frontiers in Ecology and Evolution

REVIEW
published: 23 March 2022
doi: 10.3389/fevo.2022.813600

Reconsidering the "War on Rats": What We Know From Over a Century of Research Into Municipal Rat Management

Michael J. Lee[1,2], Kaylee A. Byers[1,2], Craig Stephen[1,3], David M. Patrick[1,4], Robert Corrigan[5], Stefan Iwasawa[6] and Chelsea G. Himsworth[1,2,7]*

[1] School of Population and Public Health, The University of British Columbia, Vancouver, BC, Canada, [2] Canadian Wildlife Health Cooperative, Animal Health Centre, Abbotsford, BC, Canada, [3] School of Veterinary Medicine, Ross University, Basseterre, Saint Kitts and Nevis, [4] British Columbia Centre for Disease Control, Vancouver, BC, Canada, [5] Corrigan Consulting, Chappaqua, NY, United States, [6] Centre for Coastal Health, Nanaimo, BC, Canada, [7] Animal Health Centre, British Columbia Ministry of Agriculture, Abbotsford, BC, Canada

OPEN ACCESS

Edited by:
Bastiaan G. Meerburg, Wageningen University & Research, Netherlands

Reviewed by:
Inge Milou Krijger, Dutch Pest & Wildlife Expertise Centre (KAD), Netherlands
Theo Van Der Lee, Wageningen University & Research, Netherlands

***Correspondence:**
Michael J. Lee
m.lee@ubc.ca

Specialty section:
This article was submitted to Urban Ecology, a section of the journal Frontiers in Ecology and Evolution

Received: *12 November 2021*
Accepted: *25 February 2022*
Published: *23 March 2022*

Citation:
Lee MJ, Byers KA, Stephen C, Patrick DM, Corrigan R, Iwasawa S and Himsworth CG (2022) Reconsidering the "War on Rats": What We Know From Over a Century of Research Into Municipal Rat Management. Front. Ecol. Evol. 10:813600. doi: 10.3389/fevo.2022.813600

To sustainably control urban rat infestations, management efforts need to encompass large areas of urban centers. Therefore, the objective of this review and narrative synthesis was to collate what is known about municipal-scale rat management. We explored the management frameworks that have been used at a large scale in cities and we describe the expectations of experts who have designed and implemented these frameworks. We found that there has been a persistent "war on rats" paradigm driving this literature since the early 1900s. Not only was there little quantitative evidence to support this paradigm and associated methodologies, but together, they failed to meet the expectations of those who designed and implemented them due to real-world constraints (i.e., limited resources). To improve the field of municipal management, we identify two distinct options. First, stakeholders may continue to wage the "war on rats" while improving existing strategies within this paradigm. Key pathways forward include developing evaluation metrics aligned with program objectives, establishing the cost-effectiveness of methodologies, and improving control efficacy. Second, we suggest a new paradigm, one that considers that rat management is a complex system that must be approached by first mapping its complexity to highlight and prioritize the many complex upstream determinants of infestations. This perspective highlights how rat management may be a wicked problem for which there is no overarching solution and instead can only be managed by making incremental gains in individual components of the problem over time. Importantly, we propose an alternative management objective that places a priority on improving the overall health of the community, instead of on eliminating rats, and we stress that management goals must address stakeholders' goals as their investment is essential for a sustained program.

Keywords: rats, municipal rat management, municipal, urban, literature review, wicked problem

INTRODUCTION

Rats (*Rattus* spp.) are ubiquitous in cities globally where they have caused significant illness and untold economic harm (Aplin et al., 2003). Not only can rats transmit pathogens to people (Battersby et al., 2008), but they also act as chronic stressors adding anxiety and fear into the tapestry of issues that people face daily (German and Latkin, 2016; Byers et al., 2019; Murray et al., 2021). Rats negatively impact urban economies via several insidious pathways including damaging infrastructure and buildings (Tobin and Fall, 2004), the direct costs of rodent control measures (Almeida et al., 2013), destroying personal belongings, and contaminating foodstuffs (Battersby et al., 2008; Garba et al., 2014) leading to business closures, reputation loss, and decreasing public space utilization. With increasing global urbanization (United Nations, 2019) cities require effective strategies to prevent, eliminate, and monitor rat populations and their impacts – henceforth collectively referred to as management.

To sustainably manage urban rats, strategies must encompass the extent of infestations and their causes. Rats have high fecundity, readily move around urban environments, and can thrive on a diversity of food, water, and harborage (FWAH). As a result, failing to significantly eliminate rats and/or their causes allows populations to rapidly return to pre-control levels (Davis, 1953; Lambropoulos et al., 1999; Fernández et al., 2007). Further, many of the FWAH factors that contribute to the presence of rats may extend beyond any given property such that reduction of these factors in one area may not address all the resources available to rats (Corrigan, 2006; Johnson et al., 2016). Taking these issues together, experts have concluded that sustainable approaches require large- or municipal-scale (i.e., a city and/or its local governing body) strategies to comprehensively address infestations and their causes which commonly extend throughout communities and cities (Lantz, 1909; Drummond, 1970; Bajomi et al., 1996).

The objective of this study was to review and synthesize the body of municipal rat management literature to address the following research questions: (1) What are authors' expectations for municipal rat management? (2) Have municipal approaches met those expectations? (3) Why or why haven't municipal approaches met expectations? (4) What is the way forward? Importantly, because we found that these expectations and others have been summarized and synthesized in other detailed reviews, opinion pieces, and book chapters (Davis and Jackson, 1981; Kaukeinen, 1994; Colvin and Jackson, 1999; Meyer, 1999; Corrigan, 2006) we focused this review primarily on whether those expectations have been achieved. We synthesized this information with a view toward identifying options to improve the field of municipal rat management.

MATERIALS AND METHODS

Inclusion Criteria

Publications were included if they focused on monitoring and/or controlling rats at a municipal scale in urban settings. 'Municipal scale' was defined as a single continuous neighborhood or larger. This included both primary (i.e., original research) and secondary (i.e., guidelines, textbooks, reviews, and commentaries) literature. Studies were excluded if they focused on describing the wildlife species present in a city, disease surveillance/sampling, describing rat genetic structures, and/or performing ectoparasite surveys, or only consisted of an abstract. The study title, abstract, and/or the full text were scrutinized as necessary to accurately assess the inclusion criteria. Only English language literature was included.

Search Strategy

Early searches revealed that relevant publications were present in a variety of locations beyond scientific databases. To maximize the breadth of studies found, the search strategy consisted of five components (**Figure 1**): (1) systematic database search; (2) conference proceedings; (3) author search; (4) gray literature, and; (5) citation searching. The first component comprised a systematic search of the peer reviewed literature from the earliest date available to May 2020 in the databases – Web of Science, CAB direct, MEDLINE, Zoological record and BIOSIS Previews. We searched keywords relating to the concepts urban, rats, monitoring, management, and programs. Concepts were combined using the Boolean operator 'AND' in three separate searches repeated in each database: search (1) "urban AND rats AND data collection AND management AND program"; search (2) "urban AND rats AND data collection AND management"; search (3) "urban AND rats AND management AND program". Within each concept, keywords were combined with 'OR.' See **Table 1** for details.

Two international pest conferences, the International Conference on Urban Pests and the Vertebrate Pest Conference, were selected for further investigation because they contained relevant publications found in the database search. Proceedings were reviewed for additional publications meeting the inclusion criteria. While the proceedings for all nine of the International Conference on Urban Pests were present online, most of the proceedings (n = 28) for the Vertebrate Pest Conference from 1962 to 2018 were found at one of two online sources (Digital Commons, University of Nebraska Lincoln, and escholarship, University of California).

Author searching consisted of searching all known publications of any lead, secondary, or last author, in the databases PubMed and Web of Science, who appeared in more than one source from the conferences or systematic search or who was known to the authors of this review to have contributed substantially to this field. Initially, the authors' (n = 54) full last name and first initial were used. However, if the number of hits exceeded 200 then the same search was run with "rat OR rodent." If the number of publications still exceeded 200, then only the first 100 were examined.

The gray literature search consisted of entering the database search strings (**Table 1**) into Google and Bing. The hits were sorted by 'relevance' and 'date,' and the first fifty were examined. Additional publications were added though citation searches.

The overall search and primary inclusion/exclusion were conducted by co-author (SI). Publications that met the primary inclusion round were reassessed by author (MJL) using the same

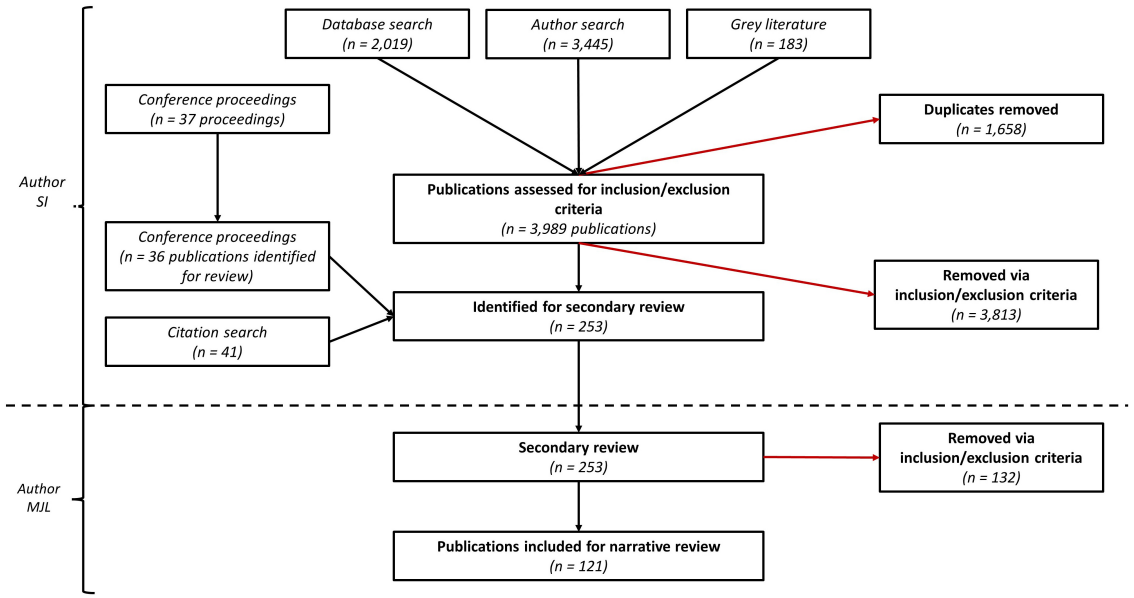

FIGURE 1 | Overall search strategy. The overall search strategy consisted of five components to maximize the breadth of literature found. Initial searches were carried out by co-author SI. A secondary review of publications found by SI was carried about by the first author (MJL). A total of 129 publications were included for narrative review and synthesis.

TABLE 1 | Search strings.

Search string	Concepts	Keywords
1	Urban AND rats AND data collection AND management AND program	(cities OR city OR municipal* OR urban OR residential OR metropol*) AND ("rattus rattus" OR "roof rat*" OR "black rat" OR "ship rat" OR "rattus norvegicus" OR "brown rat" OR "Norway rat" OR "pacific rat" OR "rattus exulans" OR "Polynesian rat") AND (surveillance OR track* OR monitor* OR record* OR survey* OR investigate* OR observ* OR study OR studies) AND (mange* OR control* OR extermin* OR eradicat* OR eliminat* OR mitigate*) AND (program* OR polic* OR report* OR strategy* OR plan* OR procedure* OR approach* OR design* OR process* OR practice* OR method*)
2	Urban AND rats AND data collection AND management	*(cities OR city OR municipal* OR urban OR residential OR metropol*)* AND *("rattus rattus" OR "roof rat*" OR "black rat" OR "ship rat" OR "rattus norvegicus" OR "brown rat" OR "Norway rat" OR "pacific rat" OR "rattus exulans" OR "Polynesian rat")* AND *(surveillance OR track* OR monitor* OR record* OR survey* OR investigate* OR observ* OR study OR studies)* AND *(mange* OR control* OR extermin* OR eradicat* OR eliminat* OR mitigate*)*
3	Urban AND rats AND management AND program	*(cities OR city OR municipal* OR urban OR residential OR metropol*)* AND *("rattus rattus" OR "roof rat*" OR "black rat" OR "ship rat" OR "rattus norvegicus" OR "brown rat" OR "Norway rat" OR "pacific rat" OR "rattus exulans" OR "Polynesian rat")* AND *(mange* OR control* OR extermin* OR eradicat* OR eliminat* OR mitigate*)* AND *(program* OR polic* OR report* OR strategy* OR plan* OR procedure* OR approach* OR design* OR process* OR practice* OR method*)*

Each search string was used to systematically search the databases Web of Science CORE, CAB direct, MEDLINE, Zoological Record, and BIOSIS previews from the earliest cut-off date available to May 2020. Keywords were entered as written into each database. The asterisk (*) indicates a search "wildcard" in which the search engine looks for different forms of a word, e.g., municipal searches for municipal, municipality, municipalities.*

inclusion/exclusion criteria. All searches were carried out in the winter to spring of 2020.

The search strategy was inclusive of the three most widespread rat species that live in close association with people in urban areas, Norway rats (*Rattus norvegicus*), roof rats (*Rattus rattus*), and Polynesian rats (*Rattus exulans*) (Aplin et al., 2003). In this manuscript, we do not distinguish between these species because some of the included studies did not differentiate between species and/or they considered them together as 'rats.' Because these species have different ecologies (i.e., roof rats may live in elevated locations; Norway rats burrow in the ground), management techniques, like specific FWAH reduction targets, may vary between species (Battersby et al., 2008). While future work might benefit from differentiating between species specific management techniques, we focus here on broader categories of management, such as FWAH reduction (as opposed to the specific targets of FWAH reduction).

Narrative Review

Publications were reviewed in full and were synthesized using a narrative framework synthesis approach (Barnett-Page and Thomas, 2009). Themes related to the municipal management

of rats were developed *a priori* and included; data collection methods, control methods, general management plan/design, justification for management, data use to inform control, measurement of management success, dissemination/education, and municipal and rat program structure. *A priori* themes were summarized for each study in a spreadsheet with themes as columns and publications as rows. Emergent themes were identified as papers were read, and included: lack of specific objectives; methods of scaling-up rat reduction; management attributes (and related subthemes); lack of evaluation of specified objectives; inability to meet specified objectives; difficulties with sustainably reducing rats; author dissatisfaction; lack of interest; complexity; and changing residents' behaviors.

Themes were then grouped into subsections within each of the four overarching research questions. This framework, depicted in **Figure 2**, was used to organize the "Results and Discussion" Section. Within each of these subsections, we compared across studies to synthesize a cohesive description and narrative.

RESULTS AND DISCUSSION

Overview of the Search Results

A total of 4,066 publications were located via the five search strategies (**Figure 1**). Of these, 121 met the inclusion criteria and were carried forward into the narrative review. These 121 studies consisted of textbook chapters, primary research studies, descriptions and comparisons of municipal rat control programs, and expert commentaries on municipal rat management. Studies focused on Africa ($n = 3$), Asia ($n = 4$), Europe ($n = 38$), Middle East ($n = 2$), North America ($N = 57$), South America ($n = 12$), or were non-specific or unspecified ($n = 5$).

Importantly, because of the scope of the locations and types of publications in which rat management literature was published, it was not possible to systematically review the entirety of the existing literature. We made every attempt to include all relevant studies, yet our search strategies may have missed specific articles, types, and locations of publications (i.e., databases, proceedings, textbooks, blogs, and reports). In addition, because studies varied considerably in their level of rat management detail, we chose not to enumerate the number of studies with a particular attribute (e.g., the number of programs which responded to complaints) or expressing a particular opinion (e.g., author frequency regarding the ineffectiveness of complaint response). This approach enabled us to share a breadth and depth of content, without misrepresenting the relative significance of a single study or idea.

What Are the Expectations for Municipal Rat Management?

Outcome Expectations

Outcome expectations were those focused on the goals of rat management initiatives. Such expectations have been centered on an overarching paradigm since the early 1900s (Lantz, 1909; Sherrard, 1943; Drummond, 1970; Colvin, 2000; Bajomi et al., 2013). This paradigm is a view of management as an effort to eliminate existing rat infestations across the urban landscape. The primary objective of these initiatives was either to reduce rats to a specified threshold (e.g., reduce the proportion of infested properties to 2% or less in a defined area; Centers for Disease Control and Prevention, 2006), or to reduce them as much as possible without pre-defining a specific threshold (Bajomi, 1980; Al-Sanei et al., 1984; Lambropoulos et al., 1999). Management also aimed to stop disease outbreaks in human populations by reducing the number of rats and their ectoparasites (Hundley and Nasi, 1944; Macchiavello, 1946; Davis, 1947). Regardless of the specific threshold, authors stressed the need for management initiatives to evaluate their success in meeting these outcome expectations over time (Margulis, 1977; Richards, 1988).

Within this literature, pest management professionals, researchers, and municipalities have focused on describing and designing (Sherrard, 1943; Colvin, 2000; Brown and Laco, 2015), testing (Lambropoulos et al., 1999; Fernández et al., 2007; Bragdon et al., 2012), and critiquing (Davis and Jackson, 1981; Kaukeinen, 1994; Colvin and Jackson, 1999) methods designed to reduce rats across large urban areas.

Methodological Expectations

Methodological expectations were expectations regarding the specific methods employed by a rat management initiative. These expectations considered whether programs should use rodenticides, FWAH reduction, or combinations of both to reduction to reduce rats. Methodological expectations fell within two closely related categories: widespread integrated pest management and reduction techniques.

Widespread Integrated Pest Management

The core expectation for the implementation of this rat-reduction paradigm has been that management should consist primarily of Integrated Pest Management (IPM) methods (Witmer and Shiels, 2018). IPM strategies are management plans focused on reducing the risks associated with rats using a combination of biological, cultural, physical, chemical, and monitoring tools to reduce rat populations and then evaluating the success of those efforts over time (Centers for Disease Control and Prevention, 2007; Ipm Institute of North America, 2021). Rat management initiatives in this review were focused on implementing IPM or IPM-like strategies at multiple locations within a city. Locations for implementing IPM were selected in two ways. The first involved conducting inspections for rats and FWAH across all properties in defined regions of a city and subsequently using the results of those inspections to target areas for control. For example, inspection data was translated into a map of the distribution of rats which was utilized to target control efforts to infested properties with severe or recurrent problems (Sherrard, 1943; Fernández et al., 2007; de Masi et al., 2009; Bragdon et al., 2012). The second approach used the locations of public complaints of infestations (Landau et al., 1999; Adrichem et al., 2013; Tamayo-Uria et al., 2013). In Shelby County, United States, when the rodent control program received complaints from residents, they sent an employee to the site of the complaint (Zerwekh and Brown, 2015). Onsite, the employee verified whether there was an infestation and "treated it" (i.e., though rodenticide application and/or FWAH reduction). The overarching expectation for management initiatives was to deploy IPM techniques to reduce rats across the city based upon data on the locations of

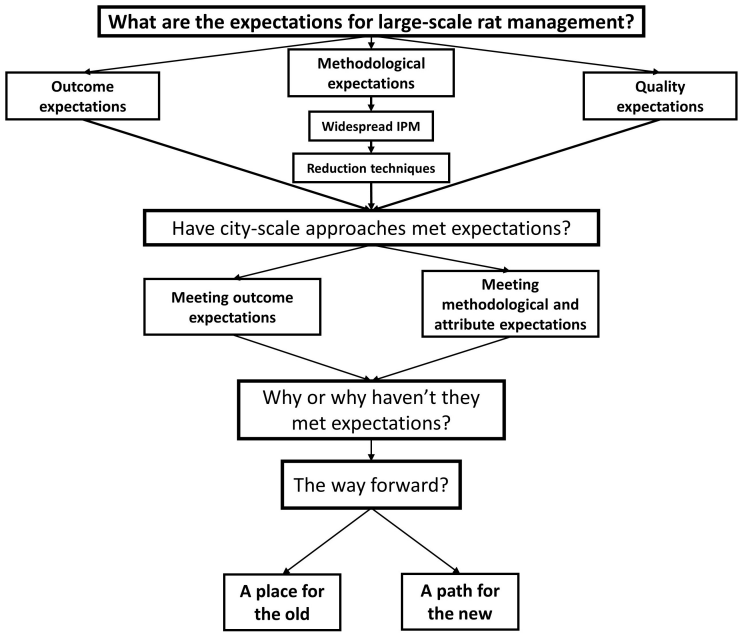

FIGURE 2 | Thematic framework. *A priori* and emergent themes were organized into subsections within each overarching research question. This framework was used to organize the Results and Discussion section.

infestations and FWAH – techniques dating back to at least the mid 1900s (Lantz, 1909; Sherrard, 1943).

Reduction Techniques

Once infestations were found via inspections or complaints, authors reported that removing FWAH was the most effective method of reducing rats (Lantz, 1909; Jackson, 1972; Who Scientific Group of Ecology and Control of Rodents of Public Health Importance, 1974; Davis and Jackson, 1981; Corrigan, 2006). For instance, Lantz (1909) described how buildings, structures, and food sources (e.g., waste management plans) could be designed to prevent rats from finding FWAH. Later, Davis (1952) experimentally demonstrated how sanitation procedures (e.g., removing clutter, junk, and garbage) could sustainably reduce rat infestations in several city blocks. Other studies focused on the application of lethal methods, such as rodenticides (Drummond, 1970; Bajomi, 1980; Al-Sanei et al., 1984), introducing a pathogen into the rat population (Jäkel et al., 2019), and traps (Taylor et al., 2008). For example, Bajomi (1980) applied rodenticide to all properties across the entire city of Budapest, Hungary and then maintained application in active areas through subsequent decades (Bajomi et al., 2013). While both FWAH reduction and rodenticides were applied above ground, FWAH reduction was not employed in subsurface areas such as sewers (Barnett, 1947; Brooks, 1962; Colvin et al., 1998; Channon et al., 2006; Fozzard et al., 2014; Why et al., 2018; Pascual et al., 2020).

To implement rat reduction techniques on a municipal scale, authors focused on activities such as: enforcing local regulations prohibiting the presence of rats and FWAH via fines (Wahlde and Colvin, 1994; Bragdon et al., 2012; Delaney and Brown, 2015); educating the public about how to recognize and manage rats on their own properties (Barnett, 1947; Who Scientific Group of Ecology and Control of Rodents of Public Health Importance, 1974; Lambropoulos et al., 1999; Landau et al., 1999; Wirth and Brown, 2015), and; through direct intervention, such as deploying rodenticides and removing FWAH (Bajomi et al., 1996; Murphy and Battersby, 2005; Brown and Brown, 2015; Why et al., 2018). Approaches were also combined (i.e., bylaw enforcement, education, and direct intervention), which was attributed and/or expected to improve program effectiveness (Sherrard, 1943; Who Scientific Group of Ecology and Control of Rodents of Public Health Importance, 1974; Davis and Jackson, 1981; Kaukeinen, 1994). For example, while Al-Sanei et al. (1984) applied rodenticide across the entire country of Kuwait, they noted that "the backbone of this rodent control success has been due to sanitation and health education."

Expectations for Management Attributes

Authors outlined expectations for the 'attributes,' or characteristics, features, and qualities of rat management initiatives. Chief among these was a shared expectation that, to achieve long-term reductions in infestations at a municipal scale, management initiatives needed to address rats and FWAH everywhere that they existed on a regular, ongoing, and comprehensive basis. Authors agreed that failing to meet any of those expectations would allow rat populations to quickly return to pre-control levels due to their high fecundity and ability to move around cities (Davis, 1953; Drummond, 1970; Colvin et al., 1990; Meyer, 1999; Corrigan, 2006; de Masi et al., 2009). This expectation was grounded in studies which found

that infestations rebounded when management programs were short-term (Barnett, 1947), when they were unable to address a rat problem on a specific property (Lambropoulos et al., 1999), and when FWAH conditions were not sustainably or completely addressed (Fernández et al., 2007). The need for such large-scale cooperative, comprehensive efforts can be traced back to the oldest study in this review in which Lantz (1909) claimed that if "farmers of an entire township or county unite in efforts to get rid of rats, much more lasting results may be attained." Lantz then proceeded to describe several historical instances in which municipalities had stimulated the cooperation of residents by incentivizing rat hunts that claimed the lives of thousands to tens of thousands of rats per year.

Authors also believed that management needed to be proactive rather than reactive by managing rats and FWAH conditions before they become problematic. They felt that the best way to achieve this was through widespread and regular inspections to locate both rats and FWAH and treat them before they became a problem (Margulis, 1977; Kaukeinen, 1994; Colvin and Jackson, 1999; Meyer, 2003). There was variability in how the term "proactive" was applied. Some authors used the term to refer to any preventative measure (Colvin and Jackson, 1999) while others used it in reference to methods, including curative measures (i.e., rodenticide), that were applied before rat problems were reported or before they became noticeably problematic (Fozzard et al., 2014). Comparatively, reactivity was either defined as applying control in response to complaints (Meyer, 2003) or in instances where lethal control was applied (Colvin and Jackson, 1999). Because of these discrepancies, we use the terms proactive and reactive to refer to approaches that are performed before or after complaints are received, respectively. To distinguish between preventative and curative approaches, we refer to methods directly (i.e., FWAH reduction or rodenticide use).

Have Municipal Approaches Met Expectations?

Did They Meet Outcome Expectations?

There were studies and programs that did not measure or directly report their success in reducing rats, even though this was their key outcome expectation. Traweger et al. (2006), for instance, reported that the City of Salzburg, Austria was federally mandated to control rats from 1925 to 2002. While the city contracted their control programs to pest management companies, they never measured the overall impact of those contracts in reducing the rat population. Nevertheless, the contracts were continuously renewed. Similarly, after much effort in developing an understanding of the health risks and FWAH conditions associated with rats, Taylor et al. (2008) was able to capitalize on that information to justify a rat control campaign to the local authority and community members. While they noted anecdotally that their program was successful in terms of its ability to engage residents and municipal officials, they did not quantify these measures of success.

Publications and programs that did directly evaluate their ability to meet outcome expectations (e.g., reducing rats), either did or did not claim success (Margulis, 1977; Lambropoulos et al., 1999; de Masi et al., 2009). Among those that did not claim success, they reported that management initiatives were unable to *sustainably* reduce infestations. For example, Fernández et al. (2007) mounted a neighborhood IPM program, but upon termination of their efforts, rat populations rebounded rapidly. In another example, while Lantz (1909) reported that a rat program in Stockholm, Sweden had removed a total of 711,797 rats over 7 years, they concluded that because the total number of rats removed each year – between 72,000 and 106,000 – was not steadily decreasing, that "the results here are hardly encouraging to those who hope for speedy extermination of these pests in large cities. It shows that the animals reproduce almost as rapidly as they are destroyed." Easterbrook et al. (2005) estimated the size of the rat population in Baltimore, United States, and compared it to estimates made in the mid 1900s. They found that the size of the rat population had remained unchanged since the earlier estimates, despite ongoing control efforts, a decrease in the human population density, and an increase in the median income over the same period, together indicating that management efforts had been unsuccessful.

Studies that did measure and claim success at meeting outcome expectations were either time-limited with funding tied to special initiatives or they were focused on intensive and widespread application of rodenticide. For instance, an IPM program in Boston, United States consisted of an intensive cross-city rat management project (i.e., it was proactive, focused on FWAH reduction, and had strong community engagement) (Colvin et al., 1990, 1992; Wahlde and Colvin, 1994; Colvin and Jackson, 1999). Despite its strong adherence to IPM principles, this program was limited to the duration and scale of a cross-city infrastructure project and its funding was tied directly to this project's $11 billion USD budget (Colvin and Jackson, 1999). As another example, Brooks (1974) reported success in their evaluation measures (e.g., a reduction in rats, rat bites, and garbage problems) during a period of funding from the United States government. However, Kaukeinen (1994) later indicated that while this government funding initiative spent around $360 million USD between 1969 and 1984 to finance rat programs in 100 different communities, when it eventually ended, many of the rat programs subsided and downscaled staff and programs [note that the specific programs described by Brooks (1974) were not implicated directly].

There were also reportedly successful long-term, municipal management programs that relied heavily on rodenticide (as opposed to FWAH reduction) in Budapest, Hungary (Bajomi et al., 1996), Kuwait (Al-Sanei et al., 1984), Alberta, Canada (Bourne, 1998), and Finland (Myllymäki, 1969). In Kuwait, the primary control methodology of a country-wide rat control campaign included "chemical control of ectoparasites and rodents on a total coverage basis" and resulted in a 99.5% reduction in rat infestations. Publications describing similarly designed programs in Budapest, Alberta, and Finland labeled their successes as a near or complete "rat-free" status. Interestingly, Bourne (1998) reported that much of the success of the rat management program in Alberta was attributable to the fact that they began their work prior to rats first invading

the province in the mid 1900s, such that infestations were never able to become established. While this does not represent the situation for most cities today because they are already infested, it highlights the utility of focusing on prevention rather than on elimination.

Did They Meet Methodological and Attribute Expectations?

Experts expressed anecdotal dissatisfaction with the overall effectiveness of municipal management approaches (Sherrard, 1943; Davis, 1952; Margulis, 1977; Davis and Jackson, 1981; Kaukeinen, 1994; Colvin and Jackson, 1999; Lambropoulos et al., 1999; Meyer, 1999, 2003; Easterbrook et al., 2005; Parsons et al., 2017; Himsworth, 2020). It appeared, based on authors descriptions, that municipal approaches failed to sustainably reduce infestations (i.e., the outcome expectations), not because there was a flaw in the long-held rat-reduction paradigm, but because cities did not adhere to a variety of methodological and attribute expectations. Authors argued that municipal approaches fell short of methodological expectations by focusing on lethal control measures rather than addressing causative FWAH (Sherrard, 1943; Jackson, 1972; Colvin and Jackson, 1999) and by implementing initiatives without robust evaluation measures (Margulis, 1977; Richards, 1988). They felt that management initiatives fell short of attribute expectations by: being time-limited instead of long-term (Sherrard, 1943; Fernández et al., 2007); being reactive by focusing on responding to complaints rather than being proactive (Kaukeinen, 1994; Meyer, 2003), and; lacking coordination across the urban ecosystem thereby failing to account for the complexity of rat management (Davis and Jackson, 1981; Meyer, 1999). For example, prior to outlining how municipalities should design a rat management program, Sherrard (1943) began with a disclaimer that rat extermination "campaigns" tended to follow a common pattern consisting of advertising the destructive and disease-causing capabilities of rats which led to a "brief flurry" of lethal control methods that quickly subsided with "dubious or negligible accomplishments." Years later, Colvin and Jackson (1999) stated that, even though the science and technology of management was robust, rat reduction initiatives tended to fail at the point of implementation largely because of a lack of coordinated and comprehensive efforts that adequately accounted for the complexity of rat management. Indeed, rat management initiatives that were implemented (as opposed to hypothesized) also fell short of specific methodological and attribute expectations. Specifically, municipal approaches were time-limited (Hundley and Nasi, 1944; Macchiavello, 1946; Davis, 1947; Colvin and Jackson, 1999; Lambropoulos et al., 1999; Fernández et al., 2007; de Masi et al., 2009), focused on responding to complaints (Landau et al., 1999; Murphy et al., 2009; Adrichem et al., 2013; Delaney and Brown, 2015; Wirth and Brown, 2015), unable to comprehensively address rats and FWAH across all problematic city jurisdictions (Bragdon et al., 2012), and/or they lacked measures of overall program success (Margulis, 1977; Traweger et al., 2006; Tamayo-Uria et al., 2013; Zerwekh and Brown, 2015).

In comparison to programs that elicited anecdotal dissatisfaction, authors who expressed clear satisfaction, did so regarding municipal programs that were focused on widespread rodenticide application. Therefore, these programs broke from the ideal-world methodological expectations and relied heavily on methods associated with significant risks. These risks include the development of rodenticide resistance (Heiberg, 2009) and secondary poisoning of non-target species (Sánchez-Barbudo et al., 2012; Smith and Shore, 2015). In fact, Emlen (1947) reported that "10 children have been reported to have eaten ANTU [rodenticide] . . . all but one had their stomachs emptied by stomach pump and none showed any ill effects." Today, rodenticide exposure is common with more than 8,500 acute human related poisonings recorded in the United States in 2019 (Gummin et al., 2020).

Why or Why Haven't Municipal Approaches Met Expectations?

Although authors believed that cities often failed to meet outcome, methodological, and attribute expectations, there was no consensus on why. However, there were four cited barriers to effective implementation. First, authors attributed failures at the municipal level to an absence of political, scientific, public health, municipal, and/or public interest in addressing or understanding rat problems. Davis (1952) concluded that "the simple objective of getting rid of rats is too narrow to merit the attention of health officers" and Colvin and Jackson (1999) reiterated this issue by explaining that persistent low political and scientific interest in rodents in the United States led to disjointed, uncoordinated control programs. This issue appears to be entrenched in the literature with similar statements made by authors from the mid to late 1900s through to recent years (Jackson, 1972; Davis and Jackson, 1981; Richards, 1988; Colvin and Jackson, 1999; Colvin, 2000; Parsons et al., 2017). This lack of interest may be tied to limited funding and resources that prohibit adherence to the expectations of the management literature (Kaukeinen, 1994; Colvin and Jackson, 1999; Colvin, 2000; Nourjah et al., 2005; Delaney and Brown, 2015; Lopez and Brown, 2015; Wirth and Brown, 2015) which require large and continuous investments. For example, Margulis (1977) and Meyer (2003), reported that with too few staff and limited funding, programs had to rely upon public complaints to find infestations.

Second, authors felt that programs were unable to account for the complexity of urban rat management (Davis and Jackson, 1981; Colvin and Jackson, 1999; Meyer, 1999; Parsons et al., 2020). Corrigan (2006) described this complexity by illustrating how the urban environment was comprised of a complex array of FWAH resources and connections between them making municipal management of rats, which can exploit nearly any resource, tremendously nuanced. Colvin and Jackson (1999) and Centers for Disease Control and Prevention (2006) extended this idea by describing how the complexity of rat ecology and the urban environment was magnified by its intersection with the complexities of the administration of programs, local politics and politicians, the public, and/or the built environment. Others alluded to these nuances by lamenting how programs were

not able to address specific intricacies of management. As an example, municipalities were rarely able to implement multi-jurisdictional approaches that accounted for rats and FWAH in all spaces where they were problematic like private residences, food establishments, parks, alleys, and municipal properties (Lantz, 1909; Kaukeinen, 1994; Meyer, 1999; Jassat et al., 2013). Additionally, while the program in NYC described by Bragdon et al. (2012) remarkably inspected and treated infestations on approximately thirty thousand properties annually for 3 years, they were not able to include sewers, or other subsurface infrastructure. Compounding such unaddressed complexity, rat control may not be "easily assignable" to any one group or discipline, such that there is often no clear leader to take on designing and coordinating municipal management strategies across the urban ecosystem (Colvin and Jackson, 1999; Parsons et al., 2020).

Third, a lack of information on the cost-effectiveness of the recommended methodologies made it difficult to justify why some methods (e.g., regular property inspections with FWAH reduction versus reactivity to complaints with rodenticide) should be chosen over alternatives (Richards, 1988; Meyer, 1999, 2003). Richards (1988) pointed out that while the literature was "full of good reports on the success of small-scale trials," there was very little information on the cost-effectiveness of approaches undertaken at a large scale. Richards felt that for municipal recommendations to be defensible or utilizable by decision makers, studies needed to outline the costs of management approaches relative to the costs of not controlling rats (i.e., the costs of structural damages and disease transmission). In this review, studies that quantified the effect of management efforts at a large scale on rat-associated impacts only measured disease prevalence in rats and cases in people (Hundley and Nasi, 1944; Macchiavello, 1946; Davis, 1947).

Finally, authors reported that it was difficult to successfully change the behaviors of residents that contributed to FWAH driving rat problems (Davis and Jackson, 1981; Kaukeinen, 1994; Nourjah et al., 2005; Zerwekh and Brown, 2015). Lambropoulos et al. (1999) deployed a comprehensive neighborhood IPM program that resulted in an initial reduction in rats across all research areas. However, in one study zone, the infestation rate returned to pre-management levels within 6 months because some residents failed to participate in FWAH reduction measures, despite an education campaign and the issuance of bylaw violations. Similarly, Kaukeinen (1994) concluded that "rodent control in the future . . . will continue to be the oldest problems of mankind, such as carelessness, poverty, poor hygiene and ignorance of rodent pests, that will create the rodent problems requiring control" and Margulis (1977) felt that rat and FWAH problems were perpetuated by residents who did not have an economic stake in maintaining their own neighborhoods. That rat management is contingent upon the effective social management of people, further highlights the overall complexity of this problem.

The Way Forward?

A Place for the Old

This review found that the paradigm and many of the management methods at the core of this body of work were well established by the early to mid 1900s. This paradigm envisions management as a "war on rats" in which the goal is to eliminate infestations across as large a scale and for as long as possible via continuous rat control measures that are focused on removing rats and their immediate FWAH causes. Methodologies to achieve this have remained centered on the same underlying principles over time, including the need to reduce FWAH, to manage rats proactively, and to address issues across all municipal jurisdictions. Despite several studies which successfully 'won' the war by relying extensively on rodenticide, the realities of management may have relegated much of this war to rat "farming" in which rats were harvested only to "regrow" and require repeat collection (Davis and Jackson, 1981; Corrigan, 2006).

While authors assumed that this paradigm and set of expectations could enable effective approaches to municipal management, there was limited quantitative proof to support this assumption. Evidence for the effectiveness of these recommendations consisted of studies/programs that were performed over small-spatial or -time scales (Davis, 1953; Colvin and Jackson, 1999), or were commentaries, opinions, anecdotes, third-party descriptions of successful initiatives, and hypothetical roadmaps for success (Sherrard, 1943; Drummond, 1970; Kaukeinen, 1994; Meyer, 1999). Among studies that did measure success at a large scale, they were either convincingly effective management programs that were not compared to alternatives (Bragdon et al., 2012) or they reported that rats rebounded despite control efforts (Margulis, 1977; Lambropoulos et al., 1999; Easterbrook et al., 2005; Fernández et al., 2007). The studies that did claim success did so through intensive rodenticide application (Myllymäki, 1969; Al-Sanei et al., 1984; Bajomi et al., 1996), a method with significant environmental impact and risks to people. Together, these studies – comprised of those that measured success on a small or time limited scale, opinions, studies without comparators, studies that measured poor success, and those that measured success using primarily rodenticide – do not provide strong evidence for the effectiveness of the combined outcome, methodological, and attribute expectations of this literature.

Despite these issues associated with management, there may still be a place for this paradigm and methodologies within modern rat management if specific aspects of this body of work are improved. First, researchers must design and implement robust impact assessments to evaluate management at a large scale. While researchers have developed resource intensive methods for doing this (i.e., performing systematic, regular, and repeat rat/FWAH inspections of all properties), these methods do not appear to be within the reality of many management programs because of resource limitations and a lack of interest in rats (Kaukeinen, 1994; Colvin and Jackson, 1999; Brown and Laco, 2015; Lee et al., 2021). In addition, Richards (1988) explained that even when there was evaluation, it often did not align with the objectives of the management program it was evaluating. Specifically, Richards pointed out that although urban rodent control was typically motivated by public health, very few studies or programs measured the impact of management on health parameters. If the goal is to protect public health, is a measurement of a reduction in rats a clear indicator of

the successful mitigation of health issues? Evaluation measures must measure the impact of management on its motivating factors and objectives.

Once clear evaluation metrics and assessments that are aligned with management objectives have been established, stakeholders should provide an economic argument to support the utility the 'best practices' within the scope of this literature. For example, research is required to demonstrate how these methodological expectations – such as the municipal IPM approach employed by Bragdon et al. (2012) – are more cost-effective than already attractive alternatives such as rodenticide, which is desirable because it is highly visible, has low up-front costs, and has rapid impacts (Meyer, 2003). Researchers must also establish the cost-benefits of their suggested management strategies relative to the costs of none or poor management. Richards (1988), explained that one path forward would be to directly measure the costs that rats incur (damages, restaurant closures, disease, etc.), and compare that to the money saved by management efforts.

Second, researchers may continue to enhance the effectiveness of municipal rat reduction strategies by continuing to improve the accuracy or utility of rat/FWAH data (Emlen et al., 1949; Brown et al., 1955; Figgs, 2011; Gräler et al., 2017) and by seeking to raise our understanding of rat ecology with a view toward increasing the efficacy of management (Pai et al., 2003; Patergnani et al., 2010; Cavia et al., 2015; Johnson et al., 2016; Panti-May et al., 2016). Barbehenn (1970) studied the ecology of rats living in sewers and drew conclusions that they felt could be used to improve the efficacy of management. They concluded that performing control efforts in late winter would have the greatest lasting impact because at that time of year, rat populations were at their lowest. Such ecological knowledge should not only be generated, but it should be utilized to increase the efficacy of control strategies. Together, these improvements would provide stakeholders with a clear and justified argument to endorse the use of these strategies while at the same time increasing their overall effectiveness.

A Path for the New

Change the Methodological and Attribute Expectations

Authors made a variety of recommendations for where they thought that municipal rat programs needed to adapt and increase their scope. First, authors indicated the need to develop better methods of organization and coordination across municipal jurisdictions (Lantz, 1909; Sherrard, 1943; Kaukeinen, 1994; Meyer, 1999). To build such comprehensive coordination, local governments might develop new and/or improved models of collaboration among their many departments with a clear delegation of responsibilities, such as interdepartmental rat task forces (Sherrard, 1943; Colvin and Jackson, 1999; Meyer, 1999; Corrigan, 2006). Second, authors felt that infestations could be more adequately addressed by considering them in urban planning processes (Kaukeinen, 1994; Colvin, 2002). Such an approach could include engineering and design that consider how to construct buildings and landscapes to minimize future FWAH (Colvin et al., 1996), as well as adapting and extending urban planning methodologies used for non-rat related issues, like strategic city plans for transportation. These plans include not only past and present needs but also future uncertainties in the context of other problems such as climate change (Ford et al., 2017; Sciara, 2017). During the electrification of transportation and cities more broadly to combat climate change, planning how to prevent rats from chewing on wires will become increasingly important and could save an immense amount of money spent on damages (Wayt, 2021).

Overall, it appears that a key impediment to the progress of municipal rat management is that the proposed solutions have not adequately accounted for the complexity of the municipal rat management problem. In this literature, municipal rat management has been defined as a problem in which there are multiple causes (i.e., FWAH, lack of good bylaws) affecting a single outcome (i.e., the presence of rats) and that the problem can be solved by addressing each of those causes individually (this type of issue has been described as a 'complicated' problem in the wider literature; Poli, 2013). This perspective is apparent in key aspects of the literature. Specifically, authors have operationalized management as a problem of identifying and locating all FWAH causes and then working to eliminate them. Corrigan (2006) explained that the many direct causes of infestations arise and persist in, and are connected across numerous sectors of the urban ecosystem. Successful management in such a system is contingent upon taking a 'total environment' approach in which all FWAH causes, anywhere in the urban environment, that might contribute to rat problems are removed (Davis, 1952; Davis and Jackson, 1981). Other aspects of the rat management problem have similarly been broken down into individual causes requiring individual solutions. FWAH causes cross multiple jurisdictions, therefore municipalities must design programs that have the capability to address FWAH in each of those jurisdictions.

Instead, municipal rat management is more complex than a set of identifiable causes that may be solved individually. Not only does rat management depend upon the relationships and collaborations between impacted municipal departments, non-governmental agencies, and the public (Sherrard, 1943; Barnett, 1947; Kaukeinen, 1994), but it also depends upon the behaviors of residents and their resistance to changing their behaviors that contribute to rat issues (Lambropoulos et al., 1999). These more nuanced components of rat management within a larger system were only acknowledged as study limitations, highlighting the fact that a view of the solution as a matter of identifying and removing FWAH factors does not adequately encompass the entirety of the rat management problem. For example, Lambropoulos et al. (1999) mounted a comprehensive IPM program, but ultimately concluded that they were limited by their inability to change the FWAH contributing behaviors of certain residents through bylaw enforcement and education. As such, it is apparent that municipal rat management is also a problem of cultural, psychological, and social management because these factors are upstream determinants of FWAH. Possibly because of the focus on removing existing FWAH and rats, no research has investigated the effectiveness of different behavioral change methods at a municipal scale and as such, both bylaw enforcement and education were the only widely used methods of doing so in this literature.

Management of the different causes of infestations each represent their own complex problem with no clear solution. For example, previous work has linked rat abundance to areas with lower socio-economic status (Easterbrook et al., 2005; Himsworth et al., 2014; Walsh, 2014). Authors have explained the existence of this association as the result of disorder, neglect, and neighborhood quality in these areas (i.e., more exposed garbage, older and degraded buildings) increasing the amount of FWAH available to rats (Kaukeinen, 1994). These particular problems, poverty, deteriorated neighborhoods and associated urban disorder, are extremely complex issues requiring their own complex management methods (Camillus, 2008; Spicker, 2016). It is therefore unlikely that rat management programs which are focused on removing existing FWAH and rats in these areas will be successful without addressing the complex set of interactions between FWAH, rats, socio-economic status, and human behavior. Other examples of the many complex upstream determinants of FWAH and rats, include building code, design, and engineering, infrastructure development and maintenance, subterranean substructures associated with sewers, water, and energy, landscaping characteristics and planning, garbage and waste management, recycling, tourism, and food and restaurant policies. Management that does not account for these complex upstream determinants will ensure that rats persist. In such a complex system, there might not be a single solution; rather incremental gains may be made over time in different aspects of the problem.

Complex issues that are comprised of many interacting problems with no clear fixes, require similarly complex management approaches. To better address the complexity of municipal rat management, future strategies might need to consider the entirety of the rat management system. The management approach described in the literature is centered on the immediate hazards posed by rats and attempts to build up to the complexity of management across the urban ecosystem by adding components linked directly to that initial hazard (e.g., reduce FWAH in the environment to reduce resources available to rats). However, this approach appears to inevitably end where it began by falling back to rat extermination methods (Kaukeinen, 1994; Colvin and Jackson, 1999; Meyer, 2003; Brown and Laco, 2015). Instead, a systems approach may start by mapping out the complexity of the rat problem across the urban ecosystem to highlight, for example, where rats are considered problematic, who is vulnerable, who is resilient, what policies are in place to address them and do they work better in some areas, and which municipal departments and sectors of the urban environment are affected. This approach would be beneficial by outlining the complexity of management and highlighting the many different opportunities and challenges. This view of the problem would also emphasize the upstream determinants of infestations and FWAH thereby enabling decision makers to develop strategic plans to address not only the symptoms of the problem but also its more distant determinants. Such a perspective would shift the expectations for management away from methods and attributes that aim to reduce rats and FWAH, onto those that consider how to manage the causes of those symptoms.

To use a metaphor, the existing approach uses a bucket to bail water out of a sinking ship (i.e., remove the rats) but acknowledges that this needs to be combined with methods to patch the holes from which the water entered (i.e., remove the FWAH). An approach which considers the complex set of upstream determinants of why the holes were there in the first place might investigate how to effect change over the materials, engineering, and design of the ship, the policies that allowed the ship to be built that way, the behaviors of the crewmates that allowed the ship to fall into disrepair, the decisions of the captain which steered the ship into shallow water, or the policies which encouraged the ship to travel in dangerous weather conditions. The result of acting upon any of these upstream determinants of the sinking ship may incrementally decrease the likelihood that such an event will reoccur in the future. A clear parallel can be drawn between this issue in rat management and health promotion approaches which focus on addressing the upstream social determinants of health disparities between different populations. For example, housing and neighborhood characteristics are associated with many health outcomes such as increased obesity and diabetes (i.e., less physical activity, less access to high quality foods, poor access/utilization of public space) (Thornton et al., 2017). A randomized control trial in the United States which provided urban residents with vouchers to live in different neighborhoods found decreased rates of obesity and diabetes as well as increased measures of reported well-being among those assigned to higher income areas (Ludwig et al., 2011, 2012). For rats, similar interventions which focus on improving the overall quality of the neighborhood rather than on changing the behavior of the individual through disincentives, could not only decrease FWAH through improvements to infrastructure, buildings and future building strategies, garbage, and rental rules and regulations, but it might also improve the physical and mental health of the people living there. Such improvements may further empower residents to address rats on their own by elevating the importance of rats relative to other daily stressors which likely took precedence prior to neighborhood improvements (Margulis, 1977; Byers et al., 2019; Lee et al., 2021).

It is important to reiterate that all the aforementioned strategies to better account for the complexity of municipal rat management are likely to face the fact that each component of the rat problem that is managed, may constitute its own highly complex problem for which there is no singular or clear solution. In fact, Parsons et al. (2017) specifically identified a single aspect of municipal rat management, urban rat research, as a 'wicked problem,' suggesting that municipal rat management may itself be a wicked problem. Wicked problems are problems which encompass all the complexities of rat management described here, and similarly cannot be solved by breaking the problem into smaller issues (Camillus, 2008). In 1973 when Rittel and Webber defined wicked problems, they outlined key features that they felt distinguished this class of problems, including: (1) "every wicked problem can be considered as a symptom of another problem", and; (2) "every wicked problem is essentially unique" (Rittel and Webber, 1973). Municipal rat management undoubtably meets both of these criteria. With regard to the first criterion, rats

are a symptom of many other problems, including upstream determinants like poor building code and landscaping practices. For the second, the diversity of FWAH sources in different circumstances means that every rat management situation has different FWAH targets, challenges, and requirements such that no two rat management problems are the same. Interestingly, this implies that there are no overarching 'best practices' for management, perhaps explaining, in part, why this body of literature has not been able to systematically identify the most effective management methods.

If municipal rat management is a wicked problem, as this literature review suggests, assessing rat management through this lens is important because wicked problems do not have a 'solution', and may instead only be managed (Bentley and Toth, 2020). This is a critical distinction because it shifts the perspective from trying to eliminate rat issues to developing strategies to 'manage' the larger problem. To remove rat issues, for instance, you would need to eliminate the factors contributing to FWAH which would require solving neighborhood disorder, deterioration, and neglect. While these qualities cannot be directly solved (Spicker, 2016), they can be managed, and incremental gains can be made over time through many different potential strategies. With such a view of the problem, it becomes important to prioritize among management options and to design strategies that provide the most benefits to the most people – should we be aiming to annually remove rats from a disordered neighborhood, or should we aim to change the waste management policy which contributed to that disorder?

While a more fulsome discussion of wicked problems and its relation to municipal rat management is beyond the scope of this review, there is an existing body of literature on wicked problems that researchers and pest management professionals may turn to, to understand the implications of using this lens to view rat management. Future work should be designed to investigate how municipal rat management is or is not a wicked problem and, most importantly, how this perspective might benefit the field of municipal rat management.

Change the Outcome Expectations

There was a disconnect between the expectations within this literature and the reality of rat management across municipalities. Specifically, rat management was framed within the "war on rats" paradigm, which may not be interesting enough to municipalities, politicians, decision makers, or the public to justify the level of funding and resources required to effectively implement approaches that meet the idealized methodological or attribute expectations of the management literature (Sherrard, 1943; Davis, 1952; Drummond, 1970; Richards, 1988; Colvin, 2000; Parsons et al., 2017, 2020; Lee et al., 2021).

This suggests that exploration of new paradigms that foster sustained community, political and other stakeholder interest is needed. Davis (1952) highlighted this when they noted that rats were too small of a concern to warrant the attention of health officers. They proposed that instead of focusing on rat reduction alone, a more "worthy" objective would be to improve the entire community to create an environment with fewer pests, fewer diseases, less housing and sanitation issues, and a decrease in any other factor that contribute to infestations. This approach is directly aligned with the upstream determinants strategy noted in the previous section. Davis felt that this objective would be more engaging to all stakeholders because each one of these issues was associated with overall public well-being.

Davis (1952) also suggested that instead of fixating on the symptoms of the problem, an alternative paradigm would be to improve the health of the overall community. Such a community approach to health has helped those designing strategies for other complex management issues. For instance, instead of focusing directly on eliminating a specific parasite in Kathmandu, Nepal, researchers took an ecosystem approach by addressing the parasite in the context of the community in which it was a problem (Bunch, 2016). They engaged with the relevant stakeholders (e.g., butchers and street sweepers) in a participatory process through which they mapped out the problem as it existed for those stakeholders and identified specific interventions and objectives that could be leveraged in each of those scenarios. As a result of this holistic, participatory process, stakeholders became empowered to make the program their own and the transmission cycle of the parasite was broken through a series of ongoing but separate and distinct interventions across the landscape. This approach enabled the program to improve community health through several distinct objectives relevant to the lives of the different stakeholders, including removing livestock from the river, ensuring proper waste disposal, and changing slaughtering practices, all of which were directly relevant to the transmission cycle of the parasite. Such an approach has obvious parallels with urban rat issues which inherently impact and result from many different intersecting aspects of the community which may all view the problem differently. Future research should investigate how such approaches can be used to engage stakeholders in both the community and the municipality by designing approaches which are directly relevant to their lives. Programs developed in this way will have interventions that meet the needs and desires of its residents, thereby fostering a higher level of interest and investment from stakeholders. This would enable sustainable stakeholder engagement with interventions and heighten overall community pressure on the rat problem. Further, perspectives of what constitutes the rat problem are likely to vary over space, time, and socio-economic status, such that there is not likely to be any singular objective or strategy that works in all communities. This underlines the importance of regular and sustained engagement with all management stakeholders. These final points are critical, because if the management program is not addressing issues that people actually care about in a given space and time, funding and resources for rat management are likely to always be limited and program sustainability will be minimal.

Key findings and recommendations of this review are shown in **Table 2**.

Limitations

Although the breadth of studies included in this review facilitated a comprehensive analysis of rat management strategies, it also made the enumeration of trends in specific programs and expectations unreliable. We examined publications that: focused on describing the structure and function of ongoing municipal programs; assessed the effectiveness of a one-time

TABLE 2 | Key findings and recommendations of this literature review.

Category	Key expectations	Were expectations met?	Why or why not?	The way forward
Outcome expectations	• Rat management is a "war on rats."	• Many studies did not measure whether they met their outcome expectations.	• Studies and management initiatives largely did not meet many expectations.	***A place for the old:***
	• Rats should be reduced to the greatest extent possible.	• Many studies that did measure their ability to meet outcome expectations did not claim success.	• Low levels of political, scientific, public health, and/or public interest in rat management limited the amount of funding and resources invested in management initiatives.	• Develop clear, feasible management impact assessments that evaluate a program's ability to effect change over its primary objectives.
	• Aim for long-term and sustained reductions in rat populations.	• Studies that did measure and claim success did not meet all attribute/methodological expectations.	• Not enough funding and resources to adhere to the literatures' expectations.	• Establish clear economic arguments for the use of the current paradigm and associated methods at a large scale.
			• Inability to comprehensively address the complexity of urban rat problems.	• Enhance the effectiveness of municipal rat reduction techniques.
			• A lack of information on the cost-effectiveness of recommended strategies.	***A path for the new:***
			• Inability to successfully, sustainably, or comprehensively change the behaviors of residents that contribute to FWAH[b].	• Change the quality and methodological expectations.
			• There was limited quantitative evidence to support the effectiveness of the current expectations for municipal rat management, making justification of the use of these expectations difficult.	• Develop and evaluate new models of collaboration, organization, and coordination across the many stakeholders.
				• Consider rats in all aspects of the urban planning process and borrow techniques from other urban planning issues such as transportation.
				• Management needs to move away from a perspective of the problem which assumes that rat management is comprised of individually solvable issues.
				• Map the complexity of entire problem to highlight, act upon, and prioritize among the many nuanced upstream determinants of FWAH and rats, rather than focusing on removing existing symptoms of these determinants.
				• Rat management may be a wicked problem for which there is no overarching solution and instead can only be managed, making incremental gains in different aspects of the problem over time.
				• Move away from the "war on rats" paradigm.
				• Explore paradigms and that foster sustainable community, political, and other stakeholder interest in the problem and management of it.

(Continued)

TABLE 2 | (Continued)

Category	Key expectations	Were expectations met?	Why or why not?	The way forward
Methodological expectations	• Employ IPM[a] related activities over as large an area as possible. • Deploy IPM[a] via data collection on the distribution of rats and FWAH. • Primary focus of management should be on reducing FWAH[b] using a variety of techniques.	• Dissatisfaction among authors with management adherence to methodological expectations. • Every rat management initiative in this review fell short of methodological expectations.		• Alternative paradigms might consider defining objectives that focus on improving the overall health community. • Define objectives that meet the needs and desires of residents/stakeholder to whom management is ultimately designed to help and whose interest and participation in the program is necessary for success.
Attribute expectations	• Address rats and FWAH[b] everywhere they exist regularly, continuously, and comprehensively. • Proactivity should be prioritized over reactivity: rats and FWAH[b] need to be addressed before they become problematic.	• Dissatisfaction among authors with adherence to attribute expectations. • Every rat management initiative in this review fell short of attribute expectations.		

[a]*IPM, integrated pest management.*
[b]*FWAH, food, water, and harborage.*
Expectations are strategies, techniques, and overall approaches that authors reported were the most effective methods for municipal rat management.

control program; used data from existing programs for a specific research purpose; provided expert opinions in research studies, commentaries, and textbooks; and made references to programs that authors had knowledge of or direct experience with. The level of detail provided for different programs in this literature varied immensely. An author might have described a single attribute of an existing program (i.e., that it was reliant upon complaints), or they might have holistically described and assessed a program. Consequently, although we were able to extract general trends, recommendations, and critiques, we were unable to assess each publication for certain program traits or expectations (e.g., how many programs had versus did not have evaluation) to produce quantitative descriptions of the literature. Importantly, this issue is a direct result of the way in which information has been made available on large-scale municipal rat management (i.e., reporting is not consistent across the relevant publications), highlighting that a key limitation of this literature was a lack of comparability between different programs and/or studies.

Importantly, while we included studies regardless of region, this review did not include publications in languages other than English and therefore from different parts of the world. Indeed, much of the work in this review came from North America and parts of Europe. As a result, it is important to recognize that this review might not account for management as it exists globally. However, given that these other regions may have different expectations, challenges, priorities, cultures, and socio-economic situations dictating the structure and function of municipal rat management, it likely that their inclusion would strengthen the overall conclusions of this review that municipal rat management is a highly complex endeavor, potentially a wicked problem, for which there might not be a solution.

CONCLUSION

This study reviewed the literature on municipal rat management and found that research, management initiatives, and expert opinions have been driven by a single paradigm since the early 1900s. This "war on rats" paradigm, is strongly focused on eliminating existing infestations across as large a scale and for as long as possible via the removal of rats and their immediate FWAH causes. However, there was little evidence to support the superiority of this paradigm and its associated methodologies at a municipal scale. Further, it failed to meet the expectations of those who designed and implemented it due to real-world constraints. To move the field of municipal rat management forward, there are two distinct options. First, stakeholders may continue to wage the "war on rats" by working to improve existing methodologies and strategies to increase the magnitude and duration of rat reduction success. Key pathways include developing clear evaluation metrics aligned with program objectives, establishing the cost-effectiveness of the paradigm and methodologies, and improving the efficacy of control efforts (e.g., best practices of baiting, bait alternatives, novel FWAH approaches, etc.). However, this strategy is limited in its view of municipal rat management as a set of individually solvable sub-problems.

Therefore, the second option to move municipal rat management forward, and the one that we recommend, is to define an entirely new paradigm and methodologies that adequately encompass the complexity of municipal rat management. As such, we propose that an important alternative paradigm would begin by mapping the complexity of the rat management problem to highlight, act upon, and prioritize among the multiple complex upstream determinants of infestations and their FWAH causes. This perspective of the issue emphasizes how municipal rat management may be a wicked problem for which there is no overarching solution. Instead, the problem can only be managed, making incremental gains in different aspects of the problem over time. Whichever approach is taken, we note that it is essential for the objectives of management initiatives to shift to goals that foster sustained and significant interest among stakeholders to facilitate long-term and adequate resourcing and funding. While we propose an alternative objective that focuses on improving the overall health of the community, it is clear that the goal of management must be to address the evolving needs and desires of the stakeholders whose investment in the strategy is necessary to achieve true program sustainability.

AUTHOR CONTRIBUTIONS

ML synthesized and interpreted the literature and wrote the manuscript. ML, KB, and CH contributed to the review conception and search design. KB, CS, DP, RC, and CH contributed to the interpretation of the evidence, synthesis content, and edited the manuscript. ML and SI performed the literature search. SI edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This work was funded by the City of Vancouver's 2018–2020 Street Cleaning Grant Program in support of their efforts to establish suitable rat management protocols for Vancouver.

ACKNOWLEDGMENTS

We would like to thank Carl Ribble and the Centre for Coastal Health for their help with devising and carrying out the literature search.

REFERENCES

Adrichem, M. H. C., Buijs, J. A., Goedhart, P. W., and Verboom, J. (2013). Factors influencing the density of the brown rat (*Rattus norvegicus*) in and around houses in Amsterdam. *Lutra* 56, 77–91.

Almeida, A., Corrigan, R., and Sarno, R. (2013). The economic impact of commensal rodents on small businesses in Manhattan's chinatown: trends and possible causes. *Suburb. Sustain* 1:2. doi: 10.5038/2164-0866.1.1.2

Al-Sanei, K. S., Zaghloul, T. M., Salit, A. M., Omar, M. T., and Balba, M. M. (1984). "Success in rat control in Kuwait," in *Proceedings of the Eleventh Vertebrate Pest Conference*, (Sacramento). doi: 10.1016/j.ijpharm.2020.119782

Aplin, K. P., Chesser, T., and Ten Have, J. (2003). "Evolutionary biology of the genus *Rattus*: profile of an archetypal rodent past," in *Rats, mice and people: rodent biology and management*, eds G. R. Singleton, L. A. Hinds, C. J. Krebs, and D. M. Spratt (Canberra, AU: ACIAR Monograph Series), 487–498.

Bajomi, D. (1980). "Deratization of Budapest and five years of follow-up control measures," in *Proceedings of the Ninth Vertebrate Pest Conference*, (Fresno).

Bajomi, D., Guthy, C. S., and Markos, T. (1996). "Efficacy of large-scale rat and cockroach control actions in Budapest as shown by experiences over a 23-year period," in *Proceedings of the Second International Conference on Urban Pests*, (Urban Environment).

Bajomi, D., Kiss, Z., and Nagai, Y. (2013). 40 Years of rat control in Budapest: The importance of sewer treatments for effective rat control in urban areas. *Int. Pest Control* 55, 22–25.

Barbehenn, K. R. (1970). "Notes on the ecology of sewer rats in St. Louis," in *Proceedings of the Fourth Vertebrate Pest Conference*, (Oakland).

Barnett, S. A. (1947). Rodent control in towns. *Proc. Assoc. Appl. Biol.* 34, 297–303. doi: 10.1111/j.1744-7348.1947.tb06365.x

Barnett-Page, E., and Thomas, J. (2009). Methods for the synthesis of qualitative research: a critical review. *BMC Med. Res. Methodol.* 9:59. doi: 10.1186/1471-2288-9-59

Battersby, S., Hirschhorn, R. B., and Amman, B. R. (2008). "Commensal Rodents," in *Public Health Significance of Urban Pests*, eds X. Bonnefoy, H. Kampen, and K. Sweeney (Copenhagen, DK: World Health Organization), 387–419.

Bentley, J., and Toth, M. (2020). *Exploring wicked problems what they are and why they are important*. Bloomington: Archway Publishing.

Bourne, J. B. (1998). "Norway rat exclusion in Alberta," in *Proceedings of the Eighteenth Vertebrate Pest Conference*, (Costa Mesa).

Bragdon, C., Kass, D., Matte, T., Merlino, M., Bonaparte, S., Johnson, S., et al. (2012). Evaluation of a neighborhood rat-management program - New York City, December 2007-August 2009. *Morb. Mortal. Wkly. Rep.* 61, 733–736.

Brooks, J. E. (1962). "Methods of sewer rat control," in *Proceedings of the First Vertebrate Pest Conference*, (Sacramento).

Brooks, J. E. (1974). "A review of rodent control programs in New York State," in *Proceedings of the sixth Vertebrate Pest Conference*, (ANAHEIM).

Brown, G., and Brown, L. (2015). *Rodent control program assessment: Washington DC Department of Health. National Association of County & City Health Officials*. Available online at: https://www.cdc.gov/nceh/ehs/docs/vector-profiles/washington-dc.pdf. (Accessed November 11, 2021).

Brown, L. M., and Laco, J. (2015). *Rodent control and public health an assessment of U.S. local rodent control programs. National Association of County & City Health Officials*. Available online at: https://www.cdc.gov/nceh/ehs/docs/vector-profiles/assess-rodent-programs.pdf. (Accessed November 11, 2021)

Brown, R. Z., Sallow, W., Davis, D. E., and Cochran, W. G. (1955). The rat population of Baltimore, 1952. *Am. J. Hyg.* 61, 89–102. doi: 10.1093/oxfordjournals.aje.a119743

Bunch, M. J. (2016). Ecosystem approaches to health and well-being: navigating complexity, promoting health in social–ecological systems. *Syst. Res. Behav. Sci.* 33, 614–632. doi: 10.1002/sres.2429

Byers, K. A., Cox, S. M., Lam, R., and Himsworth, C. G. (2019). "They're always there": resident experiences of living with rats in a disadvantaged urban neighbourhood. *BMC Public Health* 19:853. doi: 10.1186/s12889-019-7202-6

Camillus, J. C. (2008). *Strategy as a wicked problem. Harvard Business Review: Strategic Planning*. Available online at: https://hbr.org/2008/05/strategy-as-a-wicked-problem (Accessed November 11, 2021).

Cavia, R., Muschetto, E., Cueto, G. R., and Suárez, O. V. (2015). Commensal rodents in the city of Buenos Aires: a temporal, spatial, and environmental analysis at the whole city level. *Ecohealth* 12, 468–479. doi: 10.1007/s10393-015-1013-8

Centers for Disease Control and Prevention (2006). *Integrated pest management: conducting urban rodent surveys*. Atlanta: US Department of Health and Human Services.

Centers for Disease Control and Prevention (2007). *What is integrated pest management*. Available online at: https://www.cdc.gov/nceh/publications/factsheets/What%20Is%20Integrated%20Pest%20Management.pdf. (Accessed November 11, 2021).

Channon, D., Channon, E., Roberts, T., and Haines, R. (2006). Hotspots: are some areas of sewer network prone to re-infestation by rats (*Rattus norvegicus*) year after year? *Epidemiol. Infect*. 134, 41–48. doi: 10.1017/s0950268805004607

Colvin, B. A. (2000). "A comprehensive rodent control program for Washington D.C," in *Proceedings of the Nineteenth Vertebrate Pest Conference*, (Washington D.C).

Colvin, B. A. (2002). "Rodent control as part of engineering and construction projects," in *Proceedings of the Twentieth Vertebrate Pest Conference*, (Davis).

Colvin, B. A., Ashton, D., McCartney, W. G., and Jackson, W. B. (1990). "Planning rodent control for Boston's central artery/tunnel project," in *Proceedings of the Fourteenth Vertebrate Pest Conference*, (Sacramento).

Colvin, B. A., Degregorio, R., and Fleetwood, C. (1996). "Norway rat infestation of urban landscaping and preventative design criteria," in *Proceedings of the Seventeenth Vertebrate Pest Conference*, (Davis).

Colvin, B. A., and Jackson, W. B. (1999). "Urban rodent control programs for the 21st century," in *Ecologically-based Rodent Management*, eds G. R. Singleton, L. A. Hinds, H. Liers, and Z. Zang (Canberra, AU: Australian Centre for International Agricultural Research), 243–257.

Colvin, B. A., Meininger, C. A., and Grealy, M. J. (1992). "Administrative procedures and contracts for vertebrate pest programs," in *Proceedings of the Fifteenth Vertebrate Pest Conference*, (Newport Beach).

Colvin, B. A., Swift, T. B., and Fothergill, F. E. (1998). "Control of Norway rats in sewer and utility systems using pulsed baiting methods," in *Proceedings of the Eighteenth Vertebrate Pest Conference*, (Costa Mesa).

Corrigan, R. M. (2006). "A profile of the Norway rat, *Rattus norvegicus*, in New York City: its impact on city operations and the need for collaborative interagency rat management programs," in *Proceedings of the Twenty-Second Vertebrate Pest Conference*, (Davis), doi: 10.5070/V422110040

Davis, D. E. (1947). The use of DDT to control murine typhus fever in San Antonia, Texas. *Public Health Rep*. 62, 449–463.

Davis, D. E. (1952). A perspective on rat control. *Public Health Rep*. 67, 888–893.

Davis, D. E. (1953). The characteristics of rat populations. *Q. Rev. Biol*. 28, 373–401. doi: 10.1086/399860

Davis, D. E., and Jackson, W. B. (1981). "Rat control," in *Advances in Applied Biology*, (Cambridge, MA: Academic Press), 221–277.

de Masi, E., Vilaça, P. J., and Razzolini, M. T. P. (2009). Evaluation on the effectiveness of actions for controlling infestation by rodents in Campo Limpo region, São Paulo Municipality, Brazil. *Int. J. Environ. Health Res.* 19, 291–304. doi: 10.1080/09603120802592723

Delaney, R., and Brown, L. (2015). *Rodent control program assessment: Philadelphia department of public health. National Association of County & City Health Officials*. Available online at: https://www.naccho.org/uploads/downloadable-resources/NA687PDF-Philadelphia.pdf. (Accessed November 11, 2021)

Drummond, D. C. (1970). Rat free towns the strategy of area control. *J. Royal Soc. Promot. Heal.* 90, 131–133. doi: 10.1177/146642407009000305

Easterbrook, J. D., Shields, T., Klein, S. L., and Glass, G. E. (2005). Norway rat population in Baltimore, Maryland 2004. *Vector Borne Zoonotic Dis.* 5:296. doi: 10.1089/vbz.2005.5.296

Emlen, J. T. (1947). Baltimore's community rat program. *Am. J. Public Health Nations Health* 37, 721–727.

Emlen, J. T., Stokes, A. W., and Davis, D. E. (1949). Methods for estimating populations of brown rats in urban habitats. *Ecology* 30:442. doi: 10.2307/1932446

Fernández, M. S., Cavia, R., Cueto, G. R., and Suárez, O. V. (2007). Implementation and evaluation of an integrated program for rodent control in a shantytown of Buenos Aires city. *Argentina. Ecohealth* 4, 271–277. doi: 10.1007/s10393-007-0122-4

Figgs, L. W. (2011). Assessing the association between brown rat (*Rattus norvegicus*) activity and food and harbourage characteristics in a residential community of a medium-sized United States city. *Int. J. Pest Manage.* 57, 217–222. doi: 10.1080/09670874.2011.567307

Ford, A., Dawson, R., Blythe, P., and Barr, S. (2017). Land-use transport models for climate change mitigation and adaptation planning. *J. Transp. Land Use* 11:1209. doi: 10.5198/jtlu.2018.1209

Fozzard, J., Murphy, G., Oldbury, D., and Fearon, S. (2014). "Sewer baiting for rats in the United Kingdom - is it money down the drain?," in *Proceedings of the Eighth International Conference on Urban Pests*, (wetlands).

Garba, M., Kane, M., Gagare, S., Kadaoure, I., Sidikou, R., Rossi, J.-P., et al. (2014). Local perception of rodent-associated problems in Sahelian urban areas: a survey in Niamey, Niger. *Urban Ecosyst*. 17, 573–584. doi: 10.1007/s11252-013-0336-x

German, D., and Latkin, C. A. (2016). Exposure to urban rats as a community stressor among low-income urban residents. *J. Comm. Psychol*. 44, 249–262. doi: 10.1002/jcop.21762

Gräler, B., Ayyad, C., and Mateu, J. (2017). Modelling count data based on weakly dependent spatial covariates using a copula approach: application to rat sightings. *Environ. Ecol. Stat*. 24, 433–448. doi: 10.1007/s10651-017-0379-x

Gummin, D. D., Mowry, J. B., Beuhler, M. C., Spyker, D. A., Brooks, D. E., Dibert, K. W., et al. (2020). 2019 Annual report of the American Association of Poison Control Centers' National Poison Data System (n.d.): 37th annual report. *Clin. Toxicol*. 58, 1360–1541. doi: 10.1080/15563650.2020.1834219

Heiberg, A.-C. (2009). Anticoagulant resistance: a relevant issue in sewer rat (*Rattus norvegicus*) control? *Pest Manag. Sci*. 65:449. doi: 10.1002/ps.1709

Himsworth, C. G. (2020). "Living with rats: could an ecosystem lens provide new insights into urban rat control," in *Animals, health, and society: health promotion, harm reduction, and health equity in a one health world*, ed. C. Stephen (London: CRC Press), 281–289.

Himsworth, C. G., Parsons, K. L., Feng, A. Y. T., Kerr, T., Jardine, C. M., and Patrick, D. M. (2014). A mixed methods approach to exploring the relationship between Norway rat (*Rattus norvegicus*) abundance and features of the urban environment in an inner-city neighborhood of Vancouver. Canada. *PLoS One* 9:e97776. doi: 10.1371/journal.pone.0097776

Hundley, J. M., and Nasi, K. W. (1944). Anti-plague measures in Tacoma, Washington. *Public Health Rep*. 59, 1239–1255. doi: 10.2307/4585031

Ipm Institute of North America (2021). *What is integrated pest management*. Available online at: https://ipminstitute.org/what-is-integrated-pest-management/ (Accessed July 7, 2021).

Jackson, W. B. (1972). Biological and behavioural studies of rodents as a basis for control. *Bull. World Health Org.* 47, 281–286.

Jäkel, T., Promkerd, P., Sitthirath, R., Guedant, P., and Khoprasert, Y. (2019). Biocontrol of rats in an urban environment in Southeast Asia using *Sarcocystis singaporensis*. *Pest Manag. Sci*. 75, 2148–2157. doi: 10.1002/ps.5335

Jassat, W., Naicker, N., Naidoo, S., and Mathee, A. (2013). Rodent control in urban communities in Johannesburg, South Africa: from research to action. *Int. J. Environ. Health Res.* 23, 474–483. doi: 10.1080/09603123.2012.755156

Johnson, S., Bragdon, C., Olson, C., Merlino, M., and Bonaparte, S. (2016). Characteristics of the built environment and the presence of the Norway rat in New York City: results from a neighborhood rat surveillance program, 2008-2010. *J. Environ. Health* 2016:78.

Kaukeinen, D. E. (1994). "Rodent control in practice: householders, pest control operators, and municipal authorities," in *Rodent Pests and their Controls*, eds A. P. Buckle and R. H. Smith (Oxfordshire: CAB International), 249–271.

Lambropoulos, A. S., Fine, J. B., Perbeck, A., Torres, D., Glass, G. E., McHugh, P., et al. (1999). Rodent control in urban areas an interdisciplinary approach. *J. Environ. Health* 61, 12–17.

Landau, I., Muller, G., and Schmidt, M. (1999). "The urban pest advisory service of Zurich (Switzerland) and the situation of some selected pests," in *Proceedings of the Third International Conference on Urban Pests*, (Prague).

Lantz, D. E. (1909). *The brown rat in the United States*. Washington: U.S. Department of Agriculture, Biological Survey, 33.

Lee, M. J., Byers, K. A., Cox, S. M., Stephen, C., Patrick, D. M., and Himsworth, C. G. (2021). Stakeholder perspectives on the development and implementation of approaches to municipal rat management. *J. Urban Ecol*. 2021:13. doi: 10.1093/jue/juab013

Lopez, D., and Brown, L. (2015). *Rodent control program assessment: Austin/Travis County (TX) health and human services department. National Association of County & City Health Officials*. Available online at: https://www.naccho.org/uploads/downloadable-resources/NA682PDF-Austin-Travis-TX.pdf. (Accessed November 11, 2021)

Ludwig, J., Duncan, G. J., Gennetian, L. A., Katz, L. F., Kessler, R. C., Kling, J. R., et al. (2012). Neighborhood effects on the long-term well-being of low-income adults. *Science* 337, 1505–1510. doi: 10.1126/science.1224648

Ludwig, J., Sanbonmatsu, L., Gennetian, L., Adam, E., Duncan, G. J., Katz, L. F., et al. (2011). Neighborhoods, obesity, and diabetes – A randomized social experiment. *N. Engl. J. Med.* 365, 1509–1519. doi: 10.1056/nejmsa1103216

Macchiavello, A. (1946). Plague control with DDT and "1080.". *Am. J. Public Health* 36, 843–854. doi: 10.2105/ajph.36.8.842

Margulis, H. L. (1977). Rat fields, neighborhood sanitation, and rat complaints in Newark. *New Jersey. Geogr. Rev.* 67, 221–231. doi: 10.2307/214022

Meyer, A. (1999). "Commensal rodent control: challenges for the new millennium," in *Third International Conference on Urban Pests*, (Grafickeì zaìvody).

Meyer, A. (2003). "Urban commensal rodent control: fact or fiction?," in *Rats, mice and people: rodent biology and management*, eds G. R. Singleton, L. A. Hinds, C. J. Krebs, and D. M. Spratt (Canberra, AU: ACIAR Monograph Series), 446–450.

Murphy, G., Battersby, S., and Oldbury, D. (2009). The organisation of local authority pest management services in the UK. *J. Environ. Health Res.* 9, 25–32.

Murphy, R. G., and Battersby, S. (2005). "Local authority pest management services in the UK," in *Proceedings of the Fifth International Conference on Urban Pests*, (Singapore).

Murray, M. H., Byers, K. A., Buckley, J., Magle, S. B., Maffei, D., Waite, P., et al. (2021). "I don't feel safe sitting in my own yard": Chicago resident experiences with urban rats during a COVID-19 stay-at-home order. *BMC Public Health* 21:1008. doi: 10.1186/s12889-021-11095-y

Myllymäki, A. (1969). An early approach to a rat-free town in Finland. *Schriftenreihe des Vereins fur Wasser-, Boden-und Lufthygiene* 32, 161–166.

Nourjah, N., Chavshin, A. R., Baniardalani, M., and Azad, A. A. S. (2005). "Evaluation of the performance of exterminators for rodent control in five regions of the Tehran municipality," in *Proceedings of the Fifth International Conference on Urban Pests*, (Malaysia).

Pai, H.-H., Hong, Y.-J., and Wang, C.-H. (2003). A community-based surveillance on determinants of rodent infestation. *Kaohsiung J. Med. Sci.* 19, 13–17. doi: 10.1016/s1607-551x(09)70442-5

Panti-May, J. A., Carvalho-Pereira, T. S. A., Serrano, S., Pedra, G. G., Taylor, J., Pertile, A. C., et al. (2016). A two-year ecological study of Norway rats (*Rattus norvegicus*) in a Brazilian urban slum. *PLoS One* 11:e0152511. doi: 10.1371/journal.pone.0152511

Parsons, M. H., Banks, P. B., Deutsch, M. A., Corrigan, R. F., and Munshi-South, J. (2017). Trends in urban rat ecology: a framework to define the prevailing knowledge gaps and incentives for academia, pest management professionals (PMPs) and public health agencies to participate. *J. Urban Ecol.* 3:jux005. doi: 10.1093/jue/jux005

Parsons, M. H., Jardine, C. M., Crowther, M. S., and Himsworth, C. G. (2020). Editorial: trends in urban rodent monitoring and mitigation: improving our understanding of population and disease ecology, surveillance and control. *Front. Ecol. Evol.* 7:522. doi: 10.3389/fevo.2019.00522

Pascual, J., Franco, S., Bueno-Marí, R., Peracho, V., and Montalvo, T. (2020). Demography and ecology of Norway rats, *Rattus norvegicus*, in the sewer system of Barcelona (Catalonia, Spain). *J. Pest Sci.* 93, 711–722. doi: 10.1007/s10340-019-01178-6

Patergnani, M., Gras, L. M., Poglayen, G., Gelli, A., Pasqualucci, F., Farina, M., et al. (2010). Environmental influence on urban rodent bait consumption. *J. Pest Sci.* 83, 347–359. doi: 10.1007/s10340-010-0304-7

Poli, R. (2013). A note on the difference between complicated and complex social systems. *Cadmus* 2013, 2.

Richards, C. (1988). "Large-scale evaluation of rodent control technologies," in *Rodent pest management*, ed. I. Prakash (Boca Raton, FL: CRC Press Inc), 269–285.

Rittel, H. W. J., and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sci.* 4, 155–119.

Sánchez-Barbudo, I. S., Camarero, P. R., and Mateo, R. (2012). Primary and secondary poisoning by anticoagulant rodenticides of non-target animals in Spain. *Sci. Total Environ.* 420, 280–288. doi: 10.1016/j.scitotenv.2012.01.028

Sciara, G.-C. (2017). Metropolitan transportation planning: lessons from the past, institutions for the future. *J. Am. Plann. Assoc.* 83, 262–276. doi: 10.1080/01944363.2017.1322526

Sherrard, G. C. (1943). A plan for rodent control in cities. *Public Health Rep.* 58, 825–832. doi: 10.2307/4584472

Smith, R.H., and Shore, R.F. (2015). "Rodent control in practice: householders, pest control operators, and municipal authorities," *Rodent pests and their control*, eds A. Buckle and R. Smith (Wallingford: CAB International). doi: 10.1079/9781845938178.0330.

Spicker, P. (2016). Poverty as a wicked problem. *CROP Pov. Brief* 2016:35.

Tamayo-Uria, I., Mateu, J., Escobar, F., and Gras, L. M. (2013). Risk factors and spatial distribution of urban rat infestations. *J. Pest Sci.* 87:115. doi: 10.1007/s10340-013-0530-x

Taylor, P. J., Arntzen, L., Hayter, M., Iles, M., Frean, J., and Belmain, S. (2008). Understanding and managing sanitary risks due to rodent zoonoses in an African city: beyond the Boston Model. *Integr. Zool.* 3, 38–50. doi: 10.1111/j.1749-4877.2008.00072.x

Thornton, R. L. J., Glover, C. M., Cené, C. W., Glik, D. C., Henderson, J. A., and Williams, D. R. (2017). Evaluating strategies for reducing health disparities by addressing the social determinants of health. *Health Aff.* 35, 1416–1423. doi: 10.1377/hlthaff.2015.1357

Tobin, M. E., and Fall, M. W. (2004). "Pest control: rodents," in *Agricultural Sciences: Encyclopedia of Life Support Systems*, ed. R. Lal (Oxford: UNESCO).

Traweger, D., Travnitzky, R., Moser, C., Walzer, C., and Bernatzky, G. (2006). Habitat preferences and distribution of the brown rat (*Rattus norvegicus* Berk.) in the city of Salzburg (Austria): implications for an urban rat management. *J. Pest Sci.* 79:125. doi: 10.1007/s10340-006-0123-z

United Nations (2019). *World urbanization Ppospects: The 2018 Revision*. New York: United Nations. Availble online at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf. (Accessed November 11, 2021).

Wahlde, M., and Colvin, B. (1994). "Using geographic information systems for tracking an urban rodent control program," in *Proceedings of the sixteenth vertebrate pest conference*, (Santa Clara).

Walsh, M. G. (2014). Rat sightings in New York City are associated with neighborhood sociodemographics, housing characteristics, and proximity to open public space. *Peerj* 2:e533. doi: 10.7717/peerj.533

Wayt, T. (2021). *Rodents chow down on Teslas, causing thousands in damage. NY Post*. Available online at: https://nypost.com/2021/07/11/rodents-chow-down-on-teslas-causing-thousands-in-damage/. (Accessed February 12, 2022).

Who Scientific Group of Ecology and Control of Rodents of Public Health Importance (1974). *Ecology and control of rodents of public health importance*. Available online at: https://apps.who.int/iris/handle/10665/41097. (Accessed November 11, 2021).

Why, A. M., James, D. K., and Gay, R. B. (2018). "Norway rat sewer baiting program in the city of Oakland," in *Proceedings of the Twenty-Eighth Vertebrate Pest Conference*, (Independently published), doi: 10.5070/v42811010

Wirth, C., and Brown, L. (2015). *Rodent control program assessment: Multnomah County (OR) department of public health. National Association of County & City Health Officials*. Available online at: https://www.naccho.org/uploads/downloadable-resources/NA681PDF-Multnomah-County.pdf. (Accessed November 11, 2021).

Witmer, G. W., and Shiels, A. B. (2018). "Ecology, impacts, and management of invasive rodents in the United States," in *Ecology and Management of Terrestrial Vertebrate Invasive Species in the United States*, eds W. C. Pitt, J. C. Beasley, and G. W. Witmer (Boca Raton, Fl: CRC Press), 193–219.

Zerwekh, T., and Brown, L. (2015). *Rodent control program assessment: Shelby County (TN) health department. National Association of County & City Health Officials*. Available online at: https://www.naccho.org/uploads/downloadable-resources/NA684PDF-Shelby-County-TN.pdf. (Accessed November 11, 2021).

Conflict of Interest: RC was employed by Corrigan Consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Lee, Byers, Stephen, Patrick, Corrigan, Iwasawa and Himsworth. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.