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Peri-urban black rats host a rich assembly of ticks and healthier rats have more ticks

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ABSTRACT

The black rat *Rattus rattus* has a distribution that includes much of Earth's terrestrial surface, and has adapted to exploit both habitats extensively modified by humans and rural habitats. Despite the fact that *R. rattus* are nearly ubiquitous, few studies have investigated urban or peri-urban *R. rattus* as potential hosts for ticks. In this study, we identified the species of ticks that parasitize *R. rattus* in a remnant bush area within Sydney, Australia. We then examined the relationship between ticks and *R. rattus* by testing several rat body characteristics as predictors of tick abundance. We show that larva and nymphs of five species of native Australian tick parasitize *R. rattus* in urban Australia. The most abundance species was *Ixodes holocyclus*, a tick of veterinary and human health concern. We found that ticks were more abundant on *R. rattus* in better condition, for larva and nymphs of *I. holocyclus* and *I. tasmani*. *Rattus rattus* supports a rich assembly of ticks in a remnant forest in urban Australia, and as the *R. rattus* in best condition have the most ticks, tick parasitism at the levels observed does not appear to negatively impact *R. rattus*. Our findings illustrate that *R. rattus*, and other human commensal species, may be important hosts for ticks in human modified environments.

1. Introduction

Few animals are as intrinsically associated with disease in popular culture as rats. Rats, and specifically the black rat *Rattus rattus*, have been feared as spreaders of disease in the western canon ever since the plague (likely caused by *Yersinia pestis*) swept across Europe during the Black Death (Keeling and Gilligan, 2000; Zietz and Dunkelberg, 2004). *Rattus rattus* are well adapted to living in habitats that have been highly modified by humans, as well as those that have not (Hulme-Beaman et al., 2016); however *R. rattus* are rarely important hosts for ticks of public health concern. Nevertheless, *R. rattus* represents one of the most likely potential hosts for ticks in or near urban areas in much of the world. Human populations have rapidly increased and urbanized over the last two centuries, and this trend is likely to continue (Seto et al., 2012). While ticks are often associated with natural or rural habitats, ticks can persist and survive even in urban areas. In this context, it is important to investigate the ecological interactions between *R. rattus* and ticks. In this study, we explore interactions between *R. rattus* and ticks in an urban remnant forest in Australia.

We also investigated one of the key questions about tick and general parasite ecology: what factors make some hosts carry more parasites than other hosts in a population (Bize et al., 2008). There are numerous potential reasons why some hosts are either more susceptible to ticks or more likely to encounter ticks. Hosts with compromised immune systems or responses, or simply in worse body condition, may be less able to avoid or groom off parasites (Krasnov et al., 2005). In social animals (like *R. rattus*), individuals of lower social status may have less access to social grooming and thus suffer from higher parasite loads (Viljoen et al., 2011). To explore these questions, we tested the role of body condition, sex, and social status in predicting tick abundance on *R. rattus*.

In urban areas and adjacent remnant forests, introduced animals like *R. rattus* are far more abundant than native species, representing important potential hosts for the tick community in these areas. Native Australian wildlife, particularly smaller marsupials like the long-nosed bandicoot *Perameles nasuta* have been associated as hosts of the Australian paralysis tick *Ixodes holocyclus* (the most medically and economically significant tick in Australia) (Barker and Walker, 2014). However, few studies have investigated the relative importance of different host species in supporting *I. holocyclus* or most other tick species (Lydecker et al., 2015). *Ixodes holocyclus* has been found on *R. rattus* in both rural (Jackson et al., 2007) and urban (Lydecker et al., 2019) areas, however currently there is little information what species of ticks parasitize *R. rattus* in Australia, or even on the basic ecology of

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many tick species.

In this study, we investigated ticks feeding on *R. rattus* in a remnant forest inside of a major Australian city to identify what species of tick parasitize this introduced species. We also explored the relationship between ticks and *R. rattus* by testing the relationship between physical traits of *R. rattus* and tick abundance. We conclude by discussing several hypotheses that could explain our observations; and the implications of our results on the broader ecology of *R. rattus* and ticks in urban areas in Australia and around the world.

2. Methods

The setting for our study was North Head, a part of Sydney Harbour National Park. North Head is a 3.85 km^2 promontory that is in effect an island of remnant heathland and Eucalypt wet sclerophyll forest amidst the metropolis of Sydney. North Head is located directly adjacent to Manly, part of the Northern Beaches local government area, which is a region known for concerns about ticks (Lydecker et al., 2015). North Head is also home to many thousands of *R. rattus*, and was the site of historical rat culls to combat outbreaks of *Yersinia pestis* in the 1900s.

We examined ticks on 90 *R. rattus* culled during routine surveys of mammal fauna at North Head by the Australian Wildlife Conservancy (AWC) in June 2014 (30 rats) and July 2015 (60 rats). June and July are winter months, during which larva and nymphs are most abundant for ticks like *I. holocyclus* (Doube, 1979). Animals were trapped using wire-cage traps (65 cm × 22 cm × 22 cm) with a bait basket trigger mechanism baited with a peanut butter, oats, and honey (Petit and Waudby, 2012). Rats were euthanized using lethal injections of sodium pentobarbital or cervical dislocation by AWC staff. All animals were immediately placed into plastic Ziploc®-style bags post-mortem and frozen either individually, or as a group in the rare event that multiple rats came from one trap. As we were using animal cadavers not killed for the purposes of teaching or research, no specific ethical approval was required for this project.

We performed post-mortem examinations of *R. rattus* for ticks and measurements of several physical traits of *R. rattus*. After brief thawing to make manipulation of the specimens easier (approximately 20 min per specimen), we made initial measurements of rat morphometric traits for later analysis of their use in predicting tick burdens. We measured body weight using an electronic scale to the nearest 0.1 g. We recorded basic body measurements using callipers to 0.5 mm for pes length and a ruler to 1 mm for all other measures (body, head, and tail lengths). Sex was identified by examining external genitalia (Aplin et al., 2003). After examining each specimen for ticks, we also recorded visible lacerations or punctures of the epidermis that fit within descriptions of intraspecific conflict in rats (Takahashi and Lore, 1982), as a proxy for rat social status.

We also calculated body condition, which is a rough measure of relative body health – analogous to body mass index – frequently used in studies of rodents. We calculated a body condition index score by dividing the observed weight measurements by weight measurements predicted based upon body length using a log-log linear regression (Krebs and Singleton, 1993) modelled in R (R Development Core Team, 2008). We used a natural log to transform observed weight and length values for modelling the linear relationship and calculating body condition scores to stabilise variance (Krebs and Singleton, 1993). Using this calculation, individuals with scores less than 1 are in worse condition and individuals with scores higher than 1 are in better condition.

We systematically examined specimens for ticks for 30 min. Examination length was based on previous experience examining live *R. rattus* for ticks, and after consulting similar studies of ticks that used post-mortem examinations on small mammal hosts. We located ticks and other ectoparasites by brushing through the fur against the grain using a combination of gloved fingers ("palpation") and combing with forceps. Ticks were carefully removed using fine tip forceps. All ectoparasites, including ticks, fleas, and mites, were stored in vials with 70% ethanol for later identification.

We identified tick specimens to stage and species using morphological keys and a light microscope (Barker and Walker, 2014; Roberts, 1960, 1970). Morphological identification is very reliable with adults, however as nearly all of the ticks that we found were larva or nymphs, we had to rely on what information is present in the limited larval keys (Roberts, 1960, 1970), scant notes on nymph identification in publications, and comparison with the more complete adult keys (Barker and Walker, 2014). Reliable molecular assays for individual larva specimens are not currently available for Australian ticks. Therefore, the species identifications we have provided are best estimates based on current knowledge.

We calculated descriptive statistics for all of our data in Microsoft Excel. Of particular importance to parasites is index of dispersion (also known as variance to mean ratio), which is used as a measure of aggregation: we calculated index of dispersion for each stage of each species of tick that we found, as well as for pooled larva, nymphs, and total ticks observed.

In addition to presenting our observations of the ticks and other ectoparasites living on *R. rattus* in Sydney, we analysed the relationships between host traits and the number of ticks observed. We fit generalized linear models (GLMs) using Poisson regression to investigate how host body measurements (body, head, pes, and tail lengths as well as body weight) and the interactions between these measurements relate to the number of ticks on the host. We used negative binomial GLMs to test condition index score as a predictor of tick abundance. We used Pearson's Chi Squared test to determine if our categorical variables, sex and wound presence, were independent. We then used a binomial regression GLM to test sex and wound presence separately as predictors of tick abundance. As each tick life stage and species has unique ecology, we performed analysis individually for each combination of tick species and life stage, as well as in pooled larva, nymphs, and total ticks observed. All statistical analysis was done in R (R Development Core Team, 2008).

3. Results

From the 90 *R. rattus* that we examined, we found 838 ticks (Fig. 1). We found six species of tick, all of which are native to Australia. Over half (458, 54.7%) of the ticks that we identified were *Ixodes holocyclus*. Four other *Ixodes* species – *I. tasmani* (224, 26.7%), *I. hirsti* (139, 16.6%), *I. fecialis* (14, 1.67%), and *I. trichosuri* (3, 0.36%) – made up the rest of the ticks that we found, excluding one individual *Haemaphysalis bancrofti* larva (0.12%). Almost all ticks were either in either larval (459, 54.8%) or nymphal (378, 45.1%) stages, and we only found one adult (0.001%) *I. hirsti*. Some degree of tick parasitism was almost ubiquitous: only 8 *R. rattus* were found to have no ticks. The mean

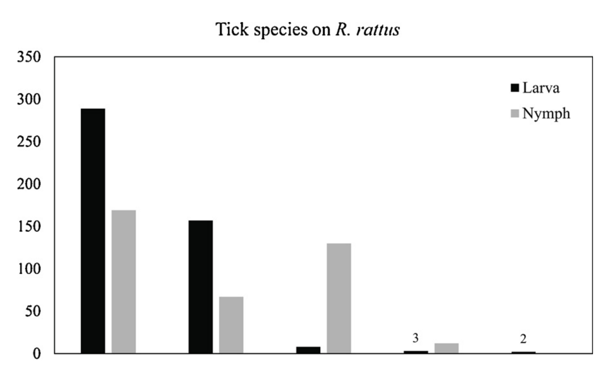

Fig. 1. The five most common species of tick found on *R. rattus* in an urban forest fragment, all of which belong to the genus *Ixodes*. For both *I. holocyclus* and *I. tasmani*, larva were more common than nymphs, as is expected during the Australian winter.

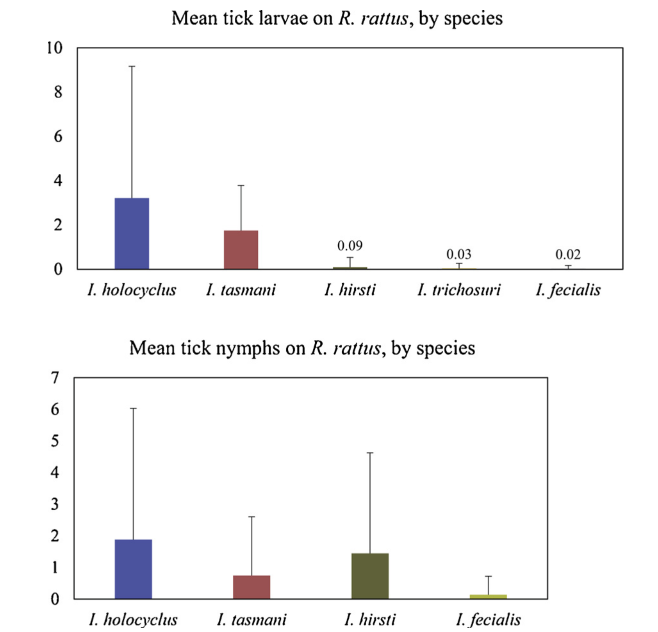

Fig. 2. Mean (± standard deviation) tick abundance for each species of tick for both larvae (A) and nymphs (B) is highly variable, with standard deviations much larger than the observed means.

number of ticks on *R. rattus* was 9.31.

We used index of dispersion to describe the distribution of ticks on *R. rattus* for each stage/species combination. As the standard deviations we observed were far larger than means (Fig. 2), index of dispersion was > 1, suggesting that the data follows a negative binomial distribution. *Ixodes fecialis* larva had an index of dispersion of 1, which normally suggests a Poisson distribution. As we only observed 2 *I. fecialis* larva, we also used a negative binomial distribution to describe this zero inflated dataset.

We fit GLMs using negative binomial distributions to predict the number of ticks on *R. rattus* using pes length, body length, and weight as possible predictors, and we tested interactions between all of these variables. No variables were significant individually; however body length and weight as well as pes length, body length, and weight were significant together (Table 1). However, due to high deviance (null: 807.89, df = 89; residual: 641.31, df = 82), these are relatively weak models.

There were significantly more ticks on *R. rattus* with above average condition than in those with below average condition ($F(45,43) = 4.831014$, $p < 0.001$) (Fig. 3). Using a negative binomial GLM, total tick abundance is significantly positively correlated with *R. rattus* condition ($F(1) = 6.069$, $p = 0.024$) (Fig. 3). However, when separating out ticks into larva and nymph for each species, only *I. holocyclus* and *I. tasmani* showed the same positive correlation with body condition (Table 2).

Table 1
Combined length and weight measures were significant explanatory variables for tick burden using a Poisson GLM.

Predictor	Estimate	Std. Error	z value	Pr(> |z|)	Significance
(Intercept)	5.89E+00	4.32E+00	1.364	0.1725	
Pes	−4.51E-02	1.60E-01	−0.281	0.7785	
Body	−6.63E-02	3.54E-02	−1.874	0.0609	
Weight	−9.74E-02	5.35E-02	−1.822	0.0685	
Pes:Body	1.42E-03	1.19E-03	1.197	0.2314	
Pes:Weight	2.70E-03	1.66E-03	1.626	0.1039	
Body:Weight	7.52E-04	2.93E-04	2.563	0.0104	*
Pes:Body:Weight	−2.00E-05	9.08E-06	−2.201	0.0277	*

* indicates significant at $p < 0.05$.

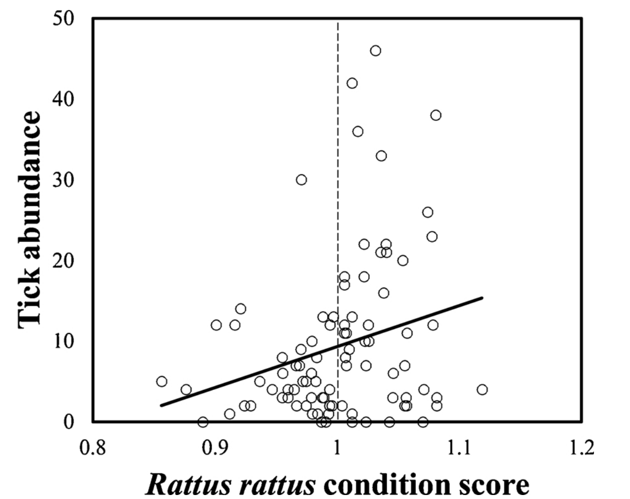

Fig. 3. *Rattus rattus* (n = 90) have significantly more ticks as body condition increases, based on linear regression (solid line). A condition score of 1 represents average condition (dashed vertical line), scores less than 1 represent below than average condition, and scores above 1 represent above average condition. Individual analysis for each stage and species of tick are in Table 2.

Table 2
Body condition is a significant predictor of tick abundance for total ticks, larvae, nymphs, as well as for two most common observed tick species.

	n	mean	Estimate	Standard Error	z value	Pr(> |z|)
All Ticks	838	9.311	6.194	2.168	2.857	0.00427**
All Nymphs	378	4.2	7.738	3.445	2.246	0.0247*
All Larvae	459	5.1	5.261	2.329	2.259	0.0239*
I. holocyclus	458	5.089	7.15	2.701	2.647	0.0081**
Nymphs	169	1.878	8.639	4.596	1.88	0.0602
Larvae	289	3.211	6.527	3.163	2.064	0.0391*
I. tasmani	224	2.489	5.531	2.18	2.537	0.0112*
Nymphs	67	0.744	14.874	4.65	3.198	0.0014**
Larvae	157	1.744	2.729	2.278	1.198	0.231
I. hirsti	138	1.533	4.217	4.776	0.883	0.377
Nymphs	130	1.444	3.535	4.838	0.731	0.465
Larvae	8	0.089	15.78	14.2	1.112	0.266
I. trichosuri	3	0.033	10.74	18.51	0.58	0.562
Nymphs	0	–	–	–	–	–
Larvae	3	0.033	10.74	18.51	0.58	0.562
I. fecialis	14	0.156	3.531	8.842	0.399	0.69
Nymphs	12	0.133	7.275	10.987	0.662	0.508
Larvae	2	0.022	−7.859	13.311	−0.59	0.555

* indicates significant at $p < 0.05$ and ** indicates significance at $p < 0.01$.

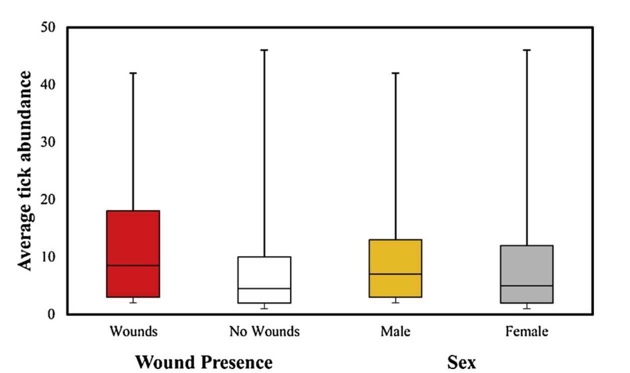

Fig. 4. The abundance of ticks on *R. rattus* can be predicted by wound presence ($z = 2.020$, $p = 0.043$), but not by sex ($z = -0.869$, $p = 0.385$). In both cases, tick abundance is highly variable.

Rattus rattus sex and wound presence were independent variables (X^2 (1) = 2.205, p = 0.138), so we analysed each separately. Wound presence was a significant predictor of tick abundance using a binomial GLM (z = 2.020, p = 0.043) (Fig. 4), however the small effect size and high variance make this result of questionable biological importance. Sex was not a significant predictor of tick abundance (z = -0.869, p = 0.385) (Fig. 4). GLMs using either variable had similar AIC values (123.07 for wound presence, 127.99 for sex). There was no difference in *R. rattus* condition between sexes (t (87) = 1.053, p = 0.295). Wounded *R. rattus* had significantly higher condition scores than those without wounds (f (49,39) = 1.776, p = 0.03).

4. Discussion

Our findings show that *R. rattus* hosts at least six species of native tick in a remnant forest inside of a major Australian city. The most abundant tick species, *I. holocyclus*, is the most medically and economically important tick species in Australia, and our study provides evidence that this tick can persist in an urban forest remanent and feed on *R. rattus*. Previous studies have found *I. holocyclus* on *R. rattus* outside of Brisbane (Doube, 1979) and in rural north eastern Victoria (Jackson et al., 2007), however ours is the first to find *I. holocyclus* parasitizing *R. rattus* within remnant bushland in a major city like Sydney. Because *R. rattus* is highly abundant in urban areas and the surrounding bush areas (approx. 10 rats/ha Banks et al unpublished), *R. rattus* may serve to support urban tick populations by providing food resources and potentially transporting ticks between habitat patches.

Unlike in our study, *Rattus rattus* are rarely found to either carry many ticks or play important roles in tick ecology. However, rodents in general are often important hosts for many species of tick. Many *Ixodes* ticks are generalists and can adapt to feed on different species of hosts depending on what hosts are available: in urban remnant forests *R. rattus* may provide a viable substitute host in lieu of whatever hosts the tick has evolved to use. Before Europeans brought *R. rattus* to Australia, native ticks such as *I. holocyclus* would have frequently interacted with native placental rodents like *R. fuscipes* and marsupial rodents like *Antechinus flavipes* (indeed both of these species are known to host *I. holocyclus* and several other Australian ticks). With introduced rodents like *R. rattus* replacing native hosts, Australian ticks would then need to adapt to surviving on introduced hosts. There are significant gaps in our understanding of the host preferences of many species of Australian tick, both in areas with more intact native host assemblages and highly modified urban and agricultural landscapes. However as rodent and small mammal species including *R. rattus* have been found to host all of the species of tick that we observed (Barker and Walker, 2014; Roberts, 1960), rodents and small mammals are likely important hosts for all of these tick species.

Tick ecology usually varies between tick species and stages; however, our results show that different stages and species of ticks can exhibit similar ecology. Two species of tick (*I. holocyclus* and *I. tasmani*) showed a similar response to host body condition for both nymphs and larva. This could be explained by several factors. First, these tick species may have similar preferences for hosts in both their larval and nymphal stages. Second, host preferences for these two ticks (both known to be relatively generalist (Doube, 1979; Murdoch and Spratt, 2005)) could be highly plastic, and driven purely by the high population density of *R. rattus* relative to any other potential host in the study area. Tick abundance did not show any association with host body condition for the other four tick species. This result could be driven by the low sample sizes that we obtained for all other tick species. In general, we found that tick abundance increased with *R. rattus* body condition, regardless of tick stage, suggesting that body condition preferences may not vary between tick stages.

Body size has frequently been positively correlated with tick parasitism (Kiffner et al., 2011; Ruiz-Fons et al., 2013), and our study provides further support for this pattern. Larger animals have more surface area than smaller animals, greater surface area provides more contact with vegetation, and in turn, more contact with questing ticks. Greater surface area also provides more space for potential tick attachment and reduces inter and intra specific competition for attachment site choice. Larger body mass may also provide a greater volume of blood, which could support more ticks – however the relationship between body mass and blood volume or pressure in wild rats is not clear.

While sex based differences in tick parasitism rates have been found in some cases (Ruiz-Fons et al., 2013), our study and others (Colombo et al., 2015; Kiffner et al., 2011; Vor et al., 2010) suggest that sex does not impact the number of ticks on a host animal. Sexual dimorphism in both biology and learned behaviour has been extensively studied in lab rats, however more in depth and long-term study is needed to untangle the relationship between *R. rattus* sex and tick abundance.

The positive correlation between *R. rattus* body condition and tick abundance that we observed can be explained by many potential reasons. Animals in better condition may be more active and utilize a greater home range, thus encountering more vegetation with active questing ticks. Animals in better condition may also be more socially and sexually active, which could lead to more movement and greater stress, which could detract from the individual's ability to groom and remove ticks. The link between stress and body condition is also supported by our finding that wounded rats were in better condition than rats without wounds. While we did find that rats with wounds had more ticks than those without, the effect size and variance make these results of limited biological importance. Finally, animals in better condition may be more attractive to ticks. Body condition is a relatively crude measurement (Green, 2001; Wilder et al., 2016), and without further study, it is difficulty to make broader conclusions about the mechanisms that drive the relationship between tick abundance and *R. rattus* body condition.

Globally distributed human commensal species, such as *R. rattus*, may be an important part in supporting tick and other ectoparasite populations in and near human modified habitats. Our study shows that multiple species of Australian tick, several of which are of importance to human or domestic animal health, will parasitize *R. rattus* in an isolated fragment of bush land within Sydney, Australia. Tick abundance on *R. rattus* increases with *R. rattus* condition, suggesting that *R. rattus* is able to effectively mitigate the negative impacts of tick parasitism. In the Anthropocene, ecological interactions between ticks and hosts will continue to shift. Species that are well adapted to using natural systems and human modified systems – like *R. rattus* – may provide a pathway for parasites to move between urban areas and non-urban areas (Loss et al., 2016). In addition, urban populations of human commensal species may be able to support emerging infectious diseases and their vectors within our cities (Hamer et al., 2012; Rizzoli et al., 2014). While rats may have an undeserved reputation for pestilence, they may serve an unwitting role in supporting urban tick populations.

Declarations of interest

None.

Author contributions

HWL designed and carried out the study, conducted data analysis, wrote and edited the manuscript, and developed figures. DFH and PBB assisted with study design, data analysis, writing, and editing the manuscript. PBB facilitated the research through providing the initial connection with the source of specimens.

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Data accessibility

The full data set used in this study is available on the Open Science Framework (Lydecker, H. (2018, September 19). Ticks of peri urban black rats in Sydney Australia. Retrieved from osf.io/4mcjq).

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