequent bush-turkey sightings ($\chi^2 = 20.30$, df = 2, $P = < 0.001$), but we excluded this variable from all models due to the large number of respondents that did not report on the area of mulch. We excluded variables yard type and watering from this model because these variables were associated with multiple variables in the model.

Landscape-scale drivers of tick encounters

There was a 50% decrease in the odds of reporting tick encounters in the yard with increasing "Distance to wet sclerophyll forest" (Fig. 4) whereas "Distance to dry sclerophyll forest" and "Distance to urban/exotic vegetation" were not associated with tick encounters in the yard (Table 4). We found no interaction between wet sclerophyll forest and bandicoot sightings, yet both variables were associated with tick encounters (Table 4). There was a 30% decrease in the odds of reporting tick encounters in the yard with increasing population density at 500 m (Table 3).

Discussion

We found that tick encounters and wildlife sightings in yards were common in a peri-urban tick endemic region of Australia. Importantly, we found that the presence of potential

Table 3 Coefficient estimates (log odds), odds ratios (OR) and p-values of logistic regression models investigating the relationship between yard traits and a) bandicoot sightings (n = 220) and b) brush-turkey sightings (n = 292) (frequent sightings vs. no sightings)

Predictors	Estimate	SE	Z	OR (CI 95%)	*p*
a) Bandicoot sightings					
(Intercept)	-0.865	0.988	-0.876	0.42 (0.05 – 2.96)	0.381
Yard mostly grass or garden	0.240	0.310	0.772	1.27 (0.69 – 2.35)	0.440
Adjacent to bush	-0.343	0.333	-1.030	0.71 (0.37 – 1.37)	0.303
Daily yard time	1.055	0.970	1.088	2.87 (0.43 – 23.81)	0.276
Weekly yard time	0.811	0.989	0.820	2.25 (0.32 – 19.19)	0.412
Garden mulching	0.875	0.308	2.845	**2.40 (1.32 – 4.42)**	**0.004**
Lush lawn no litter	0.472	0.356	1.326	1.60 (0.80 – 3.26)	0.185
Moderate to dense leaf litter cover	0.509	0.387	1.315	1.66 (0.79 – 3.61)	0.188
Cat and dog	-1.324	0.517	-2.560	**0.27 (0.09 – 0.72)**	**0.010**
Cat	0.046	0.472	0.097	1.05 (0.42 – 2.71)	0.923
Dog	-0.283	0.358	-0.792	0.75 (0.37 – 1.51)	0.428
b) Brush-turkey sightings					
(Intercept)	-1.582	0.999	-1.584	0.21 (0.03 – 1.38)	0.113
Townhouse	-1.285	0.820	-1.566	0.28 (0.05 – 1.22)	0.117
Adjacent to bush	2.178	0.345	6.316	**8.82 (4.63 – 18.03)**	**< 0.001**
Weekly yard time	1.016	0.979	1.038	2.76 (0.42 – 20.43)	0.299
Daily yard time	1.069	0.956	1.118	2.91 (0.46 – 20.74)	0.264
Garden mulching	-0.175	0.291	-0.602	0.84 (0.47 – 1.48)	0.547
Minimal litter	0.594	0.325	1.826	1.81 (0.96 – 3.46)	0.068
Moderate to dense leaf litter	0.938	0.378	2.481	**2.55 (1.23 – 5.43)**	**0.013**
Both	-0.569	0.486	-1.170	0.57 (0.21 – 1.46)	0.242
Cat	0.759	0.443	1.714	2.14 (0.92 – 5.25)	0.087
Dog	-0.188	0.315	-0.598	0.83 (0.45 – 1.54)	0.550

Traits in bold are statistically significant at the $p<0.05$ level

wildlife hosts, such as bandicoots and brush-turkeys, and landscape features, including living adjacent to bushland, distance to wet sclerophyll forest, and human population density, may be more important drivers of reported tick encounters than individual yard traits such as garden mulching and leaf litter cover on lawns. Those traits, however, likely influence host activity in yards.

Yards mostly compromised of green space and yards adjacent to bush were associated with frequent tick encounters in our study. This is possibly because yards with more greenspace are more likely to provide opportunities for tick survival and/or refuge or foraging opportunities for hosts. However, the type of greenspace matters given that ticks can be more abundant in forest and edge habitat on properties compared with lawns and ornamental plantings (Maupin et al. 1991; Frank et al. 1998). In our system, it is also likely bushland adjacent to yards provide refuge for tick hosts like bandicoots and rats (Cox et al. 2000; Chambers and Dickman 2002) and ticks on hosts visiting yards can then drop off, metamorphose, and bite people or pets for their next blood meal. In the United States, woodland on properties (Frank et al. 1998) or within 100 m of properties (Smith et al. 2001) is associated with high nymph density and increased Lyme Disease risk respectively. Similarly, tick abundance is higher on lawns adjacent to woodland compared to lawns adjacent to other lawns (Carroll et al. 1992). Although spending time in the yard daily (compared to monthly or hardly ever) was also a significant predictor of frequent tick encounters, this finding should be interpreted with caution due to the low sample size in the "monthly or hardly ever" category. Nevertheless, this finding is consistent with previous studies in the Northern Hemisphere investigating yard-scale drivers of tick encounters (Smith et al. 2001; Mead et al. 2018).

We found no association between frequent human-tick encounters and traits that can influence microclimate such as mulching in gardens or leaf litter cover on lawns (Vail and Smith 2002; Hubálek et al. 2004). This suggests that these traits alone may not be important drivers of tick encounters in yards. Removal of leaf litter in woodland surrounding a residential area can suppress nymphal tick density by more than 75% (Schulze et al. 1995) whereas leaf litter removal at the individual yard level may be less effective due to factors operating in neighbouring yards and in the broader

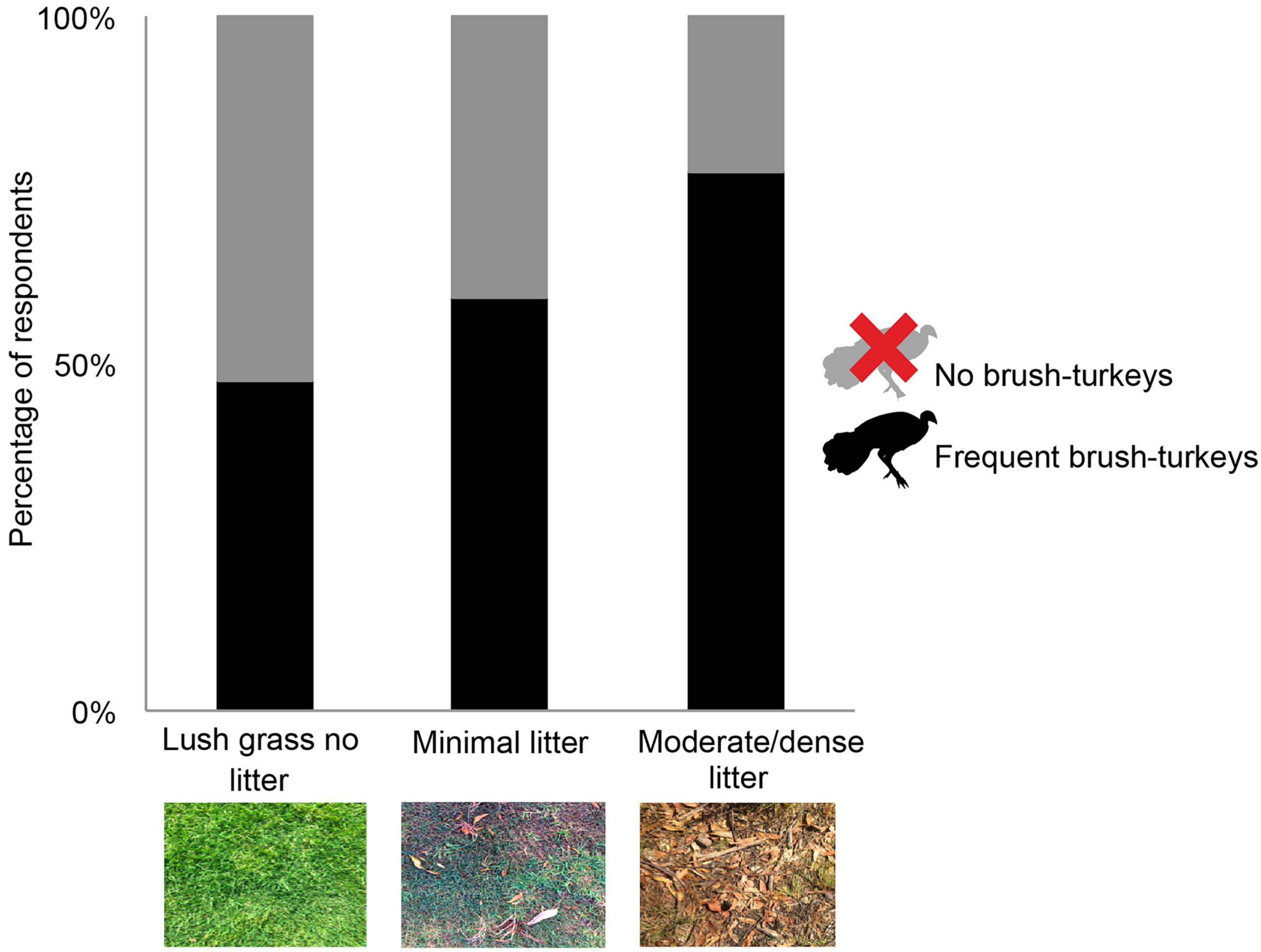


Fig. 3 A greater percentage of respondents with moderate to dense leaf litter on lawns see brush-turkeys frequently compared to those that have minimal or no leaf litter (images in Figure were provided to residents to select the category which best represents their lawn)

landscape. Indeed, a meta-analysis found that the risk of exposure to blacklegged ticks in the United States was greatest at the neighbourhood scale (the area within 500 m from the yard excluding the yard itself), compared to the yard scale or beyond the neighbourhood (Fischhoff et al. 2019a). The possibility of clearing leaf litter on a landscape scale, for example, creating a cleared buffer between bushland and residential areas, has not been explored in our system but could be an effective strategy if employed as part of an integrated control program (Schulze et al. 1995; Eisen and Dolan 2016).

Understanding how different vegetation types within bushland remnants influence tick abundance can aid decisions about where to target tick management strategies. We found residents near wet sclerophyll forest were more likely to report tick encounters in their yard suggesting that wet sclerophyll forest may provide suitable habitat for ticks or their hosts leading to tick encounters in nearby yards. The absence of reports of tick encounters near wet sclerophyll forest between the suburbs North Narrabeen and Newport (Fig. 2) likely reflects a lack of residential housing adjacent to that forest remnant. A possible explanation for our finding is that greater canopy cover, and thus moisture retention in the humus layer (Florence 2004) could provide suitable conditions for ticks during their time off-host increasing survival rates and leading to overall higher tick densities in wet sclerophyll forest compared to other vegetation types. Alternatively, increased bandicoot activity in wet sclerophyll forest remnants could explain increased tick encounters in those areas. Long-nosed bandicoots prefer forest and woodland over heath (Dexter et al. 2011), including areas with dense ground cover and fewer tree stems (Vernes 2003) which are two characteristics of wet sclerophyll forest. Further work into how these vegetation types influence microclimate for ticks will help explain how vegetation is a predictor of tick occurrence (Estrada-Peña et al. 2013). Nevertheless, local governments should prioritise public engagement

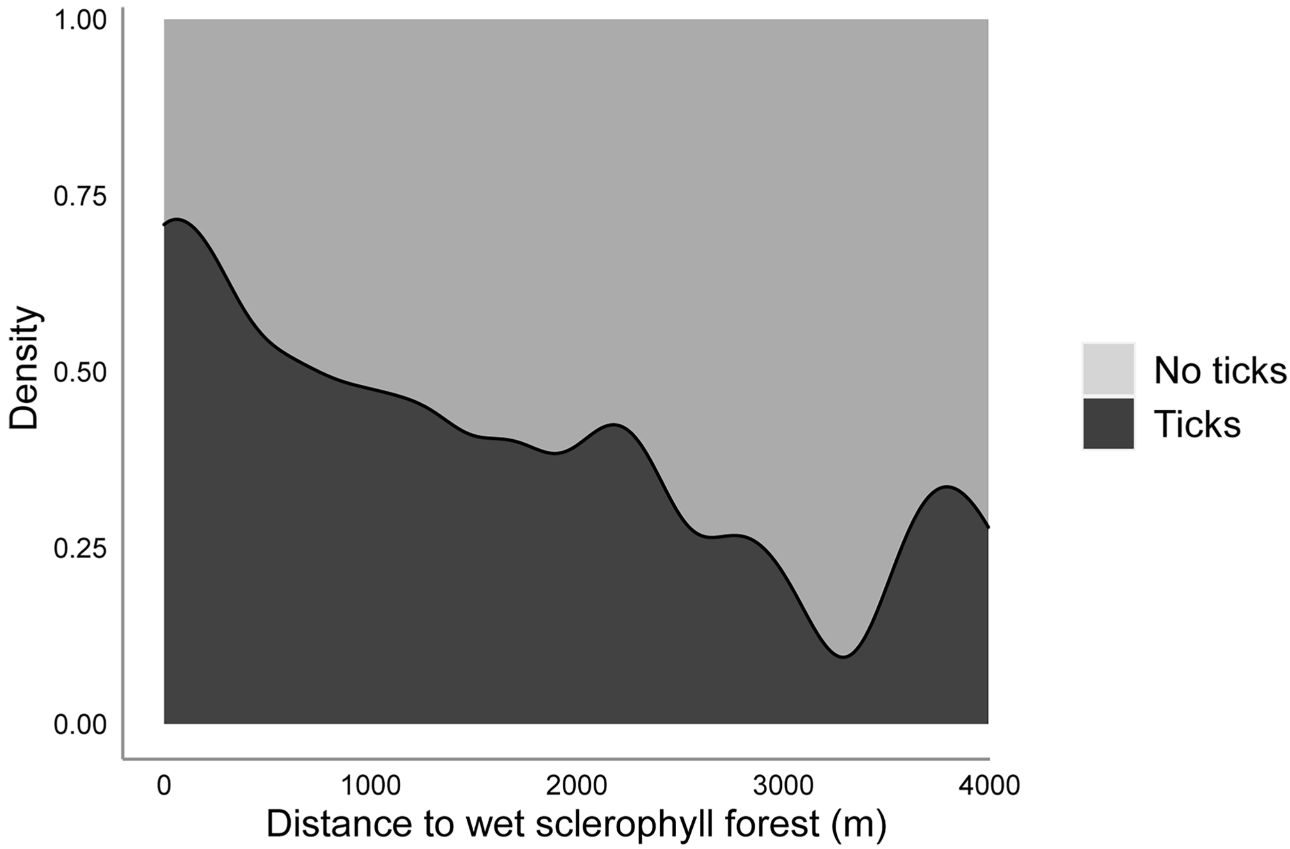


Fig. 4 Conditional density plot shows how conditional distribution of reported tick encounters (yes or no) changes as distance to wet sclerophyll forest (m) increases. Plot generated using cdplot function in R Studio

Table 4 Coefficient estimates (log odds), odds ratios (OR) and p-values of logistic regression models investigating the relationships between reported tick encounters (tick encounters vs. no tick encounters) and a) distance to vegetation (n = 474) and b) population density (n = 516)

a) Distance to vegetation					
Predictors	Estimate	SE	Z	OR (CI 95%)	*p*
(Intercept)	1.192	0.375	3.180	3.29 (1.61 – 7.03)	0.001
Distance to wet sclerophyll forest	-0.731	0.212	-3.45	**0.48 (0.31 – 0.72)**	**0.001**
Distance to dry sclerophyll forest	-0.315	0.383	-0.821	0.73 (0.35 – 1.58)	0.411
Distance to urban/exotic vegetation	0.216	0.931	0.232	1.24 (0.23 – 9.28)	0.817
Frequent bandicoot sightings	1.541	0.476	3.236	**4.67 (1.87 – 12.30)**	**0.001**
Occasional bandicoot sightings	0.367	0.384	0.955	1.44 (0.67 – 3.05)	0.34
Frequent brush-turkey sightings	0.028	0.303	0.093	1.03 (0.56 – 1.86)	0.926
Occasional brush-turkey sightings	0.182	0.322	0.565	1.2 (0.64 – 2.26)	0.572
Distance to wet sclerophyll forest: Frequent bandicoot sightings	0.358	0.337	1.062	1.43 (0.75 – 2.87)	0.288
Distance to wet sclerophyll forest: Occasional bandicoot sightings	0.456	0.270	1.689	1.58 (0.94 – 2.73)	0.091
b) Population Density					
(Intercept)	2.548	0.339	7.528	12.78 (6.7 – 25.33)	< 0.0001
Population density (100 m buffer)	-0.271	0.632	-0.428	0.76 (0.23 – 2.78)	0.668
Population density (500 m buffer)	-0.361	0.102	-3.528	**0.70 (0.57 – 0.85)**	**< 0.0001**

Traits in bold are statistically significant at the $p<0.05$ level with residents living near vegetation types associated with ticks to monitor awareness and uptake of personal protection strategies.

The decrease in tick encounters with increasing population density in our study suggests that highly urbanised areas are not suitable for tick survival likely due to the associated lack of habitat and hosts in general; a phenomenon that is probably consistent globally (Kilpatrick et al. 2017). The density of nymphs infected with *Borrelia* decreases with increasing urbanisation in Europe (Heylen et al. 2019), but tick-borne disease risk is highly variable and hard to predict in semi-urban fragmented or peri-urban areas due to the multitude of factors influencing ticks and tick-borne pathogen transmission (Kilpatrick et al. 2017).

Residents reported a range of potential wildlife hosts using their yard with 99.5% of respondents reporting observations of possums, bandicoots, or brush-turkeys. We suspect that reports of potential hosts will be strongly influenced by detectability. Possums are nocturnal but are large and often loud when moving along and sheltering in roofs. Brush-turkeys are active during the day and leave conspicuous scratchings in gardens while foraging and gathering leaf litter for their mounds. Bandicoots also commonly forage in open grassed areas (Scott et al. 1999), leaving conspicuous conical diggings easily identifiable to residents (Carthey and Banks 2012). A study in Western Australia found 80% agreement between residents and ecologists on the presence or absence of possums in yards as well as a high level of accuracy in residents' ability to distinguish between the two possum species, *Pseudocheirus occidentalis* and *T. vulpecula* (Steven et al. 2021). However, rats are more cryptic and we suspect they have been underreported in our study. Follow up camera trapping in a subset of yards for another study (n = 46) showed that 56% of residents who reported not seeing rats frequently in our survey reported on here had rats visiting their yard multiple times over a 3-day period (mean number of rat visits over 3 days = 9.91) (Taylor et al. 2023).

Despite wildlife hosts being widely observed across the study area, only conspicuous hosts including bandicoots and brush-turkeys were associated with frequent tick encounters. Whether the association between bandicoots and tick encounters is causal i.e., that bandicoot presence in yards leads to tick encounters is not clear. Long-nosed bandicoots are well known as tick hosts and there exists a strong perception that they are the primary host in the literature (Lydecker et al. 2015) and in the general community (Chen 2013). As a result, it is possible that residents may have been primed to associate bandicoot sightings with tick encounters in their yards and overlook other factors, for example, the presence of other urban hosts. Importantly, although we found no relationship between black rat sightings and reported tick encounters, camera trapping data showed black rats, known hosts of Australian ticks (Lydecker et al. 2019), were the most active small mammal in yards in our study area (Taylor et al. 2023).

It is unclear whether brush-turkeys are simply attracted to similar yard types as bandicoots or whether they influence tick dynamics. There are anecdotal reports and photographic evidence of fully engorged adult ticks attached to the head of a small number of brush-turkeys, but there have been no systematic investigations into brush-turkeys and ticks to our knowledge. Globally, Galliformes, which includes ground-feeding birds like turkeys, chickens, grouse, and jungle fowl, can host ticks (Lane et al. 2006; Scott et al. 2010) but also predate upon them (Duffy et al. 1992). It is possible that brush-turkey mounds play a role in tick dynamics given that ticks can be found on mounds (Birks 1992), possibly because mounds are a concentrated source of moisture and heat due to decomposing organic matter (namely soil and leaf litter) (Jones 1988a). However, we did not ask residents about the presence of mounds in yards. More field studies are needed to quantify the relative role of different urban tick hosts before decisions regarding host-targeted tick management.

Male brush-turkeys prefer to build mounds in areas with greater canopy cover, where adequate leaf litter and shade is present (Jones 1988a). This may explain the association between brush-turkey sightings and moderate to dense leaf litter cover on lawns and living adjacent to bush in our study. Brush-turkeys will even use other materials such as bark, lawn clippings and compost heap materials (Jones and Everding 1991) for mounds, which might explain the association between brush-turkey sightings and the use of mulch in gardens over an area greater than $20m^2$. Our findings suggest that yard management strategies like clearing leaf litter and avoiding the use of mulch could be implemented to discourage potential wildlife hosts rather than controlling host populations to reduce tick abundance in the environment. Field studies are needed to confirm that such strategies lead to a reduction in tick abundance.

Our finding that garden mulching was associated with frequent bandicoot sightings aligns with other work in Sydney that showed bandicoot sightings and diggings were positively associated with the use of mulch in yards. This finding was later confirmed with the experimental addition of mulch which led to more invertebrate food sources (Price 2013; unpublished). Similarly, our finding that bandicoots were less likely to be sighted frequently in yards with both a cat and dog, also aligns with earlier work that found bandicoot diggings were less frequent and in lower quantities in yards with dogs compared to yard without pets, suggesting that bandicoots perceive domestic dogs as a threat (Carthey and Banks 2012).

We did not explore human behavioural drivers of tick encounters such as wearing protective clothing or tick repellent. We have received anecdotal reports of residents engaging in both behaviours when spending prolonged periods of time in their yard, for example, while gardening. Future studies should ask questions about the type of personal protection used to understand the how human behaviour influences tick encounters in Australia. We also assumed that tick encounters reported here occurred in yards, but ticks may have attached to residents in other locations, such as parks or nearby reserves. Future surveys should incorporate demographic questions, such as age and gender that may affect yard activities and therefore tick encounter probability. Further, techniques such as flagging and counting ticks on hosts in yards could provide additional information on the risk of tick encounter in residential yards.

Our study provides the first extensive broad-scale dataset to associate wildlife sightings and tick encounters with yard and landscape traits in a peri-urban tick hotspot of Australia. The key associations we found provide testable hypotheses for field studies to explore the mechanisms driving urban tick encounters and inform tick management. We predict that broader landscape traits, such as living adjacent to bushland, proximity to wet sclerophyll forest, and the presence of hosts, are more important drivers of tick encounters compared to yard traits such as garden mulching and leaf litter cover on lawns. Nevertheless, given that yard traits like garden mulching, leaf litter cover and pets were associated the presence of hosts, we suggest residents may be able manage their yard to discourage hosts and in turn reduce tick abundance. Understanding the complex relationships between vectors, their wildlife hosts and the surrounding environment is key to devising effective management solutions in urban areas.

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Author contributions All authors contributed to the study conception and design. CT prepared the survey, analysed the data, and created figures and illustrations with input from PB, DH, and HL. The first draft of the manuscript was written by CT and all authors contributed to the final manuscript. All authors read and approved the final manuscript.

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Data availability Data will be made available on request.

Declarations

Conflicts of interest None.

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