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Basic urban services fail to neutralise environmental determinants of 'rattiness', a composite metric of rat abundance

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Abstract
Globally, low-income urban communities suffer from poor provision of services and degraded environments, favouring opportunistic zoonotic reservoirs, such as rats. Large-scale infrastructural improvements in these contexts are limited, but targeted control of disease reservoirs has sometimes been achieved. A starting point for the targeted control of rats is assessing the impact of existing basic services on rat abundance. However, there is no gold-standard metric for rat abundance, and studies have used different or multiple metrics. Here, therefore, in four low-income urban Brazilian communities, we address the question of whether basic urban services (BUS) – trash collection, rodenticide application and health community agent visits – affect rat abundance, through the first application of the *rattiness* modelling framework. This recently-developed geostatistical method combines multiple abundance metrics (here, three) to generate *rattiness,* a proxy for rat abundance, a spatially-continuous latent process common to all metrics. In a cross-sectional study, we exploited spatial heterogeneities in BUS to evaluate its association with the presence of rat signs, rat marks on track plates, and live-trapped rats, and with *rattiness*, which combined these three imperfect metrics. *Rattiness* proved to be a useful tool for pooling information among the three 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. The strong association of baseline environmental variables with rat abundance highlights the need for targeted, small-scale environmental modifications to reduce resources for rats.

Keywords Abundance metrics · Basic urban services · Low-income urban communities · Local interventions · *Rattiness* model · *Rattus norvegicus*

Introduction

Many of the conditions which characterise informal urban settlements, currently home to more than a billion people worldwide, 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 (UN-HABITAT 2016). Inequities in the provision of BUS are part of the historical problem of exclusion of people in Latin America (De Ferranti et al. 2003). Typically, such exclusion is

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not adequately addressed by local government policies, which are often short-term and designed to maximise visible outputs for political capital (Jones et al. 2014). Further, socioeconomic vulnerability, insecurity of tenure, and low levels of access to formal education contribute to reduced community mobilization towards demanding improved BUS (Jones et al. 2014). 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 (Hagan et al. 2016; Walsh 2014), as a taxonomically and functionally simplified, homogenized assemblage (McKinney and Lockwood 1999; McKinney 2002), including several reservoirs and/or vectors of zoonoses (McKinney and Lockwood 1999). Of these, rats are the most successful and widespread (Morand et al. 2015). 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 (Childs et al. 1998; Costa et al. 2014a; Santos et al. 2017).

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 1 million cases of leptospirosis worldwide with 58,000 reported deaths, and informal settlement dwellers are among the most affected by the disease (Costa et al. 2015). Norway rats are also carriers of many other micro- and macrozoonotic parasites (Carvalho-Pereira et al. 2018; Costa et al. 2014b; Rothenburger et al. 2017) and their presence has been shown to have a detrimental effect on both physical and mental health of local inhabitants (Battersby et al. 2008; Byers et al. 2019a). Additionally, they can have a negative economic effect by damaging agricultural crops and stored food, and by destroying building structures (Almeida et al. 2013; Montes De Oca et al. 2017; Singleton et al. 2003). As a result, the assessment and control of rat populations are common elements of disease prevention programs. Campaigns in resource-rich informal settlement areas based on chemical control have often been shown to be ineffective in the long term (de Masi et al. 2009; Fernández et al. 2007), 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 difficulties of obtaining absolute numbers for rats, relative abundance and activity metrics are often used (Cavia et al. 2012), but there is no gold-standard metric for rat abundance. Hence, ecologists must balance the need to identify the most valuable metric for rat abundance with operational considerations (cost, ease of use and other practicalities) to obtain the most information from the metrics available (Byers et al. 2019a; Cavia et al. 2012; Childs et al. 1998; Costa et al. 2014a; Himsworth et al. 2014). Trapping methods, for example, need to ensure that there is a sufficiently long sampling duration and adequate site coverage to ensure that the sample population is representative of the target population, but doing so increases equipment and labour costs (Byers et al. 2019b). On the other hand, such methods allow for the measurement of parasite load in rat populations, which is important for multidisciplinary eco-epidemiological approaches to disease control (Khalil et al. 2021; Rothenburger et al. 2017). 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 (Hacker et al. 2016).

Systematic sampling using more than one metric is common, but there are few methods for combining multiple abundance metrics whilst accounting for spatial correlation. The *rattiness* framework (Eyre et al. 2020) is a multivariate geostatistical modelling framework that 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. The *rattiness* process is a latent spatial process that is common to all of the metrics and is considered 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 throughout the reservoir population (Eyre et al. 2022). *Rattiness* values are driven by the value of both the rat abundance metrics and a spatial stochastic process and can consequently be considered a composite measure of these variables. This is particularly useful when the application of different metrics is not possible at all sampling locations (Cavia et al. 2012), or when measurement tools are lost (e.g., lost due to vandalism or weathering) – a common occurrence in urban informal settlements (Hacker et al. 2016; Panti-May et al. 2016).

In this study, we address the question of whether BUS are associated with rat abundance in an impoverished urban community in Brazil 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

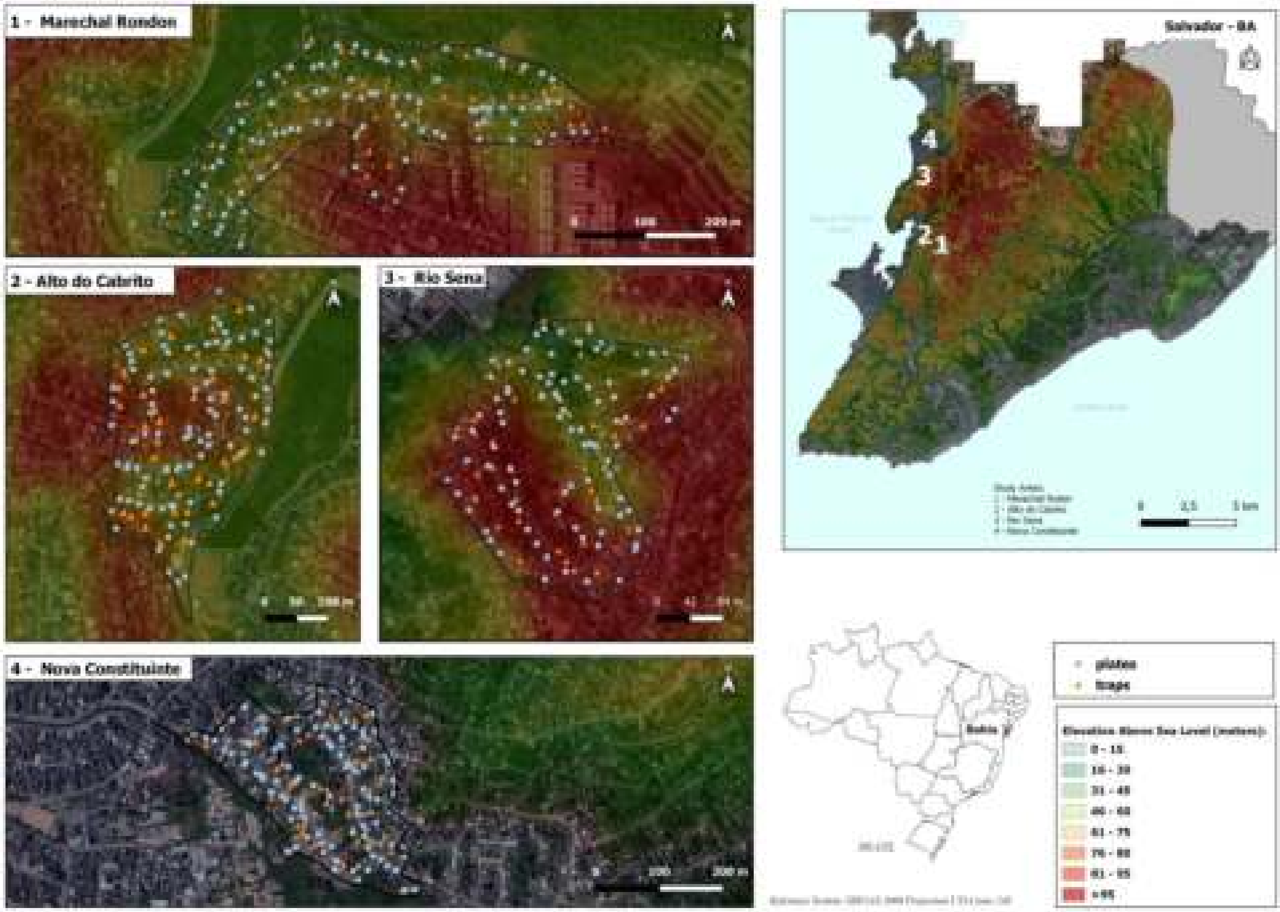

Fig. 1 Map of the sampling sites and locations, with elevation gradient. Track plate locations can be found in light blue circles, and live trapping locations in orange triangles in each study site (rat signs were surveyed in all the sampling locations)

application and visits from health community agents – was associated with a reduction in rat abundance, after controlling for environmental 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, and then evaluated its association with *rattiness*. We expect that *rattiness* will provide more interpretable results than those for each individual metric taken separately, and will have greater capability, with finer grain resolution, of representing 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 such 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 km^2, 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 (Fig. 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.

In Salvador, the frequency of trash collection service can vary from daily (77%), to twice or three times a week (Salvador 2022). 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 decision to use indirect trash collection is mainly determined by the accesibility of the trash collection truck (Salvador 2022). As part of Brazil's National Primary Care Policy, the health community agents have, as their 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 communities (Brasil 2012). In the visits, the health community agents guide the families on the use of available health services, and it is expected that more vulnerable areas will be visited with higher frequency (monthly). Separate agencies are more focused on the prevention and control of infectious diseases such as Dengue, Zika and leptospirosis (Torres 2009). In Brazil, the Centres for the Control of Zoonosis (CCZ) are responsible for this task and, focusing on rodent control, CCZ agents follow standard protocols – designed to screen a whole community area, identifying households in need for rat control through the identification of rat signs and resources for rats - to conduct chemical interventions together with educational actions in areas usually associated with risk of rodent-borne diseases (Brasil 2002; Pertile et al. 2022).

Study design/data collection

The study was cross-sectional, with data georeferenced and collected between April–June 2018 (the wet season, though variation in rat abundance between seasons was not expected as shown in a nearby community (Panti-May et al. 2016)). 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 (Hacker et al. 2016; Panti-May et al. 2016), as further detailed in Fig. 2. A team of 4 pairs of technicians comprising student interns and two collaborator agents from the CCZ was trained and directly supervised by two 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 (≥20 m apart) for the track plates sampling in each site, with an additional 5 'close-pair' locations (≤5 m 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 (≥15 m apart) 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 Fig. 2a, with further details on protocols described in Fig. 2b.

At each track plate and live trapping location, the team conducted an ecological survey once within an area with a 10 m 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 BUS provision and on baseline environmental factors that could predict rat abundance (Fig. 2a). While the rat signs survey was conducted, data were collected within the 10 m-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) (Costa et al. 2014a; Traweger et al. 2006).

In the domiciliary survey, 955 previously censused households over the four sampling sites were surveyed regarding the local provision of BUS. To ensure the reliability of the obtained information, the head of the household was identified – individuals aged 18 or older who has responsibilities in the household or who is viewed by the other family members as the central figure – given he/she makes decisions related to the family's health and is the primary individual accessed during visits by the healthcare agents, and census surveys carried out by the Brazilian Institute of Geography and Statistics (IBGE) for socioeconomics and household conditions (Brasil 2014; IBGE 2013). 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 for rodenticide application in the 6 months prior 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 (QGIS 2016). Land cover data were created by applying the maximum likelihood supervised classification tool in QGIS to WorldView-3 satellite images (resolution of 0.3 m by 0.3 m) 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-m radius of each sampling location. Elevation (metres) was calculated for each sampling location relative to the bottom of its respective study site (resolution of 5 m by 5 m) and this was also used to calculate the three-dimensional distance between each sampling location

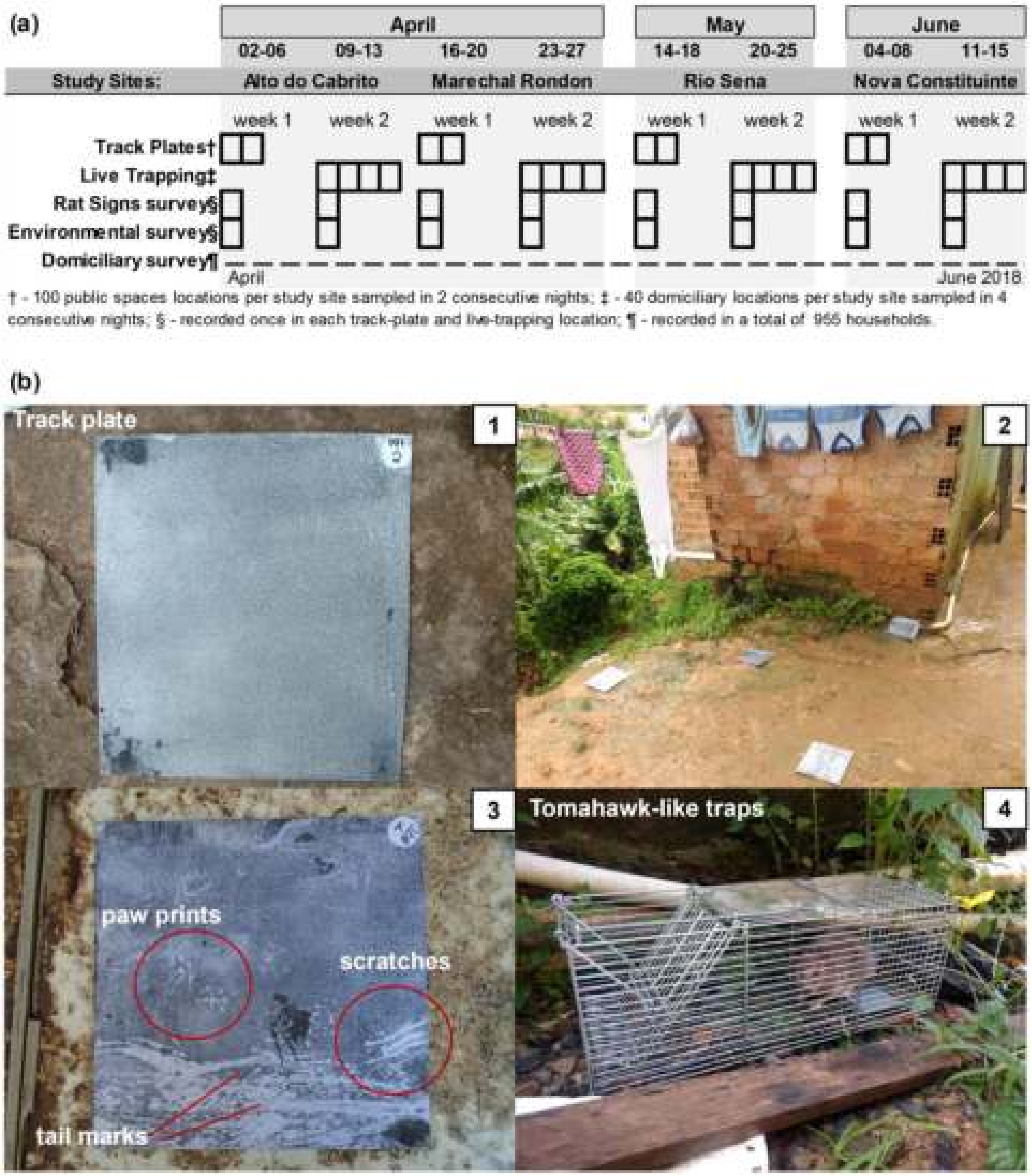

Fig. 2 **a** Timeline of the study. Each box represents the number of in-field days each sampling lasted. Numbered annotations disclaim the effort applied. **b** Sampling and tools. Five polyvinyl plates painted in lampblack-alcohol solution (1) were set in each location in a diamond shape, usually against walls or curbs (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 and verified after each night for the presence of rats (4), in which case traps were replaced. Live rats were transported to a field laboratory (Mills et al. 1995) for euthanasia and collection of the tissues of interest for associated studies (Zeppelini et al. 2020). Photo credit: Ticiana Carvalho-Pereira

and public trash piles. Elevation was considered in the analysis because it has been shown to be an important predictor of rat abundance in this setting (Eyre et al. 2020) and is known to capture spatial variation in household socioeconomic status, environmental degradation and flooding risk within similar neighbouring communities (Hagan et al. 2016; Eyre et al. 2022), three variables that are challenging to measure.

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) – n°041/17, n° protocol 2.245.914.

Statistical analysis

The frequency of positive locations for rat signs and for rat marks on track plates, and the trap success (Cavia et al. 2012) were calculated. For the statistical modelling, the following steps were followed: i) variable selection was performed for each rat abundance outcome separately, considering just environmental variables first and then basic urban services (BUS) variables, with estimates reported for the final models for each outcome; ii) selected variables across the three models were included in the joint *rattiness* model and model estimates were reported. Detailed description of the statistical models used and modelling steps is presented below.

Definition of rat abundance single outcome models

In this section we describe the three rat abundance outcomes and the univariate models used to model each of them separately, with an overview provided in Table 1.

The presence of rat signs outcome is a binary indicator taking value 1 if at least one sign of rat infestation was found and 0 otherwise. We model the probability of finding a sign of rat infestation, μ_1, using logistic regression of form $log\{\mu_1/(1-\mu_1)\}=d^T\beta$, where d are a set of explanatory variables and β are their corresponding regression coefficients.

The rat trap outcome is a binomial variable representing the number of traps in which rats were captured. To account for trap malfunctions (due to other animals or tampering with the trap), the same methodology used previously (Eyre et al. 2020; Eyre et al. 2022) was used, with the times of rat captures from a trap assumed to follow a time-varying inhomogeneous Poisson process with intensity $t\mu_2$, where t is the time (in days) for which a trap is operative and we define $log\{\mu_2\}=d^T\beta$. It follows that the probability, p, of capturing a rat is $1-exp\{-t\mu_2\}$. If a trap is found closed without a rat, we assume that the trap was disturbed and impute $t=0.5$ based on our best guess that it closed halfway through the trapping period. In all other cases, we set $t=1$. This outcome was modelled as a binomial regression with a complementary log-log link function such that $log\{-\log(1-p)\}=d^T\beta+\log(t)+Z$, where Z is an intercept-only normally-distributed zero-mean random variable included to account for repeated measurements at each location (4 sampling nights per location).

The track-plate outcome is a binomial variable representing the number of track-plates with rat markings out of the total number of plates remaining at each location after each 24 hr. period (track plates can be lost or moved during this period). We model the probability of a positive track-plate, μ_3, as a logistic regression of form $\log\left\{\frac{\mu_3}{1-\mu_3}\right\}=d^T\beta+Z$, where Z is an intercept-only normally-distributed zero-mean random variable included to account for repeated measurements at each location (2 sampling nights per location).

Table 1 Overview of statistical models used

Analysis	Outcome (metric)	Origin	Type	Model type	Function family	Model equation
Single rat abundance metric	Rat signs	surveyed	binary	generalized linear model (GLM)	binomial	$\log\left\{\frac{\mu_1}{1-\mu_1}\right\}=d^T\beta$
Single rat abundance metric	Live trapped rats	surveyed	binary	generalized linear mixed model (GLMM)	binomial (cloglog link)	$log\{-\log(1-p)\}=d^T\beta+\log(t)+Z$ where, $p=1-exp\{-\tau\mu_2\}$
Single rat abundance metric	Rat marks on track plates	surveyed	binary	GLMM	binomial	$\log\left\{\frac{\mu_3}{1-\mu_3}\right\}=d^T\beta+Z$
Joint *rattiness* model of three metrics	Rattiness (Rat signs)	surveyed	binary	*Rattiness* model	binomial	$log\{\mu_1(x_i)/(1-\mu_1(x_i))\}=\alpha_1+\sigma_1R(x_i)$
	Rattiness (Live trapped rats)	surveyed	binary		binomial (cloglog link)	$log\{\mu_2(x_i)\}=\alpha_2+\sigma_2R(x_i)$ where, $p=1-exp\{-t\mu_2(x_i)\}$
	Rattiness (Rat marks on track plates)	surveyed	binary		binomial	$log\{\mu_3(x_i)/(1-\mu_3(x_i))\}=\alpha_3+\sigma_3R(x_i)$

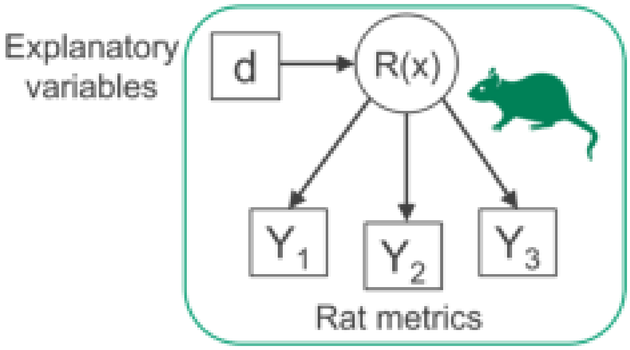

Fig. 3 Directed acyclic graph of the *rattiness* model. R(x) is the value of a spatially continuous stochastic process at location x. The outcome variables Y_j: j = 1, …, J are a set of rat abundance metrics that provide information about R(x). The term d represents a set of explanatory variables that contribute to the spatial variation in R(x). Square objects correspond to observable variables and circles to latent random variables

The rat sign model was fitted using the generalized linear model (GLM) package glm in R and the rat trap and track-plate models were fitted using the generalized linear mixed model (GLMM) fitting package lme4 in R. Study site was controlled for as a fixed effect in all three models. All statistical analyses were performed in R Core Team (2022), using the packages tidyverse, stats, lme4, MuMin and DHARMa (Bates et al. 2015; Bartoń 2022; Hartig 2022; Wickham et al. 2019).

Definition of the joint *rattiness* model

The *rattiness* model used is a multivariate geostatistical model that jointly models the three rat abundance outcomes (Eyre et al. 2020) as measurements of a common latent process, *rattiness. Rattiness,* denoted R(x) is a real-valued and spatially continuous stochastic process and is analogous to a composite metric because its value at a location is driven by the measured values of the three metrics in addition to a spatial Gaussian process. The modelling framework is shown in Fig. 3. The data consist of a set of outcomes $Y_i = (Y_{i,j} : j = 1, 2, 3)$ for $i = 1, \ldots, N$, collected at a discrete set of locations $X = \{x_i : i = 1, \ldots, N\}$. The outcome variables

Table 2 Description of environmental (baseline) and basic urban services (BUS) variables

	Variable	Origin	Type	Description
Environmental[a]	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 10 m 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
BUS[b]	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 community agent 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

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

[b]Collected in a 30 m radius of the geolocated sampling point

$Y_j : j = 1, 2, 3$ are the set of metrics that provide information about R(x): rat signs ($j = 1$), traps ($j = 2$) and plates ($j = 3$). Let $g_j(\bullet)$ and $\eta_j(x_i)$ denote the link function and linear predictor for the outcome variables $Y_{i,j} : i = 1, \ldots, N$. (Hence,)

$$g_j\{u_j(x_i)\} = \eta_j(x_i) = \alpha_j + \sigma_j R(x_i)$$

$$R(x_i) = d^T(x_i)\beta + S(x_i)$$

where $d(x_i)$ is a vector of explanatory variables with associated regression coefficents β,spatially structured variation modelled as a stationary and isotropic spatial Gaussian process, S(x). $\sigma_j > 0 : j = 1, 2, 3$ are scale parameters that account for the different scales of variation of the linear predictors of each outcome $Y_{i,j}$. We specify an exponential spatial correlation function

$$Corr\{S(x), S(x')\} = e^{-u/\phi}$$

where $u = |||x - x^{'}|||$ is the Euclidean distance between x and x', and ϕ regulates the rate of spatial correlation decay to zero with increasing distance u.

For each of the rat abundance outcomes we follow the modelling approach described previously by Eyre et al. (2020), using the same modelling assumptions as outlined for the single outcome rat abundance models in the previous section with the only change being to the linear predictor, with *rattiness*, R(x), being included. For the rat signs metric, $Y_{i,1}$ is a binomial variable for which we model the probability of finding a sign of rat infestation at location x_i, $\mu_1(x_i)$, using a logit-linear regression $log\{\mu_1(x_i)/(1 - \mu_1(x_i))\} = \alpha_1 + \sigma_1 R(x_i)$. For the rat trapping metric, $Y_{i,2}$ is a binomial variable representing the number of traps, out of $n_{i,1}$, in which rats were captured at location x_i. The times of rat captures from a trap are assumed to follow a time-varying inhomogeneous Poisson process with intensity $t_i\mu_2(x_i)$, t_i is the time (in days) for which a trap is operative and $log\{\mu_2(x_i)\} = \alpha_2 + \sigma_2 R(x_i)$. It follows that the probability of capturing a rat is $1 - exp\{-t_i\mu_2(x_i)\}$. For the track-plates metric, $Y_{i,3}$ is a binomial variable representing the number of track-plates, out of $n_{i,3}$, with rat markings. We model this as a binomial variable with $n_{i,3}$ trials and probability $\mu_3(x_i)$, using a logit-linear regression $log\{\mu_3(x_i)/(1 - \mu_3(x_i))\} = \alpha_3 + \sigma_3 R(x_i)$.

Model fitting for the *rattiness* model followed the Monte Carlo maximum likelihood (MCML) method described in Online Resource 1: Section S1 and described previously (Eyre et al. 2020) with confidence intervals for the *rattiness* parameters estimated using parametric bootstrapping.

Definition of predictors

Environmental variables Information obtained in the environmental questionnaire was converted to environmental variables – potential resources for rats (Costa et al. 2014a;

Table 3 Final models of the probability of occurrence of each single outcome

Model	Variable	OR/Rate (95% CI)	sig.
Rat signs	Intercept	0.008 (0.002–0.028)	***
	Access to sewer within 10 m	3.634 (1.910–7.128)	***
	Earth-mixed ground	3.207 (1.618–6.742)	**
	Proportion pervious land cover (<=40%)[a]	1.168 (0.986–1.386)	.
	Proportion pervious land cover (>40%)[a]	0.902 (0.670–1.214)	.
	Presence of uncontained trash within 10 m	1.882 (1.217–2.924)	**
	Presence of pet food within 10 m	4.050 (2.504–6.647)	***
	Proportion of houses with CCZ visit in 30 m[a]	1.182 (1.090–1.285)	***
	Proportion of trash container use in 30 m[a]	1.088 (1.008–1.177)	*
	Number of households in 30 m	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)	
Live trapped rats	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 marks on track plates	–	–	–

OR Odds Ratio, *Sig.* significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1–

[a]Estimate associated with a 10% increase in the proportion variable

Santos et al. 2017) – to be assessed as rat abundance predictors: access to sewer, type of ground, presence of uncontained trash, accumulated material, pet food and vegetation (Table 2). For the continuous 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 outcome variable was approximately linear or 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 Online Resource 2: Figs. S1-S3).

Basic urban services (BUS) variables Four local BUS variables were created from the domiciliary survey questions. To reflect the provision of BUS more realistically, a buffer of 30 m 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 2). For the two trash collection survey questions (trash truck collection and street container use), the same procedure was followed. A likelihood-ratio test for each single outcome variable was performed to define which of the two trash collection variables would be selected for the multivariable modelling stage.

Model selection

Single metrics stage one: Environmental variables Firstly, variable selection of environmental variables (Table 2) was conducted for each single outcome (rat signs, rat marks on track plates, rats trapped) separately to identify important environmental determinants of rat abundance in the study sites. Model selection was performed by stepwise backward elimination by Akaike Information Criterion corrected for small samples (AICc) (Hurvich and Tsai 1989). For parsimony, all models fit during the stepwise selection were then ranked by AICc and if there were multiple possible models within a threshold of $\Delta AICc = 2$ of the best model, the model with the fewest variables was selected as the final model (shown in Online Resource 3: Table S1). The final models for each outcome were then used as baseline models in for the subsequent stage two selection of BUS variables.

Single metrics stage two: BUS variables To identify which BUS variables were important predictors of rat abundance, the three BUS variables were added into each of the three single outcome baseline models and for each outcome separately the variable selection process described in stage one was repeated (backward elimination by AICc, ranking of stepwise models by AICc and selection of the most parsimonious model within $\Delta AICc = 2$ of the best model - shown in Online Resource 3: Table S2) for the three BUS variables to obtain a final model consisting of environmental variables selected in stage one and BUS variable selected in stage two for each outcome. To account for housing density, the number of households within the 30 m buffer was also included as a covariate. The median number of households within the buffer varied from 6 (interquartile range IQR 4, 8) in Alto do Cabrito to 5 (IQR 3, 7) in all the other three areas.

Model selection for the joint *rattiness* model All variables selected for the three final single outcome models were included in the *rattiness* model, after verification of non-collinearity. To check for collinearity between the selected variables we followed the exploratory methods detailed previously (Eyre et al. 2020) 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 fitted to this mean predicted *rattiness* with all variables in the final single outcomes models 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 metrics in the rattiness model we followed the methodology described previously (Eyre et al. 2020). We fitted four independent rattiness models, one with all three metrics and the other three models each with one metric left out. We then carried out likelihood ratio tests to determine whether each index should be included in the full model for the three hypotheses H0: $\sigma j = 0$ for $j = 1, 2, 3.$, with all three yielding p-values less than 0.0001, supporting the use of a rattiness model that included all three metrics.

Results

Trapping data were obtained from 158 locations (representing 99% of the trapping total locations), 40 (25%) of them being positive. Sixty-three rats were trapped, after a corrected effort of 936 trap-nights, which resulted in a trap success of 6.73%. Track plate information was recovered from a total of 372 locations (93% of the sampling total), but only 33 (9%) 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 unknown sources.

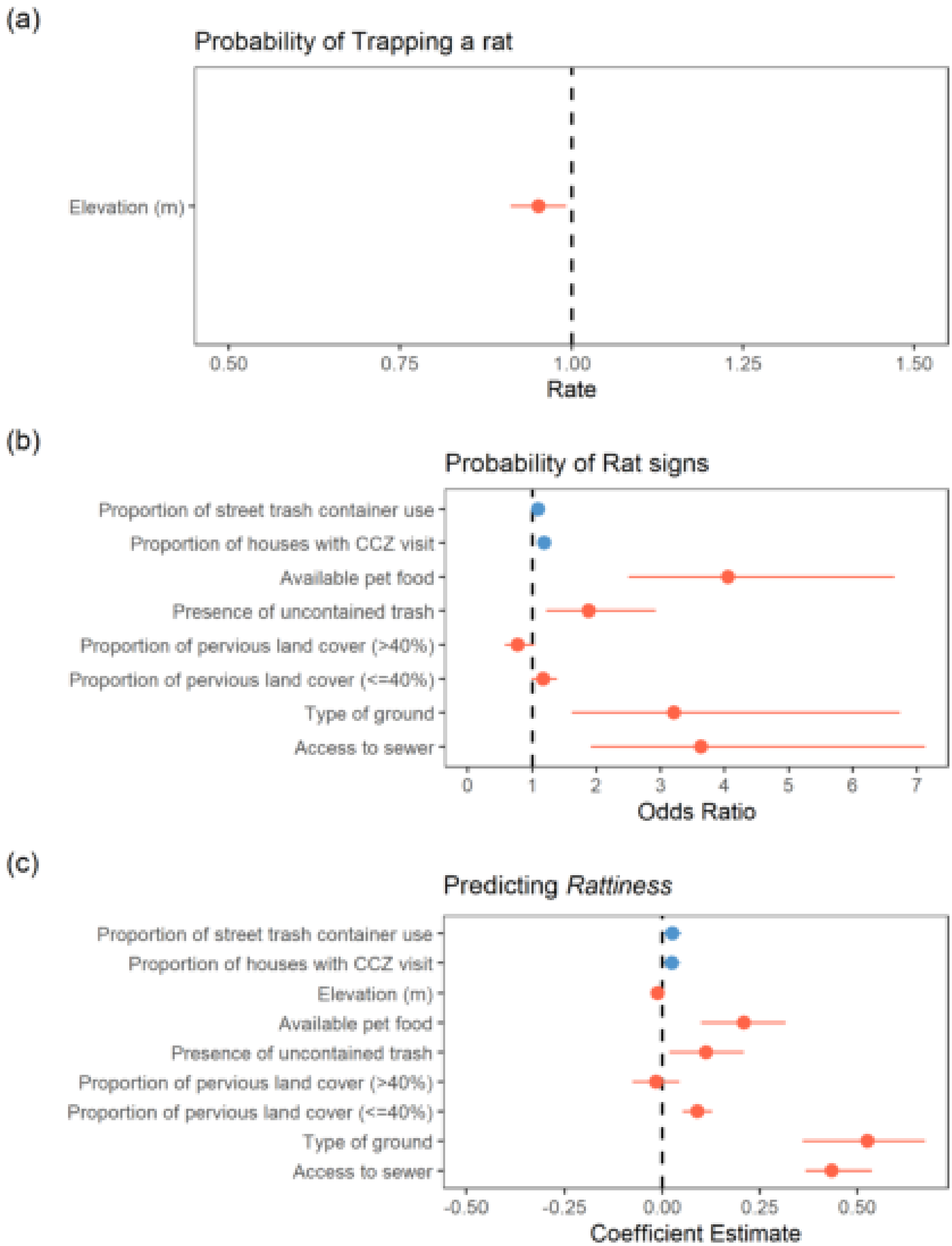

Fig. 4 Predicted results of the single outcomes (**a**, **b**) and *rattiness* (**c**) models. Baseline predictors are found in red and BUS in blue

Results for the final single outcome models can be seen in Table 3. 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 (Fig. 4a). For each metre increase in elevation (relative elevation in the four communities ranged from 0 m to 63 m), 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

Table 4 Summary of *rattiness* model outputs

Parameter/Variable	Estimate (95% CI)	p < 0.05
α1	1.125 (0.913, 1.340)	
α2	−1.145 (−1.294, −1.006)	
α3	−0.430 (−0.556, −0.304)	
σ1	0.914 (0.421, 1.306)	
σ2	1.804 (1.666, 1.953)	
σ3	3.084 (2.987, 3.187)	
Access to sewer within 10 m	0.434 (0.367, 0.537)	x
Earth-mixed Ground	0.525 (0.360, 0.673)	x
Proportion pervious land cover (<=40%)[a]	0.090 (0.053, 0.128)	x
Proportion pervious land cover (>40%)[a]	−0.016 (−0.075, 0.044)	
Presence of uncontained trash within 10 m	0.113 (0.019, 0.209)	x
Presence of pet food within 10 m	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 30 m[a]	0.025 (0.004, 0.046)	x
Proportion of trash container use in 30 m[a]	0.026 (0.003, 0.049)	x
Number of households in 30 m	0.042 (0.019, 0.066)	x
Residual Spatial Correlation (φ) (m)	95.972 (52.607–149.940)	x

α1, α2 and α3 (and σ1, σ2 and σ3) denote the coefficients for Rat signs, Live trapped rats and Rat marks on track plates, respectively

[a]Estimate associated with a 10% increase in the proportion variable

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) (Fig. 4b). 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).

All the environmental variables associated with the single outcomes were significantly associated with *rattiness,* a real-valued, continuous outcome, in the *rattiness* model (Fig. 4c). 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 4. There was evidence of residual spatial correlation not explained by the included explanatory variables, with an estimate for the scale parameter of spatial correlation of about 96.0 m (95% CI 52.6–149.9). This corresponds to a spatial correlation range (the distance at which the correlation reduces to 5%) of approximately 290 m (95%CI 160–450). The proportion of households visited by health community agents in the previous 6 months was not significantly associated with any of the abundance metrics.

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* modelling framework to assess the effects of environmental factors and BUS on urban rat populations.

The fact that all three metrics were included in the final *rattiness* model shows that they all contributed materially 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). In contrast, *rattiness* proved to be an effective tool for pooling information over all three metrics, resulting in greater power than could be obtained with any single metric, as reflected in the number of variables included in the final model. Future studies may benefit from integrating other low-cost rat abundance metrics, such as reported community rat sightings or participant perceptions of rat abundance, as additional layers of information in the *rattiness* model. While the *rattiness* model was primarily designed for ecological and epidemiological studies, it could also be cost-effectively applied in municipal rat control programmes to help integrate additional low-cost metrics into their assessments. However, this would be dependent on the availability of personnel with experience of fitting complex geostatistical models in the R statistical language.

The estimated residual spatial correlation range in the *rattiness* model of approximately 290 m 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 (Byers et al. 2019c). This figure, though, is significantly larger than the estimate of 40 m in a previous application of the *rattiness* modelling framework in a low-income community in Salvador (Eyre et al. 2020). This can be explained by the use of survey questions here to collect environmental variables, which appear to be more effective at capturing household-level environmental exposures than the remotely sensed variables used previously in Eyre et al. (2020). This is supported by the fact that the survey variables here were more strongly associated with *rattiness* than the remotely sensed variables in Eyre et al. (2020). This difference may also be driven by differences in the environment in terms of fewer barriers to movement and accessibility of resources between the four study sites in this study and the Pau da Lima community studied by Eyre et al. 2020.

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 community members.

Rodenticide application programs for rodent control and/or eradication, despite being standard practice, are known for their limited effectiveness 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 (Parsons et al. 2017). Baiting programs also typically lack efficacy evaluations and tend to be designed with little to no basic knowledge of the target population (Costa et al. 2014a; Zeppelini et al. 2020). Recently, Pertile et al. (2022) observed no effects of a chemical control conducted by CCZ in a nearby community in reducing rat abundance or modifying other demographic features after 3 and 6 months of the chemical control. Additionally, many other limitations may affect the success of these programs. In their study, the proportion of closed households for initial inspection was 32%, and among the inspected in need of rat control a low number (12%) received the full chemical action protocol, usually due to absence of residents during one of the CCZ visits (Pertile et al. 2022). The present results suggest that although CCZ agents can identify the locations for rat control, they might encounter similar or other limitations, such as presence of small children and pets in the household. We highlight the need for further work to understand how CCZ control is carried out in the studied communities 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, their limited impact on rat abundance may result from the health education provided focusing more on individual prevention practices and self-protection, rather than on ensuring high levels of hygiene in the local environment, but the focus could be expanded to include the latter.

The apparent inability of the BUS provision examined in this study to drive down rat populations may also be attributable to a need for it 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 community agent visits might be insufficient to reduce rat density in an environment so rich in resources for rats. The urban communities considered as study sites were usually located in valleys, with the lowest areas coinciding with proximity to open sewers, whilst the highest areas with proximity to the main (paved) avenues, also characterized by better quality housing (both in terms of building material and backyard area maintenance). The negative effect of elevation on *rattiness* may have translated the resource reduction, but further analysis is needed to address this. Nonetheless, our results are part of a growing body of evidence of the need for targeted, participative, small-scale environmental interventions to reduce access to resources, such as road paving, maintenance of vacant lots (Zeppelini et al. 2020) and increased rates of garbage removal and barriers to its access by rats (Murray et al. 2018), in addition to reducing access to available water sources (Colvin et al. 1996). 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 (Traweger et al. 2006), 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 hampered 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 we sought to minimise potential biases in responses by aggregating their values across surveyed households within an area (30 m 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. 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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Author 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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Data availability Data will be available from the Zenodo repository https://doi.org/10.5281/zenodo.5920038.

Declarations

Competing interests The authors declare no competing interests.

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