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The interplay between urban greenspace, cats and the occurrence of rats and mice in private gardens in the Netherlands

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Abstract

Muridae such as rats and mice are important hosts of (zoonotic) pathogens in urbanized environments. Controlling their population size is an important component of public health policies to reduce human disease risk. Recent studies suggest that rodent populations may increase due to urban greening, but this could also be counteracted by domestic cats and wild predators that inhabit urban greenspaces. Here, we assessed how the presence of brown rats (*Rattus norvegicus*) and mice (i.e., the house mouse (*Mus musculus*), wood mouse (*Apodemus sylvaticus*), and voles (*Microtus* spp.)) in urban environments relates to neighbourhood greenness and the occurrence of predators. We used camera traps to survey the occurrence of rats, mice, and their predators in 758 private gardens located along gradients of greenness in 25 municipalities across the Netherlands. Detection and occupancy were modelled using logistic mixed models and occupancy models. Mice were detected in 40.6% of the gardens and rats in 9.6%. Detection of rats and mice could not be explained by greenness but was negatively related to the presence of domestic cats. Rat detection was positively associated with the availability of open water and negatively associated with neighborhood wealth. Mice occupancy was positively associated with the presence of mustelids and brown rats, greenness, the availability of open water and human population density. Our results suggest that greenness is a less important driver than the presence of domestic cats for the mere presence of rats and mice in private gardens in urban environments.

Keywords Urban greenspace · Camera trapping · Occupancy · Urban ecology · Epidemiology · Zoonoses

Introduction

Rodents are important hosts of pathogens in urbanized environments. The brown rat (*Rattus norvegicus*), the black rat (*R. rattus*) and the house mouse (*Mus musculus*) pose a particularly high risk for pathogen (e.g., leptospirosis, hantavirus) transmission to humans, most frequently via contact with urine or faeces (Daniels and Hutchings 2001; Mayer-Scholl et al. 2014; Vaheri et al. 2013). A rise in the abundance of rodents in cities is of concern, as it could result in increased density-dependent transmission of (zoonotic) pathogens to humans and other wild or domestic animals (Anderson and May 1979; Himsworth et al. 2013). Areas near human habitation, such as private gardens adjacent to households, are especially likely to increase exposure to, and risk of, zoonotic diseases in humans. In addition, heightened rat and mouse abundance might lead to increased gnawing damage, food contamination, and negative impacts on

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human mental health (Jurišić et al. 2022; Lam et al. 2018). Control of rodent populations is therefore of importance to public health to reduce disease risk.

Recent studies suggest that rodent presence may be facilitated by urban greening, implemented to increase biodiversity and to counter the negative side-effects of urbanization, such as air pollution, decreased water quality and heat island effects (Aronson et al. 2014; Beninde et al. 2015; de Cock et al. 2024; Quaranta et al. 2021). Urban greening may facilitate rodent occupancy by providing shelter and food (Bolund and Hunhammar 1999; Tamayo-Uria et al. 2014) and the anthropophilic nature of rodents likely bolsters their adaptability to new environments so they can thrive in the urban matrix (Feng and Himsworth 2014). The negative effects of rodenticides, e.g., secondary poisoning and rodenticide resistance, necessitate an increased focus on preventive strategies rather than control. Therefore, understanding which factors determine the presence and occupancy of rodents in urban greenspaces is important to improve disease surveillance and rodent population control measures.

Living close to humans provides rodents with access to abundant food resources that are less likely to be affected by seasonal fluctuations (e.g., household waste, pet and bird food, chicken coops and compost heaps) (Hansen et al. 2020; Himsworth et al. 2014b; Masi et al. 2010; Miller and Bromley 1988; Traweger et al. 2006). These type of food resources are especially suitable for rats, as they are opportunistic omnivores that can make use of a large variety of food resources (Guiry and Buckley 2018; Traweger and Slotta-Bachmayr 2005; Traweger et al. 2006). Mice and voles (*Microtus* spp.) consume more natural food resources such as plants (mainly seeds) and invertebrates (including beetles, moths, insect larvae and spiders) (Faber and Ma 1986; Jacob and Tkadlec 2010; Watts 1968). In addition to providing food resources, urban greenspaces could also provide shelter in the form of stone- and woodpiles, natural vegetation, sheds, and cavity walls (Himsworth et al. 2014b; Masi et al. 2010; Miller and Bromley 1988; Traweger et al. 2006).

Urban areas harbour extremely high densities of domestic cats (*Felis silvestris catus*) (Mahlaba et al. 2017; Mendoza Roldan and Otranto 2023; Silva-Rodríguez and Sieving 2011), many of which roam freely and hunt for small prey such as mice, voles and juvenile rats (Childs 1986; Woods et al. 2003). Furthermore, rats and house mice seem to actively avoid cats (Dickman 1992; Parsons et al. 2018), thus the presence of cats can reduce mouse abundance (Baker et al. 2003; Silva-Rodríguez and Sieving 2011; Woods et al. 2003). Urban greenspaces can further harbour wild predators such as mustelids, red foxes (*Vulpes vulpes*), and birds of prey (Blackwell et al. 2001; Taylor 1978), but the extent of predation by wild predators on rodents in cities is unclear (Bateman and Fleming 2012; Contesse et al. 2004). In general, abundance of small mammals with the exception of rats, is limited more by predators (i.e., top-down control) than by food resources (i.e., bottom-up control) (Feng and Himsworth 2014; Sinclair and Krebs 2002). However, predator pressure may differ between urbanized and more natural environments (Bateman and Fleming 2012). It is thus possible that the benefits of urban greening for rodents are counterbalanced by the presence of domestic cats and wild predators.

In this study, we investigated factors determining the presence of rats and mice in private gardens. We used camera traps to detect rats and mice in 758 private gardens with varying degrees of greenness across 25 different municipalities in the Netherlands and related this to neighbourhood properties and the activity of domestic cats and wild predators. Specifically, we tested the predictions that rat and mouse detection by camera traps (1) increases with greenness, (2) declines with increased presence of cats and wild carnivores, and that (3) the increase in greenness is countered by the activity of predators.

Materials & methods

Study area

This study was conducted in 758 private gardens in the Netherlands, a country characterized by a large concentration of people in towns and cities with a short urbanisation gradient that are separated by agricultural land and nature areas. The gardens were located along urban-to-rural gradients in 25 different municipalities, with 15 to 64 gardens per municipality (Fig. 1). Data was collected from 2016 until 2023 as part of a citizen science project set up by the Dutch Mammal Society (DMS), Silvavir ecological consultants, and Wageningen University (WUR) (Westra et al. 2016, 2020).

Camera trapping

Mammal presence was measured using camera traps with infrared sensors, that were aimed parallel to the ground surface with the lens at approximately 20 cm above the ground (one camera trap per garden). Multiple camera types were deployed: Reconyx HC500, Reconyx HC600, Reconyx HS2X, Bushnell agressor, Bushnell core DS Low Glow, Browning Strike force HD-X, Browning 2020 Spec Ops Edge, and Spypoint Force-Dark. All camera traps were positioned with an unblocked view of at least 2 m and were aimed to be deployed for a minimum of three weeks. To increase the detectability of mammals within a garden – i.e.,

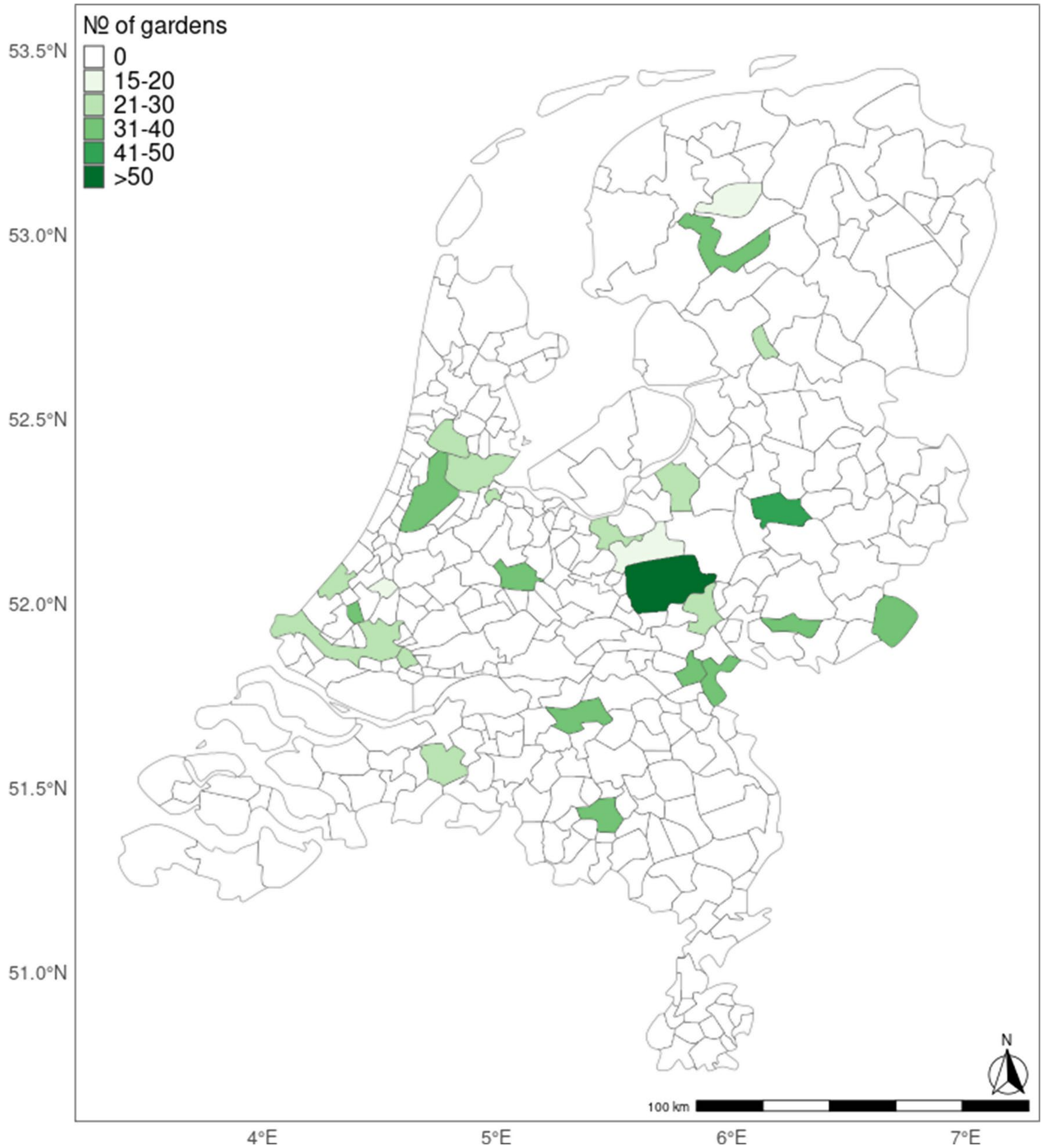

Fig. 1 Map of municipalities across the Netherlands in which private gardens were sampled with camera traps (min = 15, max = 64 gardens per municipality)

the likelihood that any mammal present in a garden would enter the detection zone of the camera – a leaking can of sardines (with two screw holes per can) was attached to a tree or pole in front of the camera at 15 cm above ground and at a distance of 1.5–2 m from the camera trap (Westra et al. 2016; Westra et al. 2021). Sardines were chosen because they attracted the highest diversity of animal species in a pilot study in which different lures (i.e., can of sardines, fish oil, peanut butter, and valerian oil) were compared. The lure was assumed to attract animals into the camera detection zone (i.e., increasing detectability), but not into gardens (i.e., not affecting occupancy). The number of photos per burst was set to ten with no pause between bursts. To create a record of camera operation time (i.e., effort), time-lapse photos were taken every 12 h.

Images were annotated and stored using the software Agouti (https://www.agouti.eu/) (Casaer et al. 2019). Phot os were automatically grouped into sequences at a threshold difference of 120 s between sequences. The sequences were annotated manually (98.8%) or by artificial intelligence (AI; 1.2%). Time-lapse photos were excluded from annotation. Rats and predators could be identified to species level, whereas mice and voles could not and were therefore grouped into the category "mice". Shrews were not included in the species category "mice". This study includes only gardens with completely annotated deployments, valid camera set-ups, and correct coordinates.

We obtained a record of detections for each species category that could be used to compare detection versus non-detection between gardens, and to assess occupancy. Gardens were considered positive for brown rats or mice in case of at least one detection of these species. The presence of predators was expressed as the proportion of sampling days in which a predator was photographed. Predators for rats included cats, dogs (*Canis lupus familiaris*), mustelids (*Martes fiona*, *Martes martes*, *Meles meles*, *Mustela nivalis*, *and Mustela putorius*), and red foxes (Mahlaba et al. 2017; Mendoza Roldan and Otranto 2023; Zoogdiervereniging 2024). As predators for mice, we additionally included rats (Zoogdiervereniging 2024).

Environmental variables

Environmental and socioeconomic variables of each individual garden were derived from existing geodata. The geographical coordinates of camera traps were used as centroids to create circular buffers with a radius of 150 m for rats and a radius of 50 m for mice, representing their average home range (Badi et al. 1992; Grilo et al. 2018). To quantify greenness per buffer area, we used the NDVI map from 2021 (100 m^2 resolution). The NDVI is a dimensionless index between zero and one, which visualises the difference between near-infrared and visible reflectance of vegetation cover (Weier and Herring 2000). Prior to calculating the greenness within the buffers, water bodies were masked from the NDVI map using ArcGIS (ESRI ArcGIS™ version 10.8, CA, USA).

Based on data from Wageningen Environmental Research's national land-use database (LGN2020), we determined the landscape composition (25 m^2 resolution; (WUR 2020). To calculate water and road density, we georeferenced the LGN categories fresh water and infrastructure, respectively, within the buffers (i.e., 150 m for rats, and 50 m for mice) surrounding each camera trap. Four-digit (PC4) and six-digit (PC6) postal codes were assigned to camera trap geolocations to subtract data available on PC4 or PC6 level. Human population density was collected on PC6 level. The percentage of buildings built before 1945 and the median disposable income were collected on PC4 level.

Data analyses

To gain a complete understanding of rat and mouse ecology and to identify variables that could serve as indicators of a high likelihood of rat and mouse presence we used two methods: logistic mixed modelling (LogMM) and occupancy modelling. Preceding analyses, numerical variables ranging between zero and one (e.g., variables regarding predator presence, and the degree of greenness) were logit-transformed. If values were zero or one, a constant value (i.e., half of the minimum value) was added or subtracted, respectively, to allow transformation. All other numerical variables were standardized by subtracting the mean and dividing by the standard deviation (SD), i.e., to a mean of zero and a SD of one. R version 4.3.2 (2023-10-31) was used for data extraction and all statistical analyses (RCoreTeam 2022).

Logistic models

Some gardens may have had camera deployment durations that were too short to reliably detect rats and mice. To reduce such false negatives, we established the minimum deployment period needed to reliably detect the presence of rats, mice, and their predators, respectively, using a Kaplan-Meier survival analysis with all gardens in which the target species had been detected, i.e., was known to occur. Here, an event was defined as the first photographic detection of rats, mice and predators (Cf. (Bischof et al. 2014)). We used the time at which approximately 75% of these gardens have had their first detection of the focal species as the minimum deployment period. In addition, some gardens had very long deployments. To reduce this imbalance, these deployments were cut off at the time point at which the target species had been detected in 99% of the gardens in which it was present.

LogMMs were used to investigate associations between the detection or non-detection of rats and mice and potential explanatory variables (Table 1). Separate models were created for rats and mice. Explanatory variables were evaluated for multicollinearity by using the variance inflation factor (VIF $<$ 5). Interactions were tested between predators and greenness. Interaction effects were only included for predators that were significantly associated with rat or mouse detection. P-values below 0.05 were considered to be significant. To assess the strength of associations between presence of the target species and explanatory variables, the log odds and corresponding 95% confidence intervals (CIs) were calculated. Because all explanatory variables were selected based on their hypothesized effect on murid presence, model reduction was not performed.

Occupancy models

We fitted occupancy models to estimate occupancy and the detection probability of rats and mice. Occupancy was defined as the probability that a rat or mouse used the garden

Table 1 Description of included covariables

Model	Type of variable	Variable	Description	Hypothesized direction effect	Spatial resolution of map	External data source
Variables	Predator	Domestic cat	Proportion (%) of days a domestic cat was detected per deployment.	Negative	Individual garden	-
	Predator	Red fox	Proportion (%) of days a red fox was detected per deployment.	Negative	Individual garden	-
	Predator	Mustelid	Proportion (%) of days a mustelid was detected per deployment.	Negative	Individual garden	-
	Predator	Dog	Proportion (%) of days a dog was detected per deployment.	Negative	Individual garden	-
	Predator	Rat	Proportion (%) of days a brown rat was detected per deployment.	Negative	Individual garden	-
	Environmental	Greenness	Degree of greenness present within buffers based on NDVI data (0–1) from 2021, corrected for the presence of water.	Positive	100 m^2	(Groenmonitor 2022)
	Environmental	Road density	Total density of roads within a buffer area derived from the LGN2020 spatial layer.	Negative	25 m^2	(WUR 2020)
	Environmental	Water density	Total density of fresh water within buffers derived from the LGN2020 spatial layer.	Positive	25 m^2	(WUR 2020)
	Environmental	Building period < 1945	Proportion (%) of buildings built before 1945.	Positive	PC4	(CBS 2020)
	Socio-economic	Human population density	Human population density per PC6 area.	Positive	PC6	Statistics Netherlands (CBS)
	Socio-economic	Median disposable income	Median disposable income per PC4 area.	Negative	PC4	Statistics Netherlands (CBS)
	Time	Season	Season of deployment start date (winter, spring, summer, autumn) [b]	1, Positive, positive, positive	-	-

[a] Year was not included as a random factor due to high overlap with municipality (Supplemental Table S1)

[b] The following categorization for season was applied: Winter (i.e., December, January, and February), Spring (i.e., March, April, May), Summer (i.e., June, July, August) and Autumn (i.e., September, October, November). Winter was used as the reference category

at any time during the deployment period (MacKenzie et al. 2002), and detection probability as the likelihood of detecting a species in a garden given that it was present (Zimmermann and Foresti 2016). As camera-trap data frequently exhibits significant heterogeneity, we used the Royle-Nichols (RN) occupancy model variant, which outperforms standard occupancy models in such situations (Tobler et al. 2015). For these analyses, we used the "unmarked" package version 1.2.5 (Fiske and Chandler 2011).

Occupancy models require (semi)-continuous data that is reformatted into detection/non-detection data per time interval. To determine the time interval (dT) that should be used as well as the minimum number of intervals (nT) for a location to be included in the analysis, we used a novel method by De Jager et al. (de Jager et al. 2024). Occupancy modelling will only be performed in case of sufficient sightings of our target species, since this is required to determine dT and nT. The number of detections (1) and non-detections (0) per time interval were used to generate a vector containing zeros and ones per target species per camera trap. This data was compiled within a matrix containing all valid sites (camera traps) and used to estimate occupancy and detection probability in our single-species occupancy models (Zimmermann and Foresti 2016). We estimated occupancy with biological, environmental, and socio-economic covariates (Table 1). Detectability was assumed to be equal across all gardens.

Results

Gardens were surveyed for 31 ± 12.2 days, ranging from 2 to 137 days (Supplemental Fig. S1). During the study, the number of deployed camera traps varied across seasons, with the highest number of cameras deployed in autumn ($N = 263$), followed by spring ($N = 194$), summer ($N = 152$), and winter ($N = 149$; Fig. S2 and Table S3).

In total, the cameras yielded 96,121 observations of 104 species. This included 6,756 detections of either brown rats ($n = 1{,}002$) or mice ($n = 5{,}754$; Supplemental Table S2). The percentage of gardens in which rats were detected ranged from 0 to 36.0% per municipality, and for mice

Table 2 Overview of camera trapping data and the detection of rats and mice per municipality[¥]

Municipality	№ Gardens	Rats detected (%)	Mice detected (%)	Cats detected (%)
Amsterdam	25	36	24.0	84.0
Arnhem	25	16	48.0	100.0
Barneveld	20	5.0	35.0	95.0
Berg en Dal	37	16.2	67.6	91.9
Breda	27	11.1	44.4	96.3
Delft	32	6.2	40.6	93.8
Deventer	43	7.0	65.1	97.7
Doetinchem	37	8.1	16.2	94.6
Ede	64	7.8	48.4	96.9
Eindhoven	35	5.7	68.6	91.4
Haarlemmermeer	32	12.5	40.6	100.0
Heerenveen	31	6.5	6.5	93.5
Meppel	22	0.0	31.8	95.5
Nijkerk	21	9.5	4.8	95.2
Nijmegen	39	7.7	38.5	92.3
Nunspeet	22	0.0	40.9	100.0
Ridderkerk	27	11.1	48.1	96.3
Rotterdam	29	17.2	34.5	89.7
‘s-Gravenhage	24	12.5	33.3	95.8
‘s-Hertogenbosch	38	7.9	52.6	94.7
Smallingerland	15	0.0	13.3	100.0
Utrecht	40	7.5	15.0	100.0
Winterswijk	32	3.1	65.6	87.5
Zaanstad	21	14.3	28.6	100.0
Zoetermeer	20	10.0	40.0	100.0
Total	**758**	**9.5**[a]	**40.2**[a]	**95.1**[a]

[a] Mean overall percentage (%)

from 0 to 68.6% (Table 2). Domestic cats were by far the most observed predator species (detected in 95.1% of all gardens), followed by mustelids (26.3%), dogs (25.1%), and red foxes (6.6%; Fig. 2). The most common species co-occurrence was observed for domestic cats – mice ($N=123$ gardens), followed by domestic cats – dogs ($N=78$). The most common triple species occurrence was observed for domestic cats – mice – mustelids ($N=49$ gardens; Fig. 2).

Correlates of rat and mouse detection in gardens

Logistic models

Across all 758 gardens, about 75% of the rat and mouse detections happened within the first 13 and 16 days of camera deployment, respectively (Kaplan-Meier survival analyses), while there were no new detections after approximately 38 and 50 days (Supplemental Fig. S3 – S4). Therefore, a minimum deployment duration of 16 days (rats) and 13 days (mice) was established, and any long deployments were cut short at 50 days. This left a total of 696 and 731 gardens for the LogMMs with brown rats and mice, respectively.

Greenness alone did not explain rat and mouse detection (LogMM, Figs. 3a, b, 4 and 5). We did find a negative association between the percentage of domestic cats and rats (Log odds = -0.18 (-0.31 – -0.06), $p=0.004$) and mice (Log odds = -0.09 (-0.17 – -0.02), p-value = 0.018; Figs. 3a – b, 4 and 5). Furthermore, we found a negative association between rat detection and median disposable income (Log odds = -0.28 (-0.57 – -0.00), $p=0.049$), and a positive association with autumn (Log odds = 1.03 (0.20–1.85), $p=0.014$) and water density (Log odds = 0.25 (0.03–0.47), $p=0.019$; Figs. 3a and 4). Details on the distribution of explanatory variables can be found in Fig. S6.

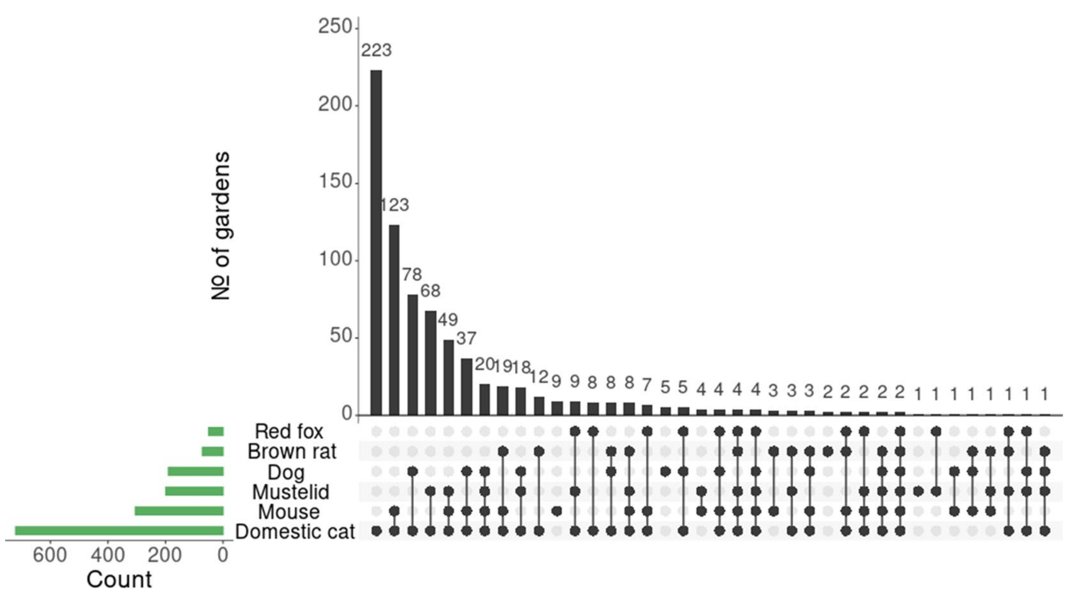

Fig. 2 Upset plot of single species occurrence data and species co-occurrence data. The main bar plot illustrates gardens in which either one species or multiple species were detected. The green side bar plot illustrates data for individual species without subtracting the co-occurrences

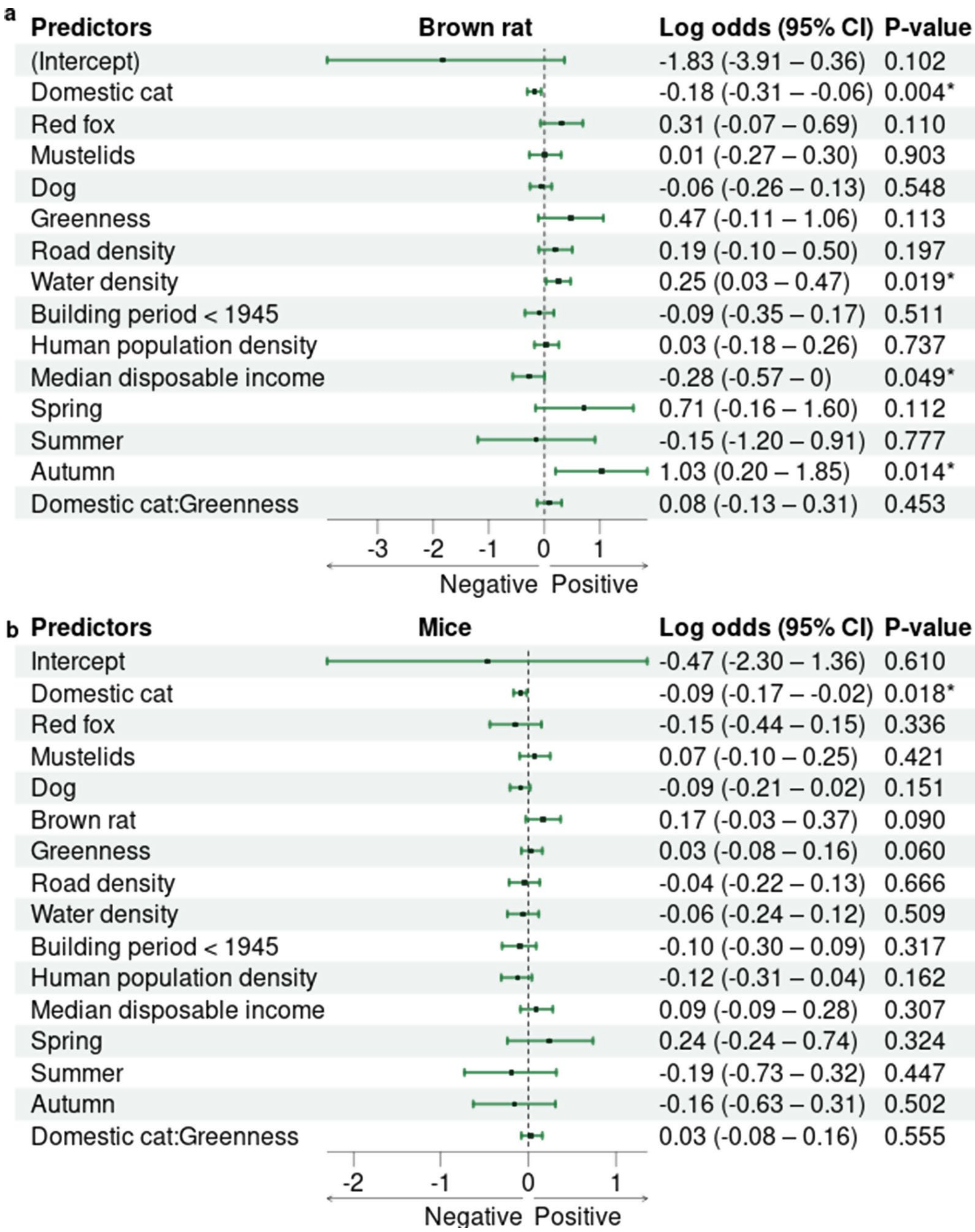

Fig. 3 Model output of the detection of rats (Fig. 3a, $N=696$) and mice (Fig. 3b, $N=731$) in relation to explanatory variables. *Statistically significant. VIF values are given in Supplemental table S5 – S6. The model without duration cap based on Kaplan-Meier curves has been provided in Analysis S1

Occupancy models

For mice, the optimal combination of dT and nT was dT = 7 and nT = 5 (Fig. S8). Mice had an average occupancy of 0.66 (95% CI: 0.60–0.74) and a detection probability of 0.27 (95% CI: 0.25–0.29). Similar to mice detection in the LogMM, mice occupancy was negatively associated with the percentage of domestic cats. In addition, the mice occupancy was positively associated with the percentage of mustelids, the percentage of brown rats, greenness and the interaction between greenness and the percentage of domestic cats, and negatively associated with water density, human population density, and the season summer (Table 3). Due to the relatively low number of detections of rats throughout the study (< 10% of the gardens; Fig. S7), it was not possible to establish an optimal dT or to determine the nT. As a result, reliable occupancy modelling for brown rats could not be performed.

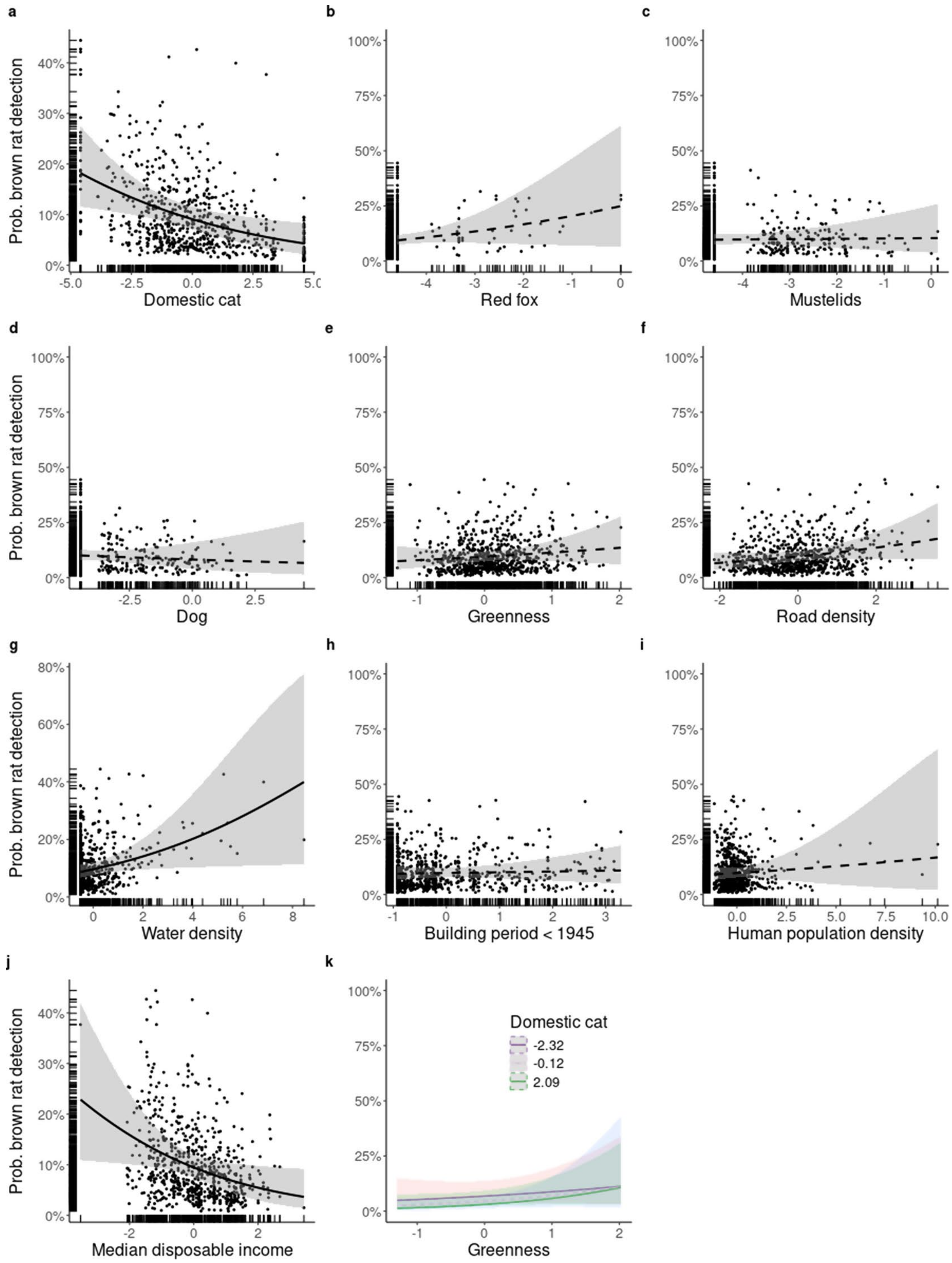

Fig. 4 Predicted probability of rat (*Rattus norvegicus*) detection per environmental variable (**a-k**). Significant associations are displayed with solid lines, non-significant associations are displayed with dashed lines. Light grey areas display 95% CI. Figure 4k represents interaction between greenness and cat detection

Discussion

Understanding the drivers of rodent populations in urban areas will contribute to more effective control measures to limit disease risk. This is especially important in light of increased urban greening, which affects both rodent and predator populations. Therefore, we investigated whether predators, environmental factors and socio-economic factors could be associated with the presence of rats and mice in private gardens in the Netherlands. Our analyses relied

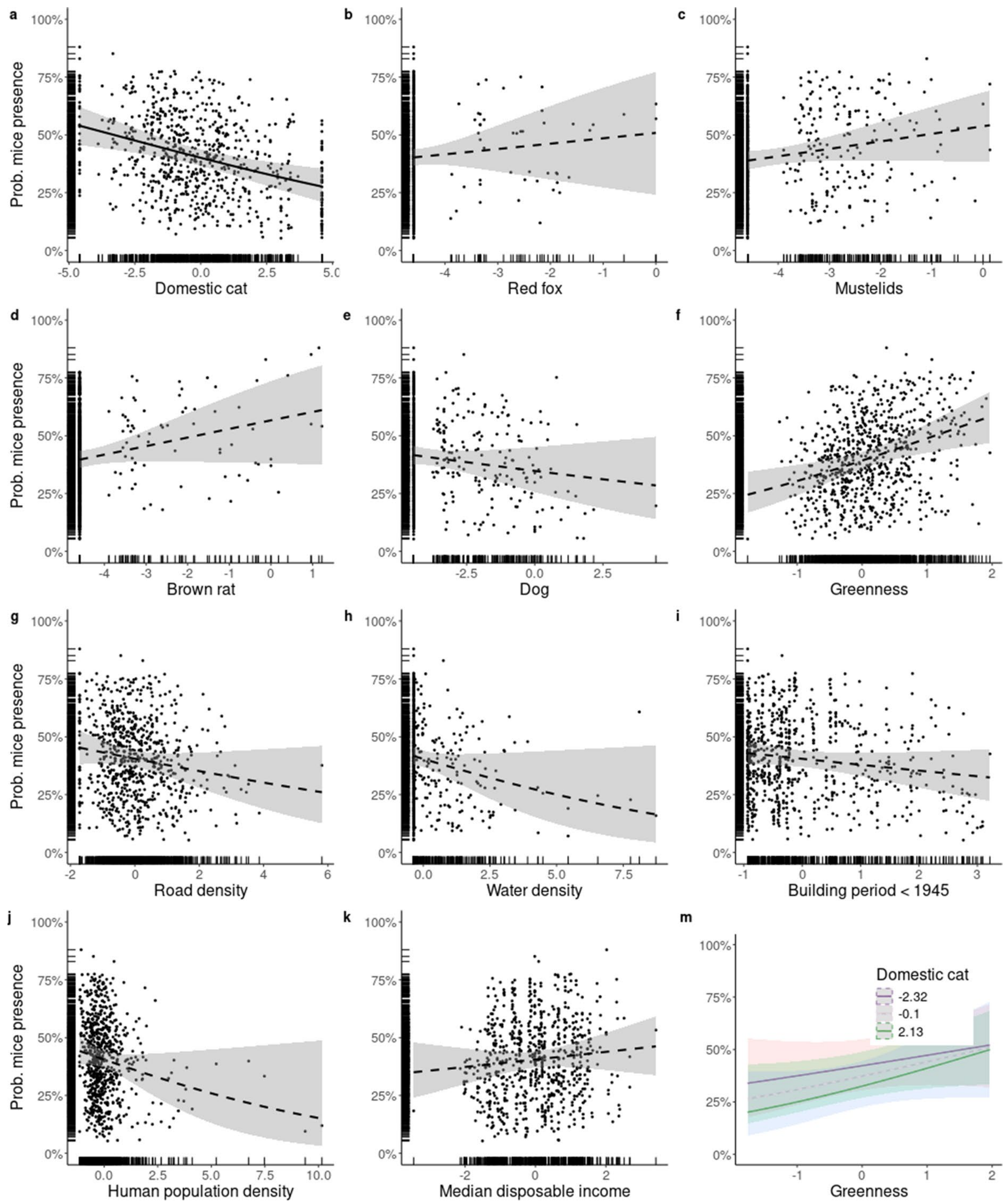

Fig. 5 Predicted probability of mice detection per environmental variable (**a** – **m**). Significant associations are displayed with solid lines, non-significant associations are displayed with dashed lines. Light grey areas display 95% CI. Figure 5m represents interaction between greenness and cat detection

on camera trapping data, which we analysed using two approaches (i.e., LogMMs and occupancy models). We observed that the presence of domestic cats affected both the detection of rats and mice, as well as mice occupancy, additionally greenness affected mice occupancy.

Relationships between rats, mice, predators, and greenness

We observed a negative relationship between the presence of rats or mice and the presence of domestic cats, and cats

Table 3 Summary statistics for the mouse occupancy model ($n = 737$) and logistic model ($n = 731$)

Explanatory variables	Occupancy model			Mixed logistic regression model	
	Estimate	SE	*P* value	Log odds (95%CI)	*P*-value
(Intercept)	0.049	0.492	0.920	-0.47 (-2.30–1.36)	0.610
Domestic cat [a]	-0.129	0.024	< 0.001*	-0.09 (-0.17 – -0.02)	0.018*
Red fox	-0.100	0.078	0.195	-0.15 (-0.44–0.15)	0.336
Mustelids [b]	0.096	0.041	0.020*	0.07 (-0.10–0.25)	0.421
Dog	-0.048	0.040	0.235	-0.09 (-0.21–0.02)	0.151
Brown rat [b]	0.134	0.044	0.002*	0.17 (-0.03–0.37)	0.090
Greenness [b]	0.214	0.095	0.024*	0.03 (-0.08–0.16)	0.060
Road density	-0.036	0.056	0.526	-0.04 (-0.22–0.13)	0.666
Water density [b]	-0.140	0.068	0.039*	-0.06 (-0.24–0.12)	0.509
Building period < 1945	-0.115	0.059	0.053	-0.10 (-0.30–0.09)	0.317
Human population density [b]	-0.142	0.064	0.026*	-0.12 (-0.31–0.04)	0.162
Median disposable income	0.080	0.056	0.154	0.09 (-0.09–0.28)	0.307
Spring	-0.142	0.144	0.323	0.24 (-0.24–0.74)	0.324
Summer [b]	-0.313	0.159	0.049*	-0.19 (-0.73–0.32)	0.447
Autumn	-0.149	0.138	0.280	-0.16 (-0.63–0.31)	0.502
Domestic cat: Greenness [b]	0.087	0.037	0.018*	0.03 (-0.08–0.16)	0.555

[*] Statistically significant

[a] Similar between LogMM and occupancy model

[b] Different between LogMM and occupancy model

seemed to influence both the presence and occupancy of mice. These findings coincide with previous research showing that rats seemed to avoid cats and that they prey upon mice and juvenile rats (Baker et al. 2003; Blackwell et al. 2001; Childs 1986; Parsons et al. 2018; Silva-Rodríguez and Sieving 2011; Woods et al. 2003).

With respect to other predator species, mice occupancy was positively associated with the presence of mustelids and brown rats. This could be due to urban ecosystems tending to have small, disconnected habitats that may constrain prey (i.e., mice) within predators' ranges (i.e., brown rat and mustelid) or vice versa (Decker et al. 2000; Gese et al. 2012). The positive association between rats and mice may also indicate that rats prey less actively on mice than we previously believed. Besides that, mice and rats may compete for similar resources, which might also explain their positive relationship (Courchamp and Caut 2006).

Although the occupancy of mice tended to increase with greenness, overall rat and mouse presence was poorly explained by this predictor, which is in apparent disagreement with the positive associations found in previous studies (de Cock et al. 2024; Traweger et al. 2006; van Adrichem et al. 2013). One reason may be that we measured detection/non-detection and occupancy, whereas previous studies focused on rat abundance (measured using either snap traps or live traps), or were based on municipal complaint data. However, none of these methods are a perfect representation of reality, but they can complement each other. Also, the degree of greenness possibly does not influence the mere detection or non-detection of rats and mice but does influence their abundance. We further found a positive interaction between domestic cat presence and greenness, which implies that the positive effect of greenness on mice abundance is slightly countered by the presence of domestic cats.

Our study suggests that domestic cats are more important than greenness for predicting the detection and/or occupancy of brown rats and mice in gardens. For effective biological control, however, predation of brown rats and mice is often insufficient to reduce their population sizes. In case of small population sizes, predators may be able to prevent re-infestation of unwanted urban rodents (Marsh 1994). From a public health perspective, it is important to realize that predator species may also carry and introduce zoonotic pathogens (Lempp et al. 2017; Mackenstedt et al. 2015; Plumer et al. 2014). The disease risk posed by rodents and predators may however differ.

Relationships with other environmental and socio-economic variables

In accordance with our predictions (Table 1), this study showed that gardens with a higher water density and areas with an overall lower median disposable income were associated with a higher probability of brown rat detection. A positive association with water was expected, because areas that include water bodies surrounded by natural vegetation are favoured by brown rats (Traweger et al. 2006) as it provides water and allows them to create burrows (Lore and Schultz 1989). Additionally, our findings correspond with those of, Himsworth et al. 2014a, b who reported that areas with a high rat trap success were those with a higher proportion of low-income apartments (Himsworth, Parsons, et al., 2014), which is likely related to food and shelter availability.

In contrast to Antonelli et al. 2022; mice occupancy was negatively associated with human population density and the availability of open water (Antonelli et al. 2022). Antonelli et al. 2022; however, only investigated house mice, which prefer to live close to humans, whereas wood mice prefer more natural environments (Heyman et al. 2009; Rychlik 2000). The grouping of voles, house- and wood mice in one group 'mice' may thus have biased this relationship. We further observed that a greater presence of older housing in the area tended to decrease the occupancy of mice. This finding was counterintuitive, as we hypothesized that older buildings are more likely to have structural issues (e.g., gaps, deteriorated materials), as well as aged wiring and plumbing, which may provide easier access to rodents (Langton et al. 2001; van Adrichem et al. 2013).

Finally, season appeared to affect rat detection and mice occupancy. In literature, however, there is considerable disagreement with regard to the effect of season on rodents in urban ecosystems, partly because rather than by season, urban rodent populations are controlled by humans (Cueto et al. 2008; Davis 1953; Easterbrook et al. 2007; Himsworth et al. 2014a; Psaroulaki et al. 2010). Given that individual gardens were mostly monitored within a single season, we cannot conclusively state we have truly demonstrated a seasonal pattern or if variations detected between seasons resulted from methodological variability (Himsworth et al. 2014a; Krebs 1999).

Strengths and limitations

A strength of this study is that it comprises a very large dataset, which makes the observed relationships reliable. In addition, we based the minimal duration period of the camera traps in the LogMMs on Kaplan-Meier survival analyses of actual detections of brown rats, mice, and their predators, instead of a pre-defined duration period. A recent study determined that a duration period of three to four weeks is needed to obtain precise detection estimates, which is similar to the minimal duration period resulting from the Kaplan-Meier curves seen here and which is also often used in other studies (Hansen et al. 2020; Kays et al. 2020; Parsons et al. 2019). Future research might even strive for a longer minimum duration (e.g., approximately 50 days) to get more reliable estimates of animal presence and fewer false negatives. By using a new method to determine the optimal occupancy interval criteria (De Jager et al. 2024), we observed that the camera trap data for rats was unsuitable (too few rat observations) to reliably model occupancy with meaningful results. This highlights the importance of checking the suitability of your data before analysis.

Limitations of this study included the grouping of mouse and vole species because of difficulties in reliably identifying voles, house- and wood mice to species level from camera trap images. Voles, house- and wood mice differ in terms of ecology. For example, wood mice prefer more vegetation cover and greenness, whereas house mice prefer to live in human population dense areas, and voles (e.g., bank voles (*Myodes glareolus*)) prefer meadows (Antonelli et al. 2022; Boitani et al. 1985; Jacob et al. 2014; Rinke 1990). Grouping these species together may thus have masked differential relationships between individual species and certain explanatory variables. Secondly, the measure that we used for greenness (NDVI) can consist of many different combinations of plant species and structures, which could have different effects on the detection and/or occupancy of rats and mice. Unfortunately, we were not able to include more specific information in this study due to the absence of suitable data. A third limitation of this study was the lack of data on the availability of food resources such as bird feed, garbage and compost heaps, which is likely a very strong predictor of rodent occurrence in gardens (Feng and Himsworth 2014; Hunter and Price 1992). Fourthly, the lure we used, specifically a leaking can of sardines, may have differentially influenced the detection probability of various animal species. Predators could have been more attracted to the lure, resulting in a higher probability of detection (Zoogdiervereniging 2024). Conversely, prey species might have avoided the bait altogether (Rocha et al. 2016), therefore potentially weakening the observed relationships due to false negatives for rats and mice. We however expect that the lure we used has not led to differential bias between gardens, as the expected effect of lure on the detectability of species is assumed to be equal across all gardens. In addition, based on a pilot study this lure did attract the highest diversity of animal species.

Conclusions

We conclude that the prevalence of predators, in particular domestic cats, is a better predictor for the presence of rats and mice in private gardens in the Netherlands than greenness. However, it remains unknown to what extent predators reduce the population sizes of rats and mice in urbanized areas. As greenness only showed a positive relationship with the occupancy of mice and not with their presence, this may indicate that greenness could influence mouse abundance and not their mere detection/non-detection. Since rat and mouse populations can contribute to zoonotic disease risk in urban environments, especially in private gardens with potential high exposure, it remains important to monitor the population sizes of these species and to further increase our understanding of the factors influencing their presence, and the efficiency of predation by their predators.

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Data availability Data can be made available upon request.

Declarations

Ethical approval Not applicable.

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