Urban Ecosystems (2021) 24:481–489
https://doi.org/10.1007/s11252-020-01046-7

Population increase and synurbization of the yellow-necked mouse *Apodemus flavicollis* in some wooded areas of Warsaw agglomeration, Poland, in the years 1983–2018

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Published online: 25 August 2020

Abstract
Studies on the contribution of the yellow-necked mouse *Apodemus flavicollis* and of other vertebrates to the diet of the tawny owl *Strix aluco* were carried out in Warsaw (central Poland) in the years 1983–2018. The frequency of the yellow-necked mouse in owl pellets increased at the break of the 20th and 21st centuries, particularly in some woodlands in the peri-urban area of the agglomeration. In the second half of the first decade of the twenty-first century, this mouse species colonised a park in the city centre. The yellow-necked mouse may become an important competitor for the synurbic population of the striped field mouse *Apodemus agrarius*.

Keywords Urban environment · City park · Suburban forest · Synurbization · Terrestrial rodents · Central Europe

Introduction

Studies on small terrestrial mammals inhabiting urban areas have been carried out in various regions of the world (Andrzejewski et al. 1978; Dickman and Doncaster 1987; Goszczyński et al. 1993; Chernousova 1996; Baker et al. 2003; Mahan and O'Connel 2005; Gryz et al. 2008; Cavia et al. 2009; Garden et al. 2010; Gomes et al. 2011; Khlyap et al. 2012; Łopucki et al. 2013; Klimant et al. 2017; Łopucki and Kitowski 2017). These groups of animals, which have relatively low dispersal abilities, find it difficult to penetrate areas strongly modified by human activity. Animals are particularly threatened by habitat fragmentation (Angold et al. 2006; Vergnes et al. 2013; Gomes et al. 2011; Gryz et al. 2017b) and road mortality (Hodson 1960; Bąkowski and Kozakiewicz 1988; Orłowski and Nowak 2006; Gryz and Krauze 2008). Therefore, the centres of large urban agglomerations host few small mammal species (Goszczyński et al. 1993; McKinney 2008; Buckmaster et al. 2010). Moreover, native species are more sensitive to urbanization than alien species (Cavia et al. 2009).

The yellow-necked mouse *Apodemus flavicollis* (Melchior, 1834), widespread in most parts of Europe and the Middle East (Amori et al. 2016), is a species associated with woodlands and mature forests (Pucek et al. 1993, Mazurkiewicz and Rajska-Jurgiel 1998; Marsh and Harris 2000; Juškaitis 2002), where it often dominates the terrestrial rodent communities (Pucek et al. 1993; Mazurkiewicz and Rajska-Jurgiel 1998), but prefers forest edges (Montgomery 1999; Hille and Mortelliti 2010). It is a ground dwelling species with a high capacity for climbing trees (Štěpánková and Vohrálik 2009) and frequently occupies bird nest boxes (Juškaitis 2000). The yellow-necked mouse is typically nocturnal (Wójcik and Wołk 1985) and its home range size is approximately 0.4–5 ha (Stradiotto et al. 2009). The species has a broad food niche that includes plants, fungi and animal prey (Drożdż 1966; Abt and Bock 1998). This species sometimes but rarely penetrates habitats modified by human activity, such as agrocoenoses (Hoffmeyer 1973; Popov 1993) and urban areas, e.g., in Vienna, the yellow-necked mouse has been reported to occur in parks and green spaces (Mitter et al. 2015). During density peaks, caused by oak mast years, the species also migrates to arable land and orchards (Gryz et al. 2019; Gryz and Krauze-Gryz 2019).

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During the recent decades, large city agglomerations in Poland have been often colonized by striped field mouse *Apodemus agrarius* (Pallas, 1771), which in city parks (also in Warsaw) forms quite abundant populations (Andrzejewski et al. 1978). In the past decade, the effects of synurbization (= urbanization) were also observed in the yellow-necked mouse, whose presence was recorded in several city parks situated only several kilometres from the centre of Warsaw (Gortat et al. 2014, 2016; Krauze-Gryz et al. 2016). One may thus expect interactions between the two sympatric species (Simenowska-Nikolova 2007).

Apart from standard trapping methods, the analysis of predator diets is a method for studying rodents. The undigested remains contained in owl pellets provide valuable information on their small mammal prey species (Heisler et al. 2015). Many species of owls are opportunistic predators, which mean that the frequency of hunting for specific prey is correlated with its density in a given area (Pérez-Barbería 1991). Therefore, pellets can be used to assess the relative abundances of small mammal species (Andrade et al. 2016). The diet of tawny owl *Strix aluco* is largely determined by the structure of local prey communities (Wendland 1980; Lesiński et al. 2009). Moreover, the owl is a sedentary species (Mebs and Scherzinger 2000) with individual home ranges covering several tens of hectares (Redpath 1995; Sunde and Bølstad 2004).

The aim of this study was to evaluate the current degree of synurbization of the yellow-necked mouse in Warsaw and to determine how its contribution to urban rodent communities has changed over the recent decades. We also investigated whether the contributions of a strongly synurbic species – the striped field mouse – had changed in the Warsaw agglomeration. In this study, we used pellets that collected from 1983 to 2018.

Study area and methods

The study was carried out in the city agglomeration of Warsaw (central Poland), which is inhabited by approximately 2 million people, and in some forests outside the city. The diet of the tawny owl was analysed at ten sites: one situated in the centre of the city, five in the peri-urban zone and four outside the agglomeration (Fig. 1). Central zone is characterized by the presence of dense built-up areas, while in peri-urban zone there are more large wooded areas (Fig. 2).

The sites are described as follows:

Łazienki – city central park (2 km from the city centre) of an area of 80 ha. The area is dominated by 40- to 150-year-old woodlands, extended lawns and artificial bodies of water. Numerous historical buildings are situated in the park. Due to its historical character, the park is protected as a national heritage site and the area is frequented by many people.

Bielany – a peri-urban forest (7 km from the city centre) – an area of 130 ha that since 1978 has been protected as a multi-species broad-leaved woodland. Habitats in this reserve include oak-lime-hornbeam forest, riparian forest and alder carr. The protection of the woodland extends to a rather large area of approximately 170 ha. The oldest oak stands exceed 250 years of age. The reserve area is crossed by two small watercourses. On the eastern side, the reserve is partly separated from the Vistula River by a 3-lane expressway. In contrast, urban development is present to the west and south.

Sobieski – a peri-urban woodland reserve (10 km from the city centre) protected since 1934 and covering 115 ha. The central and southern parts retain oak tree stands that are over 170 years old, while other areas have stands dominated by oaks and Scots pines with a mix of various broad-leaved species. The reserve is part of a larger forest complex covering approximately 700 ha. This area, which lacks natural watercourses or bodies of water, is connected to a limited degree with the extensive forest areas located beyond the Warsaw city limits.

Tarchomin – a small (approximately 8 ha) peri-urban park (10 km from the city centre) surrounded by high-density housing and adjacent on one side to old-growth riparian forests growing along the Vistula River. There are dispersed old-growth stands mainly comprising deciduous trees; denser tree stands are situated near the buildings. There are also small water bodies.

Młociny – a peri-urban woodland (11 km from the city centre) with an area of approximately 1 km^2, partly of a park character. On the east, the area borders the Vistula River (narrow strip of mature alder wood) and on the south – an exclusive residential district. The tree stands were mostly mixed-species stands, and in many places were older than 100 years.

Buchnik – a peri-urban forest (15 km from the city centre) built largely by mature broad-leaved tree stands (hornbeam, oak) adjacent to residential areas and to the Vistula River valley. Owl pellets were collected under trees, mainly under holes in deciduous species (hornbeam, oak), which were used as nesting and resting places. Distance from city centre – ca. 15 km.

Dziekanów Leśny – a forest outside city (19 km from the city centre), eastern edge of the Kampinos Forest, a large (approximately 30 thousand ha) forest complex protected as a national park. The tree stands are mainly composed of pine and mixed forests bordering dispersed building developments. Several hundred metres from the buildings, there are fragments of alder woods and small deciduous forests.

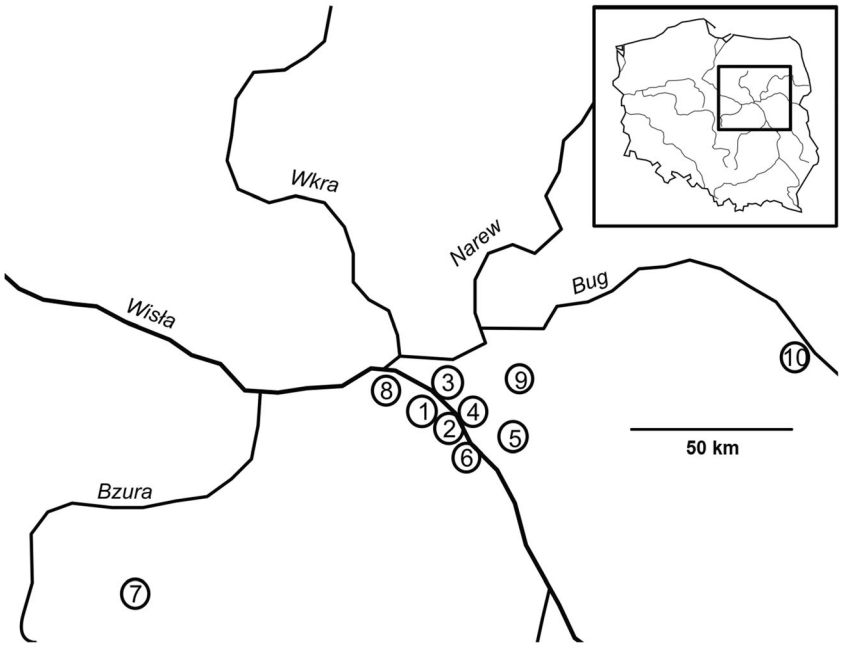

Fig. 1 Distribution of sites of the tawny owl involved in the long-term study in Warsaw agglomeration: 1 – Młociny, 2 – Bielany, 3 – Buchnik, 4 – Tarchomin, 5 – Sobieski, 6 – Łazienki and outside the city: 7 – Rogów, 8 – Dziekanów Leśny, 9 – Klembów, 10 – Natolin near Nur

Klembów – old-growth hornbeam deciduous forest outside city (35 km from the city centre) protected in nature reserve "Dębina" with an area of approximately 50 ha. The tree stand is composed of many 200-year-old hornbeam and oak trees. The nature reserve is surrounded by pine forests in coniferous habitats.

Rogów – a forest outside city (90 km from the city centre) with a study area covering 105 km^2 of a field-forest

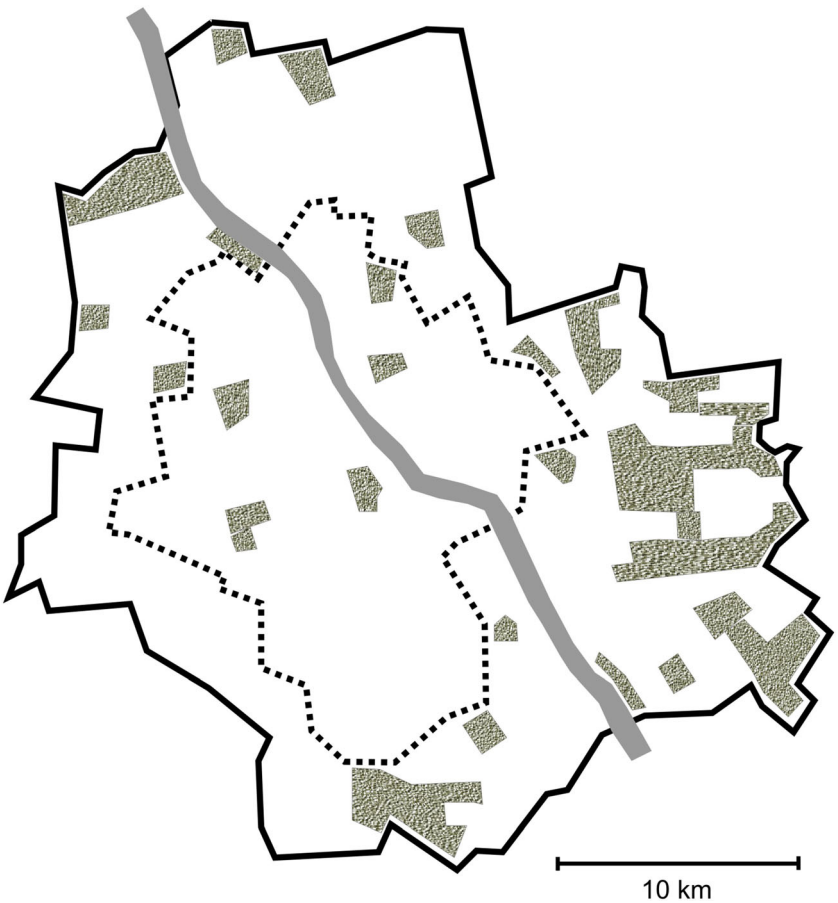

Fig. 2 Main wooded areas in Warsaw agglomeration. Dashed line is a border of central zone

Table 1 Study sites and years when owl pellets were collected

Site	Type of site	Study years
Młociny	Peri-urban	1983–1984, 2007–2018
Bielany	Peri-urban	1984, 2007–2018
Buchnik	Peri-urban	2007–2018
Tarchomin	Peri-urban	2008–2018
Sobieski	Peri-urban	1995–1996, 2009, 2014–2018
Łazienki	Urban	2004–2008, 2009, 2012–2018
Rogów	Nonurban	2004–2008, 2010–2018
Dziekanów Leśny	Nonurban	1984, 2000–2007
Klembów	Nonurban	2007–2018
Natolin near Nur	Nonurban	2004–2018

mosaic, where forests occupy approximately 24% of the area growing in 8 forest complexes of an area from 70 to 1000 ha. The main forest-forming species was Scots pine, which dominated 50% of the forested area. The contribution of oak was more than 20% and that of beech was almost 10%. The main habitat types were mixed fresh forest and fresh forest. The remaining parts of the area were occupied by arable lands (59%) and to a lesser extent by orchards, permanent grasslands and dispersed building developments.

Natolin, near Nur – an edge of a forest complex outside city (110 km from the city centre) called the Sterdyń Forest, with an area of 25 km^2. The tree stand adjacent to the site is dominated by 40- to 60-year-old pine trees; in some places, there are small fragments of more fertile forests with oaks and hornbeams. The forest borders small arable lands, a small village and large flooded meadows in the Bug River valley.

Pellets were collected irregularly throughout many years (Table 1) usually a few times per year. Pellets were soaked in water to extract diagnostic bone remains. The rodents of the genus *Apodemus* were determined to species based on the skulls using the keys edited by Pucek (1981) and the descriptive criteria given by Ruprecht (1979). The yellow-necked mouse was distinguished from the striped field mouse based on the morphology of the cusps on M^1 and M^2 and the structure of the upper side of the skull. Moreover, the proportion of the length of the *foramen incisivum* to the length of diastema was also considered. The yellow-necked mouse was distinguished from the wood mouse based on the length of the upper molar rows, the width of I^1, the crown width of M^1, the proportion of the length of the *foramen incisivum* to the length of the diastema and on the depth of the *foramen infraorbitale*.

Three study periods were distinguished: 1983–1984, 1995–2009 and 2010–2018. Both partially published data from the analysis of owl diets in the study area (Goszczyński et al. 1993; Lesiński and Stolarz 1999; Gryz et al. 2008; Lesiński and Gryz 2012; Gryz et al. 2017b) and unpublished data were used.

Data were expressed as percent relative frequency (number of individuals of each species / total number of individuals). Chi-square χ^2 tests for 2×2 contingency tables with Yates' correction were used to compare of the raw frequency data of each species remains. Spearman's (r_s) correlation coefficient was used to analyse the year-to-year variation in the ratio of yellow-necked mice to striped field mice. Significance level $\alpha = 0.05$. Statistica 12 software was used for calculations.

Results

When comparing the contributions of the yellow-necked mouse and striped field mouse to owl diets during two study periods (1995–2009 and 2010–2018), we found differences between areas situated in the city and outside the city. In the city the first species showed increasing trend, while decreasing trend outside the city. The contribution of striped field mouse decreased in the city and showed no significant changes outside the city (Table 2).

Within the Warsaw agglomeration in the case of yellow-necked mouse we found an increasing trend for the central zone and for three areas in the peri-urban zone. In two peri-urban areas and in one site outside of the city, we either found a decline in the contribution of the yellow-necked mouse or

Table 2 Changes in the proportion of *Apodemus flavicollis* (Af) and *Apodemus agrarius* (Aa) to other vertebrate prey of the tawny owl in wooded areas of Warsaw city agglomeration and outside the city in the years 1995–2009 and 2010–2018

Area	1995–2009 Af: remaining prey	2010–2018 Af: remaining prey	Chi^2	Significance of differences Trend	1995–2009 Aa: remaining prey	2010–2018 Aa: remaining prey	Chi^2	Significance of differences Trend
City (6 sites)	145: 1490	776: 4109	**49.14**	***P* < 0.001** ↑	328: 1307	572: 4312	**71.06**	***P* < 0.001** ↓
Outside the city (3 sites)	690: 2505	606: 3292	**42.63**	***P* < 0.001** ↓	104: 3091	103: 3795	2.12	*P* = 0.127

Differences statistically important in bold. ↑ – upward trend, ↓ – downward trend

Table 3 Changes in the proportion of *Apodemus flavicollis* (Af) and *Apodemus agrarius* (Aa) to other vertebrate prey of the tawny owl in wooded areas of Warsaw agglomeration and in sites outside the city in the years 1995–2009 and 2010–2018

Site (location)	1995–2009 Af: remaining prey	2010–2018 Af: remaining prey	Chi^2	Significance of differences Trend	1995–2009 Aa: remaining prey	2010–2018 Aa: remaining prey	Chi^2	Significance of differences Trend
Łazienki (CC)	0: 329	31: 344	**26.52**	***P* < 0.001** ↑	61: 268	47: 328	**4.41**	***P* = 0.036** ↓
Tarchomin (PU)	2: 264	144: 1065	**22.90**	***P* < 0.001** ↑	49: 217	181: 1027	1.70	*P* = 0.192
Buchnik (PU)	13: 468	163: 1219	**33.42**	***P* < 0.001** ↑	177: 304	177: 1205	**131.88**	***P* < 0.001** ↓
Sobieski (PU)	2: 156	240: 726	**43.30**	***P* < 0.001** ↑	10: 148	100: 866	2.05	*P* = 0.152
Bielany (PU)	85: 144	126: 336	**6.54**	***P* = 0.011** ↓	14: 215	26: 436	0.01	*P* = 0.933
Młociny (PU)	43: 129	72: 419	**8.78**	***P* = 0.003** ↓	17: 155	41: 450	0.21	*P* = 0.649
Klembów (OC)	170: 784	323: 1973	**7.08**	***P* = 0.008** ↓	32: 922	63: 2233	0.68	*P* = 0.409
Natolin n. Nur (OC)	95: 776	78: 907	**4.54**	***P* = 0.033** ↓	8: 863	9: 976	0.05	*P* = 0.816
Rogów (OC)	425: 945	205: 412	0.85	*P* = 0.355	64: 1306	31: 586	0.05	*P* = 0.820

Differences statistically important in bold. CC – city centre, PU – peri-urban zones, OC – outside city areas, ↑ – upward trend, ↓ – downward trend

noted no changes (Table 3, Fig. 3). In only two sites (Łazienki – central zone and Buchnik – peri-urban zone), the striped field mouse decreased in the diet of the tawny owl. No statistically significant changes were noted in the other areas (Table 3).

Differences (increasing trend) were found in the peri-urban sites (Młociny, Bielany) when comparing the contribution of the yellow-necked mouse to the diet of the tawny owl between the periods 1983–1984 and 1995–2009 (Table 4, Fig. 3). At the same sites, the contribution of the striped field mouse decreased in the Bielany site and did not change in Młociny. In the area farther from the city (Dziekanów Leśny), no significant changes in the contributions of either rodent species to the owl diets were noted during the same time period.

The yellow-necked mouse was found in the diet of the tawny owl in Łazienki Park (city centre) in 2013; until 2018, its contribution among vertebrate prey varied from 0.02 to 0.15 (0.09 on average). In the years 2008–2012, this species was not found, but the collected samples were very small (2–9 vertebrate prey items). The yellow-necked mouse was not present in the owl diets in the years 2004–2007, although the sample sizes were markedly larger (30–156 vertebrate prey items) (Table 5).

In the last 6 years of the study, the yellow-necked mouse was less numerous than the striped field mouse in Łazienki Park. The proportion of the yellow-necked mouse in the years 2013–2018 varied from 0.05 to 0.67 (0.29 on average) (Table 5) and showed an increasing albeit statistically insignificant ($n = 6$, $r_s = 0.58$, $p = 0.23$) trend.

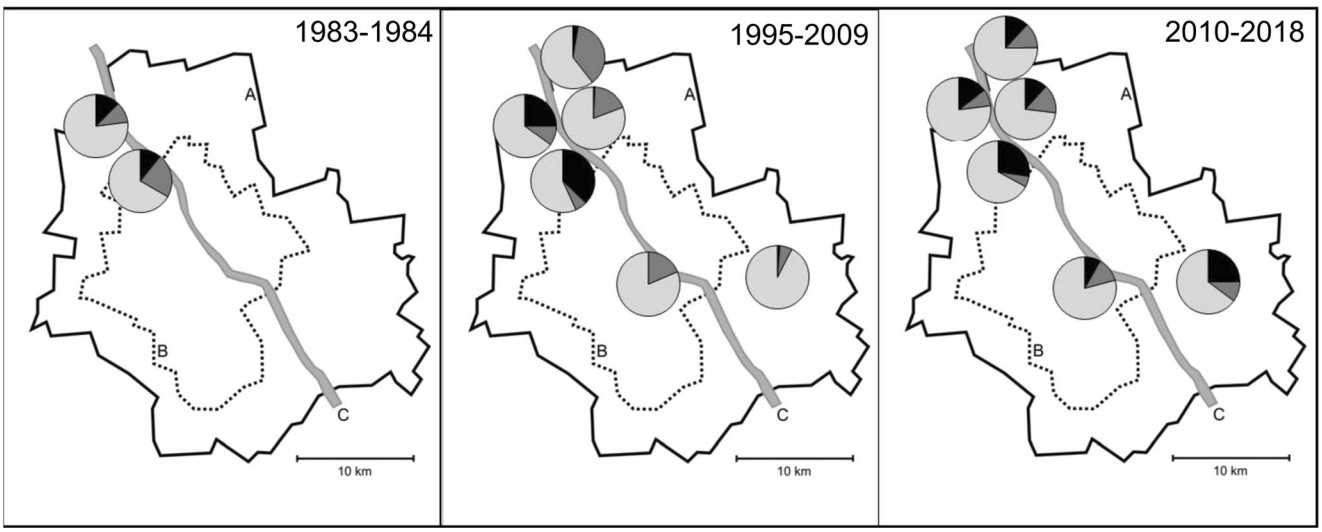

Fig. 3 Contribution of *Apodemus flavicollis* (black), *A. agrarius* (dark grey) and other vertebrate species (light grey) in owls' diet in peri-urban (**a**) and central (**b**) zones (**c**) Vistula river

Table 4 Changes in the proportion of *Apodemus flavicollis* (Af) and *Apodemus agrarius* (Aa) to other vertebrate prey items of the tawny owl in two peripheral sites and in one outside the city between the years 1983–1984 and 1995–2009

Site (location)	1983–1984 Af: remaining prey	1995–2009 Af: remaining prey	Chi^2	Significance of differences Trend	1983–1984 Aa: remaining prey	1995–2009 Aa: remaining prey	Chi^2	Significance of differences Trend
Bielany (PU)	10: 83	85: 144	**20.86**	***P* < 0.001** ↑	21: 72	14: 215	**16.85**	*P* < 0.001 ↓
Młociny (PU)	34: 230	43: 129	**9.71**	***P* = 0.002** ↑	29: 235	17: 155	0.04	*P* = 0.837
Dziekanów Leśny (OC)	5: 124	4: 113	0.02	*P* = 0.881	5: 124	1: 116	1.26	*P* = 0.263

Abbreviations as in Table 1

Discussion

In recent decades, synurbization in the Warsaw agglomeration has involved several species of vertebrates, especially birds such as the fieldfare *Turdus pilaris* (Nowicki 2001), magpie *Pica pica* (Lesiński 1998; Luniak et al. 2001), hooded crow *Corvus cornix* (Węgrzynowicz 2013), and by mammals such as the parti-coloured bat *Vespertilio murinus* (Lesiński et al. 2001) or the fox *Vulpes vulpes* (Gryz et al. 2017a).

Species of the genus *Apodemus* show different degrees of synurbization throughout Europe. In Great Britain, it is the wood mouse that undergoes synurbization (Dickman and Doncaster 1987). The same is true for this species in the Czech Republic and Germany – see the examples from Prague (Mikulová and Frynta 2001) and from Berlin (Elvers and Elvers 1984). In Polish towns, synurbization is often shown by the striped field mouse, such as in Warsaw (Andrzejewski et al. 1978) or in Lublin in eastern Poland (Wiącek et al. 2009). The latter species is also dominant in the small mammal communities in Russian Yekaterinburg (Ural) (Chernousova 1996) and in some urban areas of the European part of Russia (Khlyap et al. 2012). The yellow-necked mouse is rarely frequent in cities such as Vilnius (Baranauskas et al. 2005) and Vienna (Mitter et al. 2015).

In wooded areas of the peri-urban zones of Warsaw, the yellow-necked mouse has shown a marked increase in population densities, and the results of our studies show that the process probably started earlier in north-western part of Warsaw agglomeration (Młociny, Bielany – in 1983–1984 its contribution was more than 10% - Table 4, Fig. 3) than in the eastern part (Buchnik, Tarchomin, Sobieski – even in years 1995–2009 its contribution was much lower than 5% - Table 3, Fig. 3). In the first two sites, the rise of the number of mice ended at the end of the twentieth century, while in the eastern part of the city, it lasted during the first two decades of the twenty-first century. Notably, different trends were demonstrated in sites situated on opposite banks sides of the Vistula River: Młociny and Bielany on the left bank and Buchnik and Tarchomin on the right bank (Figs. 1 and 3). This may suggest that this large river (300–500 m wide) may be an important barrier hindering the exchange of individuals in populations of small rodents.

Overcrowding of the population in the peri-urban zones and in suburbia is an important phenomenon stimulating the start of synurbization. This was described for some animals that had already previously formed city populations, such as the woodpigeon *Columba palumbus* (Tomiałojć 1976). The same mechanism most likely operates in the case of the

Table 5 Presence of the yellow-necked mouse (Af) in the diet of the tawny owl from Łazienki Park (central part of the city) and the ratio of the yellow-necked to striped field mice (Aa) in the years (Aa) w latach 2004–2018

Year	N vertebrate prey	N Af (share among vertebrate prey)	N Af/N Aa
2004	41	0	0
2005	156	0	0
2006	97	0	0
2007	30	0	0
2008	2	0	0
2009	3	0	0
2012	9	0	0
2013	92	5 (0.05)	0.19
2014	80	12 (0.15)	0.38
2015	49	1 (0.02)	0.05
2016	14	2 (0.14)	0.67
2017	48	5 (0.10)	0.38
2018	56	5 (0.09)	0.50

yellow-necked mouse in Warsaw. In the central part of the Warsaw agglomeration (Łazienki), the yellow-necked mouse was not found either at the beginning of the 1990s (Goszczyński et al. 1993) or in 2006 (Gryz et al. 2008). It was first recorded during trapping surveys in the green areas of Warsaw (including Łazienki) in the years 2010–2011 (Gortat et al. 2014). In the diet of the tawny owl, it was identified 2 years later (Table 5). Considering the absence of the yellow-necked mouse in the large samples from the years 2005–2006, one might expect that the park near the centre of Warsaw was colonized at the beginning of the twenty-first century at the earliest and most likely in the second half of the first decade of the 2000s.

The behaviour of city populations of several species differs from that of populations dwelling in natural or seminatural habitats because of the presence of people (Gliwicz et al. 1994; Luniak 2004; Ditchkoff et al. 2006). Human noise has been shown to affect the behaviour of the yellow-necked mouse, which shortens the distance of movements (Pieniążek et al. 2017). Human disturbance could modify the activity of newly formed synurbic populations. The species is known for its high level of movements (Montgomery and Gurnell 1985) both on ground and climbing on trees (Štěpánková and Vohrálik 2009), which could have translated into a slightly higher risk of attacks by the tawny owl than seen in, for example, the striped field mouse. Moreover, the two rodent species differ in their peak activity times: the yellow-necked mouse is most active in the night (Wójcik and Wołk 1985; Kołakowski et al. 2018), while the striped field mouse can be active in any time and has a high activity percentage in the daytime (Gliwicz and Kryštufek 1999; Gryz et al. 2008; Tulis et al. 2016). If this difference in activity times was true in city parks, then the observed percentage contribution of the yellow-necked mouse to the owl's diet would be slightly greater than its actual proportion in the small mammal community.

In the forests outside the town, no increase (but sometimes a decrease, such as that observed in Klembów or Natolin near Nur – Table 3) in the contribution of the yellow-necked mouse to owl diets has been noted in recent decades. This might suggest the lack of a generally increasing trend of this rodent in central Poland. The colonization of Warsaw and the expansion of this species into urban areas might be an effect of local adaptations to urban life similar to that observed earlier in the striped field mouse and common pine vole *Microtus subterraneus* (Andrzejewski et al. 1978; Goszczyński et al. 1993; Lesiński, Gryz 2012). Since the yellow-necked mouse is a highly competitive species in comparison with other small rodents (Gliwicz 1981), one may expect that the structure of small mammal communities in the wooded areas of the Warsaw agglomeration will soon change significantly. Thus far, there is no definitive evidence of the exclusion of the striped field mouse by the yellow-necked mouse, although our preliminary data might suggest a slight decline of the first species. To demonstrate this, one should undertake monitoring of both populations in the Warsaw area, especially in central quarters of the city. Both the trapping method and analysis of owl diets should be used for this purpose.

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