Hunger Pandemic: Urban Rodents' Boom and Bust During COVID-19

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Abstract

Shortly after the enactment of restrictions aimed at limiting the spread of COVID-19, local governments and public health authorities around the world reported an increased sighting of rats. We combined multi-catch rodent station data, rodent bait stations data, and rodent-related residents' complaints data to explore the effects that social distancing and lockdown measures might have had on the rodent population within the City of Sydney, Australia. We found that rodent captures, activity, and rodent related residents' complaints increased during the COVID-19 related lockdown period, followed by a steep decline post-lockdown. We found no changes in the geographical distribution of any of our indices of rodent abundance. We hypothesize that lockdown measures resulted in an increase in rodent activity driven by a reduction in human-derived food resources. This might have increased the mortality rate, triggering a population crash. There is a high chance that the surviving individuals might be rodenticide resistant. It is possible that the onset of COVID-19 might have disrupted commensal rodent populations, with profound implications for the future management of these ubiquitous urban indicator species.

Introduction

Commensal rodents are abundant and pervasive pest species that cause vast damage to infrastructure, destroy crops, and spread diseases throughout the world ¹⁻⁴. In urban areas throughout the world, when a rodent pest becomes overabundant they contaminate food, damage infrastructure, increase risk of fire by gnawing on electrical wiring and pose a risk to public health as diseases carriers ^{2,5-14}. Annually, pest rodents cost billions of dollars in losses of food ^{15,16}. In many cases, pest rodents have become dependent on humans for food and harborage. Changes in human behaviors are known to affect commensal rodent populations ¹⁷. Rodent abundance in cities has been found to be closely linked to socioeconomic conditions, accessibility to structures that offer nesting places, and human-derived food resources ^{18,19}. For these reasons, rodent control methods commonly include strategies to limit access to public garbage containers and potential nesting places to reduce rodent abundance ²⁰.

Previous studies have suggested that changes in human behavior following natural catastrophes typically result in changes in rat populations ²¹⁻²³. For example, large storms such as hurricanes, can often cause large spikes in rodent abundance ^{22,23}. It is thought that in urban environments, where this pattern has been recorded, the increased rodent abundance might be due to a process of counter-urbanization ²⁴⁻²⁶. Shortly after a natural disaster, the urban human population decreases via emigration, which increases the abandonment of idle or degraded infrastructure and thus increases the availability of habitat for pest species ²⁷. For example, greater levels of abandonment in New Orleans following Hurricane Katrina appeared to cause an increase in the commensal rodent populations ²⁶. This increase in commensal rodent abundance can potentially increase the risk of zoonotic diseases transmission in the area ¹⁰⁻¹².

The appearance and rapid spread of SARS-CoV-2 in the human population during 2020 can arguably be classified as a natural disaster and, as such, it is expected to have a similar effect on rodent pest populations around the world. Following the rapid increase in COVID-19 cases at the beginning of 2020, governments around the world started to enact preventative measures aimed at limiting the spread of SARS-CoV-2. Shortly after, reports from local governments and public health authorities around the world implicated the closures of restaurants and food-related venues with increased sightings of rats ²⁸⁻³⁴. In some cases, these reports have

included rodents engaging in aberrant behaviors, such as rats being active during the day and in close proximity to humans^{31,35,36}, as well as rats consuming conspecifics (e.g. muricide or cannibalism)^{31,37}. A perceived increase in the abundance of rats is sufficient to cause intense fear and have severe negative effects on mental health³⁸⁻⁴⁰. These effects on mental health can be potentiated by an increased use of social media during the pandemic^{41,42} and the spread of 'panic' across the population⁴³. Thus, given the very significant implications for public health risk pest rodents pose^{7-9,38-40,44}, it is critical to better understand how pest rodents respond to global events such as COVID-19.

Recently, Parsons, *et al*/2020 released a study preprint in which they investigated how stay-at-home measures affected rat sightings. They analyzed rat-related public complaints in New York City and Tokyo, Japan and surveyed pest control companies in the United States, Canada, Japan and Poland⁴⁵. They found that rat sightings were geographically specific, with each city showing different patterns of rat-related public requests either increasing (i.e. Tokyo) or decreasing (i.e. New York City)⁴⁵. Further, they reported a positive association between rat sightings and food service establishments in both cities, with the formation of new rat sighting hotspots during the lockdown period⁴⁵. Parsons, *et al*/2020 argued that the strong association between rat sightings and cafes or restaurants, as well as the development of new rat sightings hotspots suggests mass movements of rats triggered by lockdown. Moreover, they suggest that this pattern is not observed in Warsaw, Poland due to the lack of clustering of restaurants⁴⁵. An important caveat of the Parsons, *et al*/2020 study is that it used public perception as a proxy for rodent abundance and movements. Although previous studies have found a reliable relationship between public complaints and rodent abundance⁴⁶, these measurements have not been validated during disruptive periods such as COVID-19. It has been suggested that public perceptions can be affected by cognitive biases potentiated by COVID-19 restrictions and the increased use of social media⁴¹⁻⁴³.

Building on anecdotal reports, we investigated how the COVID-19 pandemic restrictions affected pest rodent trapping success, activity, and residents' perceptions within the City of Sydney Local Government Area, New South Wales, Australia. From January 2020, the Australian Federal Government enacted a series of preventative measures to limit the spread of COVID-19. These preventative measures included limits on the number of attendees at social gatherings, mandatory 14 days self-quarantine of all travelers entering Australia, mandatory closure of all non-essential businesses, as well as border closures. Similar to other parts of the world, shortly after these measurements were put in place, different media outlets started to report a seemingly increase in rodent sightings³¹⁻³³. We used data on rodent trapping success, rodent activity and rodent related resident's complaints received by the City of Sydney Council as part of their pest monitoring and control program to determine whether the enactment of COVID-19 preventative measures affected the rodent pest population, as well as the residents' perception of the abundance of rodent pests.

Results

Multi-Catch rodent stations

Multi-Catch rodent stations captured 851 rodents during 305 days of deployment (mean: $2.79 \pm \text{SE: } 0.469$ animals per trap day). The number of catches per trap day was associated with period ($\chi^2_2 = 8.579$; $P=0.014$; Table 1) and the interaction between date and period ($\chi^2_2 = 9.570$; $P=0.008$; Table 1), but not date alone ($\chi^2_1 = 0.273$; $P=0.601$; Table 1). There were more catches during lockdown than post-lockdown (Conditional model:

Tukey's HSD, $P=0.043$, Table 1, Fig. 1A), but catches did not differ between pre-lockdown and lockdown periods (Conditional model: Tukey's HSD, $P=0.274$, Table 1, Fig. 1A) or pre-lockdown and post-lockdown (Conditional Model: Tukey's HSD, $P=0.113$, Table 1, Fig. 1A). The probability of a catch did not differ between any of the periods (Zero-inflated model: Tukey's HSD; pre- and post-lockdown $P=0.967$, pre-lockdown and lockdown $P=0.210$, and lockdown and post-lockdown $P=0.295$; Table 1). Post-lockdown, catches increased over time compared to pre-lockdown (Conditional model: $z= 2.328$; $P=0.020$; Table 1, Fig 2A), and during lockdown the number of catches and the probability of a catch decreased rapidly over time (Conditional model: $z= -1.960$; $P=0.050$; Zero-inflated model: $z= -3.043$; $P=0.002$; Table 1, Fig 2A).

Rodent bait stations

Due to bait station relocations, a total of 12502 locations were recorded. Average rodent activity at bait stations over 345 days of deployment was recorded as $0.516 \pm \text{SE: } 0.052$ (0 = low activity and 1= high activity). Rodent activity showed a relationship with date ($\chi^2_1= 683.92$; $P<0.001$; Table 2), period ($\chi^2_2= 14587000$; $P<0.0001$; Table 2) and the interaction between date and period ($\chi^2_2= 14194000$; $P<0.0001$; Table 2). Rodent activity was highest during lockdown (Tukey's HSD, $P<0.0001$, Table 2, Fig. 1B), lowest post-lockdown (Tukey's HSD, $P<0.0001$, Table 2, Fig. 1B) and intermediate pre-lockdown (Tukey's HSD, $P<0.0001$, Table 2, Fig. 1B). Overall, rodent activity increased over time ($z= 26.150$; $P<0.0001$; Table 2, Fig 2B). Compared to pre-lockdown, during lockdown and post-lockdown, rodent activity decreased over time ($z= -3758.740$; $P<0.0001$; and $z= -352.470$; $P<0.0001$, respectively; Table 2, Fig 2B).

Rodent related residents' complaints

The City of Sydney Council received 242 rodent related complaints during the 572 days (from January 7th, 2019 to August 31st, 2020; mean: $0.423 \pm \text{SE: } 0.031$ complaints per day). The number of complaints received was associated with period ($\chi^2_2= 6.260$; $P=0.044$; Table 3) but not date ($\chi^2_1= 0.951$; $P=0.329$; Table 3). The interaction between period and date was removed from the final model based on AIC_c (Δm : 3.6). More complaints were received during lockdown compared to post-lockdown (Tukey's HSD, $P=0.036$, Table 3, Fig. 1C), while the number of complaints received pre-lockdown did not differ from the number of complaints received during lockdown (Tukey's HSD, $P=0.548$, Table 3, Fig. 1C) or post-lockdown (Tukey's HSD, $P=0.242$, Table 3, Fig. 1C).

Spatial analysis of Multi-Catch stations, bait stations and residents' complaints

Multi-Catch rodent stations were operated within seven of the eleven Statistical Areas Level 2 (SA2) within the Council, whereas rodent bait stations were operated in all eleven SA2. Rodent related residents' complaints were made in all SA2 (Fig. 3). For all three measures, their mean centers and directional ellipses were approximately equivalent in the pre-lockdown, lockdown and post-lockdown periods (Fig. 4). Significant correlations were found between residents' complaints pre-lockdown versus both lockdown ($r_{SP} 0.791$, $P = 0.004$) and post-lockdown ($r_{SP} 0.709$, $P = 0.015$) periods. Multi-catch rodent stations pre- versus post-lockdown periods ($r_{SP} 0.829$, $P = 0.021$), and multi-catch rodent stations versus bait stations pre-lockdown ($r_{SP} -0.775$, $P = 0.041$) were also correlated.

Discussion

Overall, we found the general patterns of rodent catches, rodent activity and rodent related residents' complaints to be consistent across measurements (Tables 1, 2 and 3; Fig 1). All three measurements were highest during the lockdown period and lowest post-lockdown (Fig 1). Rodent catches were slowly declining pre-lockdown, while an abrupt spike in catches during lockdown was seen, with an almost immediate crash and a slow recovery during post-lockdown (Table 1, Fig 2A). In contrast, rodent activity seemed to have been on the rise pre-lockdown, with lockdown triggering a steep decline in activity that continued post-lockdown (Table 2, Fig 2B). We found no temporal changes in the number of rodent related complaints received by the council (Table 3, Fig. 4). We found no spatial changes for any of the measurements between pre-lockdown, lockdown and post-lockdown periods (Fig. 4). The spatial distribution of multi-catch rodent stations seemed to have changed during lockdown and returned to the pre-lockdown distribution in the post-lockdown. Multi-catch and bait stations data pre-lockdown appear related, but this relationship seemed to have been disrupted during lockdown and continued to be disrupted post-lockdown.

Despite the higher levels of rodent catches, activity and sighting during lockdown is consistent with rodent population observations after hurricanes^{22,23}, whereas the rapid decline at the end of the lockdown period is not. We hypothesize that this might be due to the undeniable temporal and physical differences between a climatic event and a pandemic. Hurricanes are short-lived, with vast physical effects on the landscape, while the COVID-19 pandemic has had a long-term effect on human behavior and no tangible physical consequences in terms of infrastructure. Hurricanes might cause a shift in habitat characteristics, potentially increasing landscape heterogeneity thus encouraging rodent abundance^{2,47}. In contrast, social restriction, which involves closure of restaurants, cafes and other food venues⁴⁸, might have only reduced or eliminated human-derived food resources where they have been plentiful before. Commensal rodents show high levels of neophobia^{49,50} and taste aversion^{51,52} resulting in high levels of 'trap-shyness'^{53,54} and low bait acceptance^{55,56}. However, a reduction in food resources might have driven animals to engage in "bold" behaviors during foraging whilst in a lower physiological state⁵⁷⁻⁶⁰. These hunger-driven behaviors might explain reports of rats feeding in close proximity to humans^{31,35,36} as well cannibalism^{31,37}. Ultimately, hunger might have caused these animals to overcome their neophobia and taste aversion, resulting in a decrease in trap shyness and higher bait acceptance, driving an increase in mortality by electrocution or poisoning.

A higher mortality by lethal traps and rodenticide, as well as the decrease in carrying capacity by the reduction of food resources, can explain the steep decline in catches, activity and sightings that we found after the lockdown period^{61,62}. Moreover, it is highly unlikely that the peaks in rodent activity, catches and complaints would be due to an increase in the rodent population, given that the lockdown period lasted only 45 days. Even rats, which are known for their prolific reproduction^{63,64}, would not be able to reproduce and mature in such a limited time frame. The recovery in the population is therefore expected to be more gradual, like the steady but slow increase in activity and rodent catches we found in the post-lockdown period. Remarkably, rodent related residents' complaints seem to mirror rodent activity and tradability, similarly to what has been reported during periods of no disturbance⁴⁶. This is regardless of the potential for cognitive biases in residents perceptions that have been reported during COVID-19⁴¹⁻⁴³.

Given that our data did not cover several years, we were unable to account for natural seasonal cycles in the rodent population. Several studies have shown that urban rodent populations follow a seasonal gradient that reflect both human changes in behaviors and temperature^{19,46,65,66}. Colder months seem to trigger lower rodent

activity, that then increase towards spring and peaks in summer^{46,65,66}. Our pre-lockdown multi-catch station data seems to support this, but not so our bait station data. It is possible that in a subtropical City such as Sydney (average minimum temperature 15.7°C⁶⁷) the effect of seasonal changes in temperature might not be as strong as that detected in laboratory studies^{65,66} and more temperate cities⁴⁶. Additionally, it has been well documented that cities are “heat islands” that experience significantly milder winters than surrounding areas⁶⁸. This might be more pronounced in coastal cities like Sydney. Moreover, the expected seasonal changes in rodent activity cannot explain the abrupt increase and decline in catches, nor the abrupt decline in rodent activity during lockdown. Therefore, we argue that the effects we report are solely due to the changes in human behaviors, and unintended effects on the rodent population, elicited by the COVID-19 restrictions.

Interestingly, we found no evidence of spatial changes driven by the lockdown. This supports the findings Parsons *et. al* 2020 reported from Warsaw, Poland but contrast with their results from New York City and Tokyo⁴⁵. They suggested that COVID-19 lockdown measures trigger an increase in rodent movement and potential massive migrations, based on the increased association of rats and food service establishments and the formation of new hotspots of rat sightings in New York City⁴⁵. Our data suggest the contrary and based on the well-known site fidelity pest rodents species show⁶⁹, it is difficult to reconcile that the effects measured are not localized. In the case of Tokyo and New York City, the result may reflect cognitive bias where residents are spending more time at home during social distancing measure are more likely to see rodents in a different area, and thus report and call pest controllers. Parsons *et. al* 2020, does suggest that this pattern of movement was not recorded in Warsaw, potentially because of the lack of restaurant clusters in that city, a situation that maybe be similar to the one in Sydney.

If the peak in rodent activity was indeed due to abnormal foraging behavior caused by starvation followed by a population crash, it is highly possible that the lockdown acted as a genetic bottleneck. The City of Sydney Council currently has 942 rodent bait stations deployed, versus a maximum of 60 multi-catch rodent stations deployed on any one day. It follows that rodents would be significantly more likely to encounter a bait station than a multi-catch trap. Thus, an increase in acceptance of rodenticide baits could be the main cause of a population crash, driven by the reduction of human-derived food resources during lockdown. Similarly to other reported cases, after such a mortality event, the genetic variation within the remaining population could be up to 90% lower than the original population⁷⁰. Australia is currently one of the only countries in the world where rodenticide resistance has not yet been detected. Thus far a limited number of studies have looked into the subject, either through feeding trials^{71,72} or genetic detection of reported mutations in the VKORC1 gene responsible for conferring such resistance⁷³. Thus, there is a high possibility some individuals inhabiting Australian urban areas may carry mutations, either novel or previously reported⁷⁴, conferring on them rodenticide resistance. It follows that a higher proportion of the lockdown surviving individuals could be genetically resistant to rodenticides⁷⁵. These remaining individuals would then become the “founding gene pool” that would give rise to a genetically distinct and potentially rodenticide resistant population. This “new” population would not take long to recover and repopulate the area⁶⁴, evident by the rapid increase in rodent catches and activity we report post-lockdown. This is a very different interpretation to that offered by Parsons *et. al* 2020, where the assumption of the mass movement of rats might drive an increase in genetic variation due to interbreeding between not previously connected populations^{76,77}.

Although the risks of commensal rodents to be infected or transmit SARS-CoV-2 are low ⁷⁸, we know that these animals pose other health risks ^{2,7-14}. Thus, an increase in rodent-human interactions has the potential to place further strains on health systems around the world. This could become even more pronounced if rodenticide resistance in these pests become widespread ⁷⁹. It is possible that the onset of COVID-19 might have disrupted not only human behavior, but also commensal rodent populations, with profound implications for the future management of these species.

Materials And Methods

Study Area

The City of Sydney (hereafter Council) is the largest city, by population, in Australia, with 240,229 residents ⁸⁰. It borders Port Jackson in the north, the Woollahra Municipal Council area and Randwick City in the east, the Bayside Council area in the south, and the Inner West Council area in the west ⁸⁰. Sydney has a humid subtropical climate (average maximum = 21.3°C; average minimum = 15.7°C; ⁶⁷. The Council is composed of 33 suburbs and 23 localities.

Data sourcing

All data used in this research was obtained from the Council. As part of Council's ongoing rodent control operations, pest management contractors have deployed multi-catch rodent stations as well as rodent bait stations across the Council. Rodent captures and activity are recorded regularly, and the data is stored by the Council. The Council also receives residents' complaints through phone calls, emails or through electronic complaint forms found on the Council's website. These complaints are compiled and stored by the Council.

Multi-Catch rodent stations dataset

Flick SMART Multi-Catch rodent station is an internationally patented rodent trap design ⁸¹. This trap consists of a trigger mechanism that kills the animal by an electric current. The trap has a built-in programmable computer with a SIM card, enabling it to communicate via the mobile network when it has been activated. This trap can catch multiple animals (eight maximum), before it needs to be serviced.

Under a pest management contract between the Council and Flick Anticimex Pty Ltd, 20 to 60 multi-catch rodent stations were deployed across the council from October 2019 to July 2020. Deployment was non-random and guided by strategic pest management priority zoning. These stations were baited with barbeque grease and commercially available rodent attractants. The Council receives monthly reports from Flick Anticimex Pty Ltd that contained the number of traps active, their location in latitude and longitude coordinates and the number of captures per day per each trap.

Rodent bait stations dataset

Additionally, 942 bait stations (PROTECTA EVO Ambush and PROTECTA LP, Bell Laboratories, Inc.) were deployed across the council from September 2019 to August 2020. Deployment was non-random and guided by strategic pest management priority zoning. These stations were baited with commercial poisoned baits (Bromadiolone: Contrac Blox and Contrac Soft Bait; Brodifacoum: Ditrac Blox; Difethialone: Generation Block and Rodilon Soft

Block; Flocoumafen: Storm Secure Block and Storm Soft Bait). Baits were randomly rotated at each station, to prevent rodents developing aversion to any bait. Each station was checked regularly (mean: 10.56 Days $\pm$ SE: 0.06) and scored according to the rodent activity i.e. low: no bait consumed and no visual signs; or high: bait consumed and visual signs present. Following strategic pest management, bait station with consistent low activity score were relocated. The location for all bait stations was recorded in UTM coordinates to facilitate spatial analyses.

Rodent related residents' complaints dataset

We accessed all rodent related complaints made to the Council from January 2019 to August 2020. Complaints were received through phone calls, emails or through electronic complaint forms found on the Council's website. All complaints contained the date and street address. Identifying information was removed from the complaint dataset, with street address transformed to UTM coordinates to facilitate spatial analyses.

COVID-19 pandemic restrictions

Following the rapid increase in COVID-19 cases at the beginning of 2020, the Australian Federal Government enacted a series of preventative measures to limit the spread of the disease. These preventative measures included limits in the number of attendees at social gatherings, mandatory 14 days self-quarantine of all travelers entering Australia, mandatory closure of all non-essential businesses, as well as border closures. We used the publicly available timeline of these measures⁴⁸, to classify the datasets into three "Periods". *Pre-lockdown* was defined as the period prior to March 31st, 2020; the *Lockdown* was defined as the period from the April 1st to May 15th, 2020; and *Post-lockdown* was defined as the period from May 16th onwards.

Statistical Analyses

We first wanted to explore if there was any effect of Covid-19 restrictions overall on pest rodent population and residents' perception within the Council. For this purpose, we performed statistical analyses in R 4.0.2 (R Development Core Team, 2019). The Multi-Catch rodent station dataset was analyzed by Generalized Linear Mixed Models (GLMM) using the functions *lmer*, *glmer* and *glmer.nb* from the package "lme4" version 1.1.23⁸² and the function *glmmTMB* from the package "glmmTMB" version 1.0.2.1⁸³ for model construction. The rodent bait station dataset was also analyzed by GLMMs with a binomial distribution, using the function *glmer* from the package "lme4" version 1.1.23 (Bates et al., 2015). The rodent related residents' complaints dataset was analyzed by General Linear Models (GLM) using the functions *lm*, *glm* and *glm.nb* from the package MASS version 7.3.51.6⁸⁴ for model construction. With the exception of the models constructed to test the rodent bait station dataset, residual plots and the Pearson's dispersion test were used to identify the best distribution and link for each model⁸⁵. For model selection and refinement we used the function *AICc* from the package "MuMIn" version 1.43.17⁸⁶. We calculated Δm between models and excluded models with $\Delta m > 2$ as having substantially less support⁸⁷.

To generate *P*-values, Wald Chi-square tests were applied to both GLMMs and a Chi-square analysis of deviance was applied to the GLM using the function *Anova* from the package "car" version 3.0.9⁸⁸. Post-hoc pairwise comparisons with Tukey adjustments were carried out by the functions *emmeans*, and *pairs* from the package

“emmeans” version 1.5.0 ⁸⁹, and the function *cld* from the package “multcomp” version 1.4.13 ⁹⁰. Graphs were constructed using package “ggplot2” version 3.3.2 ⁹¹.

Each model used aimed to test the effects of COVID-19 restrictions on the number of rodent catches per day (Multi-Catch rodent stations), the level of rodent activity (Rodent bait stations) and residents’ perceptions of rodent activity (number of complaints). Period (i.e. Pre-lockdown, Lockdown and Post-lockdown), date, and the interaction between date and period were included as fixed factors. To account for intrinsic differences in rodent catches and/or activity based on location, the models aimed to test rodent catches and rodent activity included location as the only random factor. Additionally, in the case of the Multi-Catch rodent station data set, to account for differences in trapping effort due to variable number of traps deployed across the sampling period, the number of active traps was included in the models as an offset.

The spatial distribution of total rodent catches (Multi-Catch rodent stations), the level of rodent activity (Rodent bait stations with high activity) and residents’ perceptions of rodent activity (total number of complaints) were visualized by creating dot maps based on latitude and longitude or UTM and the Inner Sydney and Eastern Suburbs–North polygons of the Statistical Areas Level 3 (SA3) dataset set 2016 (Geographic Datum of Australia 1994). Data were projected in UTM 56S using ArcGIS 10.5 ⁹². For each dataset overall and for the three study periods, mean centers and directional ellipses were calculated (Spatial Statistics. ArcGIS 10.5. ESRI). Rodent catch and activity and complaints data were summed to SA2 areas: the 10 areas which make up Inner Sydney SA3 and the adjacent Paddington-Moore Park SA2 which lies within SA3 Eastern Suburbs–North. The correlations (r_{sp}) between these data by SA2 were calculated on SPSS v24 ⁹³.

Declarations

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AUTHOR CONTRIBUTIONS

MBP, MPW and MSC conceived and designed research. MBP and ML obtained and processed the data. MBP and MPW analyzed data. MBP and ML wrote the manuscript. All authors read and approved the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

Most of the data that supports the findings of this study are available from Dryad ⁹⁴ but restrictions apply to the availability of the rodent related residents’ complaints data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the Council of the City of Sydney.

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Tables

Table 1. Model summary, Analysis of deviance (Wald Chi-squared tests) and Post-hoc Tukey adjusted pairwise comparisons for the final model constructed to test number of catches per Multi-Catch Rodent station and day according to date and COVID-19 restriction period. Final model: Catches ~ Date x Period + offset (Log (Active Traps)) + Random (Location); Zero-inflation: ~ Date x Period; Family: Negative Binomial. Data comprised daily catches from 20 to 60 multi-catch rodent stations deployed across the Council of the City of Sydney from October 2019 to July 2020.

Conditional model fixed effects	Estimate	SE	z	P	
(Intercept)	-2.639	0.325	-8.115	<0.0001	
Date	-0.001	0.002	-0.522	0.601	
Lockdown	4.497	2.286	1.967	0.049	
Post-lockdown	-5.133	2.372	-2.164	0.031	
Date x Lockdown	-0.022	0.011	-1.960	0.050	
Date x Post-lockdown	0.021	0.009	2.328	0.020	
Zero-inflation model fixed effects	Estimate	SE	z	P	
(Intercept)	-2.013	1.326	-1.518	0.129	
Date	0.004	0.006	0.699	0.485	
Lockdown	35.800	11.514	3.109	0.002	
Post-lockdown	-2.771	3.715	-0.746	0.456	
Date x Lockdown	-0.183	0.060	-3.043	0.002	
Date x Post-lockdown	0.014	0.015	0.984	0.325	
Analysis of Deviance Table (Type III Wald chi-square tests)					
Fixed factors			d.f.	Wald- χ^2	P
(Intercept)			1	65.857	<0.0001
Date			1	0.273	0.601
Period			2	8.579	0.014
Date x Period			2	9.570	0.008
Post-hoc Tukey adjusted pairwise comparison on the conditional model					
Period contrast	Ratio	SE	d.f.	t ratio	P
Pre-lockdown / Lockdown	0.691	0.233	5251	-1.094	0.274
Pre-lockdown / Post-lockdown	3.165	2.301	5251	1.585	0.113
Lockdown / Post-lockdown	4.581	3.439	5251	2.027	0.043
Post-hoc Tukey adjusted pairwise comparison on the zero-inflated model					
Period contrast	Odds ratio	SE	d.f.	t ratio	P
Pre-lockdown / Lockdown	0.279	0.284	5251	-1.253	0.210
Pre-lockdown / Post-lockdown	1.058	1.459	5251	0.041	0.967
Lockdown / Post-lockdown	3.793	4.824	5251	1.048	0.295

Table 2. Model summary, Analysis of Deviance (Wald Chi-squared tests) and Post-hoc Tukey adjusted pairwise comparisons for the final model constructed to test rodent activity scores from bait stations according to date and COVID-19 restriction period. Final model: Activity Score ~ Date x Period + Random (Location); Family: Binomial. Data comprised rodent activity score (i.e. low = 0 or high = 1) from 942 bait stations deployed across the Council of the City of Sydney from September 2019 to August 2020.

Fixed effects	Estimate	SE	z	P
(Intercept)	-12.450	0.482	-25.820	<0.0001
Date	0.001	0.000	26.150	<0.0001
Lockdown	737.500	0.193	3817.970	<0.0001
Post-lockdown	128.900	0.375	344.190	<0.0001
Date x Lockdown	-0.040	0.000	-3758.740	<0.0001
Date x Post-lockdown	-0.007	0.000	-352.470	<0.0001
Analysis of Deviance Table (Type III Wald chi-square tests)				
Fixed factors		d.f.	Wald- χ^2	P
(Intercept)		1	666.580	<0.0001
Date		1	683.920	<0.0001
Period		2	14587000.000	<0.0001
Date x Period		2	14194000.000	<0.0001
Post-hoc Tukey adjusted pairwise comparison				
Period contrast	Odds ratio	SE	z ratio	P
Pre-lockdown / Lockdown	0.095	0.007	-31.225	<0.0001
Pre-lockdown / Post-lockdown	3.010	0.220	15.089	<0.0001
Lockdown / Post-lockdown	31.711	2.996	36.581	<0.0001

Table 3. Model summary, Analysis of Deviance and Post-hoc Tukey adjusted pairwise comparisons for the final model constructed to test number of rodent related residents' complaints according to date and COVID-19 restriction period. Final model: Complaints ~ Date + Period; Family: Negative binomial. Data comprised the number of rodent related residents' complaints received by the Council of the City of Sydney from January 2019 to August 2020.

Fixed effects	Estimate	SE	z	P	
(Intercept)	-11.670	11.170	-1.045	0.296	
Date	0.001	0.001	0.968	0.333	
Lockdown	0.284	0.272	1.046	0.296	
Post-lockdown	-0.479	0.298	-1.608	0.108	
Analysis of Deviance Table					
Fixed factors			d.f.	χ^2	P
Date			1	0.951	0.329
Period			2	6.260	0.044
Post-hoc Tukey adjusted pairwise comparison					
Period Contrast	Ratio	SE	z ratio	P	
Pre-lockdown / Lockdown	0.753	0.204	-1.046	0.548	
Pre-lockdown / Post-lockdown	1.615	0.481	1.608	0.242	
Lockdown / Post-lockdown	2.145	0.662	2.473	0.036	

Figures

Figure 1

Estimates of rodent catches (A), rodent activity (B) and rodent related residents' complaints received by the Council of the City of Sydney, in relation to COVID-19 restrictions and social distancing measures imposed by the Australian Federal government (Mean $\pm$ SE). Calculated from data collected from September 2019 to August 2020. Superscripts represent Tukey-adjusted pairwise comparisons ($\alpha=0.05$).

Figure 2

Estimates of rodent catches (A) and rodent activity (B) within the Council of the City of Sydney over time, and in relation to COVID-19 restrictions and social distancing measures imposed by the Australian Federal government. Calculated from data collected from September 2019 to August 2020. The shaded grey area represents the standard error of the mean (SE). Dashed vertical lines represent the start and end points of mandatory lockdowns.

Figure 3

Locations of multi-catch rodent stations (●), rodent bait stations (●) and residents' rodent complaints (●) within the Council of the City of Sydney. The eleven Statistical Area 2 (SA2) which make up the City of Sydney are shown. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

A

B

C

Figure 4

Distribution of multi-catch rodent stations (A), rodent bait stations (B) and residents' rodent complaints (C) within the Council of the City of Sydney and their mean centers and associated directional ellipses during pre-lockdown (●), lockdown (□) and post-lockdown (△) periods.