Ecological Applications

Article

The provision of basic urban services (BUS) in low-income Brazilian communities fails to neutralise environmental determinants of 'rattiness', a composite metric of rat abundance

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Key-words

Abundance metrics; basic urban services; local interventions; low-income urban communities; rattiness framework; Rattus norvegicus; urban rats; zoonotic diseases.

Abstract

Globally, low-income urban communities suffer from social and economic inequity, poor provision of services and degraded environments, making them home to many opportunistic zoonotic reservoirs, such as rats. While there are limited opportunities for large-scale infrastructural improvements in these contexts, targeted control of disease reservoirs has been achieved in some settings. Before adopting this strategy for urban rats, a starting point is to assess the impact of existing basic services on rat abundance. The evaluation of rat control is complicated by the absence of a gold-standard metric for rat abundance and studies often evaluate more than one metric, making results less interpretable. Herein, we address the question of whether basic urban services (BUS) – trash collection, rodenticide application and visits from health community agents – affect rat abundance in four low-income urban Brazilian communities by the unprecedent application of the *rattiness* framework – a recently developed geostatistical method for combining multiple abundance metrics which are not necessarily sampled at the same locations. *Rattiness,* our proxy for rat abundance, is the spatially continuous latent process which is common to all three metrics. In a cross-sectional study, we exploited spatial heterogeneities in the delivery of BUS in our study area to evaluate its association with the presence of rat signs, rat marks on track plates and live-trapped rats, individually, sampled at 560 locations. These imperfect metrics were then jointly modelled to explore the relationship between BUS and *rattiness.* All selected models included environmental and socioeconomic variables as baseline predictors for rat abundance. *Rattiness* proved to be a useful tool for pooling information between the three abundance metrics and was associated with a greater range of baseline predictors than any single metric. Rat signs and *rattiness* were positively associated with higher levels of BUS provision and environmental variables known to provide resources for rats. While we recommend

participative action in evaluating BUS, the evidence that baseline environmental variables (e.g., access to sewers, presence of uncontained trash and permeable soil) were strongly associated with rat abundance highlights the need for targeted, small-scale environmental modifications to reduce resources for rats.

Introduction

Many of the conditions which define informal urban settlements, currently home to more than a billion people, are linked to the poor provision of basic urban services (BUS) within these communities, such as trash collection, adequate sanitation infrastructure and access to clean water and health provision [1]. Inequities in the provision of BUS are part of a problem of historical exclusion in Latin America [2], not adequately addressed by local government policies, which are often short-term and designed to maximise visible outputs for political capital [3]. Further, socioeconomic vulnerability, insecurity of tenure and low levels of access to formal education contribute to reduced community mobilization towards demanding improved BUS [3]. The result is a disadvantaged urban environment, which combines poverty and social inequities, with little prospect of long-term change.

Here, too, the synanthropic fauna encounters its closest proximity to humans [4,5], as a (taxonomically and functionally) simplified, homogenized assemblage [6,7], including several reservoirs and/or vectors of zoonoses [6]. Of these, rats are the most successful and widespread [8]. In particular, conditions such as uncontained trash, access to water sources (e.g., puddles, leakages and open sewers), discarded construction material and abandoned houses present an abundance of food and shelter for rat populations in peridomiciliary areas [9-11].

The near-ubiquitous Norway rat, *Rattus norvegicus,* is one of the main reservoirs of *Leptospira* bacteria in the urban environment. Annually, there are more than one million cases of leptospirosis worldwide with 58,000 reported deaths, and informal settlement dwellers are among the most affected by the disease [12]. Norway rats are also carriers of many other micro- and macro-zoonotic parasites [13-15] and their presence has been shown to have a detrimental effect on both physical and mental health of local inhabitants [16,17]. Additionally, they can have a negative economic effect by damaging agricultural crops and stored food, and by destroying building structures [18-20]. As a result, the assessment and control of rat populations are common strategies for disease prevention. Control efforts in resource-rich informal settlement areas that are based on chemical control have been shown to be ineffective in the long term [21,22], but it should be noted that both the planning of such interventions and their evaluation are complicated by difficulties in measuring rat abundance itself.

In view of the impracticability of obtaining absolute numbers for rats, relative abundance and activity metrics are often pursued [23]. Given that there is no gold-standard metric for rat abundance, ecologists must balance the need to identify the most suitable metric for rat abundance with operational considerations (cost, ease of use and other practicalities) to obtain the most information from the chosen metrics [9,11,17,23,24]. Trapping methods, for example, need to ensure that there is a sufficiently long sampling duration and adequate site coverage to capture demographical variation in the population and ensure that the sample population is representative of the target population. Doing so, however, increases equipment and labour costs [25], but on the other hand, allows for the measurement of parasite load in rat populations, which is important for multidisciplinary eco-epidemiological approaches to disease control [15,26]. An alternative track plate method, which samples rat marks on pre-prepared plates, entails lower costs and can amplify site coverage, but provides a measure of activity rather than abundance [27]. Although systematic sampling using more than one metric is common, there are few methods for combining multiple abundance metrics whilst accounting for spatial correlation. The *rattiness* framework [28] was recently developed for this purpose, with the advantage that it allows metrics that are sampled at different locations to be jointly modelled as a single *rattiness* process - a proxy for rat abundance, defined to denote all ecological processes that are associated with animal abundance (both presence and activity) and that can be used to quantify exposure, including spatial variation in exposure, to a disease of interest when prevalence is high and homogeneously distributed across the reservoir population [29]. This is particularly useful when the application of different metrics is not possible at all sampling locations [23], or when measurement tools are lost (e.g., lost due to vandalism or weathering) – a common occurrence in urban informal settlements [27,30].

In this study, we address the question of whether BUS are associated with rat abundance in a Brazilian poor urban community by applying the *rattiness* framework to this problem for the first time. The combination of poor infrastructure and urban planning, as well as violence associated with drug trafficking and police raids, can limit the penetration of these services. High levels of variation in these factors over small areas means that service provision can also vary significantly within a single community. This variation provided us with an opportunity to evaluate whether the provisioning of BUS – here, trash collection, rodenticide application and visits from health community agents – was associated with a reduction in rat abundance, after controlling for environmental and socioeconomic factors measured using ecological surveys and through conversion into mapped variables. We first evaluated the association of BUS with each of our current and imperfect metrics (the presence of rat signs, rat marks on track plates, and live-trapped rats) individually. We then combined these three metrics to define a spatially continuous latent process common to all of them, *rattiness*, to be used as a proxy for rat abundance in the investigation of BUS effects. We expect that *rattiness* will provide more interpretable results than those for each individual metric taken separately and greater capability of representing with finer grain the effects of the environmental variables on rat populations, in contrast to the discrete presence/absence and count data from individual metrics. Ultimately, this study aims to provide tools to inform stakeholders of the need to modify current BUS protocols and routines, and may guide the implementation of new, locally feasible, interventions to control rat abundance (and associated zoonoses) in the informal settlements.

Materials and methods

Study area/provisioned BUS

The study area was located in the periphery of the city of Salvador, Bahia – the third largest city of Brazil, with approximately 3 million inhabitants. The area included four different informal settlements, ranging from 0.07 to 0.09 km², within the neighbourhoods of Marechal Rondon, Alto do Cabrito, Rio Sena and Nova Constituinte. Three of the sites have significant gradients in elevation within them (Figure 1), with lower areas situated near open sewers and the highest areas characterized by better quality housing with good access to main thoroughfares. The exception, Nova Constituinte, is a flat area which is not close to main thoroughfares and has a wetland in the centre.

Insert the map here

Figure 1. Map of the sampling areas, with elevation gradient.

In Salvador, the frequency of trash collection service can vary from daily (77%), to twice or three times a week [31]. The service takes place directly, door-to-door, or indirectly, when the waste is deposited in a street container, being later collected by the urban cleaning service. The decisison for an indirect trash collection is mainly determined by the accesibility of the trash collection truck [31]. As part of Brazil's National Primary Care Policy, the health community agents have as main tasks to develop activities for health promotion, disease prevention and health surveillance, through individual and collective educational actions in the citizens households and in their community [32]. In the visits, the health communtiy agents guide the families on the use of available health services, and it is expected that more vulnerable areas are visited with higher frequency (monthly). While the health community agents have as their core task the dissemination of health and hygiene education, the endemic diseases combat agents are more focused on the prevention and control of infectious diseases such as Dengue, Zika and leptospirosis [33]. In Brazil, the Centres for the Control of Zoonosis (CCZ) are the responsible for this task and, focusing on rodent control, CCZ agents follow standard protocols and conduct chemical interventions together educational actions in areas usually associated with risk of rodent-borne diseases [34,35].

Study design/Data collection

The study was cross-sectional, with data georeferenced and collected between April-June 2018 (wet season) (rat abundance variation between seasons was not expected, Panti-May, Carvalho-Pereira [30]). Three different rat abundance metrics were obtained, namely rat marks on track plates, rats caught in live traps and removed, and presence of rat signs (faecal droppings, trails and active burrows), with sampling following protocols previously described and validated [27,30]. A team of 4 pairs of technicians composed by student interns and two collaborator agents from the Centre for the Control of Zoonoses (CCZ) was trained and directly supervised by two PhD managers to conduct the field sampling. In each area, placement of the track plates always occurred before the live trapping, so that removal of rats would not affect the recording of rat marks.

Initially, 95 locations were selected by spatially continuous restricted random sampling (≥20m apart) for the track plates sampling in each site, with an additional 5 ‘close-pair’ locations (≤5m distance from existing locations) to distinguish between short- and long-range spatial variation and underlying noise in the geostatistical model. In-field validation was conducted by the team to ensure that locations were at accessible public spaces. Similarly, 40 spatially randomized household points in each site were selected for the live trapping, and in-field validation ensured that locations were at domiciliary backyards. The sampling timeline and effort can be found in Figure 2a, with further details on protocols described in Figure 2b.

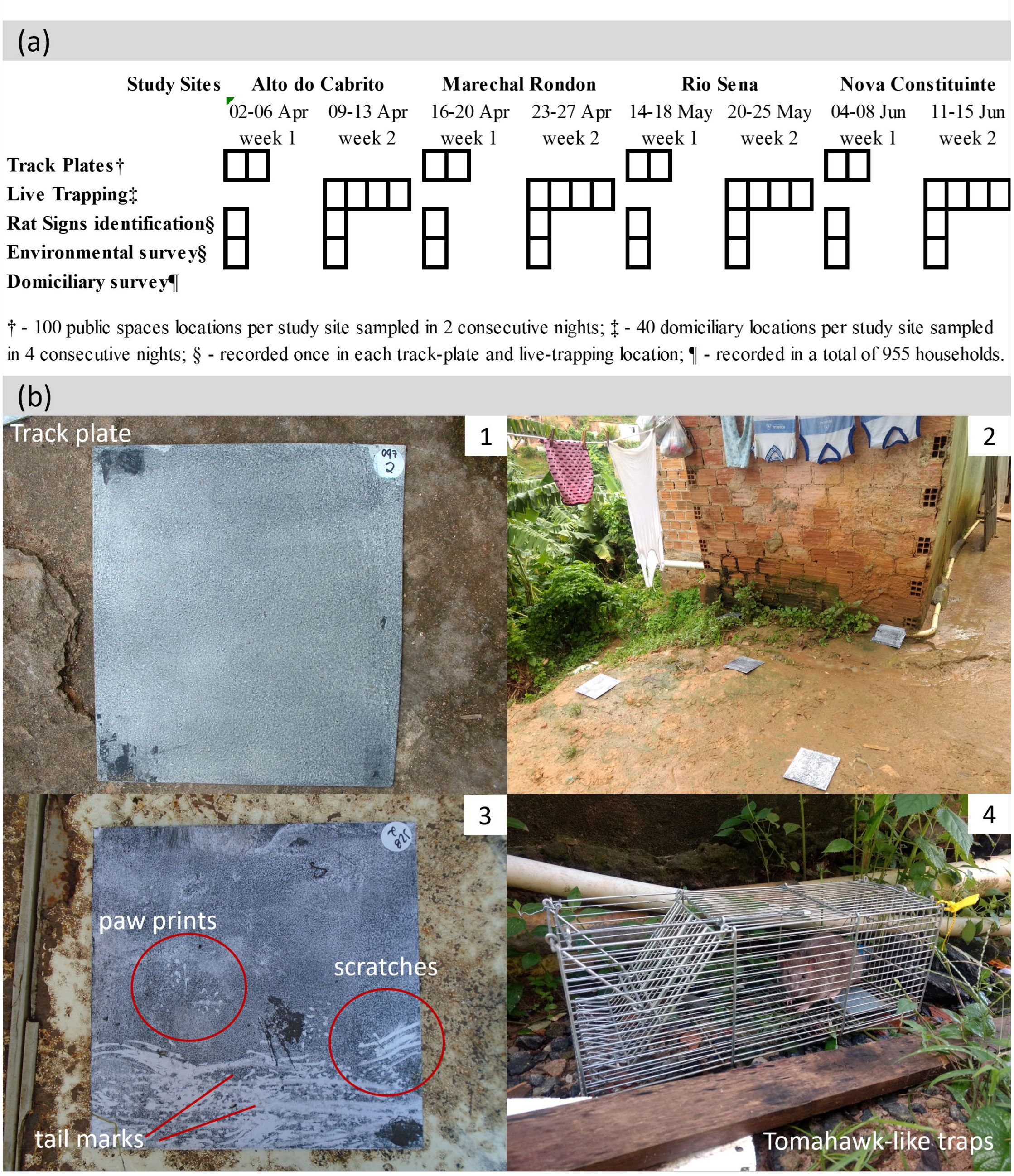

Figure 2 – a) Timeline of the study. Each box represents the number of in-field days each sampling lasted. Numbered annotations disclaim the effort applied. b) Sampling and tools. Five polyvinyl plates painted in lampblack-alcohol solution (1) were set in each location (n = 100 per site) in a diamond shape (2), checked and photographed after each night. Photographs were analysed by two independent observers to identify rat marks (3). Two Tomahawk-like traps, baited with a sausage slice, were placed within the peridomicile area in each location (n = 40 per site) and verified after each night for the

presence of rats (4), in which case traps were replaced. Live rats were transported to an open lab for euthanasia and collection of the tissues of interest for associated studies [36].

At each track plate and live trapping location, the team conducted an ecological survey once within an area with a 10m radius from the geolocated point to identify the presence of trails, faecal droppings and active burrows. When a location had at least one record of one of the above, it was considered positive for rat signs. In addition to the rat metrics, environmental and domiciliary questionnaires were completed to obtain information on baseline factors that could predict rat abundance and concerning the BUS provision (Fig. 2A). While the rat signs survey was conducted, data were collected within the 10m-radius circle for several environmental variables which have previously been reported as predictors of rat occurrence, such as presence of food resources (e.g., organic trash and pet food); availability of harbourage (e.g., accumulated construction material or inorganic rubbish, and permeable soil); and presence of water resources (e.g., open sewers) [11,37].

In the domiciliary survey, 955 previously censored households over the four sampling sites were surveyed regarding the local provision of BUS. The head of the household was approached by the team to answer closed questions concerning specifically the occurrence of visits from health community agents (proxy for health and hygiene education) and agents from the CCZ (proxy for rodenticide application) in the six months previous to rat sampling, and the provision of trash collection (if existent, and, where existent, if truck- or street container-based).

Additional sources of environmental information which were identified as being potentially relevant to rat occurrence were converted into mapped variables using QGIS [38]. Elevation (metres) was calculated for each sampling location relative to the bottom of its respective study site (resolution of 5m by 5m) and this was also used to calculate the three-dimensional distance between each sampling location and public trash piles. Land cover data were created by applying the maximum likelihood supervised classification tool in QGIS to WorldView-3 satellite images (resolution of 0.3m by 0.3m) taken on 28th May 2017. This classification was then used to derive a variable for the proportion of pervious land cover (vegetation, bare soil and water) within the 10-metre radius of each sampling location.

All the data were recorded in an online real-time database (REDCap). This work had approval by the Ethical Committee of the Animal Use (CEUA) protocol 019/2016 of IGM – Oswaldo Cruz Foundation (Fiocruz) and by the Committee of Ethics in Research of the Institute of Collective Health – Federal University of Bahia (UFBA) – nº041/17, nº protocol 2.245.914.

Statistics

Definition of response variables

The binary presence of rat signs variable was modelled using a logistic regression. Both the rat trap and track plates variables had repeated measurements at each location (4 and 2 sampling nights in total, respectively), and were modelled using generalized linear mixed models (GLMMs) with a random effect included at the placement location. For the binary rat trap variable, the rat trapping process was modelled as an inhomogeneous Poisson process where an empty closed trap was assumed to have closed halfway through the trapping period to account for the problem of closure of traps without a rat (due to other animals or tampering with the trap). This was achieved using a GLMM with a complementary log-log link function with an imputed time offset of log(0.5) for empty closed traps. The binomial track plates variable was modelled as the number of positive track plates out of the total number of plates remaining after each 24hr period, using a

GLMM with a binomial error function. Study site was controlled for as a fixed effect for all three response variables.

For the joint modelling of the three response variables, the geostatistical *rattiness* framework (Eyre et al. 2020) was used with *rattiness* considered to be a real-valued and spatially continuous stochastic process representing rat abundance. Details of its calculation are provided in Appendix S1: Section S1.

Definition of baseline predictors and first stage modelling

Information obtained in the environmental questionnaire was converted to environmental variables – potential resources for rats – to be assessed as rat abundance predictors: access to sewer, type of ground, presence of uncontained trash, accumulated material, pet food and vegetation. For the mapped variables – namely pervious land cover, distance to trash piles and elevation – we used Generalized Additive Modelling (GAM) to check whether their relationship with each link function-transformed single outcome response variable was approximately linear to determine whether the inclusion of a linear spline was necessary. The proportion of pervious land cover and elevation variables showed evidence of non-linearity for the rat signs outcome and elevation for the track plates outcome, and so knots were included at 40% of pervious land cover in the rat signs model, and 25% of elevation in each of these models (see Appendix S2: Figures S1-S3). Given the nature of locations of the track plate sampling, socioeconomic predictors based on household features would not be applicable to all single outcomes. Therefore, the mapped variable 'elevation' was used in this study as a proxy for socioeconomics, given that higher elevation areas are less prone to flooding than the lower, bottom-of-the-valley areas, and thus, more valuable [4].

Then, the set of surveyed and mapped variables (Table 1) was used in the stage one model selection process for a global multivariable model to identify important environmental and socioeconomic determinants associated with rat abundance in the urban communities, as per *a priori* expectations (Costa et al 2014; Santos et al. 2017). For each single outcome (rat signs, rat marks on track plates, rats trapped), model selection was performed by backward elimination – considering a threshold Akaike information criterion value of 2, corrected for small samples (AICc) [39] – and most parsimonious models were obtained. The final models for each outcome were then used as baseline models of rat abundance for the subsequent inclusion of BUS variables in a stage two model selection and assessment of our hypothesis.

Basic urban services (BUS) variables and second stage modelling

Four local BUS variables were created from the domiciliary survey questions. To reflect the provision of BUS more realistically, a buffer of 30m radius was defined at each sampling location, increasing the coverage of households which reported on BUS. The health and CCZ agent visit survey questions, were converted to proportions of surveyed households within the buffer which reported a visit (Table 1). For the two trash collection survey questions (trash truck collection and street container use), the same procedure was followed. A likelihood-ratio test was performed to define which of the two trash collection variables would be selected for the multivariable modelling stage.

To investigate the effect of BUS on rat abundance, the three BUS variables were added into each single outcome baseline model and backward elimination on BUS variables was performed to obtain a final model (with both baseline and BUS variables) for each outcome. To account for housing density, the number of households within the 30m buffer was also included as a covariate.

Joint modelling in the *rattiness* framework

In the joint model for abundance, all the variables present in the most parsimonious single outcome models were included in the *rattiness* model, after verification of collinearity. To check for collinearity between the selected variables we followed the exploratory methods detailed by Eyre, Carvalho-Pereira [28] and fitted a simplified *rattiness* model without covariates that did not account for spatial correlation and predicted *rattiness* at each unique location. A linear regression model was then fit to this mean predicted *rattiness* and all of the selected variables were included as covariates. The Variance Inflation Factor (VIF) was then calculated using the *car* R package. No variables were found to have VIF>5 and all were consequently kept in the model.

To test for evidence supporting the use of all three indices in the joint model we followed the methodology described previously [28]. We fitted four independent rattiness models, one with all three indices and the other three models each with one index left out. We then carried out likelihood ratio tests to test this (see Appendix S1: Section S2), with all three yielding p-values less than 0.0001, supporting the use of a joint model for all three indices.

All statistical analyses were performed in R [40], using the packages tidyverse, lme4, MuMin and DHARMa [41-44]. Model fitting for the *rattiness* model followed the method described by [28] and confidence intervals for the *rattiness* parameters were estimated by parametric bootstrapping.

Results

Trapping data were obtained from 157 locations (representing 98% of the trapping total locations), after an effort of 1209 trap-nights, which resulted in 63 rats trapped. Track plate information was recovered from a total of 372 points (93% of the sampling total), but only 33 were positive for rat marks on at least one of the verification days. Finally, rat signs information was collected in 529 sampling points, with 40% found to be positive. Loss of points and measurement tools were a result of certain locations being inaccessible for verification, or tools being lost or damaged by vandalism.

Results for the final single outcome models can be seen in Table 2. The probability of finding rat marks on track plates was not associated with any of the variables considered. The probability of finding a rat in a trap was only associated with the elevation of trap location relative to the bottom of each study site (Figure 3a). For each metre increase in elevation (relative elevation in the four communities ranged from 0m to 63m), the probability of trapping a rat per unit of time decreased by 5% (0.95, 95% confidence interval, CI 0.91 – 0.99). In contrast, the probability of finding a rat sign was positively associated with access to a sewer (OR 3.63, 95% CI 1.91 – 7.13), presence of uncontained trash (OR 1.88, 95% CI 1.22 – 2.92) and availability of pet food (OR 4.05, 95% CI 2.50 – 6.65) (Figure 3b). In terms of land cover, the odds of finding a rat sign were 3 times higher (OR 3.21 95% CI 1.62 – 6.74) in areas identified in the survey as being earth/mixed ground relative to fully paved areas.

BUS variables were only significantly associated with rat signs. Each 10% increase in the proportion of households visited by CCZ agents in the previous 6 months was associated with 1.2 times higher odds of finding rat signs (OR 1.18, 95% CI 1.09 – 1.28), while an increase of 10% in the proportion or households using street containers as a trash collection service was associated with 1.1 times increase in the chance of finding rat signs (OR 1.09, 95% CI 1.01 – 1.18). The summaries of the model selection processes are available in Appendix S3: Tables S1 and S2.

All the environmental variables associated with the single outcomes were significantly associated with *rattiness,* a real-valued, continuous outcome, in the geostatistical model

(Figure 3c). Access to sewer was associated with a 0.43 increase (95% CI 0.37 – 0.54) in the mean of *rattiness*, the presence of uncontained trash with a 0.11 increase (95% CI 0.02 – 0.21), and availability of pet food with a 0.21 increase (95% CI 0.10 – 0.32). An earth-mixed ground cover was associated with a 0.52 increase (95% CI 0.36 – 0.67) in the mean of *rattiness*, compared to fully paved ground. In addition, each 10% increase in the proportion of pervious land cover was associated with a 0.09 increase (95% CI 0.05 – 0.13) up to a threshold of 40%, after which the estimate was close to zero. Each metre increase in elevation, however, was associated with a decrease of 0.01 (95% CI -0.002 – -0.02) in the mean of *rattiness*.

Two of the BUS variables considered were significantly and positively associated with *rattiness*, with each 10% increase in either the proportion of households visited by CCZ agents in the previous 6 months or the proportion of households using a street container as a trash collection service associated with an increase of about 2.5% in the mean value of *rattiness.* Detailed results are shown in Table 3. There was evidence of residual spatial correlation not explained by the included explanatory variables, with an estimate for the scale of spatial correlation of about 96.0 metres (95% CI 52.6 – 149.9). This corresponds to a spatial correlation range (the distance at which the correlation reduces to 5%) of approximately 290m. The proportion of households visited by health workers in the previous 6 months was not significantly associated with any of the abundance metrics.

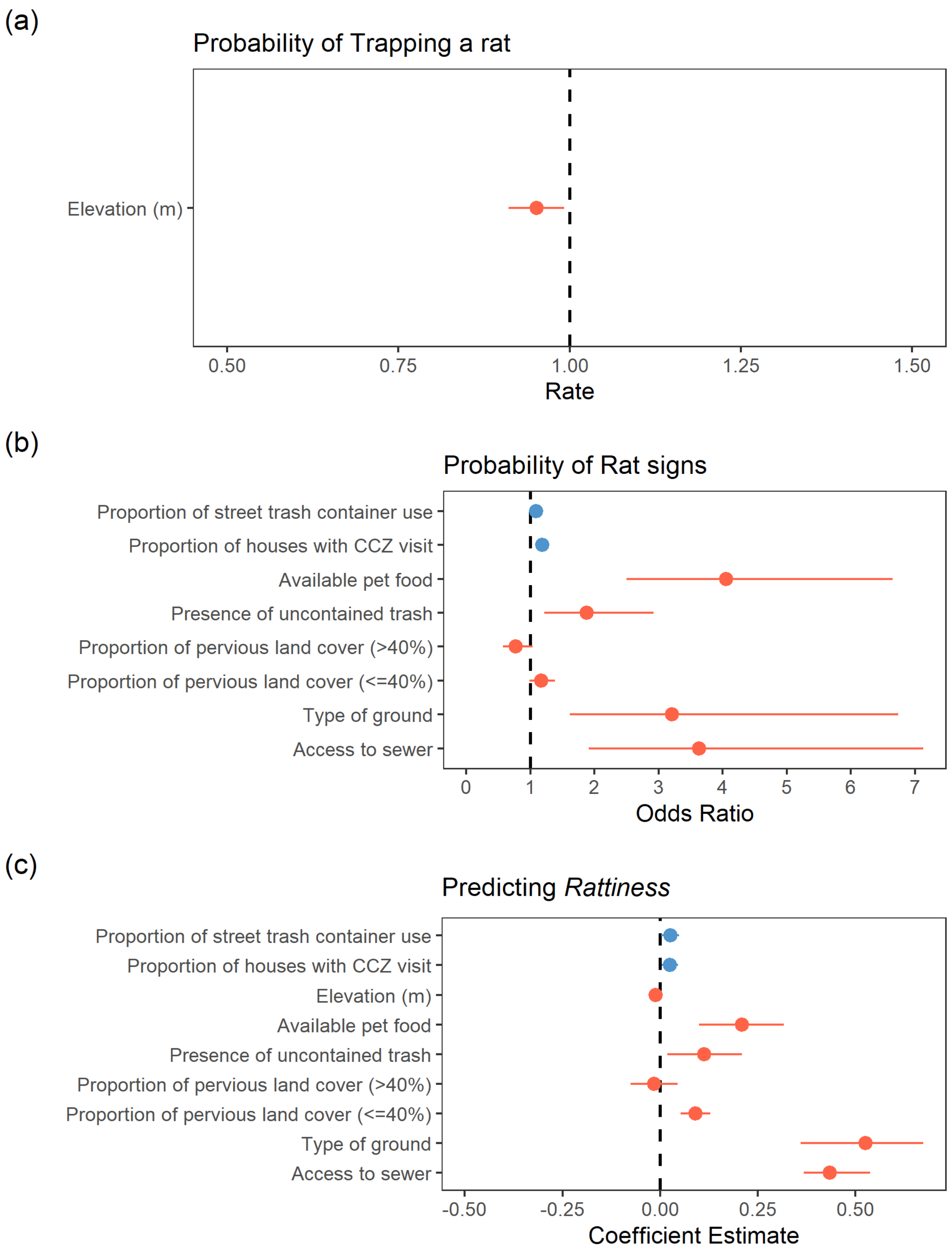

Figure 3 – Predicted results of the single outcomes (a, b) and *rattiness* (c) models. Baseline predictors are found in red and BUS in blue.

Discussion

In this study we found that both rat signs and *rattiness* were positively associated with higher levels of BUS provision and environmental variables which are known to provide food sources and harborage, including access to a sewer, presence of trash in the vicinity of the point and presence of earth-mixed ground (relative to fully paved terrain). In contrast, rat traps were only associated with elevation and track plates were not found to be associated with any variables. This study is the first to evaluate the association between BUS provision and rat abundance and is novel in using a combination of multiple imperfect metrics of abundance within the *rattiness* framework to assess the effects of environmental, socioeconomic and BUS on urban rat populations.

The fact that all three metrics were included in the final *rattiness* model shows that their measurements were sufficiently correlated to contribute to the *rattiness* process. We hypothesize that the rat traps and plates were not significantly associated with environmental variables due to a lack of statistical power (a common problem), but nonetheless, *rattiness* proved to be a useful and robust tool for pooling information between the three metrics. It was also more sensitive in detecting the effects of environmental variables, which was reflected in the breadth of variables included in the model.

The estimated residual spatial correlation range in the *rattiness* model of approximately 290m is about twice the average home range for rats in urban settings, yet still well within the known range of spatial exploration recorded for urban rats [45]. This figure, though, is significantly larger than the estimate of 40m in a previous application of the *rattiness* framework in a low-income community in Salvador [28]. This can be explained by the use of survey questions here to collect environmental variables, which appear to be more effective at capturing small-scale variation between points than the remotely sensed variables used in Eyre, Carvalho-Pereira [28]. This is supported by the fact that the survey variables here were more strongly associated with *rattiness* than the remotely sensed variables in Eyre, Carvalho-Pereira [28].

The finding that rat populations were more abundant in areas with higher levels of BUS provision may appear surprising but is likely to be a result of how these services are provided. For example, for trash collection, the use of a street container (a solution to the difficulties in access for collection trucks) may itself provide a resource for rats. Hence, the fact that the effect of trash containers on *rattiness* is small could actually be a positive sign that, while not providing a definitive solution to the impact of trash presence and accumulation, the containers are mostly successful in curbing the potentially more serious impact of diffuse refuse. This suggests a possible pathway to affect *rattiness* through participative action with the implementation of measures to reduce the residence time of trash – for example, the formation of teams or cooperatives that can transport the trash normally discarded in a street container into areas covered by daily garbage-truck routes. This could have the triple benefit of: i) reducing rat presence and infestation (and its associated disease burden); ii) generating employment; and iii) improving community integration, health and well-being. Alternatively, in adopting a participative action strategy, other solutions could be discussed and defined locally with the community members.

Rodenticide application programs for rodent control and/or eradication, despite being standard practice, are known for their limitations in effectively eliminating the target populations due to neophobia, allowing for population rebounds between baiting campaigns, and selecting populations resistant to the active ingredient in the baits, as well as for collateral risks such as bioaccumulation in the ecosystem and low target specificity [46]. Baiting programs also typically lack effectivity evaluations, and tend to be designed with little to no basic knowledge of the target population [11,36]. Clearly, the present results highlight the need for further work to understand how CCZ control is carried out and for studies designed to evaluate its effectiveness, as well as the need to evaluate other control methods that can be deployed (e.g., community-led sewer closing) to ensure that resources are being used efficiently to combat rodent-related health issues. For the health community agent visits, a reason why they may have a limited impact on rat abundance could be that the health education provided focuses more on resident individual prevention practices and self-protection, rather than ensuring high level of hygiene in the local environment, but could be expanded to include the latter.

Another reason why the BUS provision examined in this study may not have been able to drive down rat populations is that they need to be accompanied by large-scale improvements in the environmental conditions in the community. Our finding that baseline environmental variables, other than uncontained trash in the vicinities, such as presence of open sewers and ground coverage, were strongly associated with rat abundance indicates that trash collection, CCZ and health agent visits might be insufficient to reduce rat density in such a resource-rich environment. Nonetheless, our results are part of growing evidence for the need of targeted, small-scale environmental interventions to reduce access to resources, such as road pavement, maintenance of vacant lots [36] and increased rate of garbage removal and barriers to its access by rats [47], in addition to reducing access to available water sources [48]. It is also important to stress that the intensity and frequency of management activities have been found to be responsible for lowering rat density even in areas with environmental characteristics highly favourable for infestation [37], and should be considered together with the deployed measures when planning a pest management program.

A limitation of this study was its observational and cross-sectional design, which meant that we were only able to identify associations between existing provision of BUS and rat abundance, rather than test for any causal effects. However, this study explores new ways to quantify BUS service provision and describes its association with rat abundance while controlling for known environmental predictors of abundance and is an important first exploratory step in understanding the role of BUS in rodent control. Our ability to accurately characterise BUS provision was complicated by a lack of official documentation of service provision by local government and public health agencies, highlighting the difficulties faced in accurately measuring BUS provision in these low-income urban contexts. Consequently, we had to estimate BUS provision from residents' survey responses but sought to minimise potential biases in responses by aggregating their values across surveyed households within an area (30m radius from each sampling point) for which we assumed that BUS provision would be unlikely to vary. Clearly, the strength of our inferences about associations between rat abundance and BUS provision are conditional on the validity of these BUS variables and future studies should build on this work to validate BUS provision proxies and explore alternative options for quantifying service provision before rigorously testing their impact on abundance.

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218987/Z/19/Z and National Institutes of Health (US) Grant number:1 R01 TW009504 to FC.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' contributions

Our study was part of a larger study called 'Optimal control strategies for rodent-borne zoonoses in Brazilian slum settlements' funded by the Medical Research Council (UK), which had as main objective to suggest and implement new, low-cost and creative local solutions to mitigate the problem of rats and related diseases in low-income Brazilian urban communities, involving the communities' residents through participative action. Both, larger and the present study, involved a multicultural and multidisciplinary team, bringing together scientists of different countries – Brazil included – who have been engaged from the beginning and, therefore, who could bring their different perspectives to the research and ultimate goals.

In this study, Ticiana Carvalho-Pereira, Max T. Eyre, Hussein Khalil, Peter J. Diggle, Emanuele Giorgi, Federico Costa and Michael Begon conceived the ideas and/or designed methodology; Ticiana Carvalho-Pereira, Caio G. Zeppelini, Hussein Khalil, Ricardo Lustosa, Vivian F. Espirito Santo, Diogo C. Santiago, Roberta Santana and Fabiana Almerinda G. Palma collected the rat, environmental and basic urban services data; Marbrisa Reis, Ricardo Lustosa and Max T. Eyre georeferenced the locations and provided the mapped data; Ticiana Carvalho-Pereira and Max T. Eyre analysed the data; Ticiana Carvalho-Pereira designed the figures (except for the maps) and tables; Ticiana

Carvalho-Pereira, Max T. Eyre and Caio G. Zeppelini led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Table 1: Environmental and socioeconomic variables – accounted for in the assessment of basic urban services (BUS) effects on rat abundance, as well as BUS proportion variables.

	Variable	Origin	Type	Description
Baseline†	Access to sewer	surveyed	binary	presence of sewer, which could vary between an open/broken manhole or a water body (movement/accessibility for rats)
	Type of ground cover	surveyed	categorical (fully paved; earth-mixed)	source of shelter
	Pervious land cover	mapped	proportion	proportion of earth, vegetation and water by the total land cover in a 10m radius (source of shelter)
	Uncontained trash	surveyed	binary	presence of uncontained trash (food source) in the vicinity of the point
	Distance to trash piles	mapped	continuous	distance in metres from the sampling point to the closest accumulated trash pile (food source)
	Accumulated material	surveyed	binary	presence of either construction material or inorganic rubbish accumulated in the vicinity of the point (source of shelter)
	Pet food	surveyed	binary	availability of food for pets (food source) in the vicinity of the point
	Vegetation	surveyed	binary	source of food and shelter
	Elevation	mapped	continuous	distance in metres from the sampling point to the bottom of its respective study site (proxy for socioeconomics‡)
BUS§	CCZ agents visit	surveyed	proportion	sum of the households which reported visits from agents of the Centre for the Control of Zoonoses for rodenticide application 6 months prior to the rat sampling by the total of households in the buffer
	Health community agents visit	surveyed	proportion	sum of the households which reported health workers visits (health/hygiene education) 6 months prior to the rat sampling by the total of households in the buffer
	Truck-based trash collection	surveyed	proportion	sum of the households which reported truck-based trash collection service by the total of households in the buffer
	Street container trash collection	surveyed	proportion	sum of the households which reported use of street containers as trash collection solution by the total of households in the buffer

† - Except for elevation and distance to trash piles, all the baseline variables were assessed for a 10m radius relative to the centre of the geolocated sampling point.

‡ - The urban communities considered as study sites are usually located in valleys, with the lowest areas coinciding with proximity to open sewers – more prone to flooding, whilst the highest areas with proximity to the main avenues also characterized by better quality housing.

§ - Collected in a 30 m radius of the geolocated sampling point.

Table 2 – Final models of the probability of occurrence of each single outcome.

Model	Variable	OR/Rate (95% CI)	sig.
Live Trapping	Intercept	0.074 (0.025 - 0.180)	***
	Elevation (m)	0.952 (0.911 - 0.992)	*
	site_*Marechal Rondon*	0.431 (0.139 - 1.274)	
	site_*Nova Constituinte*	0.764 (0.265 - 2.251)	
	site_*Rio Sena*	2.616 (0.550 - 13.508)	
Rat signs	Intercept	0.008 (0.002 - 0.028)	***
	Access to sewer within 10m	3.634 (1.910 - 7.128)	***
	Earth-mixed ground	3.207 (1.618 - 6.742)	**
	Proportion pervious land cover (<=40%)†	1.168 (0.986 - 1.386)	.
	Proportion pervious land cover (>40%)†	0.772 (0.572 - 1.037)	.
	Presence of uncontained trash within 10m	1.882 (1.217 - 2.924)	**
	Presence of pet food within 10m	4.050 (2.504 - 6.647)	***
	Proportion of houses with CCZ visit in 30m†	1.182 (1.090 - 1.285)	***
	Proportion of trash container use in 30m†	1.088 (1.008 - 1.177)	*
	Number of households in 30m	1.079 (1.005 - 1.160)	*
	site_*Marechal Rondon*	2.250 (1.100 - 4.655)	*
	site_*Nova Constituinte*	1.722 (0.773 - 3.890)	
	site_*Rio Sena*	1.175 (0.619 - 2.246)	
Track Plates	--	--	--

OR - Odds Ratio; Sig. - significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1–.

† estimate associated with a 10% increase in the proportion variable.

Table 3 – Summary of the geostatistical model for *rattiness.*

Parameter/Variable	Estimate (95% CI)	$p<0.05$
$\alpha1$	1.125 (0.913, 1.340)	
$\alpha2$	-1.145 (-1.294, -1.006)	
$\alpha3$	-0.430 (-0.556, -0.304)	
$\sigma1$	0.914 (0.421, 1.306)	
$\sigma2$	1.804 (1.666, 1.953)	
$\sigma3$	3.084 (2.987, 3.187)	
Access to sewer within 10m	0.434 (0.367, 0.537)	x
Earth-mixed Ground	0.525 (0.360, 0.673)	x
Proportion pervious land cover (<=40%)†	0.090 (0.053, 0.128)	x
Proportion pervious land cover (>40%)†	-0.016 (-0.075, 0.044)	
Presence of uncontained trash within 10m	0.113 (0.019, 0.209)	x
Presence of pet food within 10m	0.209 (0.100, 0.316)	x
site_*Marechal Rondon*	-0.586 (-1.139, -0.044)	
site_*Nova Constituinte*	-0.391 (-0.914, 0.130)	
site_*Rio Sena*	-0.051 (-0.633, 0.570)	
Elevation (m)	-0.011 (-0.020, -0.002)	x
Proportion of houses with CCZ visit in 30m†	0.025 (0.004, 0.046)	x
Proportion of trash container use in 30m†	0.026 (0.003, 0.049)	x
Number of households in 30m	0.042 (0.019, 0.066)	x
Residual Spatial Correlation (φ) (m)	95.972 (52.607 - 149.940)	x

$\alpha1$, $\alpha2$ and $\alpha3$ (and $\sigma1$, $\sigma2$ and $\sigma3$) denote the coefficients for Rat Signs, Live Trapping and Track Plates, respectively.

† estimate associated with a 10% increase in the proportion variable.