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Cover Photograph: A raccoon exiting a stormwater sewer system near Hogtown Creek in Alachua County, Florida. Photo by Alan Ivory.

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Vertebrate Diversity in Stormwater Sewer Systems of Alachua County, Florida

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Abstract –As urbanization continues, animals are increasingly compelled to navigate human-altered environments. Here we investigate wildlife use of stormwater sewer systems (SSS), a widespread, subterranean environment resulting from urbanization. We used camera traps to reveal how wildlife exploit subterranean pathways, shedding light on their presence within this anthropogenic context in Alachua County, Florida. From February to May 2023, we documented a total of 35 species of vertebrates within SSS, including amphibians, reptiles, and birds, although mammals dominated our sample. Raccoons and Southeastern Myotis accounted for more than half of all observations, signifying their prevalence and widespread presence within SSS. Our research offers a comprehensive exploration of vertebrate diversity within an unconventional urban habitat and provides valuable insights into the relationship between SSS and species utilization patterns. Ultimately, our research lays the groundwork for future studies and informs the development of ecologically conscientious urban planning strategies.

Introduction

As urbanization accelerates, animals are increasingly forced to interact with human-modified environments (Jokimaki et al. 2011, Messmer 2009). Development of urban centers necessarily focuses on human needs and usually neglects the requirements of wildlife. In addition to direct loss of habitat, urbanization fragments habitats and may create barriers to animal movements, contributing to population declines (Czech et al. 2000, Lesbarreres and Fahrig 2012, Markovchick-Nicholls et al. 2008). Impacts are particularly severe when development and supporting infrastructure bisects or isolates wildlife habitat. For example, roads that isolate wetland breeding sites from important upland habitats can be especially detrimental to small vertebrates such as reptiles and amphibians (Schmidt and Zumbach 2008, van Gelder 1973). Roads may also be a significant source of mortality for mammals and birds (Bond and Jones 2008, Dodd et al. 2004, Husby 2016, Orlowski 2008).

To mitigate the impact of roads on vertebrates, wildlife crossings are often built to facilitate the movement of animals under or over roadways (Alexander and Waters 2000, Bond and Jones 2008, Dodd et al. 2004). Historically, wildlife crossings have been constructed primarily to promote the movement of large mammals (Askins 2012, Andis et al. 2017). However, numerous studies have demonstrated the conservation value of facilitating the movement of smaller-bodied vertebrates via the installation of simple culvert-type underpasses (Aresco 2003, 2005; Chen et al. 2021; Dodd et al. 2004). Nonetheless, due to species-specific life history traits, no single underpass design is ideal across species. Factors such as traffic noise, cover, light availability, substrate, water availability, and the dimen-

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sions of the culvert influence how likely wildlife are to use an underpass (Glista et al. 2009, Jackson and Griffin 2000).

Typically, constructed wildlife crossings demand a large footprint to connect habitats that are divided by a road (Jackson and Griffin 2000). Due to the space and resources required for such structures, they are rarely built in urban environments, even though urban areas are highly fragmented by roads, buildings, and residential areas (Andreu et al. 2017). This forces urban wildlife to regularly cross roads to meet their basic needs, leading to road mortality having a significant impact on urban animal populations (Riley et al. 2014). Despite urban areas not typically being targeted as sites for installing wildlife crossings, conservation actions in Europe have included constructing small-scale, urban passages for mesomammals, such as *Lutra lutra* Linnaeus (Eurasian Otters) and *Meles meles* Linnaeus (European Badgers; Philcox et al. 1999, Van der Zee et al. 1992). In the U.S., there has been success with salamander underpass tunnels, which facilitate animal movements between breeding and foraging locations (Aresco 2005, Bain et al. 2017, Hedrick et al. 2019). In these studies, underpasses consisted of straight culverts of varying lengths, ranging in pipe diameter from 25–100 cm. Pipes of this style and size are typical of stormwater sewer systems (SSS) across the U.S. (Tran 2016, UF/IFAS Extension 2012).

To avoid flooding, most U.S. cities have SSS that move water from areas with impervious surfaces (e.g., roads, sidewalks, parking lots) to retention ponds, lakes, and streams. This is accomplished by diverting water from rainfall via open ditch systems or in a closed stormwater sewer pipe below ground (Che et al. 2014). Throughout our study area in North Florida, SSS and sanitary sewers are separate and serve distinct purposes. Sanitary sewers transport waste from various sources to wastewater treatment plants, where it undergoes treatment before being discharged into local water bodies. In contrast, stormwater sewers channel rainwater away from roadways and other impervious surfaces via curb inlets and grates and release it untreated into natural and manmade water bodies.

Although the wildlife value of stormwater systems has been studied, there is a lack of research on how animals use the subterranean pipes of SSS. Existing studies have predominantly examined animal use of retention ponds typically associated with SSS outflows. For example, amphibians use stormwater retention ponds as breeding sites (Hale et al. 2015, Scheffers and Paszkowski 2013), whereas birds use stormwater retention ponds for foraging and breeding (Frederick and McGehee 1994, Sparling et al. 2007). Additionally, while it is established that many species of wildlife will traverse straight, relatively short culverts as road underpasses (Ascensao and Mira 2007, Bain et al. 2017, Dodd et al. 2004), the propensity of animals to use more complex SSS (with multiple points of entry, nodes, and branches) has received little attention, with the recent exception of *Rattus* sp. (Guo et al. 2023).

Many species that use SSS in urban habitats are generalists and respond positively to urbanization and human influences (Graser et al. 2012, Parsons et al. 2018, Prange et al. 2003). Likewise, population density and abundance of synanthropic species may increase near sources of water and adjacent to roads where resources may be aggregated (Bernasconi et al. 2022, Bissonette and Rosa 2009, Fidino et al. 2016, Jeffress et al. 2011). The use of an underground corridor system has the potential to increase survivorship, dispersal, and population viability of urban wildlife. Additionally, a better understanding of the spatial movement of wildlife through urban areas can help mitigate future human-wildlife conflicts (Markovchick-Nicholls et al. 2008, Villalobos-Hoffman et al. 2022).

To better understand the importance of SSS as potential habitat and movement corridors for vertebrates, we deployed wildlife cameras within pipes of SSS at numerous locations in

Alachua, Co. Florida. Our objectives were to document which species were present (e.g., diversity) in the SSS of our study area as well as their frequency of occurrence (i.e., relative abundance). We also sought to determine how various species were using these subterranean corridors. Based on a literature search, our study is one of few to document wildlife use of complex SSS beyond the use of simple culverts. Since SSS share similarities in materials and pipe diameters with culverts but are more complex, interconnected, and typically found in urban settings; they offer a unique research focus. Exploring SSS is important because they offer enhanced connectivity opportunities to wildlife beyond what simple, straight culverts can provide.

Materials and Methods

Study area

We conducted our study from February 2023 to May 2023 in Alachua County, Florida, specifically targeting the SSS of the City of Gainesville and the campus of the University of Florida. The study area is primarily urban, with intermixed swamp and hardwood upland habitat (Andreu et al. 2017). The University of Florida's Gainesville campus spans more than 800 hectares and includes approximately 400 stormwater drains. Nearly 60% of the University of Florida campus is covered by the Lake Alice sub-watershed, with about 40% of this area covered by impervious surfaces such as roads and buildings (UF/IFAS Extension 2012). All stormwater from impervious surfaces within our study area drains into an associated stormwater sewer system.

Study design

We used the Create Random Points tool in ArcGIS Pro (Environmental Systems Research Institute, ESRI 2021) to select random manholes along sewer pipes within the SSS of Alachua County. The SSS shapefiles were sourced from the City of Gainesville and the University of Florida Facilities Services (UFFS). We selected 100 random points, then removed sites if the pipe diameter was <30 cm diameter, an opening too small for a camera trap to function properly (McCleery et al. 2014). If the site was on private property or if the site was not an access point pre-approved by the City of Gainesville or the UFFS, the site was excluded from the study. We also excluded locations with damaged or broken sewer pipes.

We deployed 39 camera traps across 33 unique "sewersheds" in Alachua County, FL (Appendix 1, Fig. 1) that were each left in the field for 60 trap nights per camera to ensure sufficient sampling effort to confidently access wildlife diversity within each sewershed (Hallett et al. 2019, Silver 2004). We define a sewershed as independent sewer pipes which may or may not be connected in a network. Sewersheds with only two access points are defined as simple culverts and those with more than two access points are classified as a system (Fig. 2). Access points are where animals might enter or exit a sewershed including pipe openings at the ends of the systems (typically at a body of water), curb inlets often associated with a manhole cover (where runoff water from roads enters SSS), and grated inlets (Fig. 3). These access points may double as light sources and are important as potential ways for wildlife to enter and exit a sewershed.

For the systems we studied, pipe openings ranged from 30 to182 cm in diameter (mean = 72 cm). Sewersheds in our study ranged from 11 m to 6912 m (mean = 942 m) in pipe length and consisted of 13 simple culverts and 20 more complex systems.

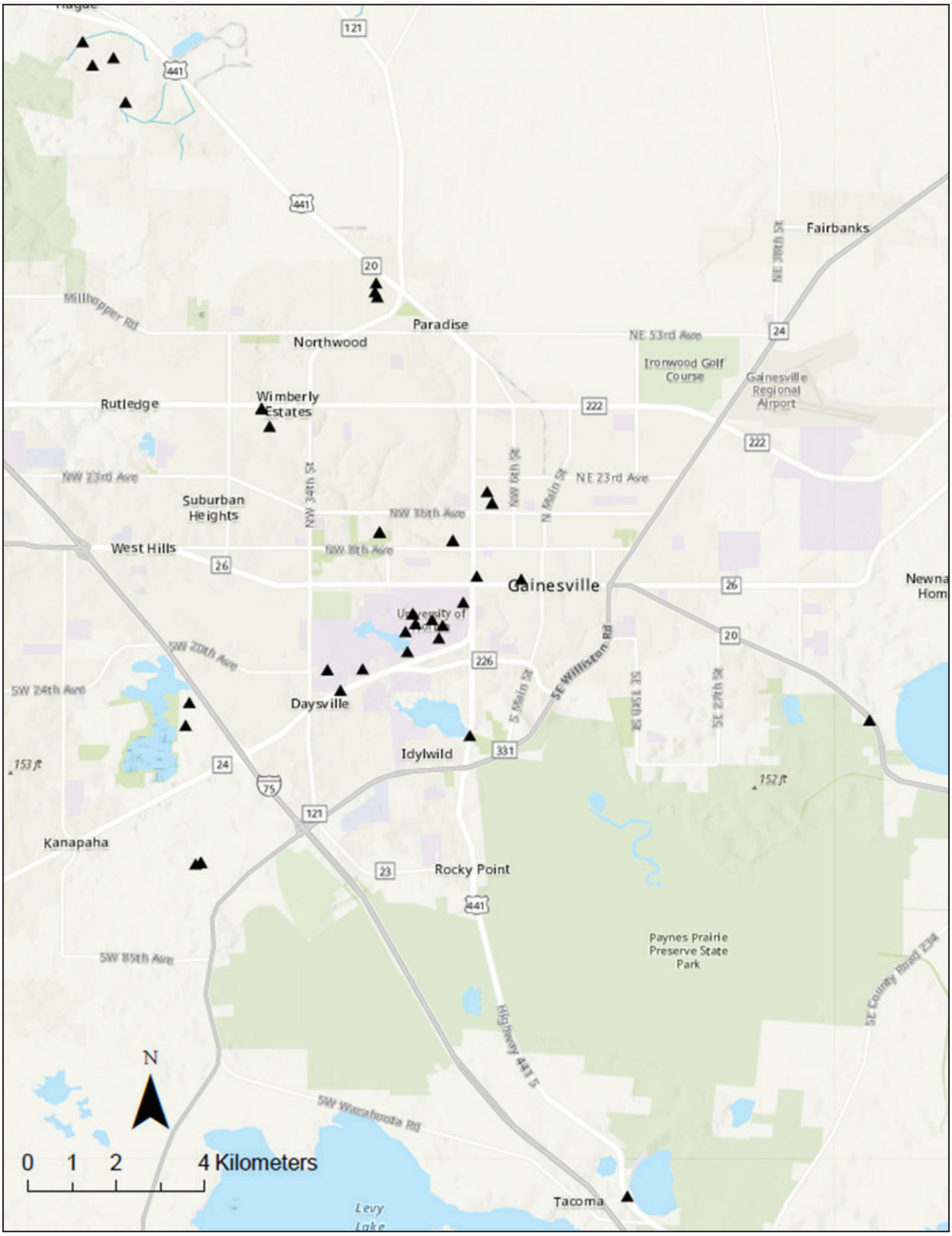

Figure 1. Locations of camera sites across Alachua County, Florida.

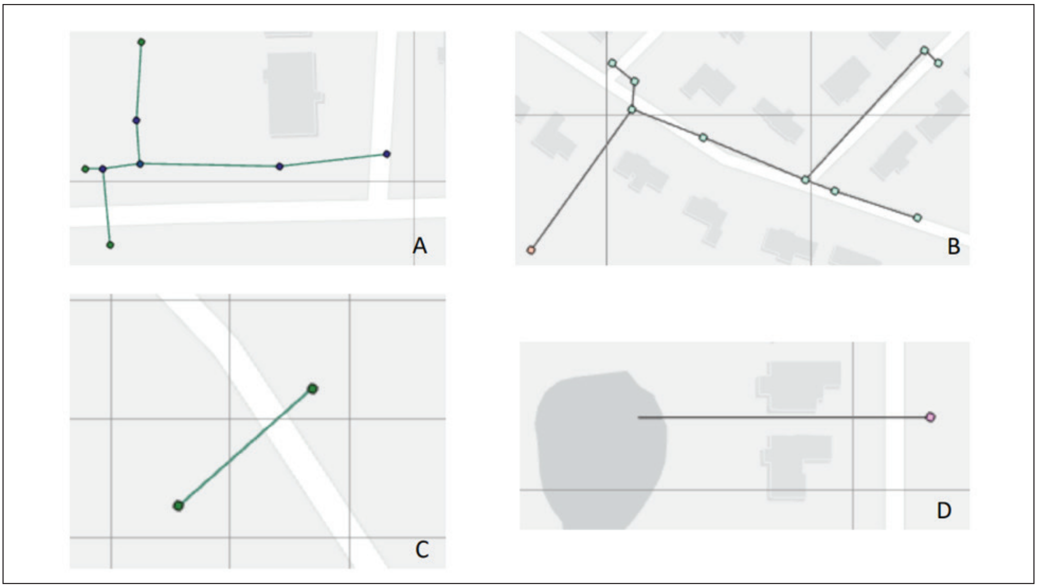

Figure 2. Examples of 4 stormwater sewersheds in Alachua County, FL. Sewershed systems with multiple access points denoted as nodes on the line features (A and B) and sewershed culverts with a maximum of two access points (C and D). Linear, white areas indicate roads and darker shapes are buildings and stormwater ponds.

Figure 3. Example access points into the SSS of Alachua County. Stormwater grate in a road (A). Pipe openings at a body of water (B and C). Curb inlet on a roadside with a manhole (D). Photo credit: Alan Ivory, UF/IFAS

Camera-trap surveys

We deployed camera traps (Bushnell Care S-4K No Glow #119949C; Prime Combo Low Glow #119932CB Bushnell®, KS, USA; Moultrie M-880 #MCG12594 Moultrie®, AL, USA) at each of the 39 sites (Fig. 1). At sites with metal attachment points (i.e., manhole cover), we used magnetic mounts to secure cameras facing down toward the entrance of

Figure 4. Example of camera-trap mount for magnetic attachment points such as manhole covers. Photo credit: Alan Ivory, UF/IFAS

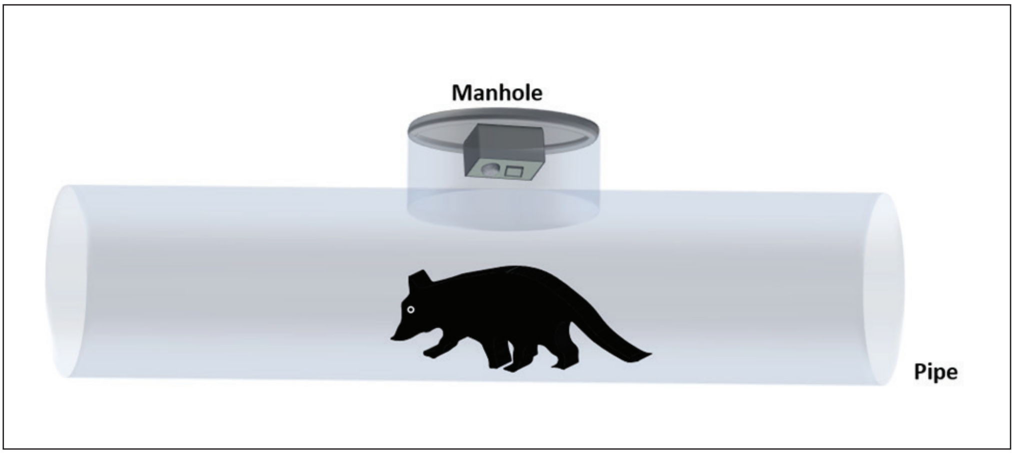

Figure 5. Diagram of camera mounting set-up in magnetic attachment points.

the pipe (Figs. 4, 5). At sites with pipes constructed of concrete or other materials that were not magnetic, we attached cameras to a tree at the entrance of the pipe. Due to the nature of stormwater sewer construction, the distance from the entrance to the pipe could not be standardized, but, when possible, we set cameras mounted within or outside of SSS within 1 m of a pipe opening (Baker 2015, McCleary et al. 2014, Zeitler et al. 2023). Cameras were active 24 hours a day, recording date and time, capturing a 10-second video upon detecting motion, followed by a 30 second delay before the next recording. We used videos, rather than still images to increase detection probability, due to the proximity of target species to the cameras. When reviewing camera trap videos, we watched the full 10-second video clip to confidently identify vertebrates to species even when an individual's entire body was not discernable. Videos of the same species that occurred within a period of 30 minutes were excluded to ensure that camera visits were independent (Silver 2004). We used data from the cameras to determine vertebrate diversity within the SSS, and to calculate the number of detections by species, species relative abundance (RA), and naïve occupancy. We calculated relative abundance by dividing the number of observations of a species by the number of trap nights and multiplying by 100. Naïve occupancy was calculated by dividing the number of sites where a species occurred by the total number of sites included in the study.

We deployed camera traps from February 2023 to May 2023, which encompasses late winter and spring in north Florida. Camera traps were active for 14–92 trap nights/camera (mean = 58.3 trap nights) for a total of 2273 trap-nights. The variation in trap nights per camera is attributed to heavy rainfall causing flooding, as well as instances of camera theft.

Results

Of the 39 camera sites, 19 (49%) had more than 50 wildlife observations and 4 sites (10%) did not record any observations. In total, we documented 3798 animal detections and recorded 35 unique vertebrate species, including 12 species of birds, four species of amphibians, seven species of reptiles, and 12 species of mammals (Table 1). The majority of species documented were detected at fewer than five camera sites, with 16 species being detected at just a single site each. Nine species, mostly mammals, were detected at five or more sites (Table 1). Among the 35 species documented, 21 were observed within a stormwater sewer system

Table 1. Number of observations (Obs), relative abundance (RA), and naïve occupancy (NO) for each species observed in Alachua County SSS. Relative abundance was calculated by dividing the number of observations of a species by the number of trap nights and multiplying by 100. Naïve occupancy was calculated by dividing the number of sites where a species occurred by the total number of sites in the study.

Scientific Name	Common Name	Authority	Obs	RA	NO
Mammal					
Dasypus novemcinctus	Nine-banded Armadillo	Linnaeus, 1758	82	3.61	0.18
Didelphis virginiana	Virginia Opossum	Kerr, 1792	321	14.12	0.23
Felis catus	Domestic Cat	Linnaeus, 1758	50	2.20	0.28
Lontra canadensis	River Otter	von Schreber, 1776	29	1.28	0.05
*Lynx rufus**	Bobcat	von Schreber, 1777	1	0.04	0.03
Myotis austroriparius	Southeastern Myotis	Rhoads, 1897	694	30.53	0.44

Table 1. Number of observations (Obs), relative abundance (RA), and naïve occupancy (NO) for each species observed in Alachua County SSS. Relative abundance was calculated by dividing the number of observations of a species by the number of trap nights and multiplying by 100. Naïve occupancy was calculated by dividing the number of sites where a species occurred by the total number of sites in the study.

Scientific Name	Common Name	Authority	Obs	RA	NO
*Odocoileus virginianus**	White-tailed Deer	Zimmermann, 1780	3	0.13	0.03
Procyon lotor	Raccoon	Linnaeus, 1758	1810	79.63	0.54
Rattus rattus	Black Rat	Linnaeus, 1758	324	14.25	0.10
Scalopus aquaticus	Eastern Mole	Linnaeus, 1758	5	0.22	0.05
Sciurus carolinensis	Eastern Gray Squirrel	J. F. Gmelin, 1788	58	2.55	0.18
Sigmodon hispidus	Hispid Cotton Rat	Say and Ord, 1825	124	5.46	0.13
Reptile					
Alligator mississippiensis	American Alligator	Daudin, 1801	50	2.20	0.13
Anolis sagrei	Brown Anole	Dumeril and Bibron, 1837	19	0.84	0.05
Coluber constrictor	Eastern Racer	Linnaeus, 1758	4	0.18	0.08
*Nerodia fasciata**	Banded Watersnake	Linnaeus, 1766	1	0.04	0.03
*Plestiodon laticeps**	Broad-headed Skink	Schneider, 1801	1	0.04	0.03
Storeria dekayi	DeKay's Brownsnake	Holbrook, 1839	2	0.09	0.03
Trachemys scripta scripta	Yellow-bellied Slider	Schoepff, 1792	27	1.19	0.08
Amphibian					
Anaxyrus terrestris	Southern Toad	Bonnaterre, 1789	1	0.04	0.03
*Osteopilus septentrionali*s	Cuban Treefrog	Duméril and Bibron, 1841	3	0.13	0.03
*Rana grylio**	Pig Frog	Stejneger, 1901	1	0.04	0.03
Scaphiopus holbrooki	Eastern Spadefoot	Harlan, 1835	127	5.59	0.10
Bird					
Anhinga anhinga	Anhinga	Linnaeus, 1766	13	0.57	0.03
*Ardea alba**	Great Egret	Linnaeus, 1758	24	1.06	0.08
*Ardea herodias**	Great Blue Heron	Linnaeus, 1758	2	0.09	0.03
*Buteo jamaicensis**	Red-tailed Hawk	Gmelin, 1788	1	0.04	0.03
*Cardinalis cardinalis**	Northern Cardinal	Linnaeus, 1758	1	0.04	0.03
*Corvus brachyrhynchos**	American Crow	Brehm, 1822	2	0.09	0.05
*Dumetella carolinensis**	Gray Catbird	Linnaeus, 1766	1	0.04	0.03
*Egretta thula**	Snowy Egret	Molina, 1782	1	0.04	0.03
Parkesia noveboracensis	Northern Waterthrush	Gmelin, 1789	3	0.13	0.03
Thryothorus ludovacianus	Carolina Wren	Latham, 1790	10	0.44	0.15
*Strix varia**	Barred Owl	Barton, 1799	1	0.04	0.03
*Zenaida macroura**	Mourning Dove	Linnaeus, 1758	2	0.09	0.03

* signifies species was not observed entering the stormwater sewer system, but was observed on the camera trap.

beyond a pipe access opening. Nine species of birds, one amphibian species, two species of reptiles, and two species of mammals were only detected at the mouth of a stormwater sewer pipe and never within a simple culvert or complex sewershed (Table 1).

Bird diversity

Of the 12 bird species documented (Table 1), only *Thryothorus ludovicianus* Latham (Carolina Wren), *Anhinga anhinga* Linnaeus (Anhinga), and *Parkesia noveboracensis* Gmelin (Northern Waterthrush) were observed within a sewershed away from a pipe opening. Carolina Wrens were observed at six sites, and occasionally with nesting material, while the other two species were observed at a single location.

Amphibian diversity

Three of the four species of anuran amphibians we documented were only detected at a single camera site, for a combined five observations (Table 1). One of these, a *Rana grylio* Stejneger (Pig Frog), was recorded at the entrance to a pipe. *Scaphiopus holbrooki* Harlan (Eastern Spadefoot Toad) was the most frequently detected amphibian and was observed at four camera sites, though 120 of the total 127 observations came from a single site.

Reptile diversity

Of the 33 sewersheds monitored in our study, only three were inundated with water for the duration of the project. These three sites accounted for all the *Trachemys scripta scripta* Schoepff (Yellow-bellied Slider) observations. An *Alligator mississippiensis* Daudin (American Alligator) was also detected at two of the three inundated sites. We also observed American alligators at three more culvert sites linked to either natural or artificial ponds, each retaining water for over half of the study duration.

Mammal diversity

In addition to being the most species-rich taxon of vertebrates observed among all sites, mammals were also observed most frequently, accounting for 3501 (92.2%) of the 3798 total camera-trap observations. We documented 12 species of mammals, ten of which were observed within a sewershed beyond the entrance of a pipe opening (Table 1).

Procyon lotor Linnaeus (Northern Raccoon) was the most commonly observed (1810 occasions) and widespread (detected at 21 of the 39 camera sites) species in our study. While raccoon detections were similar in simple culverts (865 observations) as compared to the complex sewersheds (945 observations), raccoon relative abundance index (RAI) was higher in culverts (RAI = 107.9) than in complex sewersheds (RAI = 64.2).

Among the 33 sewersheds, the second most commonly detected species was *Myotis austroriparius* Rhoads (Southeastern Myotis Bat), with 694 bat observations across 17 camera sites. Eleven of these sites were complex sewersheds and 6 sites were simple culverts, with bat abundance being higher in complex sewersheds (RAI = 46.1) compared to simple culverts (RAI = 2.0).

Both *Rattus rattus* Linnaeus (Black Rat) and *Sigmodon hispidus* Say and Ord (Hispid Cotton Rat) were commonly observed, with 324 and 124 observations, respectively. Of the four sites where we found Black Rats, 223 of the 324 observations came from one camera. While we observed *Lontra canadensis* von Schreber (North American River Otter) on 29 occasions, otters were only detected at two of our sites, both of which were simple culverts. The only mammals observed at pipe openings, and not within SSS, were *Odocoileus virginianus* Zimmermann (White-tailed Deer) and *Lynx rufus* von Schreber (Bobcat).

Discussion

Our study is one of the first to quantify the use of urban SSS by wildlife. We detected at least one species at 90% of our camera trap sites, and nearly half of the camera traps recorded at least 50 observations. While each of the classes of terrestrial vertebrates was found in the SSS of Alachua County, Florida, mammals dominated our camera trap detections, accounting for 92% of all observations. Birds, amphibians, and reptiles may not regularly use the SSS, they nonetheless are able to take advantage of the resources the systems provide as well as their associated wetlands.

We expected to detect rodents and mesomammals, such as raccoons, *Didelphis virginiana* Kerr (Virginia Possums), and *Dasypus novemcinctus* Linnaeus (Nine-banded Armadillo), based on previous corridor studies (Bond and Jones 2008, Chen et al. 2021). As there is little evidence to suggest that SSS are frequented by birds, we did not expect to observe many birds in our sites. Predators such as bobcats are known to use culvert crossings, and we expected to document more than one observation (Ascensao and Mira 2007). Additionally, foxes are common in suburban settings in Florida (Brown 1997), and we were surprised that we did not detect them during our study.

Birds

Although we documented 12 species of birds across our study area, most of the observations were dominated by just three species: Anhinga, *Ardea alba* Linnaeus (Great Egret), and Carolina Wren. Additionally, only three species of birds were detected within SSS pipes, away from a pipe opening (Anhinga, Northern Waterthrush, and Carolina Wren). The others were detected at a pipe entrance, but apparently did not enter the sewer system. Although retention ponds associated with SSS can provide foraging opportunities for birds (Fidorra et al. 2016), the subterranean sewer pipes of the culverts and complex sewersheds that we studied were apparently of little value to birds, with the possible exception of Carolina Wrens.

Anhingas were observed numerous times within a single culvert that was inundated with water throughout our study period. Anhingas appeared to be using this culvert as a thoroughfare to move between two permanent water bodies connected by this culvert. Our cameras also documented wading birds at pipe openings of several sewersheds. The birds appeared to be foraging, and it's likely they were attracted to pipe openings because such areas may concentrate prey (Frederick and McGehee 1994).

Carolina Wrens were detected at more unique camera locations (6) than any other bird in our study. Additionally, they were the only species observed carrying nest materials within a sewershed, suggesting they use SSS as nesting sites. Carolina Wrens are well known for their habit of constructing nests in man-made structures like carports and mailboxes (Laskey 1948, Nice and Thomas 1948). While their motivations for constructing nests in such locations are poorly understood, similar to carports and mailboxes, SSS likely provide sheltered areas with protection from inclement weather and nest predators, as well as a favorable microclimate for thermoregulation (Labisky and Arnett 2006).

Amphibians

It seems unlikely that the 120 detections of Eastern Spadefoot Toads at a single camera-trap location are indicative of a breeding aggregation within the sewershed, as the camera was located at a curb inlet near a retention pond within a suburban neighborhood. We suspect the toads were making terrestrial movements (possibly for breeding) and were directed to the inlet by the curb and simply fell into the storm drain and subsequently detected by the camera.

Although the sewer pipes themselves may not be important habitat for amphibians, it is well documented that stormwater ponds and wetlands directly associated with SSS are important breeding habitat (Scheffers and Paszkowski 2013, Hale et al. 2015).

Reptiles

We detected seven species of reptiles overall (3 species were only observed at a single site), and documented reptiles more often at sites that held water for more than half of the study period. The most frequently observed reptile (*Alligator mississippiensis*) was also documented across the greatest number of sites (5). The most commonly observed reptiles were aquatic and able to take advantage of the water bodies associated with the SSS (Aresco 2009).

Two of the three sites that were inundated with water for the duration of our study are complex sewershed systems, suggesting the Yellow-bellied Slider that was observed there had the opportunity to navigate the pipes further than a single road crossing. In all 3 sites that documented sliders, the SSS connected 2 or more bodies of water, so the sliders are likely using the pipes as corridors between ponds. Of the 5 sites, 4 of the sites where alligators were observed were simple culverts, and for this reason most of the alligator observations were of animals swimming from one pond to another (35 of 50 observations), thereby avoiding crossing busy roads.

Mammals

Mammals were the most frequently and widely observed taxonomic group. Eleven of the 12 mammal species were recorded more than once, and 10 of 12 species were documented at more than 1 site. Species such as raccoons, Virginia opossums, Nine-banded Armadillos, rats, and *Felis catus* Linnaeus (Domestic Cat), which dominated our observations, do well in urban environments (DeGregorio et al. 2021, Fidino et al. 2016, Graser et al. 2012, Parsons et al. 2018, Prange et al. 2003, 2004). This association with urban areas is due in part to their use of human resources, such as trash and artificial structures urban areas often provide (Feng and Himsworth 2014, Webb et al. 2021).

We mainly observed Black Rats at sites nearest to downtown Gainesville and the University of Florida campus, suggesting a positive relationship with human presence. Black Rats are excellent climbers that can easily access SSS via curb inlets and open pipes, and are known for their opportunistic foraging behavior and tolerance of human presence (Feng and Himsworth 2014). Given their climbing ability and affinity for manmade structures, it was not surprising that this introduced rodent was regularly detected by our cameras within several sewersheds. We also documented 124 observations of native Cotton Rats across several sewersheds. However, unlike Black rats, the locations of these observations were primarily at the periphery of our study area, away from heavier human presence. Although Cotton Rats are known pests of agricultural crops in rural settings and are one of the most common mammals in Florida (Brown 1997), our data indicate that they apparently do not occur in abundance in suburban and urban centers within our study area.

Many species of bats are known to inhabit urban areas (Lehrer et al. 2021, Webb et al. 2021), and it is well established that bats commonly roost in culverts and under bridges (Keeley and Tuttle 1999, Leivers et al. 2019). Culverts can provide a similar thermal regime as natural caves and are therefore attractive to bats as roosting sites (Leivers et al. 2019). However, few studies have evaluated bats in SSS. For example, Goehring (1957) documented *Eptesicus fuscus* Beauvois (Big Brown Bat) using a storm sewer in Minnesota, U.S. as a winter roost site, and Wojtaszyn et al. (2013) documented 6 species of bats (including 4 species of *Myotis*) inhabiting storm drains in Poland as winter hibernacula. Additionally, *Myotis grisescens* A. H. Howell

(Gray Bats) have been documented using storm sewers as maternity sites in Kansas (Hays and Bingham 1964) and Arkansas, U.S. (Timmerman and McDaniel 1992).

We detected Southeastern Myotis at almost half of our camera sites, including simple culverts (6 sites) and complex sewersheds (11 sites). However, based on the number of bats documented per trap-night, they appear to prefer complex sewersheds over simple culverts consisting of a single pipe open at each end. The conditions in more complex sewersheds likely provide a microclimate (e.g., light, temperature, humidity) similar to natural caves, which bats find attractive. Ten of the sites where we detected bats were in suburban neighborhoods, and an additional 2 sites were in natural areas on the University of Florida campus. Both types of sites (79.6% of total bat-occupied sites) have small roads with limited traffic. This finding reinforces previous findings (Kerth and Melber 2009), which indicated that bat activity is more common near roads with limited traffic as compared to wider, more heavily-trafficked roads.

We documented bats throughout the duration of our study, but the frequency of observations declined over time, suggesting the bats were using the SSS as winter roosts, like other species of *Myotis* (Wojtaszyn et al. 2013). Southeastern Myotis in north Florida give birth in mid-May (Elizabeth Braun de Torrez, Florida Fish and Wildlife Research Institute, Gainesville, FL; Pers. Comm.), which is when our study ended, thus precluding our ability to make any definitive statement about the utility of the sewer systems to serve as breeding sites. In addition to roosting, the bats may have also been opportunistically foraging on insects within the SSS. While their foraging behavior is typically associated with capturing flying insects, we also observed instances of Southeastern Myotis landing on the floor of the sewer pipe to capture insects. This behavior could potentially be interpreted as a substrate-gleaning foraging strategy suitable for confined environments like SSS (Razak 2018). Clearly, additional monitoring is required to better understand the importance of SSS to bats, many species of which are declining across their range.

Raccoons were observed at most sites in our study. On several occasions our cameras documented raccoons within SSS feeding on invertebrates (i.e., crayfish) and accompanied by their young. This suggests that raccoons regularly use SSS as denning sites, to forage, and possibly to avoid crossing roads. We also documented raccoons entering and exiting SSS by climbing manhole ladder rungs as well as using curb inlets as access points for some sewersheds.

Domestic cats and *Sciurus carolinensis* J.F. Gmelin (Gray Squirrels) also used curb inlets as access points. These species, like raccoons, are excellent climbers, so with the aid of ladder rungs and/or sewer wall texture they are able to move freely between SSS and the urban habitat above ground (Haigh et al. 2017, McClearn 1992, Moseby and Read 2006). Considering these behaviors as well as the number and geographic breadth of raccoon observations, it appears raccoon use of SSS of Alachua County is not by chance. Rather, our data suggest that SSS provide habitat for raccoons in suburban areas. That said, the frequency of movement between subterranean SSS and above ground habitats by raccoons is unknown and needs to be studied to assess the relative importance of SSS for this common mesocarnivore.

The SSS we studied likely mimic natural habitats, such as caves and dens, used for roosting and reproduction. For some species, the sewer systems likely provide protection from predators as well as foraging opportunities. Raccoons and opossums had a naïve occupancy of 0.54 and 0.23, respectfully; rates similar to those of other urban camera trap studies (Soultan et al. 2021). Similarly, Black Rats, opossums, raccoons, and Southeastern Myotis all have a relative abundance greater than 10 (Table 1), suggesting frequent use of SSS. Our data strongly suggest that the SSS in our study are regularly used by some mammals, namely raccoons and bats, and to a lesser extent by opossums and invasive Black Rats. However, further study is needed to determine how often these species enter stormwater sewers and the extent of their movements within the systems.

SSS management for wildlife

While it is well established that some species, including raccoons, Southeastern Myotis, alligators, and aquatic turtles, intentionally enter SSS, smaller species of herpetofauna may enter a stormwater sewer system inadvertently. For example, we documented a *Storeria dekayi* Holbrook (DeKay's Brownsnake) after a storm carried large amounts of water into the system, possibly washing this small snake into the system. Additionally, curbs and their inlets may act as a drift fence with pitfall traps for small reptiles and amphibians. Small individuals may follow curbs until they fall into SSS via curb inlets. This would explain the numerous observations of Eastern Spadefoot Toads at one of our sites. A better understanding of how amphibians and small reptiles enter SSS could help in preventing them from becoming trapped. If amphibians are falling in from the curb, and are unable to exit, exclusion devices and climbing aids could be implemented to prevent such wildlife from being trapped within SSS. In shallow curb inlets, ramps could be used to bridge the elevation gap, while in deeper locations, ropes might act as climbing vines.

Amphibians and, potentially, small reptiles are likely underrepresented due to our sampling methods and the camera traps reliance on an animal being warmer than its surroundings to trigger image capture (Meek et al. 2012, Rovero et al. 2013). Aside from the American Alligator and Yellow-bellied Slider, the remaining amphibian and reptile species likely did not trigger the camera trap themselves, but instead their presence were only documented as a byproduct of a mammal also being in the field of view. For this reason, the detection probabilities of amphibian and reptile species are likely lower than the detection of the endothermic species (mainly mammals, Hobbs and Brehme 2017)), which comprised the majority of our observations. For example, *Osteopilus septentrionalis* Duméril and Bibron (Cuban Treefrogs) are often heard calling from storm drains, and there is anecdotal evidence they will breed in SSS under certain situations (Steve A. Johnson, personal observation). This invasive frog in Florida is common in Gainesville, but we only documented three observations during our study. We suspect this underrepresents their abundance in SSS as a result of camera trap bias. To address the issue of underrepresentation of these ectothermic species, future studies could include camera traps using time lapse image capture, where regardless of animal temperature or motion, the camera records a video on a repeating interval for the duration of the study.

Our study focused on a small region in northern Florida, and future studies in other regions should be conducted to determine if our findings are an anomaly or if SSS are in fact important habitat for some species of urban wildlife. Alachua County, the UF campus, and the city of Gainesville have numerous natural areas and an extensive tree canopy, so our findings may differ from other cities where wildlife habitat is sparser. Moreover, our results are based on four months of sampling, so seasonality is an important factor to explore further in determining when and how wildlife use SSS. Nonetheless, our research appears to be among the first of its kind to evaluate the uses of SSS by vertebrates, and therefore serves as a baseline for similar studies elsewhere.

Additional research is needed to better understand the role of SSS in regions experiencing variable levels of urbanization. Wildlife may be less likely to use these subterranean corridors in less developed areas because preferred resources are available aboveground. However, in more urbanized areas, artificial roosts are beneficial in promoting urban bat populations. Bats seem to make use of SSS for roosting, but through the use of radio tracking, we could better understand bat movement through SSS.

Species from various taxonomic groups appear to use SSS as corridors to avoid roads, potentially navigating through a network of pipes that link separated patches of habitat. While we did not collect metrics related to road mortality or track movements of individuals, SSS have the potential to increase connectivity of highly fragmented environments. Alternatively, there is also the possibility that these confined corridors may lead to increased predation of some species, such as raccoons preying on bats (Wojtaszyn et al. 2013). Regardless, a diversity of vertebrates was found in the SSS of our study area, underscoring the need to consider these subterranean systems in land-use planning and their potential to help mitigate potential human-wildlife conflicts.

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Appendix 1. Camera-trap site identification and locations.

SiteID	Lat	Long	Sewershed Type	Deployment Type
13	29.6711	−82.3363	System	Manhole
16	29.7136	−82.3589	System	Open Pipe
17	29.7118	−82.3591	Culvert	Grate
21	29.6612	−82.3433	System	Manhole
23	29.6540	−82.3384	System	Manhole
24	29.6881	−82.3822	System	Manhole
25	29.6533	−82.3293	System	Manhole
48	29.6486	−82.3412	System	Grate
51	29.6462	−82.3514	System	Open Pipe
52	29.7595	−82.4124	System	Grate
53	29.7504	−82.4099	Culvert	Grate
54	29.7580	−82.4167	System	Grate
57	29.6349	−82.3688	System	Grate
59	29.7108	−82.3586	Culvert	Manhole
60	29.6845	−82.3806	System	Manhole
64	29.5954	−82.3957	System	Manhole
66	29.5957	−82.3946	System	Manhole
67	29.5957	−82.3946	System	Manhole
68	29.6386	−82.3525	System	Grate
71	29.6629	−82.3581	System	Manhole
72	29.6283	−82.3969	System	Grate
75	29.6451	−82.3475	System	Grate
76	29.6440	−82.3453	System	Manhole
77	29.6880	−82.3822	System	Manhole
78	29.6629	−82.3582	System	Manhole
79	29.6236	−82.3977	Culvert	Grate
81	29.6613	−82.3433	System	Manhole
82	29.6351	−82.3616	Culvert	Grate
83	29.6463	−82.3514	System	Open Pipe
84	29.6414	−82.3461	Culvert	Grate
85	29.6443	−82.3509	Culvert	Open Pipe
86	29.6427	−82.3529	Culvert	Open Pipe
89	29.6215	−82.3398	Culvert	Grate
90	29.5278	−82.3077	Culvert	Open Pipe
91	29.6247	−82.2584	Culvert	Open Pipe
92	29.6688	−82.3353	System	Manhole
93	29.6688	−82.3352	System	Manhole
94	29.7627	−82.4187	Culvert	Open Pipe
95	29.6307	−82.3662	Culvert	Open Pipe